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INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION

GEOGRAPHICAL STUDIES
SPECIAL ISSUE NO. 5

EVOLUTION OF THE VISTULA RIVER VALLEY DURING THE LAST 15000 YEARS

PART III

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ГЕОГРАФИЧЕСКИЕ ТРУДЫ
СПЕЦИАЛЬНОЕ ИЗДАНИЕ № 5

ЭВОЛЮЦИА ДОЛИНЫ РЕКИ ВИСЛЫ НА ПРОТЯЖЕНИИ ПОСЛЕДНИХ 15 000 ЛЕТ

III

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PART III

Editor:
LESZEK STARKEL

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CONTENTS

INTRODUCTION

THE CONCEPT

One of the principal goals of the IGCP Project 158 is to reconstruct palaeogeographical changes, but especially palaeohydrological changes which took place in the temperate zone of the northern hemisphere during the last 15,000 years. Subproject A of this problem is concerned with the evolution of fluvial environments. This subproject utilizes results of investigation of both fluvial deposits and landforms (Starkel, Thornes 1981). The valleys examined also included the Vistula Valley. The Vistula River Basin, encompassing an area of 194,000 km^2, is the tenth largest catchment in Europe. Research was undertaken by a group which was organized by L. Starkel within the Committee of Quaternary Research, Polish Academy of Sciences, in 1978. The expertise of scientists in a range of disciplines (geology, geomorphology *etc*) was used there. Much of the investigations was realized in 1981—1986 under the heading of the problem *Evolution of the geographical environment of Poland* being co-ordinated by the Institute of Geography and Spatial Organization, Polish Academy of Sciences.

The Vistula catchment is in the very centre of Europe. The nature, physiography, and history of the river basin are typical of the central European rivers (Fig. 1). The headwaters of both the Vistula and its tributaries are in the Carpathians which constitute the northernmost member of the Alpids. The river then drains the narrow stripe of uplands of Hercynian Europe, and the Central European Lowland to the Baltic Sea. During the youngest Quaternary the evolution of the upper part of the drainage basin was governed by climatically controlled factors, and by varying tectonic movements, whereas its lower part was affected by both advance and retreat of the Scandinavian inland ice, and by fluctuations of the Baltic Sea level.

The average basin height is 210 m a.s.l. Areas extending up to 200 m a.s.l. make up 64% of the total area of the catchment, although the highest peak reaches 2655 m a.s.l. (Fig. 2).

The Vistula drainage basin is asymmetrical. The left-bank part occupies 27% of the total catchment area, the right-bank part comprises

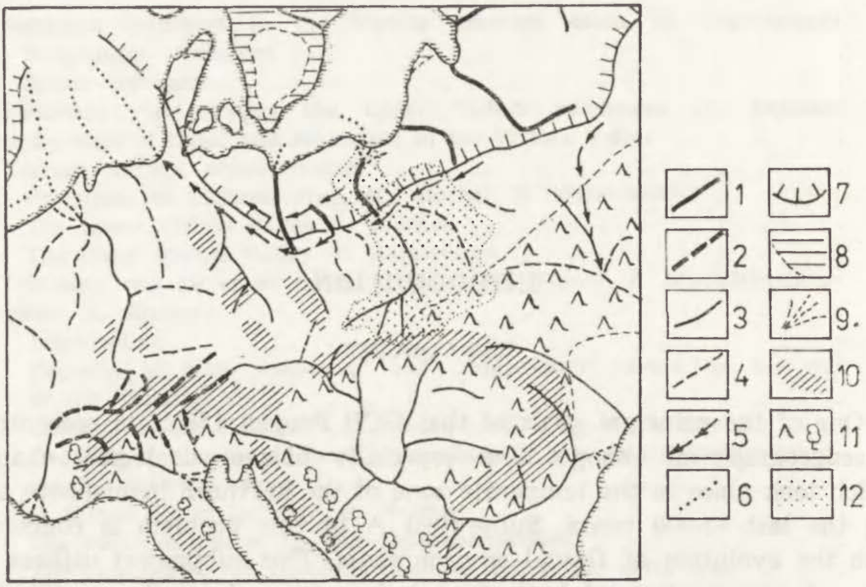

Fig. 1. The Vistula River Valley on the phone of the Central European valleys (L. Starkel)

1—valleys newly formed after the deglaciation, 2—Alpine valleys being free of ice during the Holocene, 3—valleys of the former periglacial zone fed by floods born in the mountains, 4—lowland valleys of the former periglacial zone, 5—underfit valleys formerly carrying melt-waters, 6—submerged valleys, 7—extent of the last ice-sheet, 8—previously submerged areas in the zone of glacial rebound, 9—deltas, 10—mountain ranges, 11—forest refuges during the Last Glaciation, 12—the Vistula catchment

73%. 25% of the Vistula catchment are the Carpathian and upland river basins. These show higher precipitation totals being responsible for the summer high stream discharges. Mean annual precipitation ranges from 450 to 1800 mm. The runoff coefficient in the Vistula River Basin is 29%, but in the upper Vistula catchment it increases to 35%. The continentality of climate which shows a marked increase from south to north and from west to east explains the increasing role of ice-jam-induced floods during the snowmelt period in the middle and lower reaches of the Vistula Valley (Mikulski 1963).

In 1982 and 1987 the results of investigations undertaken in 22 selected valley reaches of the Vistula and some tributaries were published in two volumes (Starkel ed. 1982, 1987b; cf. Fig. 3). The third volume synthesizes information about the features of the drainage basin, valleys, and rivers—the background to attempts of reconstruction of the fluvial processes of both erosion and sedimentation occurring along the valley. These processes resulted from the superposition of the climatic, tectonic, glaciogenic, eustatic, and anthropogenic factors. Complete palaeohydrological reconstructions are not availabe for the Vistula River, since the latter are often extremely difficult, even for valley segments

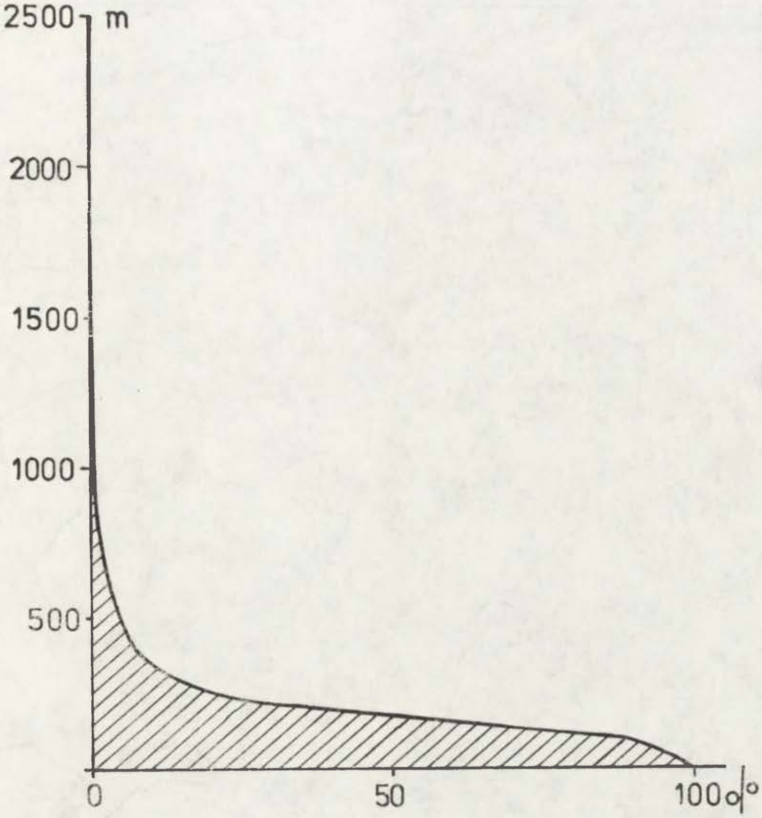

Fig. 2. Hypsographical curve of the Vistula catchment (L. Starkel)

that have been examined in great detail (cf. Rotnicki, Borówka 1985).

As the editor of the three volumes dealing with the evolution of the Vistula Valley during the last 15,000 years, I am very grateful to all scientists for their great enthusiasm and essential contribution to the recognition of the history of the greatest Polish river. I am especially grateful to the authors who have contributed papers to this volume. I also would like to thank all those specialists and assistants who were of invaluable help during the collecting and analysing of field data. Finally I am intepted to Mrs Maria Klimek who drew the figures for this book, to Dr. Sylwia Gilewska who translated the Polish text into English and to Dr. Tomasz Kalicki for secretarial help.

THE HISTORY OF RESEARCH IN THE VISTULA VALLEY

Although investigation of the Vistula Valley evolution began already before the turn of the present century, detailed studies on the genesis and age of this valley were initiated after the Second World War with the large-scale application of both palaeobotanical methods and radio-

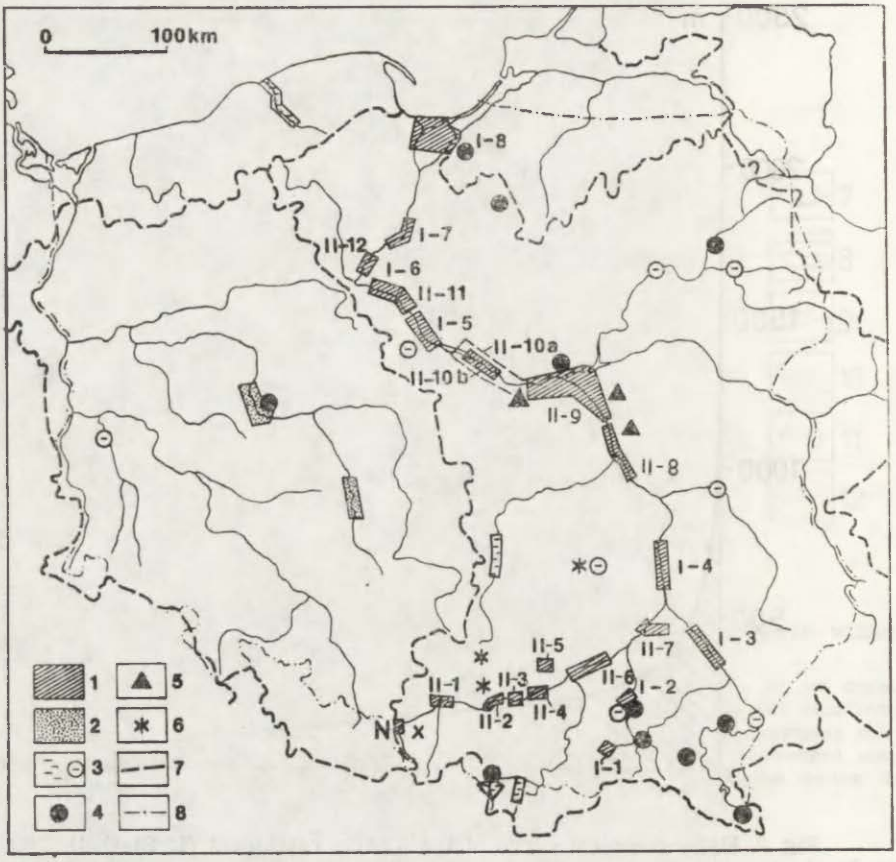

Fig. 3. The Vistula River Basin and other areas examined by different authors within the IGCP Subproject 158 A (L. Starkel)

