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THE DIVERSITY OF FLUVIAL SYSTEM RESPONSE TO THE HOLOCENE HYDROLOGICAL CHANGES USING THE VISTULA RIVER CATCHMENT AS AN EXAMPLE

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Abstract: Hydrological changes during the Holocene are expressed in the variable frequency of extreme events and reflected in fluvial sediments and landforms. The diversity of fluvial system response depends on rainfall and runoff-sediment load regime, but is specifically related to the landscape type, size of catchment, and connectivity of valley reaches in the long profile, as well as to increasing human impact. This diversity is exemplified by the Vistula River catchment, investigated in detail during the last decades, providing a basis for demonstrating how various fluvial sequences are expressing palaeohydrological changes.

Various types of flood events, ranging from those connected with heavy downpours to continuous rains and to snowmelt floods, play a leading role in catchments of various size and landscape type. Three main models of Holocene transformation of valley floors were distinguished: an incisional one in the mountain headwaters, an aggradational one in low-gradient river valleys, and transitional one reflecting phases of various frequency of extreme events (and their clusters) represented in sequences of cuts and fills. This last transitional type should characterise the middle valley courses, but is best developed slightly upstream on the direct foreland of the Carpathians, where the greatest fluctuations in the river discharge, bed load and suspended load are observed. The presence of many gaps in alluvial sequences requires a better recognition of Holocene hydrological changes and it is recommended to correlate fluvial data with other palaeorecords.

Key words: Holocene, hydrological changes, fluvial system response, flood types, Vistula River, Poland.

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INTRODUCTION

Hydrological changes of the order of centuries or millennia are expressed in the fluctuation of flood frequency (Starkel, 1983) and exhibit variations in the rainfall-runoff-sediment load regime. This is reflected in sediments and landforms of the valley floors. Especially, the runoff and sediment load have accelerated in Central Europe after deforestation and the onset of soil cultivation, starting from the late Neolithic time (Starkel, 2003b, 2005). Their connectivity in the longitudinal profile was disturbed in the last centuries by channel regulation and construction of water reservoirs.

The diversity of fluvial system response controlled by changes in the regime depends on the relief of river basin, size of catchment, reach position in the longitudinal profiles, as well as on the type and frequency of floods. The landscape of a basin may be expressed by slope and river channel gradients. These parameters, together with lithology of the substratum (rock resistance, type of soil, their permeability, etc.) and vegetation cover, decide on the dominant type of sediment load (dissolved, suspended and bed load). The character of the load and its grain-size changes with the size of river catchment and small tributary valleys differ from those of the trunk river valley. Therefore, the position of a valley reach is important for the examination of long-term changes. As it was proved in the last years by several authors (cf. Fryirs and Brierley, 2001), in various landscape zones there exist characteristic buffers and barriers, which determine the type of disconnectivity of subsequent valley reaches. Their connection in the longitudinal valley profile may occur only during extreme events, when the processes and features characteristic for the upper reach may extend downstream.

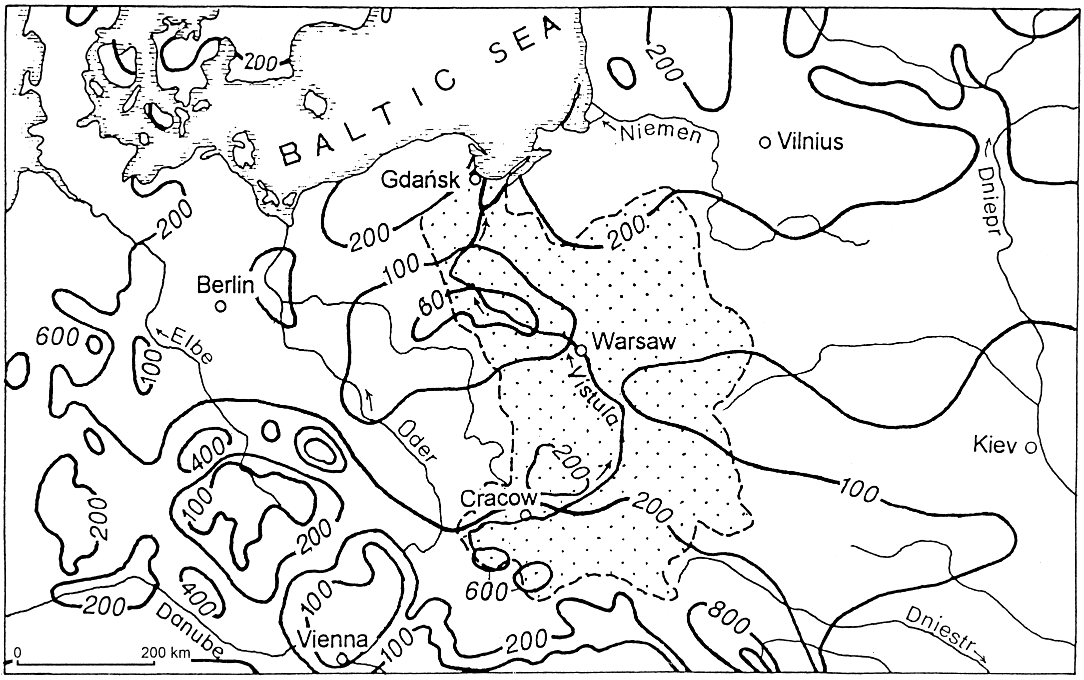

Fig. 1. Position of the Vistula River valley in Central Europe on the background of mean annual runoff in millimetres (based on various sources)

An additional factor differing the magnitude and frequency of changes in large catchments is the type of rainfall and flood. In small catchments, local heavy downpours play a triggering role (producing flash floods), while in larger ones continuous rains or snow-melt floods produce extensive long-lasting flooding. Each of these types may provoke various responses of the fluvial system.

The reaction of a fluvial system to extreme events is reflected in the downcutting or lateral erosional shift of the river channel, and in the vertical or lateral aggradation both in the channel and overbank facies (Schumm, 1977; Knox, 1995). Changes in a longer time intervals may be, therefore, documented both in the palaeochannel parameters and in sequences of alluvial sediments. More active phases (with frequent floods) in the temperate zone are expressed best in cuts and fills and related channel avulsions (Starkel, 1983, 2003a).

THE VISTULA RIVER CATCHMENT AS AN EXAMPLE

The diversity of fluvial response to hydrological changes during the Holocene is exemplified by the Vistula River basin (Fig. 1). The Vistula River catchment occupies an area of 194,424 sq. km and is drained by the trunk Vistula River, 1,092 km long, passing through several landscape zones: from the mountains in the south into the lowlands in the north, with variable rainfall and runoff regime (Fig. 2). Its valley floor has been investigated in relatively great detail both in the main valley, and in various reaches of tributaries, characteristic for different landscape zones. The results of studies of the Lateglacial and Holocene sediments and landforms were published in a series of volumes (Starkel ed., 1982, 1987, 1990, 1991, 1995, 1996, Alexandrowicz *et al.*, 1981) and in many other monographs and papers. The documentation of alternate phases of different fluvial activity is supported by age control on at least 100 localities by more than 500 radiocarbon dates (cf. Starkel *et al.*, 2006), by about 600 dendrochronologically dated subfossil oaks (Krąpiec, 1992, 1998), and by more than 30 palynological profiles.

The Vistula River basin is getting annually 500–700 mm of precipitation (up to 20% as snowfall) in the northern and central parts. Only in the Carpathians, the precipitation totals do fluctuate from 800 to 1,500 mm per year.

Specific runoff declines from >2 m^{3}sec^{-1}km^{-2} in the mountains to 0.04 m^{3}sec^{-1}km^{-2} per month. Two types of floods are characteristic for the Vistula River: summer rainy floods and spring (or winter) snowmelt floods (Soja & Mrozek, 1990, Fig. 3). The highest discharges of the Vistula River in summer time attain about 7,500 m^{3}sec^{-1} at the junction of all the Carpathian tributaries in the Sandomierz Basin, decline downstream below 6,000 m^3 and rise again to 7,850 m^3 near the mouth. The summer rainy floods originate in the Carpathians. Their highest discharges are recorded in the Vistula River and its tributaries in the Carpathian foreland. Most of the snowmelt flood discharges rise gradually in the lowland part of the basin (rarely exceeding 5,000 m^3), being partly connected with ice-jams.

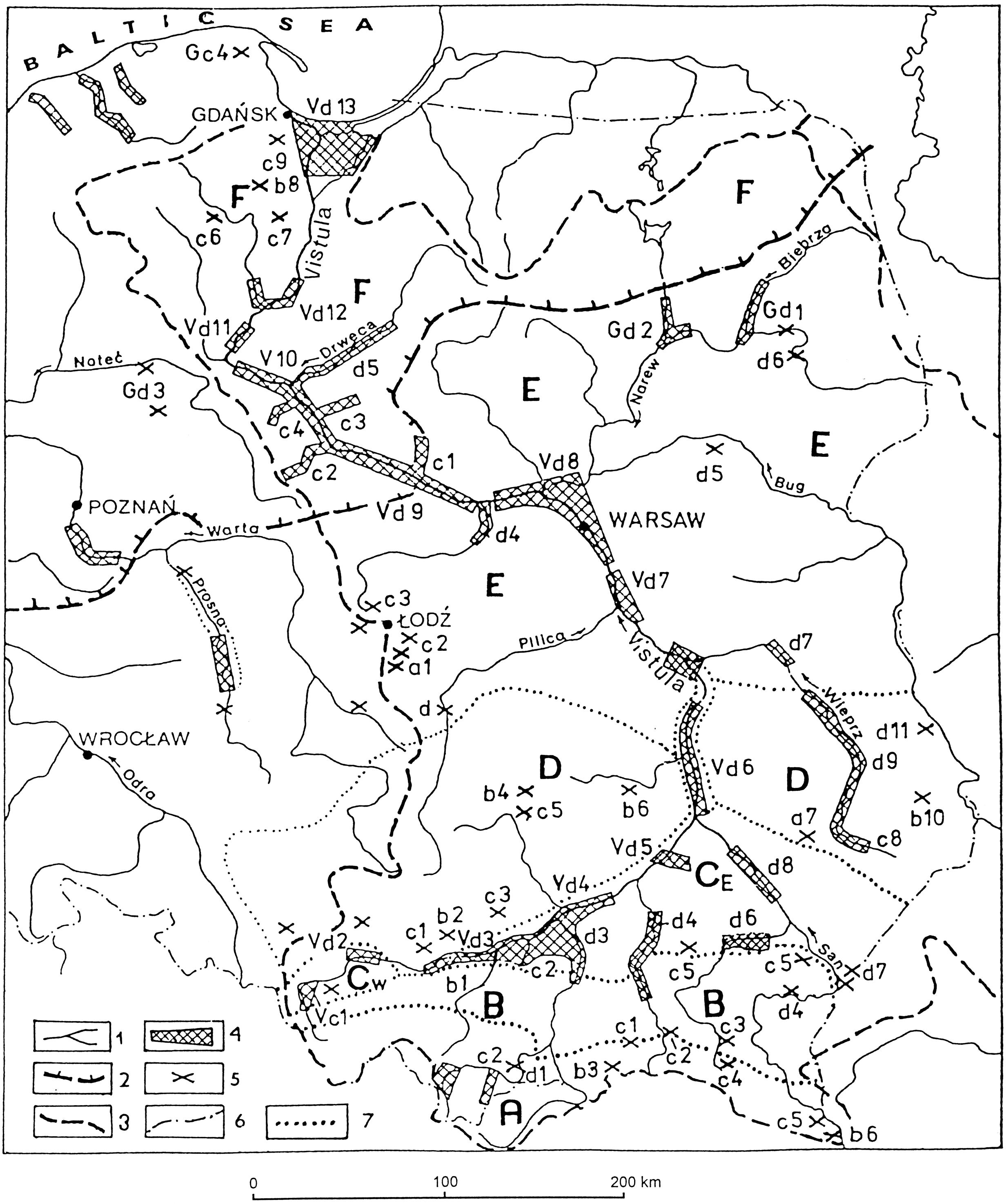

Fig. 2. Landscape zones and areas of studies of Holocene fluvial sediments: *1* – rivers, *2* – extent of the last ice sheet, *3* – watershed of the Vistula River basin, *4* – areas of detailed investigations, *5* – other localities studied in detail, *6* – state boundary, *7* – limits of landscape zones: A – Carpathian Mts., B – Carpathian foothills, C – Subcarpathian basins, D – South-Polish uplands, E – Polish Lowland (periglacial), F – lowland (young relief in zone of the last glaciation). See the list of references for respective code numbers

The suspended load reaches the highest values (up to 2 × 10^6 tons $km^{-2}yr^{-1}$) at the outlet of the Vistula River from the Subcarpathian Sandomierz Basin (Ce in Fig. 2), and the overbank and bedload deposition is very high both in this basin and farther downstream, in a gap across the South-Polish Uplands (Łajczak, 1990).