I-1 (Dauksza *et al* 1982), I-2 (Alexandrowicz *et al* 1981, Starkel *et al* 1982), I-3 (Szumański 1982), I-4 (Falkowski 1982), I-5 (Wiśniewski 1982), I-6 (Tomczak 1982), I-7 (Drozdowski 1982), I-8 (Mojski 1982), x (Niedziałkowska *et al* 1985); II-1 (Klimek 1987b), II-2 (Rutkowski 1987), II-3 (Kalicki, Starkel 1987), II-4 (Gębica, Starkel 1987), II-5 (Snieszko 1985, 1987), II-6 (Sokołowski 1987), II-7 (Mycielska-Dowgiałło 1977, 1987), II-8 (Sarnacka 1987), II-9 (Baraniecka, Konecka-Betley 1987), II-10a (Wiśniewski 1987), II-10b (Florek *et al* 1987), II-11 (Tomczak 1987), II-12 (Niewiarowski 1987b)

1—Vistula reaches studied within the IGCP Subproject 158 A, 2—Warta and Prosna reaches studied within the Subproject 158 A, 3—other detailed studies outside the project, 4—lakes and mires in the valley being important for stratigraphical purposes, 5—dunes in the valley being important for stratigraphical purposes, 6—calcareous tufa in the valley floors, 7—watersheds, 8—state boundary

carbon datings. A proposal for complex palaeogeographical research in the Vistula Valley was formulated in 1967 at a meeting in Cracow which concentrated on the palaeogeography of the Late Glacial and Holocene (Środoń, Starkel eds. 1968). By 1972 a symposium of the INQUA Commission on the Holocene was organized in Poland which enabled results of research carried out in some valleys of the Vistula drainage basin to be presented (Proceedings... 1975). In 1977 the IGCP Project 158 *Palaeohydrology of the temperate zone during the last 15,000 years* was initiated. At the same time a group for studies of the evolution of the Vistula Valley was established as an activity of the Committee for Quaternary Research, Polish Academy of Science. This work needed collaboration of geologists, geomorphologists, and other specialists coming from different scientific centres. Research has been co-ordinated in 22 valley reaches of the Vistula and its two tributaries. Results were summarized in two volumes (Starkel ed. 1982, 1987b), and in two monographs concerned with a portion of the Wisłoka tributary valley (Alexandrowicz *et al* 1981), and with the uppermost section of the Vistula Valley in the immediate Carpathian Foreland (Niedzialkowska *et al* 1985). Views on the evolution of both the upper and middle Vistula and the lower Vistula will be discussed in this chapter.

THE UPPER AND MIDDLE VISTULA VALLEY (TOGETHER WITH THE TRIBUTARY VALLEYS)

In his physiographical description of southern Poland Rehman (1895) drew attention to the active flood-caused transformation of the Vistula Valley floor. Essential progress in the recognition of alluvia has been achieved by authors of the particular sheets of the *Geological Atlas of Galicia*. As long ago as 1894 the Holocene (alluvial) valley floor in the surroundings of Cracow was mapped by Zaręczny. Later on Łomnicki (1895—1903) and Friedberg (1903) ascribed a postglacial age not only to the low flood-plain, but also to the periodically inundated 4—8 m terrace occupying the whole valley floor. The latter consists of gravel and sand overlain by alluvial loams ("mada"), the Holocene age of which is documented by numerous black oak trunks, peat intercalations, snails, and fresh cutoffs which occur on the terrace surface. In 1914 a tundra flora was found by Żmuda at Ludwinów at the level of the present valley floor. In the San Valley both Holocene floras and a Dryas flora have been recognized by Kulczyński (1932). Tree trunks were also discovered by Teisseyre (1938). Immediately after the Second World War the view prevailed that the high flood-plain (or bottom terrace) consists mostly of alluvia dating from the last glacial, and that only the topmost "mada" and locally washed sands are Holocene in age. On the basis of Kulczyński's findings and of the superposition of "mada" on the Late Glacial lacustrine sediments at Roztoki (Szafer 1948) Klimaszewski (1948) gave a general character to his view: in the Carpathians and the mountain foreland the higher loess-capped terrace was believed to belong to the Middle Polish Glaciation.

Upstream of Warsaw Ludwik Sawicki (1930) described Late Glacial dunes, with archaeological sites which occurred on the supra-flood terraces in the middle Vistula Valley.

By 1952 Środoń returned to the view that the sheets lining the valley floors within the Vistula catchment are of Holocene age. Środoń also recognized the numerous black oak trunks as evidence of flood occurrence in Subatlantic times.

In 1955 there were published the results of detailed studies made by Pożaryski in the Vistula gap in the Polish uplands. Three Late Glacial erosional steps and two Holocene alluvial sheets interrupted by peat and alluvial loams of differing age have been recognized there. In the Wisłoka Valley, and subsequently in other valleys a sequence of inserted Late Glacial and Holocene alluvia was found by Starkel (1957, 1960). Channel deposits dating from the Allerød, Atlantic and Subatlantic times were distinguished there. Doubt was thrown upon the age of the 15—20 m terrace on the Vistula which was believed to date from the Middle Polish Glaciation. It appeared that this terrace belongs to the earlier parts of the Last Glacial (Jahn 1957; Środoń, Starkel 1961). This terrace is capped either with loess or with younger Pleniglacial alluvia (Środoń 1965; Laskowska-Wysoczańska 1971; Mamakowa, Starkel 1974). In the mountains the latter sheet passes into the supra-flood-plain, and not into the valley floors. This plain is composed of solifluctional covers which interfinger with alluvia (Klimaszewski 1958; Starkel 1960).

Within the upland belt much attention was paid to deposition resulting from forest clearance in the tributary valleys (Klatka 1958, 1968), evidence of which is provied by the medieval (Nakonieczny 1975) black oak horizons (Lindner 1977), and by flood-deposited "mada" horizons in the surroundings of Cracow (Radwański 1972). The archaeological method was successfully employed to date a dune which developed on bar deposits of the Vistula at Całowanie (Schild 1969). The formerly greater extent of the floods in historical times has been stated in the surroundings of Warsaw (Biernacki 1975).

In 1967 there appeared the work of Falkowski (short English version in 1975) who found the alluvial loams to be of differing age in the Vistula gap. He also described various types of braided channels, and expressed the view that channels changed from braided in the Pleniglacial through meandering in the Late Glacial (with a short-lived tendency toward braiding during the Younger Dryas) to braided channels in the last centuries. Further progress in the investigation has taken place with the recognition of a transitional phase of Late Glacial large palaeomeander formation (comp. Szumański 1972, 1983; Kozarski, Rotnicki 1977; Alexandrowicz *et al* 1981). Evidence of the reactivation of fluvial activity and of excessive flood occurrence around 8.5—7.7 ka BP (Ralska-Jasiewiczowa, Starkel 1975; Mamakowa, Starkel 1977) is provided by sites located in the San and Wisłoka tributary valleys. Several meander generations and undisputable channel avulsions have been described from the Vistula Valley upstream of the River Raba mouth (Starkel

1967; Bzowski 1973) and from the surroundings of Tarnobrzeg (Mycielska-Dowgiałło 1977). Both channel avulsions and aggradation tend to indicate subsidence. Such movements were believed to be documented by a gravel-filled channel being 50 m deeper than the bed of the present Vistula (Połtowicz 1967). Recently it appeared that such a deep channel is not present.

Views on the age of valley deepening by the end of the last glacial vary widely. By 1960 the existence of channels deeper than the beds of the present rivers, which contain undated Allerød alluvia, was accepted by Starkel. In the middle San Valley a cutoff deeper than the bed of the present river is filled with organic deposits dating from the Allerød onwards (Mamakowa 1962). In the Wisłoka Valley erosional benches dating from the Allerød decline time and from the Younger Dryas have been found. On this basis the view has been expressed that valley deepening which proceeded by stages reached down to 3—5 m above stream channel during the Late Glacial (Alexandrowicz *et al* 1981). Similar conditions prevailed in the intramontane Orawa—Nowy Targ Basin containing an erosional terrace, with a Late Glacial peat (Klimaszewski 1961). Some authors still defend the view of the pre-Holocene age of the valley deepening (Jersak 1976).

Other explorations which have been initiated by the work of Falkowski (1967) focused upon channel changes that took place in the last centuries. Amongst others, Trafas (1975) assessed the channel downcutting from the middle 19th century onward when channel correction was undertaken on the Vistula. Both aggradation rates and the course of channel changes that have taken place since the 18th century were analysed by Klimek (Klimek, Starkel 1974). Szumański (1977) showed that the low flood-plain of the San corresponds to its dissected braided channel which antedates the engineering works.

Since 1977 investigations integrated at the conclusion of the IGCP Project 158 have been extended. There have received due attention the climatically-conditioned phases of both erosion and deposition of the inserted valley fills, channel avulsions (Alexandrowicz *et al* 1981; Starkel ed. 1982, 1987b), and phases of man-induced aggradation from the period of Lusatian Culture onward (Klimek 1987b), from the Roman period onward (Kalicki, Starkel 1987), and from the Middle Ages onward (Alexandrowicz *et al* 1981; Niedziałkowska *et al* 1985; Kosmowska-Suffczyńska 1983) have received due attention. Analyses of both heavy metals (Klimek, Zawilińska 1985; Rutkowski 1987) and coal clasts (Rutkowski 1986) have been employed to recognize the youngest deposits.