The Vistula River on its way to the Baltic Sea passes through six main landscape zones (Fig. 2). The highest part

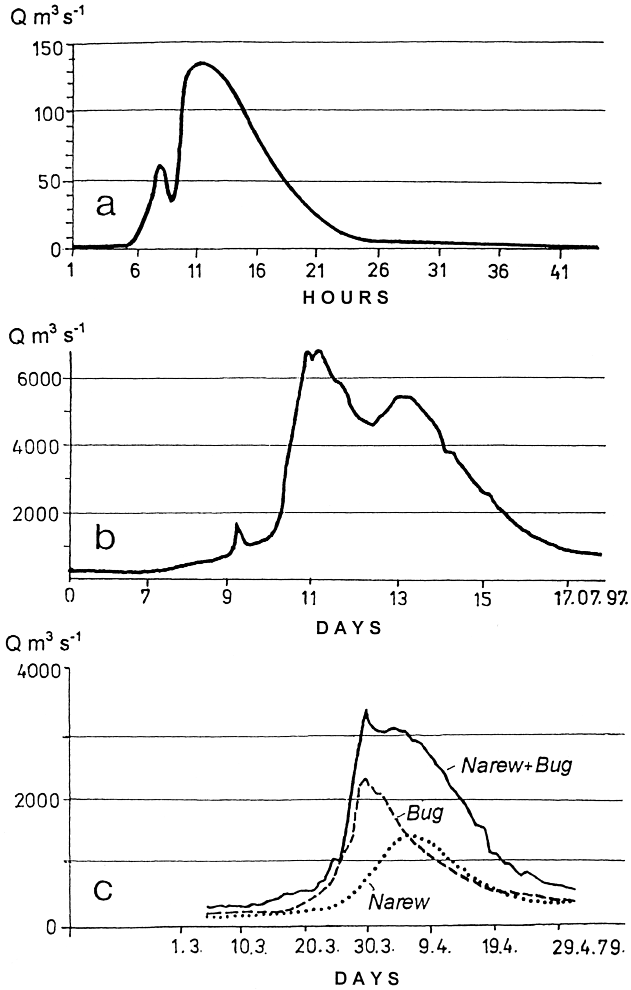

Fig. 3. Typical hydrographs of three various flood types in the Vistula catchment: **a** – flash flood in the Kalinka valley (zone D) on 15 Sept. 1995 (after Starkel ed., 1997), **b** – flood in the Vistula river valley in July 1997 at Sandomierz (after Grela *et al.*, 1999), **c** – snowmelt flood in the Bug and Narew rivers in March-April 1979 in NE Poland (after Stachy *et al.*, 1996)

of the Carpathian Mountains (zone A), elevated to 1,000–1,700 m a.s.l. (only Tatra Mts. with glacial relief rise to 2,600 m), is built mainly of flysch strata and dissected by 300–800-m-deep valleys. To the north, there extends a belt of the Carpathian Foothills (zone B), which is also built up of flysch rocks. Trunk valleys incised to 100–200 m have flat bottoms. The Carpathians are the main sediment contributing area in the whole Vistula River catchment. The Subcarpathian basins collect water and sediment load mainly from the right-side Carpathian tributaries. The gradient of wide valley floors declines to 0.3‰ and less; this is the belt of natural storage of alluvia (zone C). To the north, a broad upland (zone D) extends, which is characterised by 50–150 m relative heights, and built up of various sedimentary rocks covered in part by a thick loess cover, densely dissected by gullies. The upland zone is the second sediment contributing area in the whole catchment. The uplands decline northwards and are buried under Quaternary sediments of older Scandinavian glaciations. This flat Polish Lowland with periglacial relief features is drained by low-gradient rivers (zone E). Finally, the northern belt left by the last ice sheet (zone F) has again more diverse relief with hilly marginal zones, extensive sandur plains, latitudinally directed ice-marginal streamways and transversal valley gaps, and subglacial channels.

In the upper Vistula River basin in the Carpathian foreland, about 45 years ago Starkel (1960) proposed a concept of sequence of cuts and fills explained as phases with various frequency of extreme events, reflected in the sediments and landforms (Starkel, 1983, 2003b; Starkel ed., 1990; Kalicki, 1991; Starkel *et al.*, 1996). These active phases were dated at 8.5–8.0, 6.6–6.0, 5.5–4.9, 4.4–4.1, 3.5–3.0, 2.7–2.6, 2.3–1.8 ^{14}C ka BP, and the 5–6th, 10–11th and 16–19th cent. AD (Starkel *et al.*, 1996), and correlated with other indicators of higher humidity and extensive rainfalls, like: vegetation changes, lake level rises, advances of Alpine glaciers, precipitation of calcareous tufa, landslide activity, etc. (Fig. 9) These phases are also reflected in the newly elaborated frequency curve of radiocarbon dates, reflecting variations in fluvial activity (Starkel *et al.*, 2006) and recorded in larger valleys of the Middle and Southern Germany (Schirmer, 1995).

LEADING TYPES OF RAINFALLS AND FLOODS IN VARIOUS CATCHMENTS

The types of floods depend mainly on the character of rainfall and snowmelt (cf. Starkel, 1998; Figs 3 and 4).

Flash floods connected with local heavy downpours are most characteristic of small-size catchments in the mountains, uplands and also, to some extent, in the lowlands (Fig. 3a). The rainfall intensity exceeds 1 mm min^{-1} and rainfall totals are 50–150 mm, resulting in rapid overland flow and slope wash (Starkel ed., 1997, 1998). The specific runoff may reach 10–35 m^{3}sec^{-1}km^{-2} (Ciepielewski, 1970; Stachy *et al.*, 1996). The frequency of such events does not exceed several per cent.

Continuous rains connected with the frontal zones occupy larger areas, especially in the Carpathians, where during 2–5 days 200–500 mm of rain may fall, and in the trunk valley a flood wave is formed (Fig. 3b). The most effective is the superposition of heavy downpour over continuous rain, when simultaneously the thresholds of both slope and fluvial processes may be passed, and great masses of colluvial and washed material are delivered to the river channels and transported downstream. It was such a case in July 1997 (Starkel & Grela eds., 1998), when in various reaches of river channels the buffers and barriers were passed and exceptional connectivity of landscape zones followed. In the case of rivers passing the Subcarpathian basins, the floods originated in the Carpathians are of allochthonous character and cause mainly aggradation in the overbank facies.

In the larger flat lowland basins, the flooding can be recorded not only during continuous rains but also during long rainy seasons lasting several weeks. Such a flood is

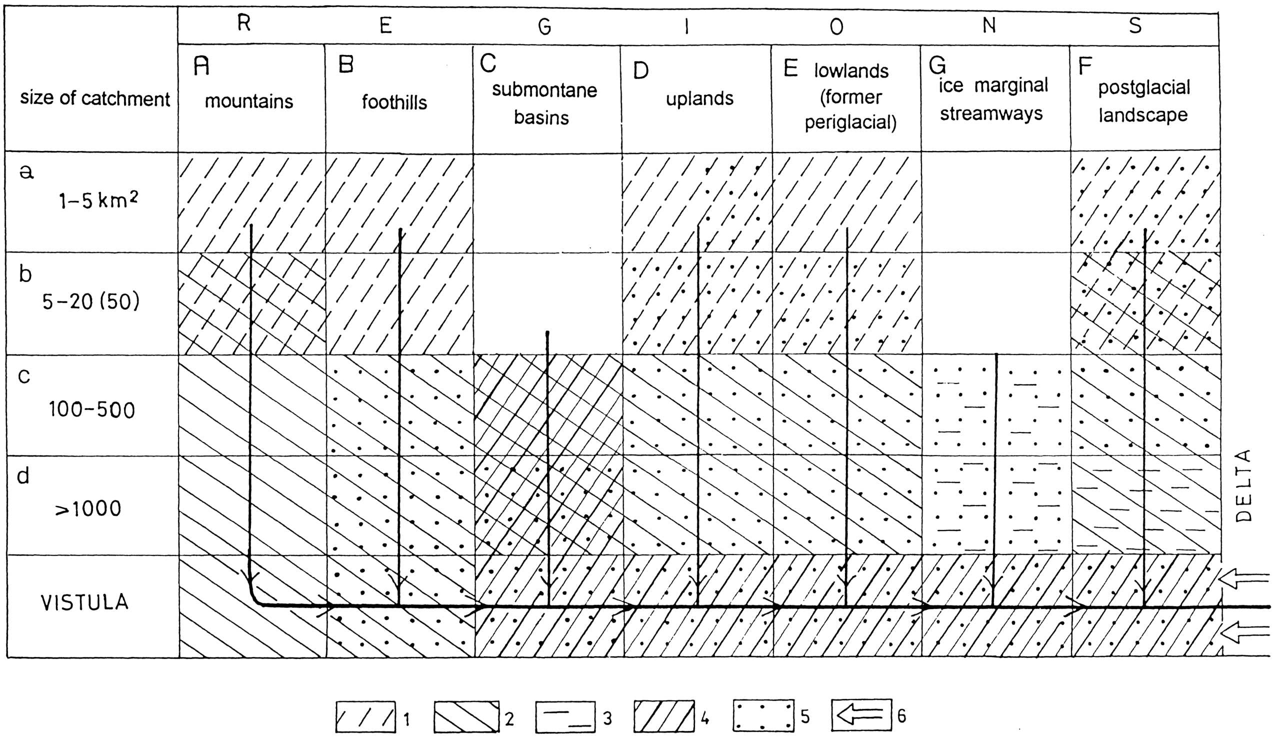

Fig. 4. Leading types of floods in various size catchments of main landscape regions in the Vistula River basin. Types of floods: *1* – downpour, *2* – continuous rain, *3* – rainy season, *4* – allochthonous flood, *5* – snowmelt, *6* – sea storm

combined with a rise of the groundwater level and is characterised by very low sediment load.

The snowmelt floods are recorded in all landscape regions of the Vistula River catchment, and especially those floods which are combined with rainfall on frozen ground cause the alluviation over floodplains (Fig. 3c). In the trunk valleys flowing towards the north, the ice-jam floods are recorded due to earlier melting of snow and river ice in the south (Soja & Mrozek, 1990).

Concluding so far, the importance of floods of different type depends on the size of a catchment (rainfall intensity and totals), characteristic landscape features, and rate of melting of the snow cover (Fig. 4).

Coastal floods in the Vistula River delta are of totally different character. These are connected with sea storms, which block the river outflow.

DIFFERENT RESPONSE TO HYDROLOGICAL CHANGES DURING THE HOLOCENE

As it was already mentioned, the main differences in response should be connected with the landscape region and catchment size (Fig. 5). In the upper catchment, distinct clusters of floods are dated at 8.5–8.0, 6.6–6.0, 5.5–4.9, 4.4–4.1, 3.5–3.0, 2.7–2.6, 2.3–1.8 ^{14}C ka BP and the 5–6-th and 16–19-th cent.AD (Starkel *et al.*, 1996).

Carpathian Mountains (Zone A)

In the first order streams, a higher frequency of extreme events is reflected in the acceleration of downcutting during downpours carrying heavy bedload (Froehlich, 1982). In the catchments of several tens of square kilometres in size (type b–c in Fig. 5), both downpours and continuous rains are frequent, and small erosional steps are cut in the bedrock, probably reflecting phases of high flood frequency (cf. Zuchiewicz, 1987; Wójcik, 1997). In the trunk valleys draining larger catchments, the sequence of terrace benches and rocky steps with alluvial coarse-grained deposits probably reflect also alternate phases of various flood frequency (cf. Froehlich *et al.*, 1972, type d). During clusterings of events, especially after deforestation, the formation of braided channels with gravel bars followed (Ziętara, 1968; Baumgart-Kotarba, 1980). Therefore, in narrow reaches the older fills have been mainly removed and only the youngest ones have survived.

Carpathian foothills (Zone B)

The first order streams react to frequent extreme rainfalls by activisation of downcutting and formation of small alluvial fans at their outlets (exemplified by an alluvial fan at Podgrodzie, dated to 8.4–7.8 ^{14}C ka BP; cf. Niedziałkowska *et al.*, 1977). In the catchments of the order of 5–20 km^2, gradual aggradation in gullies cut in the late Pleistocene sediments is observed (type b in Fig. 5). After deforestation in the last millennia, vertical aggradation in overbank

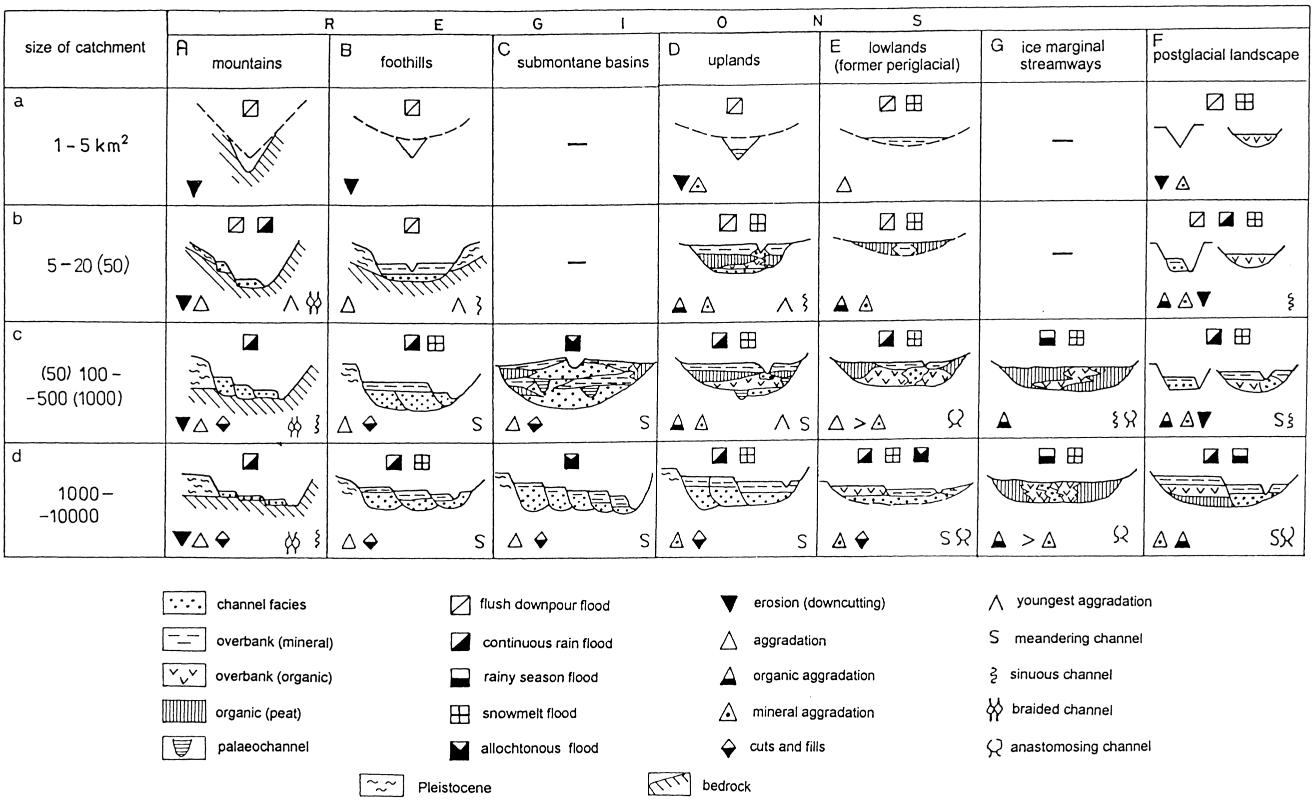

Fig. 5. Types of floods, fluvial processes and Holocene alluvial sequences in catchments of various size in the Vistula River basin