In the upland tributary valleys aggradation continued throughout the Holocene. Deposits only changed from chemical and biogenous to mineral ones (Śnieszko 1985). The first phases of deluvia accumulation correspond to the early Neolithic period (Wasylikowa *et al* 1985). It was possible to correlate the deposits corresponding to phases of the reactivation of fluvial processes with tufa profiles (Szulc 1983; Jersak, Śnieszko 1987; Pazdur *et al* 1988, in press).

Although the programme does not include the examination of calcareous tufa and of profiles of both lacustrine deposits (at Roztoki; Wójcik 1987) and peat (at Tarnawa; Ralska-Jasiewiczowa 1980), these profiles are important to the reconstruction of the activity of the fluvial system.

New data that have been obtained for the whole Vistula Valley confirm the view that downcutting reached the bed of the present Vistula or perhaps deeper at the latest during the early Allerød (Niedziałkowska *et al* 1985; Kalicki, Starkel 1987). The picture of the valley evolution is clearer. The rhythm of climatic changes is being modified by both tectonic and anthropogenic factors.

THE LOWER VISTULA VALLEY

The first works on the geomorphological evolution of the lower Vistula Valley have been done at the beginning of the 20th century (Jentzsch 1901, 1911; Keilhack 1904; Sonntag 1916). Jentzsch who discussed the genesis of the Grudziądz Basin suggested that on retreat of the inland ice an ice-dammed lake occupied the basin. Subsequently three fluvial terraces were created there. He also expressed the view—like Keilhack and Sonntag—that in the Toruń Basin a glacial lake formed at 70—75 m a.s.l. during the Pomeranian phase. The water at first drained *via* the Noteć—Warta ice-marginal channel ("pradolina"), later on the Vistula breached northward.

The concept of existence of a glacial lake in the Toruń Basin was questioned by S. Samsonowicz (1924) and Galon (1929) who also discussed the origin of the Toruń Basin. Like Jentzsch, he distinguished three terraces (upper, middle, lower) there.

In 1924 Lewiński came to the conclusion that after the last inland ice had withdrawn from the vicinity of Włocławek, a readvance of the ice resulted in the damming up of a lake being accompanied by the deposition of clay and till.

In the 1920s the developments in detailed studies of the evolution of the lower Vistula Valley were preceded by a discussion of both genesis and age of the varved sediments. In 1922 Lencewicz discovered varved clay overlain by till at 70—80 m a.s.l. in the Płock Basin. Later on he found varved sediments at other sites in the Vistula Valley extending between the Płock Basin and the Toruń Basin. In 1927 he expressed the view that the varved clay was laid down in marine and brackish water which extended up the Vistula Valley as far as Warsaw. The interglacial age of the varved sediments was also accepted by Lewiński (1924a, 1924b).

On the contrary, Limanowski (1922) at first argued that at Chełmno the varved clay was a sediment of a glacial lake as the penultimate inland ice retreated to the north. However, he found that the clay is younger, Last Glacial in age.

According to Samsonowicz (1924), in the Vistula Valley the formation of glacial lakes took place during the advance and retreat of the successive ice sheets. Both the Włocławek and Warsaw lakes were ponded during the retreat of the second ice in Poland.

Błachowski (1939) found that the varved clays do not continue at one level from Toruń to Modlin, since between Płock and Modlin the upper clay belongs to an earlier glaciation.

The history of the varved clays in the vicinity of Włocławek was indicated by the work of Galon and Passendorfer who found morainic lag deposits on the clay surface, and subsequently by Mojski (1960) who found till in some places. According to Mojski, the clays previously mentioned are the oldest deposits dating from the Vistulian Glaciation. During the advance of the last inland ice clays were deposited in the Płock Basin. However, Łyczewska (1960) and Urbaniak (1965) argued that the clays were laid down as the Middle Polish ice sheet retreated to the north.

Irrespective of the problem of both age and amount of the varved clay horizons found in the Vistula Valley, it can be concluded that their occurrence indicates the old age of the Vistula Valley. During the successive glaciations conditions were favourable for the deposition of varved sediments there.

A work summarizing the result of studies on the evolution of the entire lower Vistula Valley extending between the Warsaw Basin and the Żuławy, *ie* the Vistula River Delta during the retreat of the last inland ice is as yet lacking. By 1927 the only publication dealing with the geomorphological evolution of the long reach of the Vistula Valley connecting the Warsaw Basin with the Toruń Basin was the work of Lencewicz (1927). He suggested that the particular basins, *ie* the Warsaw Basin, the Płock Basin, and the Toruń Basin at first functioned independently. The connecting gaps are younger features. Each of the basins contained a set of four terraces. Both upper terrace systems (IV and III) are considered to be Pleistocene in age, both lower systems are of Holocene age. Terrace IV fades out in each of the basins. According to Lencewicz, in the Warsaw Basin this is the Garwolin terrace (45 m above Vistula level), in the Płock Basin it is the Ciechomice terrace at 90—92 m a.s.l., and in the Toruń Basin it is the terrace at 70—75 m a.s.l. The III terrace system, developed only after the connection with the particular basins, was established. As the Vistula escaped westward at this level *via* the Noteć—Warta "pradolina", the ice expanded as far as the Płock Basin. This valley glaciation is documented by lakes, moraines, and eskers there. The Vistula is believed to have flowed northward beneath the ice during this oscillation. The above view was criticized, amongst others, by Galon (1929). Terraces developed in the Vistula Valley were traced by Kondracki (1933) on the Bug River.

Galon (1934) was the author of the second synthesizing view on the geomorphological evolution of the Vistula Valley extending between the Toruń Basin and the Żuławy. Above the flood-plain there rise eight terraces. The upper terrace splits into three steps (V c—41 m, V b——37 m, V a—32 m above Vistula level), the middle terrace splits into two steps (the higher middle step is at 25—27 m and the lower middle step is at 17—22 m), the lower terrace is 10—15 m high. Both supra-flood terraces are at 5—9 m and 3 m. The author argued that in the Toruń Basin and in the Noteć—Warta "pradolina" the upper terrace (V c) extends into the Vistula Valley near Grudziądz. Thus, the terrace under review was the first bifurcation terrace. The bifurcation phase was believed to have lasted until the Allerød during which the lower middle terrace was created. On the basis of later researches, carried out in the Brda Valley which empties into the Toruń Basin, Galon (1953) distinguished eleven terraces (I—XI) there. The sandur terrace (XI) was related to moraines of the Pomeranian phase. The X terrace was believed to represent a transitional feature. According to Mrózek (1958), Niewiarowski and Tomczak (1973), the morainic plateaus adjacent to the Toruń Basin are locally bordered by corresponding terraces lying 75 a.s.l. and 80—82 m a.s.l. Galon (1961) was of the opinion that at both highest levels the confluent meltwaters and extraglacial Vistula waters escaped exclusively westward *via* the Noteć—Warta "pradolina".

The 1960s are marked by the appearance of numerous geological papers which also dealt with the geomorphological evolution of some reaches of the Vistula Valley. Domosławska-Baraniecka and Mojski (1960) and Mojski (1960) interpreted the geomorphological events which occurred in the western part of the Płock Basin. The above authors noted the occurrence of one accumulational terrace and two erosional ones there. They also set up the hypothesis that after the last inland ice had retreated from the Płock Basin the latter has beeen occupied by dead ice. The high watershed hindered the northward drainage of the area. According to Mojski, the mantled dead ice survived in the Płock Basin for a long period. There is disagreement as to whether the fluvial relief developed earlier in the southern part of the basin than in its northern part.

By 1961 and 1967 Różycki suggested that as the Middle Polish ice retreated at the Wkra stage, a glacial lake was established in the Warsaw Basin in which clay was deposited. This is building the Radzymin—

Błonie level today. The creation of three accumulational terraces was correlated with the three phases of the Vistulian Glaciation. These terraces are known as the Otwock terrace (II c), the Falenica terrace (II b) and the Praga terrace (II a). The Otwock terrace reached as high as the Radzymin—Błonie level.

Progress has also been made by the results of geomorphological and geological research in the Vistula Valley in the vicinity of Wyszogród (Laskowska-Wysoczańska 1964; Ruszczyńska-Szenajch 1964), of Dobrzyków (Makowska, Skompski 1966), of Ciechocinek (Kucharski 1966), and of Płock (Skompski 1961). There also appeared the first palynological datings on biogenous deposits found in the Vistula Valley (Borówko-Dłużakowa 1961; Kępczyński, Noryśkiewicz 1968). Borówko-Dłużakowa showed that on the supra-flood-plain, south of Płock the organic sediments began to accumulate from the Preboreal onwards. On the basis of research by Kępczyński and Noryśkiewicz, Roszko (1968) stated that the organic fill of Lake Fletnowskie occurring on the IV terrace in the Grudziądz Basin dates from the Younger Dryas. She also expressed the view that the IV terrace belongs to the same period. These important datings made it possible to date precisely the terraces developed in the lower Vistula Valley.

In 1969 Skompski published his work on the geomorphology and geology of the eastern part of the Płock Basin. This work includes numeorus valuable data on the stratigraphy of the Quaternary deposits, whereas his views on the origin of the higher terraces are open to doubt. He argued that the Ciechomice level corresponds to the highest sandur terrace (XI) in the Toruń Basin. Thus, he accepted Galon's opinion that between Warsaw and Toruń the "pradolina" functioned already in the Pomeranian phase. Skompski proved that in early Holocene times the Vistula cut down to the lowest level of the present flood-plain.

At the same time, in the vicinity of Warsaw, work of Biernacki (1968, 1975) has opened up possibilities for investigating the rates of alluvia deposition on the flood-plain of the Vistula by employing information from archaeological sites and radiocarbon datings. He noted the varying course of "mada" deposition due to hydrological changes in the historical period (15th to 20th centuries).

In the early 1970s there appeared works discussing the problems of the youngest activity of the Vistula in the vicinity of Toruń (Tomczak 1971), channel changes (Koc 1972), and the evolution of the Vistula Valley in the surroundings of Toruń (Niewiarowski, Tomczak 1973). Eleven terraces were distinguished there by Niewiarowski and Tomczak. Eight of them (XI—IV) were believed to have been formed in Pleniglacial decline times and during the Late Glacial. The lowest terrace is Holocene in age. Progress has also been made by geomorphological investigation which has been carried out for many years in the Grudziądz

Basin (Drozdowski 1974) and in the Vistula gap connecting the Płock Basin with the Toruń Basin (Wiśniewski 1976a, 1976b). According to Drozdowski, the Grudziądz Basin persisted from the penultimate glaciation. This landform was occupied by dead ice from the Middle Vistulian onwards until the end of the Late Glacial. Later on Drozdowski and Berglund (1976) presented new radiocarbon datings on organic deposits which showed that only the flood-plain in the Grudziądz Basin is of Holocene age. Wiśniewski, who studied the escape routes of the meltwaters and the terrace system, as well questioned the simultaneous escape southward of the sandur waters and the escape nortward of both fluvial waters and meltwaters by the way of the Vistula Valley in the Pomeranian phase. The problem of escape routes of water from the Płock Basin during the Last Glacial was also discussed by Kotarbiński and Urbaniak-Biernacka (1975). Meltwaters are believed to have escaped south-eastward *via* the Warsaw—Berlin "pradolina" in the Leszno and Poznań phases, whereas in the Kuyavy—Dobrzyń phase they already could escape into the Toruń Basin.

In the Warsaw Basin revision was made of the age of the Warsaw glacial lake (Janczyk-Kopikowa 1975; Karaszewski 1975). Organic deposits dating from the Eemian interglacial were found beneath the varved clays there. Consequently, a Vistulian age was ascribed to the clays which built up the Radzymin—Błonie level. A similar conclusion was reached by Sarnacka (1982).

A further phase of geomorphological enquiry began after 1978 within the IGCP Project 158. In 1982 there appeared publications dealing with the Vistula Valley evolution between Włocławek and Ciechocinek (Wiśniewski), between Toruń and Solec Kujawski (Tomczak), between the Chełmno Basin and the Grudziądz Basin (Drozdowski), and in the Vistula River Delta (Mojski) — see Starkel ed. 1982. Progress has been made towards the geomorphological evolution of the Vistula Valley, and numerous valuable datings have been obtained from biogenous deposits found on both the flood-plain and supra-flood terrace. A number of datings were employed in later times (Manikowska 1982; Wiśniewski 1985). This evidence indicates that between the Warsaw and Płock Basins the Vistula reached the level of the present flood-plain already in decline times of the Pomeranian phase, and at least prior to the Allerød downstream of Fordon.

The role played by crustal movements in the creation of the lower Vistula Valley is controversial. Since terraces in the Noteć Valley are not warped, Niewiarowski (1983) argued that the Kuyavy—Pomeranian Anticlinorium was stable throughout the postglacial period. It is probable that this anticlinorium became slightly downwarped. Niewiarowski also accepts downwarping of the marginal depression which may be responsible for drainage divertion of the Vistula into the Toruń Basin.

Brykczyński (1986) discussed the evolution of the valley network in the Polish Lowland. He suggested that the pre-Pleistocene Vistula Valley followed westward the axis of the Warsaw—Berlin "pradolina". On the other hand, at that time the Vistula might have entered the Płock Basin. Thence the waters also drained westward, evidence of which is provided by a parallel-running fossil valley. According to Brykczyński, west of the Toruń Basin, before the Eemian interglacial the Proto-Vistula Valley at first followed the Noteć—Warta "pradolina" and then turned northward. The Vistula divertions are believed to have been caused by halokinetic movements within the Kuyavy—Pomeranian Anticlinorium, and by glacial erosion of the Baltic depression.

In 1987 there appeared the second volume devoted to the evolution of the Vistula Valley (Starkel ed. 1987b). This volume includes papers on the lower valley reach. Both Vistulian and Holocene fluvial fills of the Warsaw Basin were described by Baraniecka and Konecka-Betley who reexamined the age of Różycki's terrace system. TL datings on the varved clays suggest a Middle Vistulian age of the Warsaw glacial lake. Between the Leszno phase and the end of the Late Glacial the Otwock terrace was inserted, in the Bølling the Falenica terrace was created, and in the Allerød the Praga terrace came into existence. In this volume Wiśniewski discusses the evolution of the Vistula Valley between the Warsaw and Płock Basins. Florek and Mycielska-Dowgiałło studied the valley reach contained between Kępa Polska and Płock, Tomczak—in the Toruń Basin, and Niewiarowski—in the Unisław Basin. These papers contain a significant number of new radiocarbon datings on the organic deposits. The results that have been obtained allow the first synthesis of the geomorphological evolution of the lower Vistula Valley to be elaborated.

METHODS OF STUDY

In this chapter methods of study are discussed which have been employed in the analysis of landforms, of deposits, and of organic remains found in the Vistula Valley. On the results obtained the reconstruction of the evolution of the Vistula Valley which took place during the last 15,000 years is grounded.

GEOMORPHOLOGICAL METHODS

The record of landforms occurring in the Vistula drainage basin is based on geomorphological and geological mapping on the scales of 1 : 10,000 and 1 : 25,000. The resulting maps were generalized to scales of 1 : 200,000—1 : 500,000 (*Przeglądowa*... 1980; Mojski 1980). Recently air photographical evidence has been used on a large scale to recognize the fluvial landforms (Falkowski 1975 and others).

The landform parameters which have been described and compared with one another include the dimensions of the fluvial forms of differing age (length, height, depth) and their shapes (sinuosity, curvature radii).

Attention was drawn to the nature of both the modern stream channel and the adjacent flood-plain in each of the valley segments, examined. Information from early topographical maps (*eg* Trafas 1975; Szumański 1977; Tomczak 1971) has been employed to reconstruct channel parameters and changes, and the evolution of the flood-plain during the last 200 years. The rates of channel deepening were obtained from analyses of the trends toward minimum water stages of the main rivers draining the Carpathian Foreland (Trafas 1975; Klimek 1983).

Terrace systems have been described in the particular valley reaches. Comparison of the terrace heights above stream level (or above sea level), and of the sedimentary sequences and ages allowed us to connect the terrace remnants. The experience gained by Galon (1934), Klimaszewski (1948), and others has been used. The height criterion was applied with considerable caution because in many cases it was treacherous (Alexandrowicz *et al* 1981; Manikowska 1985). Greater attention was, therefore, drawn to the microrelief of the flood-plain and terrace surfaces. The inventory examined included natural levees, flood basins, straight, meandering and braided palaeochannels which vary in size, crevasses and crevasse splay deposits extending in tongues, alluvial fans built up by the tributaries, and dune ridges. The mutual relation of the fluvial landforms occurring in the major valley to those within the side-valleys, and to valley sides allowed us to distinguish different terrace generations (Churska 1966; Alexandrowicz *et al* 1981). Analysis of the different palaeochannels varying in size has opened up possibilities for identifying the different generations of inserted alluvial fills of differing age. These fills are forming the apparently uniform Holocene alluvial plain (Falkowski 1975; Alexandrowicz *et al* 1981). Furthermore, in certain valley reaches the occurrence below alluvial loams of Late Glacial dune ridges suggests tendencies toward subbsidence (comp. *Geomorphological Map of Poland* 1980).

Special attention was paid to parameters of the palaeochannels which have been dated either by information from early topographical maps or by biogenous deposits. In some cases this enables us to estimate the palaeodischarges (Trafas 1975; Starkel *et al* 1982; Gębicka, Starkel 1987). However, it should be noted that the present authors less went into detail of both investigation and reconstruction than the researchers working in the adjacent valleys of the rivers Prosna (Rotnicki 1983; Rotnicki, Borówka 1985) and Warta (Kozarski 1983).

LITHOLOGICAL AND SEDIMENTOLOGICAL METHODS

In studies of the evolution of the Vistula Valley the analysis of alluvia has been adopted to define both facies and ages of the fluvial deposits, as well as the geographical milieu in which the river in question developed. Methods of study carried out by different authors vary widely in scope and detail because of the frequently different approaches to the areas of investigation and the lack of deep excavations which allow the structural properties[1] of the sediments to be measured.

In almost all of the valley reaches examined channel facies deposits, overbank deposits (together with natural levee deposits), and abandoned channel deposits have been recognized. Less emphasis has been given to the structural properties of deposits such as the type of bedding (cross-bedding, horizontal bedding, climbing—ripple lamination *etc*—Biernacki 1968, 1970; Mycielska-Dowgiałło 1978, 1987; Falkowski 1982; Rutkowski 1987; Cichosz-Kostecka *et al* 1986; Florek *et al* 1987; Klimek 1987b; Sokołowski 1987). In some works the dispersion of the dips of laminae and the size of layers in the horizontal and vertical directions were considered (Mycielska-Dowgiałło 1978, 1987; Cichosz-Kostecka *et al* 1986; Florek *et al* 1987; Rutkowski 1987). These data indicate both the channel pattern (braided, meandering) and the competence of the river. Attention was drawn to either uniform or heterogeneous composition of the whole sedimentary series of a given facies, and to the nature of the contact between the series and facies. This contact may be either sharp or gradual indicating the interfingering of deposits (Florek *et al* 1987; Gębica, Starkel 1987; Kalicki, Starkel 1987; Sokołowski 1987). Channel lag deposits enriched in boulders and gravels are a sign of the vertical extent of alluvia reworking.

Fluvial sediments may include deposits belonging to associated synchronous facies (*eg* slope sheets interfingering with alluvial deposits—Mycielska-Dowgiałło 1978; Starkel *et al* 1982; Florek *et al* 1987), permafrost structures beginning at different levels in the sediment (Mycielska-Dowgiałło 1967), and overtopping postsedimentary features such as alluvial fan sheets, slope sheets and aeolian deposits (Mycielska-Dowgiałło 1978; Starkel *et al* 1982; Tomczak 1982, 1987; Kamińska *et al* 1987; Niewiarowski 1987b).