facies prevails (cf. Kukulak, 2003). In the larger river valleys passing the foothill zone, 2–3 cuts and fills may be recognised, being connected with phases of higher flood frequency (Wójcik, 1987; Kalicki, in: Starkel *et al.*, 1999; types c and d). The number of parallel fills increases in the root zone of alluvial fans of large Carpathian rivers at the margin of the foothills, where these fills build 3–4 terrace steps (Starkel ed., 1982).

Subcarpathian Basins (Zone C)

In this landscape zone, the transfluent Carpathian rivers dominate. Depending on the catchment size and fluctuations in the sediment load, distinct cut- and-fill sequences and channel avulsions are reflected in extensive alluvial fans (type d in Fig. 5). These changes are well documented not only in the trunk Vistula valley, but also in the Wisłoka, Wisłok, San (Starkel, 1960, 1995; Alexandrowicz *et al.*, 1981) and Raba (Gębica, 1995) river valleys. On the contrary, at the outlets of smaller rivers (of catchments ranging from tens to several hundred square kilometres) aggradation does prevail (type c). The flood phases are reflected there in facies diversity and grain size changes (the uppermost Vistula River – Niedziałkowska *et al.*, 1985; Wielopolka River – Starkel *et al.*, 1999). At some distance from the mountain front, the river gradient declines to 0.25–0.30‰, and meandering palaeochannels of various size reflect well the alternate phases with various flood frequency during the Holocene (Vistula River valley – Kalicki, 1991; Starkel *et al.*, 1991, 1996; San River valley – Szumański, 1982).

South-Polish Uplands (Zone D)

Most of upland river valleys (excluding several karstic canyons) have a steeper gradient in their headwaters only, especially in loess areas, which are densely dissected by gullies. It is lithological factor, which decides that the suspended load dominates and the material available for bedload is missing. The downcutting should dominate in these portions, but due to deforestation their valley floors have been aggraded (Śnieszko, 1995; Starkel ed., 1997). In the middle-size catchments (up to several tens of square kilometres; type b in Fig. 5), during heavy downpours or rapid snowmelts, the deposition of suspended load increases (Fig. 4). In sediment sections, a distinct turn from organic and fine-grained mineral deposition during the early-mid Holocene to the aggradation of silty-sandy loams connected with forest clearance and tillage during the Neoholocene (Nakonieczny, 1975; Śnieszko, 1987; Ludwikowska-Kędzia, 2000) is clearly seen. In larger river valleys with meandering channels of the upland zone, the floods connected with either snowmelts or rare continuous rains lead to vertical upbuilding of floodplains (type c). Phases of higher flood frequency, and even two separate fills may be recognised at individual exposures (Nidzica River valley – Śnieszko, 1987; Wieprz River valley – Superson, 1996, type d in Fig. 5).

Central Polish Lowland (former periglacial Zone E)

The smallest river valleys under natural vegetation were not transformed by rare downpours and snowmelts.