In many cases the textural properties of deposits were discussed. Based on the grain-size analysis and indices that have been obtained from the Folk and Ward formulae (1957) is the characteristics of the

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[1] The terms structure and texture are defined as follows: structure — mode of grain setting in the sediment, bedding, sedimentary and postsedimentary structures; texture—grain-size distribution, quartz grain abrasion, petrographical and mineralogical composition of deposits (Reineck and Singh 1973; Mycielska-Dowgiałło 1980)

type of deposits which make up the individual facies within the sedimentary series of differing age (Mycielska-Dowgiałło 1978, 1987; Alexandrowicz *et al* 1981; Wiśniewski 1982; Niedziałkowska *et al* 1985; Cichosz-Kostecka *et al* 1986; Niewiarowski 1987b; Rutkowski 1987; Sokołowski 1987; Tomczak 1987). Considering the cumulative curves for samples obtained from the different sedimentary series, one may conclude of their differing degree of sorting, and of the different modes of transportation (suspension transport, saltation transport, traction, in a combined mode).

The second method of textural studies which has been applied in several works is the analysis of quartz grain abrasion of the sand-sized fraction by means of the Krygowski automatic graniformameter (Krygowski 1964; Mycielska-Dowgiałło 1978, 1987; Alexandrowicz *et al* 1981; Niedziałkowska *et al* 1985; Florek *et al* 1987; Niewiarowski 1987b). However, the results obtained are incomparable, since different fractions (0.5—0.8 mm and 0.8—1.0 mm) have been analysed. The results suggest that sedimentary series of differing age are characterized by a varying abrasion of the quartz grains. The maximum appeared in different grain-size classes. What strikes us is their great similarity to the abrasion of grains of different fractions forming aeolian deposits of differing age.

The third method used to identify the fluvial deposits of differing age and of different facies was the heavy mineral analysis (Mycielska-Dowgiałło 1978; Rutkowski 1986, 1987; Cichosz-Kostecka *et al* 1986; Florek *et al* 1987; Sokołowski 1987). This method allowed us to distinguish between channel deposits of the braided river and those of the meandering river. In the latter, the repeated washing and redeposition of deposits causes the successively higher lying deposits to become enriched in mineral components being more resistant to mechanical abrasion. This phenomenon has not been observed in the braided river channels.

Occasionally, the calcium carbonate content, which may be an age indicator, was analysed (Mojski 1982; Florek *et al* 1987; Śnieszko 1987). The $CaCO_3$ content depends on the processes prevailing in a given relief type rather and on the geological structure than on specific climatic conditions.

Another distinguishing criterion between the sedimentary series of a periglacial river dating from the Last Glacial and that of the Holocene river are large blocks, several metres in diameter, being scattered in the periglacial deposits. The Holocene series are characterized by the presence of biogenous matter, especially of black oak trunks. The blocks that occur far off the slopes did not fall in from the slopes. They give evidence of both marked thickness and bearing power of floes floating on the periglacial rivers during the Last Glacial (Mycielska-Dowgiałło 1967).

Periods with meandering rivers and reduced flood activity are indicated by soil processes which developed on the alluvial loams ("*mada*"). These may contain artefacts bearing witness to human occupation of the area (Falkowski 1967, 1975, 1982; Tomczak 1982, 1987).

PETROGRAPHICAL AND MINERALOGICAL METHODS

Methods of gravel study. The petrographical composition of gravels was examined on particles shaken through sieves with square holes corresponding to divisions of the *phi* scale 2—4—8—16...*n* mm. In each fraction 300 grains were analysed. In the case of the coarsest fraction, when it was impossible to obtain the right amount of grains by further sieving or collecting the material in the exposure, a smaller amount of grains was studied. The problem of the statistically significant confidence level of the results obtained has been discussed by Rutkowski (1977). The petrographical composition of particles coarser than 16 mm was analysed in the field, whereas laboratory analyses were made of the remaining particles. Each fraction was regarded as 100 per cent. The results were given in per cent of the total amount of particles. In the case of gravels the components of which show a similar density (such gravels do prevail in the upper Vistula Valley) similar results may be obtained by using the weight per cent (Rutkowski, Zuchiewicz 1987). However, the method employed by the present author is a quicker way.

Methods of study of both mineral composition and concentration of heavy metals in the Vistula "mada"[2]. In the examination of the mineral composition of the Vistula "mada" the X-ray diffractometer DRON 1.5 has been employed by using the filtered CUKα radiation. The mineral composition of particles finer than 60μ and of the clay-sized fraction (finer than 2μ) has been determined by sedimentation methods. In the identification of minerals occurring in the latter fraction standard X-ray methods were used. The technique of examining samples oriented and saturated with glycol was applied.

Concentration of heavy metals (zinc, lead, cadmium, nickel, copper, and chromium) was assessed in the fraction finer than 60 μ that has been separated from the "mada", and in the fraction finer than 2 μ contained in the bottom deposits of the upper Vistula. Concentration of heavy metals was also determined in the bulk samples of the natural and »industrial "mada"«. After the metals had been extracted with

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[2] Translated by the author

concentrated HNO_3 for two hours at 130°C, the concentration of metals was assessed in the solutions by using the method of atomic absorption spectroscopy.

PEDOLOGICAL METHODS

It is generally understood that stratified alluvia and deluvia are the parent material which determines the kind of soil that is present in a river valley. The soil formers are mineral and organic materials, together with the embedded soil organisms. These were derived from the soils which are continuously developing on the adjacent morainic plateaus, and on the upland and mountain ridges within the catchment. The above materials are being mobilized and displaced by natural processes known as soil erosion. Its intensity shows spatial and temporal variations which depend chiefly on climatic changes, on the reduced or accelerated activity of natural factors, and on human interference (Jenny 1983; Kowalkowski 1988). Some anthropogenic deposits may pollute the valley environment (*eg* Czarnowska *et al* 1983; Chudecki, Niedźwiedzki 1987).

During the last 15,000 years changes in the hydrological regime (Starkel 1983a) may well have been associated with the multiple selective redeposition of soil materials within the fluvial valleys. However, even resegregated fluvial sands kept numerous pedogenic properties (Kowalkowski, Starkel 1977; Okruszko 1969; Kowalkowski, Mycielska-Dowgiałło 1983).

Thus, deposits which occurred on the fluvial terraces show properties of living soils. In the litho- and pedogenic age sequence the earliest Pleistocene deposits were formed of material which was derived from the early Pleistocene soils, and even from pre-Pleistocene soils. However, the youngest Holocene deposits were formed of materials of differing age which have been derived from the Pleistocene and Holocene soils. For the most part, the age of soils that developed on the fluvial terraces is inversely proportional to the age of their parent material. This is exemplified by the known old alluvia and deluvia which formed of either interglacial or interstadial well developed parabrown soils at Podegrodzie and Brzeźnica in the Wisłoka Valley (Alexandrowicz *et al* 1981), and of alluvial sand and loess-like dust in the Warsaw Basin (Baraniecka, Konecka-Betley 1987). These soils have been dated at 41,800 and 22,450 years BP. The older and the more changed pedogenically are the terrace-forming deposits the greater is their resistivity to the development of new pedogenic properties, the longer do they preserve the original soil properties.

Different litho- and pedochronostratigraphical properties are characteristic of soil assemblages in the vertical section and of soil palaeocatenas in the horizontal section. Furthermore, alluvial and deluvial deposits include such indicators as cryogenic structures, malacofauna and other organic remains which may have been redeposited, together with the soil. The final phase of their deposition is always determined by the accumulation of a younger layer on their surface. Both proper recognition and classification of the soils that are present on the fluvial terraces are only possible by the application of different complex methods.

PALAEOBOTANICAL METHODS

Late Glacial and Holocene sediments covering the valley floors contain plant remains which include organic deposits (peat, gyttja) organic humus, macrofossils, pollen and small organisms, *eg* diatoms). This short chapter is not a guide to the palynological method and other methods which could be used. A thorough review of the techniques available has been provided by the *Handbook of Palaeoecology and Palaeohydrology* (Berglund ed. 1986). This chapter has been devised to show how analyses of organic remains may contribute towards more integrated understanding of the fluvial sediments.

Plant remains may indicate the absolute ages of fluvial deposits on the evidence of radiocarbon datings. Continuous sequences at specific locations can provide data on both relative ages and changes occurring in the environment through time. For the most part, fluvial sediments are interrupted by thin organic intercalations which make it possible to reconstruct hydrological conditions, plant assemblages (amongst others, the degree of deforestation), and climatic conditions as well.

On the valley floors rather undisturbed sequences of vegatational changes are found in the fills of closed-basin lakes (oxbow-lakes *etc*), in mires and in soils of dry environments, whereas in the typical channel facies deposits, flood-plain deposits, abandoned channel deposits, alluvial fan deposits and deluvial deposits both macrofossils and pollen have been mostly redeposited by water. Therefore, a fundamental role in establishing the stratigraphy of the alluvial series is played by intercalations of undisturbed organic sediments. On the other hand, plant remains, which are scattered in sediments laid down by flowing water, may better characterize the environment of both transportation and sedimentation.

In the valleys of the Vistula and its tributaries there occur numerous visible and buried palaeochannels in which organic sedimentation took place or just takes place. Its changes tend to indicate shallower water bodies and water table fluctuations, *eg* at Roztoki in the Jasiolka Valley (Alexandrowicz *et al* 1985) and Czarne Błota near Toruń (Noryśkiewicz [in:] Tomczak 1982). Such periods denote periods of flooding during which "mada" was deposited (at Tarnawa in the San Valley—Ralska-Jasiewiczowa 1983b). Most frequently the flood-deposited "mada" interrupted the organic sedimentation which took place in the cutoffs (Tomczak 1982; Gębica, Starkel 1987). In some cases the pollen analysis of peat allows us to detect hiatuses, *eg* the hiatus separating the Allerød layer from the Holocene layer (Szczepanek [in:] Niedziałkowska *et al* 1985). In the lower Vistula Valley terraces also show thaw basins containing biogenous fills, and even lakes which make it possible to date the period of melting out of the buried ice blocks and—indirectly—to date the formation of terraces (Roszko 1968; Ralska-Jasiewiczowa *et al* 1987).

Channel facies deposits may contain macrofossils, *ie* wood fragments, seeds, fruits (these may from "chaff" accumulations located off the current), and whole tree trunks. In the aquatic environment the "chaff" becomes easily destroyed. In general, those accumulations may be synchronous with the deposition of the sediment. There also may occur balls made up of earlier peat and wood fragments (Alexandrowicz *et al* 1981). Tree trunks may be older than the sediment. They may be either redeposited or left *in situ* during the "exchange" of the surrounding deposits. Therefore, the findings of tree trunks should be interpreted with considerable caution (Florek 1982). In a gravel pit at Grabiny on the Wisłoka some redeposited tree trunks which have been dated at around 5900 years BP are encased in a series dating from the early Subatlantic, evidence of which is provided by dates of the surrounding organic "mada" and by pollen analysis of the latter, with high *Abies* and *Fagus* values (Mamakowa [in:] Alexandrowicz *et al* 1981). Numerous accumulations of dated tree trunks indicate periods of flood occurrence (Becker 1982). The dendrochronological method has been successfully employed in the dating of younger Holocene valley fills in the surroundings of Cracow (Kalicki, Krąpiec 1988). Tree trunks hewn by man, which date from the first and second centuries, have also been found there (Kalicki, Starkel 1987).

The flood-plain deposits often contain silty sediments and organic bands. In the case of rapid sedimentation pollen and leaves may be preserved, *eg* in the alluvial fan deposits. This is best exemplified by the Podegrodzie alluvial fan which has been dated at 8400—7500 years BP. It contains stumps. The pollen diagram which was based on a rather good pollen frequency revealed changes not greatly different to those obtained from mire data (Mamakowa, Starkel 1977). Peat horizons preserved in the marginal parts of a flood-plain allow us to distinguish the individual horizons of deluvia due to agricultural activity from the early Neolithic onwards (Wasylikowa *et al* 1985).

In the abandoned channel fills different organic, often redeposited remains may be found. At Podegrodzie on the Wisłoka previously mentioned either presence or lack of pollen that have been derived from the close Miocene rocks made it possible to distinguish phases with a stable regime and phases with a high flood frequency, erosion and sedimentation (Mamakowa, Starkel 1977; Starkel 1983b).

It appears that the palaeobotanical methods employed in the valleys within the Vistula catchment have allowed us to distinguish both series of differing age and phases of differing hydrological regime.

THE MALACOLOGICAL ANALYSIS

Shells of both snails and bivalvia are preserved in a wide range of Quaternary deposits including fluvial formations. The occurrence and degree of concentration of the shells, their state of preservation and composition of the molluscan assemblages depend not only on conditions under which they lived but also on the dynamics of sedimentary environment, on grain-size distribution in the material, on the $CaCO_3$ and organic matter content, on the pH of the sediments, on their porosity *etc.* Because of the great genetic and facial variability of sediments left in the stream valleys, different methods of study must be employed. These include the technique of serial sampling, maceration and washing of the material, and the interpretation of the results obtained. Actuopalaeontological data are also used.

The molluscan assemblages, which are found in the fluvial deposits, may be defined as subfossil parautochtonic thanatocoenoses or allocoenoses and mixocoenoses. In some cases there appear autochtonic thanatocoenoses or necrocoenoses and allochthonous components (Ložek 1964; Alexandrowicz 1988a).

In channel facies deposits, but especially in sand and gravels, with plant remains (wood fragments, branches) molluscan shells are found locally concentrated. Concentration of abundant shells is achieved during peak flows in the loops, in places, where river gradients become disturbed, and at the outlets of side-valleys. Therefore, the recognition of both species and the subfossil malacocoenosis is a difficult task. The assemblage includes chiefly euryecological and rheophilous molluscs, and land snails. The latter are characteristic of environments occurring in the catchment area upstream of the site examined. The proportion of representatives of the particular ecological groups largely depends on the intensity of slopewash in the contributing habitats. Thus, it does not reflect directly the area of total woodland, the percentage of forest--less areas, of moist areas *etc.*

The majority of overbank deposits is represented by mineral and mineral-organic "mada", and by gyttja, silt, and sand which fill in the cutoffs. The "mada" usually contains assemblages of mixocoenosis type. They are marked by a small proportion of water molluscs, and by abundant hydrophilous and mesophilous snails, which indicate the type of habitats prevailing on the valley floor. The most interesting deposits malacologically are those of the oxbows. Characteristic assemblage sequences allow us to reconstruct the successive stages of evolution of the basin of deposition. As a rule, such sequences begin with a water fauna which gradually gives way to the mixed associations, with increasing proportions of hydrophilous, mesophilous, and meadow species. The state of preservation of the molluscan shells mostly depends on the pH of the deposition medium and on the $CaCO_3$ content of the deposits. Gyttja and calcareous silts contain a rich and well preserved fauna. On the contrary, clay, silt, and sand showing a low $CaCO_3$ content include more or less resorbed shells. As a consequence of it, their preparation by washing is impossible. In this case the specimens are identified directly on the rock. As successive layers are stripped off by a scalpel, the earlier identified specimens become destroyed.

Results are presented mainly by constructing the malacospectra of species (MSS) and the malacospectra of individuals (MSI) in Ložek's sheme (1964). Such spectra collected in stratigraphical sequences do well characterize changes in the amount of both species and molluscan schells representing the different ecological groups. Consequently, we receive an image of faunistical changes which sums up two elements: the evolution of conditions under which the molluscs lived and the variability of sedimentary conditions under which the shells were deposited. A more complete interpretation can be obtained by constructing the projection triangle which shows the generalized data of the MSI spectra. This technique allows us to group each assemblage into one of the seven ecological types and, subsequently, to determine the malacological sequence which covers a longer span of time. Each sequence characterizes changes in the palaeogeographical environment that took place in a region or physiographical unit. Zoographical spectra reflecting the dominant influences of continental, oceanic, and meridional centres as well as local elements in the particular developmental phases of the malacofauna are valuable additions to the palaeogeographical interpretation (Alexandrowicz 1988a).

The interpretation of results obtained from the malacological analysis of fluvial deposits and fills of both water bodies and depressions occurring on the valley floors is based on the exact knowledge of the distribution of molluscs in analogous modern environments (Piechocki 1969). Another useful method for reconstructing conditions of transportation, sorting, differentation, sedimentation, and destruction of the shell material is the study of the thanatocoenoses which are being formed today. As a result, such studies are the base of the propoer interpretation of subfossil materials (Wasmond 1926; Alexandrowicz 1988a).

Different types of molluscan assemblages preserved in the Late Glacial and Holocene deposits have been examined in the Vistula catchment. These assemblages do characterize the most important environments, deposits and their sequences. It is thus possible to use broadly the malacological analysis, and to make with much more certainty various stratigraphical, palaeogeographical, and palaeoclimatical reconstructions.

ARCHAEOLOGICAL AND HISTORICAL METHODS

The archaeological and historical methods employed allow us to determine the ages of both deposits and landforms, and to trace the temporal changes the record of which has been disturbed by subsequent channel changes and alluvia reworking.

Archaeological findings, but especially the traces of permanent settlements occurring on the different terrace surfaces indicate that at the time of settlement a given terrace ceased to function as a flood-plain.

It was found that in the different reaches of the Vistula Valley settlements occupied the successively lower terrace flats from the late Palaeolithic, Mesolithic, and Neolithic to as late as the historical period (Biernacki 1975; Koc 1972; Radwański 1972; Tomczak 1987). Many settlements occupied dunes, even point bars on which dunes developed in later times, *eg* a dune at Całowanie (Schild 1982).

The presence in alluvia below the "mada" of cultural horizons is important for stratigraphical purposes. Such horizons do occur from the Neolithic onward (Falkowski 1975) until the Middle Ages (Biernacki 1975; Radwański 1972). A celebrated instance are the sites within the Morava Valley which date from the period of Greater Moravia (Havliček 1983). The distribution of archaeological sites and historical changes in settlement enable Vistula diversions to be documented (Żaki *et al* 1970; Gębica, Starkel 1987). In some cases accumulation was caused by reservoir construction for purposes of the prehistorical metallurgy (Klatka 1958). Findings of single human artefacts in the channel alluvia such as broken pottery, implements and medieval bricks indicate only that the deposit cannot antedate the finding (cf. Starkel 1977b). Archaeological reconstructions of both settlements and forest clearance (Buczek 1960; Kruk 1988) throw light on the origin of thick "mada" and deluvia occurring in many regions (Śnieszko 1985; Wasylikowa *et al* 1985).

Historical methods which employ information from chronicles, maps and cadastral surveys facilitate the study of the frequency of occurrence of extreme events (floods, droughts), and of their consequences and location which may vary in extent. Unfortunately, the whole of the historical data for the Vistula Valley are not yet elaborated (cf. *Wisła*... 1982). From the Middle Ages onward, chronicles include information about flood events which have been listed by Rojecki (*Wyjątki*... 1965).

Detailed analysis of such changes has been undertaken in the surroundings of Cracow (Radwański 1972) and Toruń (Tomczak 1971), and in the Vistula Delta area on the basis of maps dating from the 17th century onward. Information from cadastral surveys was employed to document the Wisłoka diversion near Rzeszów in the 17th or 18th century (Strzelecka 1958). Detailed maps of former Austrian Galicia existing since the middle of 18th century (*eg* Miega 1779—1782) enabled the channel changes of the Vistula to be reconstructed (Trafas 1975). These maps also made it possible to recognize the mechanism of development of both the braided channel and low flood-plain of the lower San (Szumański 1977).

Documentary records and early maps also inform in detail of the location of fords, dams, water mills, and harbors. These data also allow us to reconstruct the past activity of rivers.

METHODS OF ABSOLUTE DATING[8]

There are several methods of absolute dating which may be applied in studies of the late Quaternary valley floor. The most frequently used methods include radiocarbon (^{14}C), thermoluminescence (TL), and dendrochronology. The ^{14}C method of dating should be regarded as the basic one in establishing the absolute chronology of environmental changes which occurred during the last 15,000 years. This outstanding position of the ^{14}C method is determined by the common occurrence of organic deposits, and the high accuracy of the ^{14}C dates in the considered interval of time.