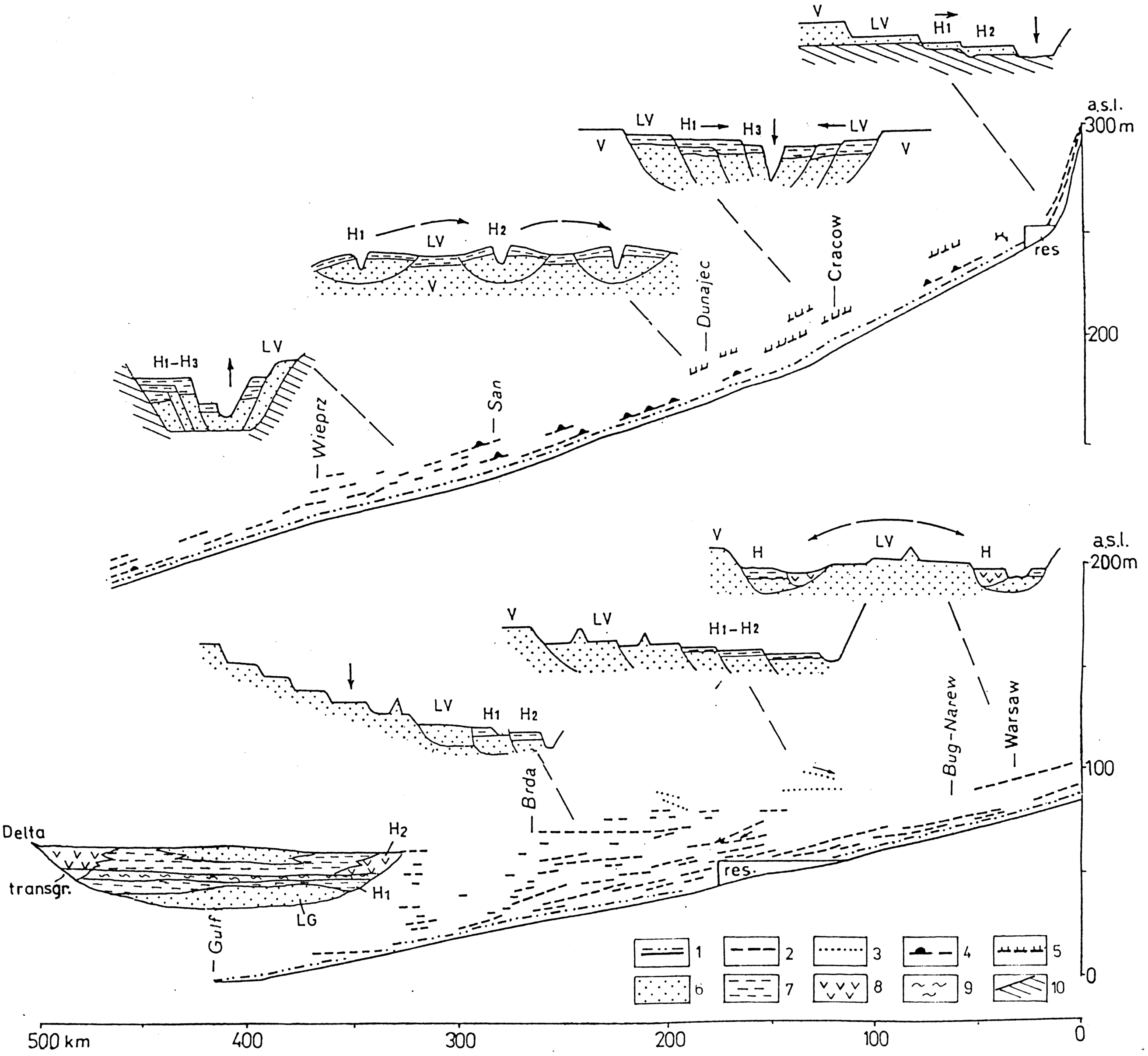

Fig. 6. Longitudinal profile and schematic transversal profiles of the Vistula River valley (partly after Starkel ed., 1990): *1* – longitudinal channel profile, *2* – fluvial terraces, *3* – glacifluvial terraces, *4* – Vistulian terrace with dunes, *5* – Vistulian terrace with loess cover, *6* – channel facies, *7* – overbank facies, *8* – organic deposits, *9* – marine deposits, *10* – bedrock. Abbreviations: V – Vistulian, LV – late Vistulian, H1–H3 – Holocene members, Res. – water reservoir

The swampy soil or peat has been developed there. Later, in the cultivated areas, the deposition of suspended load followed (Twardy, 2002). In several catchments of tens of square kilometres in area, two to three alluvial fills in the lowest sections have been recorded (Turkowska, 1988). The larger valley floors with anastomosing channels are characterised by peatbogs and mixed organic – mineral aggradation (middle course of the Narew River valley – Gradziński *et al.*, 2000). Only along river banks the deposition of fine-grained levee sediments had followed. In the largest river valleys, like Bug or lower Narew and Bzura (type d), with well developed meandering pattern, two to three generations of cut-and-fill terraces with dated palaeomeanders were recognised (Falkowski, 1975; Andrzejewski, 1991).

Ice – marginal streamways

The marginal streamways developed in the foreland of marginal zones of the last Scandinavian glaciation. These landforms are up to several kilometres wide, and they used to carry glacial meltwaters towards the west. Their long reaches, now underfit, became drained during the Holocene by small rivers, like Noteć or Biebrza (type G in Fig. 5). In

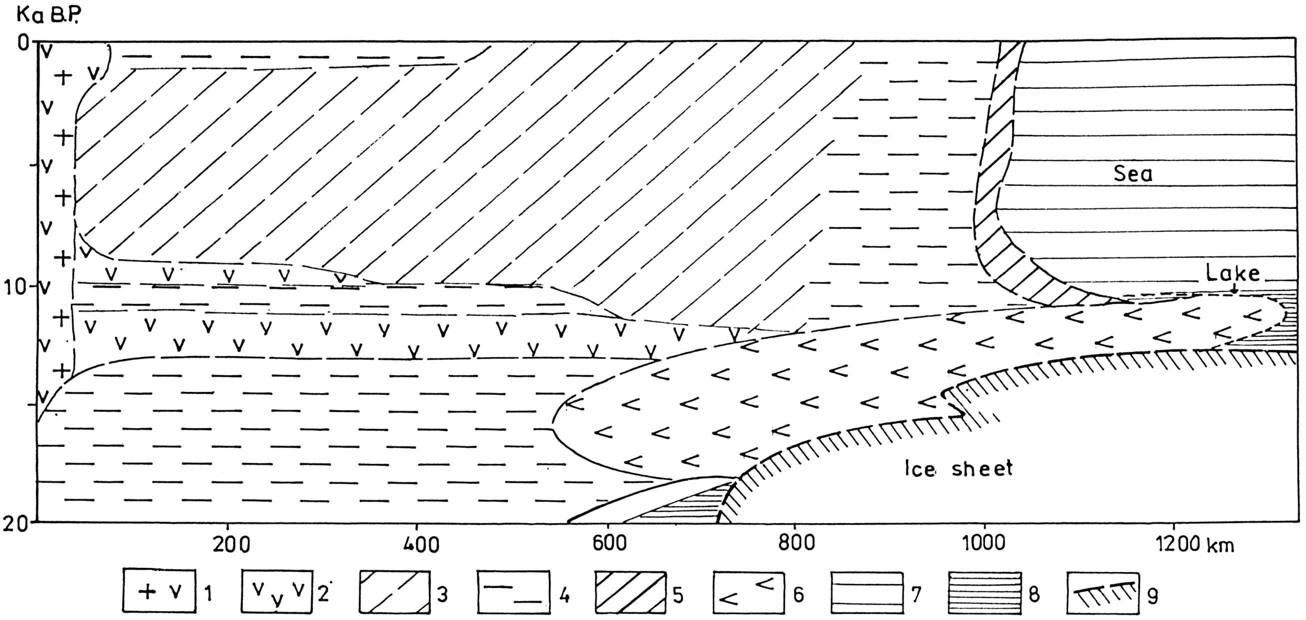

Fig. 7. Various factors influencing the diverse trends in the late Vistulian and Holocene evolution of the Vistula River valley. *1* – incision controlled by uplift and climate, *2* – climatically controlled incision, *3* – alternate cuts and fills controlled by climate, *4* – general trend to aggravation, *5* – aggradation controlled by sea level changes, *6* – downcutting controlled by lowering of the base level, *7* – Baltic Sea, *8* – ice-dam lake, *9* – ice sheet

these sections, peatbogs developed during the last 10–12 ka, and only along anastomozing channels deposition of overbank clays with rare intercalations of silts and sands of channel facies have taken place (cf. Żurek, 1984; Kozarski, 1993). The fluctuations in hydrological regime connected with flooding during rainy seasons or snowmelts are reflected in the type of peat and in the intercalations of mineral matter.

Valleys in the zone of young morainic landscape (Zone F)

After the deglaciation, in the young landscape of morainic plateaus and sandur plains with dead-ice depressions and subglacial channels, the formation of a new valley network was initiated (cf. Starkel, 2003b). The creeks draining small depressions and gullies cut in the steeper slopes are modelled during heavy downpours, continuous rains or snowmelts, and usually join larger river valleys. These valleys are composed of alternate reaches: the widenings in dead ice depressions filled by organic or mineral deposits, and transfluent lakes with deltas and narrow gaps across the morainic plateaus (types b and c in Fig. 5). Finally, such valleys join the trunk Vistula River (Koutaniemi & Rachocki, 1981; Błaszkiewicz, 1998). Only in their lower courses, the terrace systems with preserved palaeochannels did develop (type d), being partly connected with the Lateglacial lowering of the Vistula's base level (Fig. 6), and partly with fluctuations in hydrological regime during the Holocene (cf. Niewiarowski, 1968; Andrzejewski, 1995). The wetter phases coincide mainly with episodes of lake level rise (Ralska-Jasiewiczowa *et al.*, 1998).