The method of radiocarbon dating is based on two fundamental assumptions:

— the ^{14}C concentration in the atmospheric air was constant during the last 10^5 years, it was the same in all living terrestrial plants;

— changes in the ^{14}C concentration in the organic remnants after their burial were due to radioactive decay only (Olsson 1974; Pazdur 1982).

According to commonly accepted recommendations (Stuiver, Polach 1977), all ^{14}C dates should be reported as conventional radiocarbon ages. The definition of the conventional ^{14}C age implies that:

(i) dates are calculated using the Libby value for the halflife of ^{14}C (equal to 5568 years);

(ii) the NBS Oxalic Acid Standard is used as the reference sample of the modern ^{14}C activity;

(iii) dates are reported with respect to the reference year AD 1950 (denoted as BP or more explicitly as conv. BP). The notion of the con-

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[8] Translated by the author

ventional ^{14}C time scale implies that no corrections for past changes in ^{14}C activity are included in calculating these dates.

The radiocarbon dating method was used to date various types of organic materials including wood, charcoal, peat and all types of peaty silts and organic muds, soil, humus and plant detritus, animal and human bones, antler, and other special kinds of organic substances. The chronology of fluvial processes in the Vistula River Valley is based on more than 250 ^{14}C dates, with approximately the same amount of dates in the tributary valleys. In studies of fluvial processes that are taking place in the small tributary valleys of the Cracow Upland special interest was given to the calcareous tufa and their palaeoclimatical significance (A. Pazdur 1987).

During the last 15,000 years the accuracy of the ^{14}C dates is approximately constant, and is equal to *c* 1—2%. This figure is c 10 times better than the accuracy offered by the TL method, so that until now TL dates were scarcely used in studies of the evolution of the Vistula Valley. In most cases contamination of the samples does not influence significantly the results, since the contaminants may be relatively easily removed by appropriate mechanical and chemical pretreatment in the laboratory. The reworked organic matter should be regarded as the most important source of errors of the ^{14}C dates of alluvial sediments. Dating of samples with a low organic carbon content may lead to erroneous results.

The first dendrochronological studies in the Vistula River Basin were performed by Becker (1982). However, intensive studies on fossil oak trunks were recently initiated by Krąpiec in the Vistula Valley downstream of Cracow (Kalicki, Krąpiec 1988). It should be expected that those studies supported by ^{14}C datings and dendrochronological studies on living oaks in the Niepołomice Forest and at other localities (Bednarz, in press) will lead to significant improvements and refinements of the chronology of fluvial processes and their palaeoclimatical interpretation.

THE CHRONOSTRATIGRAPHICAL BASE

In the individual valley reaches of the Vistula and its tributaries the stratigraphy of deposits and phases of both erosion and sedimentation have been determined on the basis of lithostratigraphical, morphostratigraphical, and biostratigraphical criteria, and of the absolute chronology as well. In particular, the radiocarbon method has been of great importance.

The morphostratigraphical method was employed in the lower Vistula Valley showing erosional terrace systems, where the radiometric datings are few (cf. Roszko 1968; Wiśniewski 1982; and others). Within

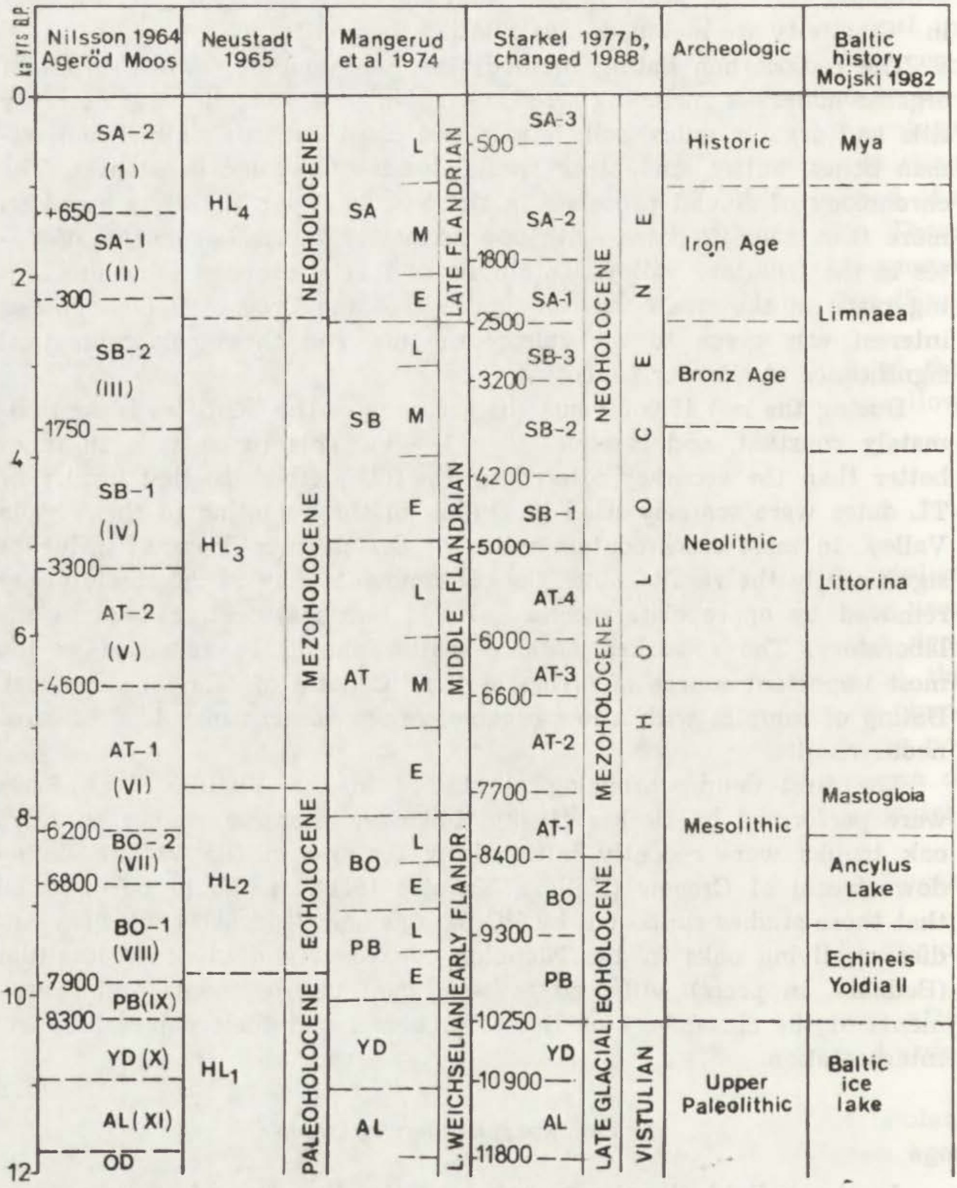

Fig. 4. Holocene stratigraphical divisions used in studies of the fluvial environment in Poland (compiled by L. Starkel)

the inserted terrace sheets the sequence of alluvial facies has been established, especially in the case of meandering rivers. Temporal differences were stated in a horizontal direction rather, and not in a vertical one. Fossil soil horizons and channel lag deposits allowed us to identify both sedimentary and erosional hiatuses. Glaciofluvial and Late

Glacial aeolian deposits are essential indicators of sedimentary environments of differing age.

Organic intercalations including characteristic pollen sequences and macrofossils (Mamakowa, Starkel 1977; Ralska-Jasiewiczowa 1983b) often allowed the age of sedimentation to be defined with fair accuracy. Thus, the ages of both channel abandonment and flood phases have been dated indirectly. Equally, the buried archaeologically-defined horizons are useful in dating the overlying overbank deposits (Radwański 1972; Falkowski 1972).

The chronostratigraphy of alluvia found in the Vistula Valley and in some tributary valleys has been established in detail by radiocarbon datings. Datings on both peaty deposits and oxbow-lake deposits date well the beginning of sedimentation and indirectly the channel abandonment by the river. Attention is drawn to the limitation of tree trunks and macrofossil clusters (branches, seeds) which may be redeposited features. Such data should be proved by other techniques (Awsiuk *et al* 1980). There are only single datings on fossil soils and carbonate deposits.

In this work non-corrected radiocarbon years have been used. Figure 4 shows Starkel's (1977b) stratigraphical scheme plotted against Mangerud's division (Mangerud *et al* 1974), the archaeological scale and the phases of evolution of the Baltic Sea. The regional scheme has been adapted because it gives the sequence of events reflecting the rhythm of both temperature and rainfall variations in Central Europe, and even throughout Europe (cf. Bortenschlager 1982; Starkel 1983a, 1985; Gaillard 1985).

PRESENT-DAY ENVIRONMENT

THE PHYSICAL SETTING

In the evolution of the Vistula Valley and catchment which took place during the last 15,000 years a fundamental part was played by elements inherited from the past and by environmental changes, both of natural and man-made origin, which occurred in this period. Different reaches of the present valley and catchment were either integrated into this system in the different periods or cut off during the glacial periods.

In general, the Vistula and its tributaries flow within two elevated zones of denudation (the Carpathians and Polish Uplands) and within two lowland zones (the Subcarpathian basins and Polish Lowland). These zones are related not only to structure, but also are expressed in the diversity of relief, climate, soils, and vegetation cover.

Finally, the catchment area has experienced a long history of man's activity. Since the Neolithic the most important changes have been those of deforestation and spread of farmland. During the last centuries changes in the course of both runoff and sediment transport are directly influenced by the effects of man on fluvial processes.

GEOLOGICAL STRUCTURE AND MORPHOLOGY

The Vistula Valley is underlain by rocks of the youngest Alpine structural stage whose ages are Cainozoic and, locally, Mesozoic. However, the foundation of the present valley, its earlier evolution and morphology greatly depend on both distribution and behaviour of the pre-Alpine structures from the Mesozoic to as late as the present time (Mojski 1980). This relationship is illustrated by the distribution of the main structural units against which the Vistula Valley shape and direction are plotted (Fig. 5).