CHANGE OF RESPONSE IN THE LONGITUDINAL PROFILE OF THE VISTULA RIVER VALLEY

The Vistula River and its tributaries cross all landscape zones on their way to the Baltic Sea. A mixed hydrological regime protects the connectivity between valley reaches during summer rainy floods, originating usually every decade in the mountains, and snowmelt floods formed in various parts of the catchment (Figs 3, 6). Therefore, most of floods passing the zone of Subcarpathian basins is of allochthonous origin (Fig. 4). The diversity of response to hydrological changes during the Holocene is also influenced by other factors in various segments of the longitudinal profile (Starkel ed., 1990; Figs 6, 7). In the upper mountain zone, beside climatic factor, tectonic uplift is responsible for channel deepening in the bedrock, down to 1–3 m. In the Subcarpathian basins, several cuts and fills reflect fluctuations in the frequency of extreme events with distinct acceleration of overbank aggradation during the last millennium. In the valley widenings, channel avulsions and crevasses are also frequent. The overdeepening of channels of the Carpathian rivers during the last century, caused by regulation works and exploitation of gravel and sand from river beds, influenced the shift of aggradation zone from the direct Carpathian foreland several tens of kilometres downstream, causing channel braiding in a gap across the uplands (Łajczak, 1997).

In this narrow gap across the South-Polish Uplands, vertical accretion instead of lateral one prevails (Pożaryski & Kalicki, 1995). The reflection of hydrological features is expressed mainly in lateral shift of the channel, and less in cuts and fills in the middle river course in the lowlands. Frequent buffers and barriers in the channel- floodplain system are resposible for the disconnectivity of reaches. Downstream of the Warsaw Basin, the Lateglacial lowering of the base level led to formation of a terrace flight (Figs 6, 7; Wiśniewski, 1987). The Vistula River valley in its lower course became deeply incised in the morainic plateaus due to rapid lowering of the base level during deglaciation. The subsequent aggradation was connected in part with a gradual sea level rise up to the Littorina transgression, and the formation of a delta (Mojski, 1990).

A comparison of alluvial sequences along various sections of the Vistula River valley shows that, besides the climatic signal of wetter phases, also an anthropogenic signal connected with deforestation has been recorded even in the lower valley course (Tomczak, 1982; Starkel ed., 1990). This tendency has been observed starting from the Roman period (1–2 cent. AD), indicating the connectivity of reaches during extreme floods that originated in the upper Vistula River catchment and carried high sediment load.

REGULARITIES OF RESPONSE TO HOLOCENE CHANGES IN THE VISTULA RIVER BASIN

The diversity of response to hydrological changes in river catchments of variable size and in different landscape zones is closely connected with the frequency of prevailing flood types of both rainfall and snowmelt origin (Figs 3, 4). As recognised in other hilly areas (Harvey, 2002; Fryirs & Brierley, 2001) in small catchments, heavy downpours cause a simultaneous disturbance of equilibrium of both the slope and channel systems. This transformation does not proceed too far downstream, being reflected in the deposition either in channel facies or (more frequently) in overbank one. In larger hilly catchments, the leading role is played by continuous rains, but the simultaneous response of slopes and valley bottoms is observed only when continuous rains are preceded by downpours. In the lowland catchments, very rare prolonged rains or rapid snowmelts may cause changes over floodplains.

The transformation of valley floors during the Holocene phases of high flood frequency had a pulsating character and proceeded in three principal directions (Fig. 8):

a) Erosional trend towards downcutting is observed in the mountainous upper reaches, being expressed in several erosional steps, and in the shifting of buffers and barriers existing in the channels and floodplains.

b) Vertical aggradational trend is characteristic for low-gradient rivers of both the upland and lowland zones (D and E zones), carrying high suspended load, especially after deforestation. The climatic variations are reflected there in various rates of deposition, changes of grain size, and by breaks of deposition marked by palaeosols organic horizons.

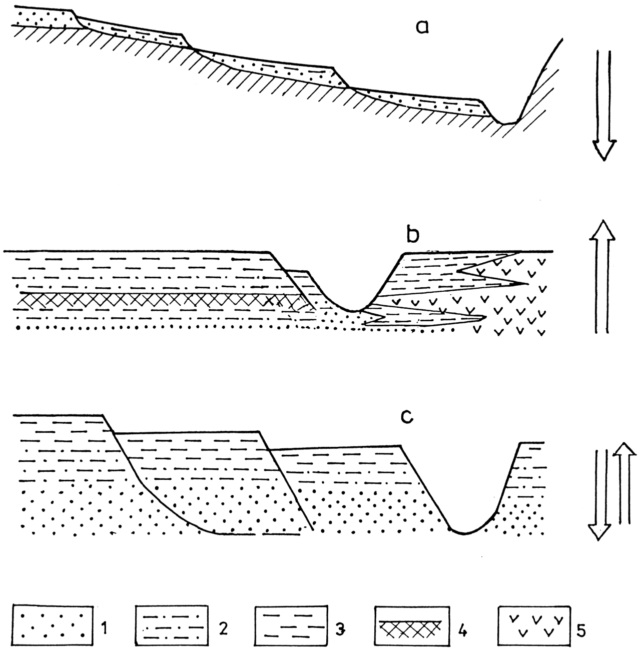

Fig. 8. Main directions of valley floor evolution reflecting rhythmic hydrological changes during the Holocene: **a** – tendency to downcutting, **b** – tendency to aggradation, **c** – cut-and-fill sequences; *1* – channel facies, *2* – coarser overbank deposits, *3* – finer overbank deposits, *4* – fossil soil, *5* – organic deposits

c) Parallel cuts and fills are created mainly by meandering rivers during the clusters of floods, leading to straightening, widening and braiding of river channels and then, frequently, to avulsions (Starkel, 1983). The most distinct changes of this type during the Holocene were recognised in the mountain foreland, where the connectivity of neighbouring valley reaches is revived during extreme floods, when both the incision and deposition occurs.

Progressing downstream in the longitudinal profile of the Vistula River, we observe a normal, gradual shift from erosional (a) to depositional (b) model (Schumm, 1977). In the lower course, this is disturbed by lowering of the base level before the Holocene (Fig. 6). In the transitional middle course, the hydrological changes are expressed in the alternation of phases with dominant either erosion or deposition. In the case of the Vistula River valley, this zone has been shifted upstream to the Subcarpathian basin, marked by the greatest fluctuations in river discharge and sediment load due to rapid decline in the river gradient, as well as due to infiltration of water in the underlying alluvia, causing a drop in the discharge.

In the Holocene alluvial records of the Vistula River catchment, an incomplete sequence of changes has been recognised in particular valley reaches especially in greater river valleys, that show a tendency to the lateral shift of channels, and where single sediment members have been eroded and are missing. Therefore, it is necessary to study not only the main river valley, but also the tributary valleys of various size, both in transversal sections across the valley

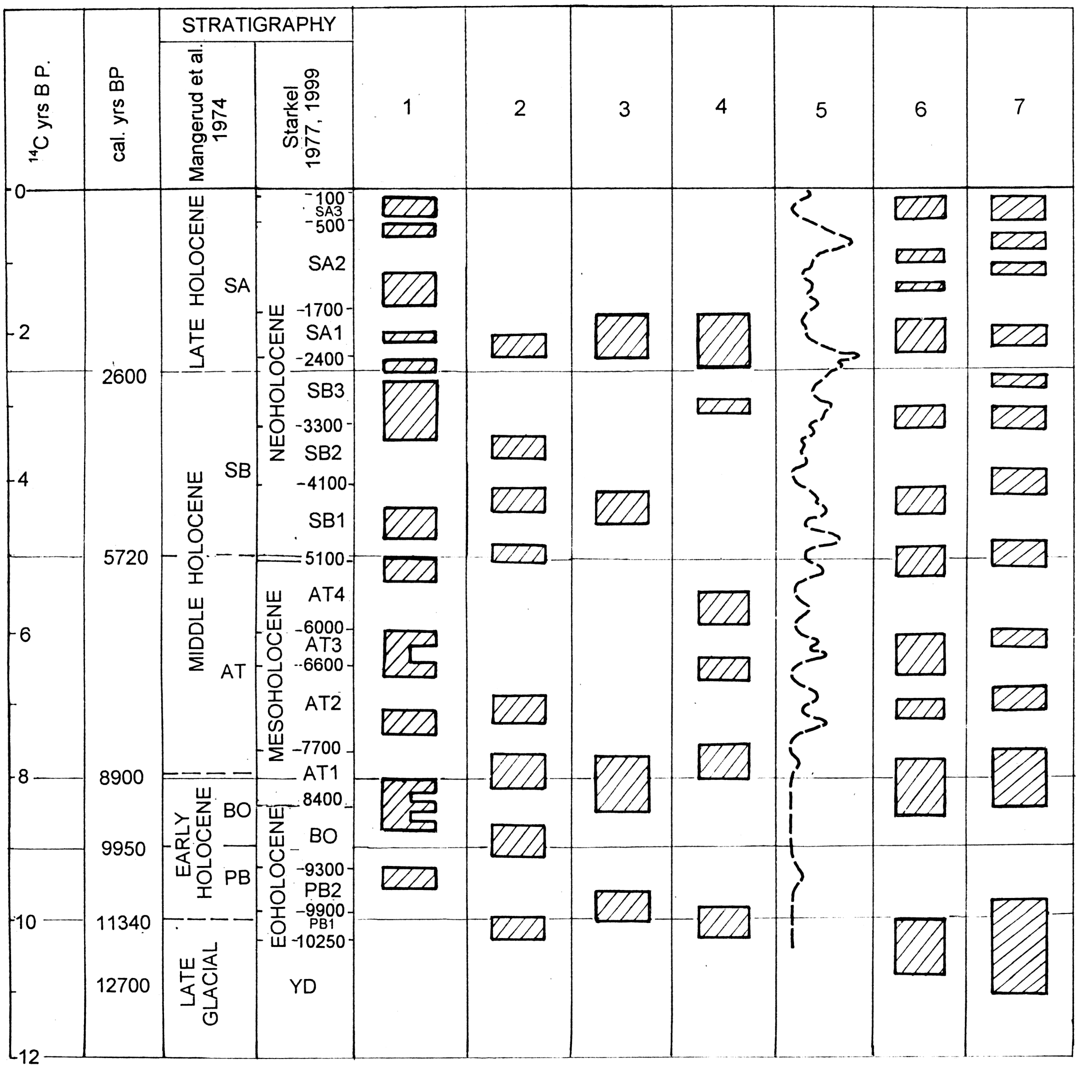

Fig. 9. Hydrological changes during the Holocene, reflected in alluvial sequences and other environmental changes in Poland (with a comparison to Alpine glaciers) (after Starkel ed., 1990; modified): 1 – advances of Alpine glaciers (Patzelt, 1977 and others), 2 – abrupt changes in vegetation (Ralska-Jasiewiczowa ed., 1989), 3 – phases of higher water level (after Ralska-Jasiewiczowa ed., 1989 and others), 4 – calcareous tufas in spring peatbogs (Dobrowolski, 1998), 5 – rate of stalagmite growth (Pazdur *et al.*, 1999), 6 – phases of high flood frequency (Starkel *et al.*, 1991, 1999; Kalicki, 1991), 7 – phases of high landslide activity in the Carpathians (Margielewski, 2000)

floor and in longitudinal profiles. It is also recommended to compare fluvial records with other facies and environments, which preserved more undisturbed and complete sequences, namely: lacustrine sediments, peatbogs, calcareous tufas, landslides, etc., at those localities where the interfingering with alluvia was recognised, as well as outside of them (Fig. 9; Ralska-Jasiewiczowa & Starkel, 1988). Therefore, so fruitful were independent, parallel studies carried out under the IGCP Project No. 158 in the 1980s, covering both fluvial and lake and bog environments (Starkel ed., 1990; Ralska-Jasiewiczowa & Latałowa, 1996; Ralska-Jasiewiczowa *et al.*, 1998). The main phases showing high frequency of fluvial extreme events, recognised in the Vistula River valley, have been identified in other facies of continental deposits (Starkel *et al.*, 1996; Starkel, 2003 a, b).

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Streszczenie

ZŁOŻONOŚĆ REAGOWANIA SYSTEMU FLUWIALNEGO NA ZMIANY HYDROLOGICZNE W HOLOCENIE (NA PRZYKŁADZIE DORZECZA WISŁY)

Leszek Starkel

Zmiany hydrologiczne w holocenie wyrażone są w różnej częstotliwości powodzi i zapisane w osadach i formach fluwialnych. Różna reakcja systemu fluwialnego zależy od reżimu opadu, odpływu i transportu rumowiska, które wiążą się z typem krajobrazu, wielkością zlewni, położeniem w profilu podłużnym rzeki, jak i narastającą ingerencją człowieka. Szczegółowe badania dolin dorzecza Wisły w ostatnich dziesięcioleciach stanowiły podstawę określenia, jak różne sekwencje osadów rzecznych odzwierciedlają zmiany paleohydrologiczne.

W różnych typach rzeźby i zlewniach różnej wielkości istotną rolę odgrywają lokalne ulewy, albo opady rozlewne lub wezbrania roztopowe. Wyróżniono trzy zasadnicze modele przekształceń den dolin w holocenie: pogłębiania erozyjnego w zlewniach górskich, agradacyjny w dolinach o małym spadku i przejściowy, zapisany w szeregu rozcięć i włożeń, odzwierciedlających fazy o różnej częstotliwości wezbrań. Ten ostatni winien charakteryzować środkowe biegi rzek, ale jest najlepiej rozwinięty na bezpośrednim przedpolu Karpat o największych wahaniach przepływów i transportu rumowiska. Częste występowanie wielu przerw w sekwencjach aluwialnych wymaga spojrzenia całościowego na zmiany hydrologiczne i korelacji środowisk fluwialnych z zapisem zmian w ewolucji szaty roślinnej, osadach jeziornych, stokowych i innych.