Among the Alpine structures, the Carpathian Foredeep and the marginal depression are being used by the Vistula Valley. These areas show tendencies toward subsidence being favourable for valley formation and persistence. In both units the Vistula Valley follows the long axis. This suggests negative crustal movements, evidence of which is provided by

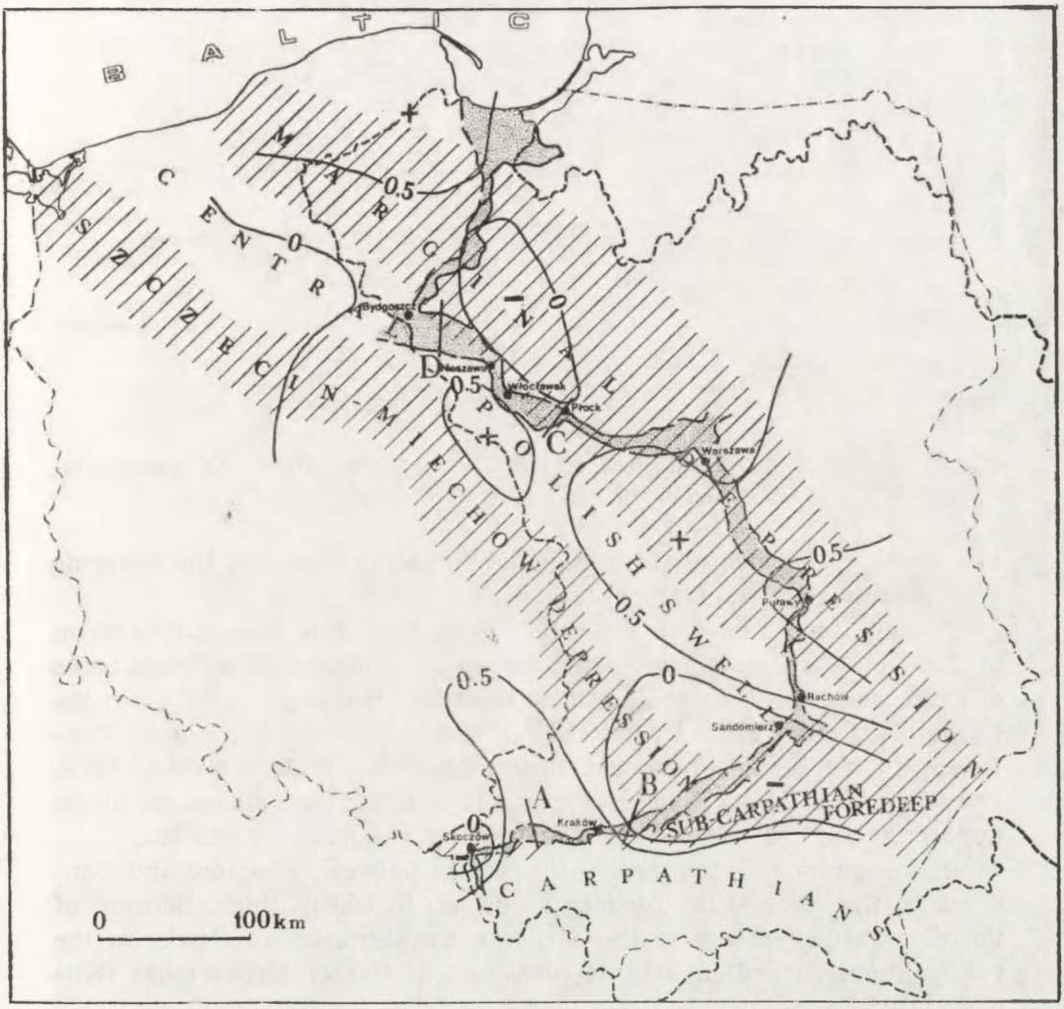

Fig. 5. The Vistula River Valley against the background of the main structural units of Poland

Dotted areas—the Vistula River Valley; diagonal lines—subsiding tectonical units; 0 and 0.5 isolines-magnitude of present-day movements of the earth crust [mm/yr] (tectonics acc. to Znosko 1968, simplified; isolines acc. to Liszkowski 1982); A,B,C, and D—geological cross-sections (see Fig. 7)

the picture of the absolute rates of earth movements of the present day (Liszkowski 1982; Fig. 5). In both units movements exhibit a negative sign, exceeding 0.5 mm/yr in the Carpathian Foredeep. In the marginal depression the average value is minus 0.5 mm/yr. The remaining parts of the Vistula Valley are located in areas which exhibit a positive sign of movements of uplift.

Although the relationships just outlined control the present location of the whole Vistula Valley, both location and morphology of the par-

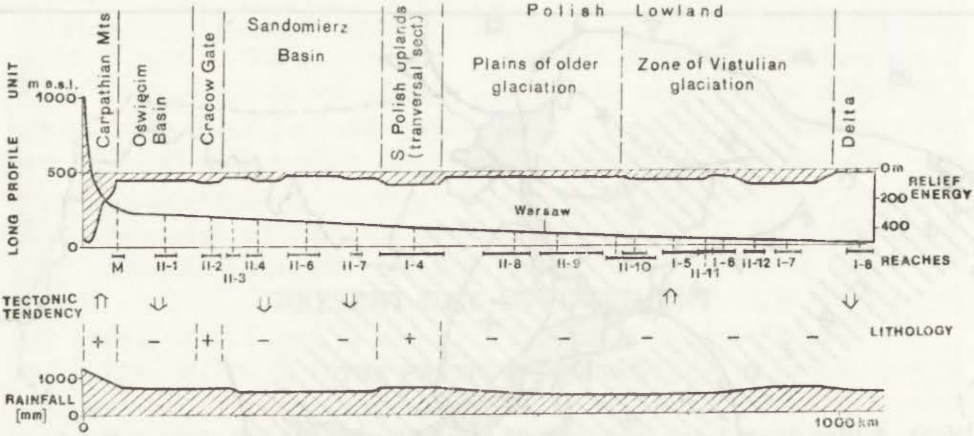

Fig. 6. Physiographical parameters of the Vistula River Valley (the reaches studied are shown in Fig. 3—L. Starkel)

ticular valley reaches relate to regional and local causes, *ie* the differing genesis and age of the features (Fig. 6).

The uppermost part of the valley extending from the sources down to the northern Carpathian margin is on the strongly folded flysch rocks of Cretaceous age. This is a pre-glacial valley. Below its outlet from the Carpathians this valley trended northward to join the Neogene or Eopleistocene depression (amongst others, Klimek 1972; Kotlicka 1975). Deepening due to Quaternary movements of uplift now dominates in the uppermost part of the Vistula Valley being millions of years old.

In the sinking Subcarpathian Foredeep, between Skoczów and Sandomierz, the river is on Tertiary rocks, up to 500 m thick. Because of the diverse movements of the earlier substratum, above Oświęcim the valley is entrenched in a horst consisting of Carboniferous rocks (Klimek 1972; Fig. 7A).

In the surroundings of Cracow the valley passes through a horst and graben region on Mesozoic rocks. These features were exhumed from beneath a cover of Tertiary rocks by glaciofluvial waters during the Southern Polish Glaciation. Consequently, river diversion took place there. From then on the uppermost Vistula drained the Oświęcim Basin to the Sandomierz Basin (Dżułyński *et al* 1966). In the Sandomierz Basin the river channel follows the northern margin of the foredeep, which may correspond to the axis of the greatest subsidence. It also may be associated with the continued valley shift. This is caused by alluvial fans built up by the Carpathian tributaries of the Vistula (Starkel 1972). Geological record (*eg* Laskowska-Wysoczańska 1971, 1983) indicates that the former central drainage line was initiated in a more southerly part of the Sandomierz Basin, where the age of the Vistula Valley may be estimated at 400—500 ka years. Doubts can be expressed as to the for-

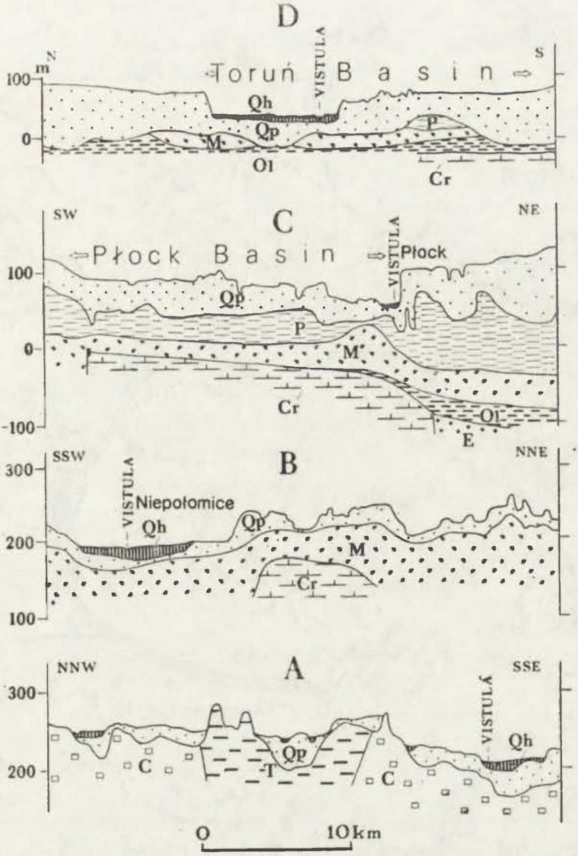

Fig. 7. Simplified geological sections across the Vistula River Valley (acc. to Mapa geologiczna Polski 1 : 200 000; Geological Map of Poland 1 : 200 000)

A—below Oświęcim (acc. to Kaziuk, Lewandowski, sheet Kraków, 1978); B—at Niepołomice (acc. to Jurkiewicz, Woiński, sheet Tarnów, 1977); C—in the Płock Basin (acc. to Baraniecka, Skompski, sheet Płock, 1976); D—in the Toruń Basin (acc. to Niewiarowski, Pasierbski, Tomczak, sheet Toruń, 1976)

C—Carboniferous, T—Triassic, Cr—Cretaceous, E—Eocene, Ol—Oligocene, M—Miocene, P—Pliocene, Qp—Quaternary: Pleistocene, Qh—Quaternary: Holocene; for location of sections see Fig. 5

mer drainage of still earlier valleys by the Proto-Vistula there (Fig. 8).

Near Sandomierz the Vistula Valley is eroded in Cambrian rocks which are part of the Palaeozoic core of the Świętokrzyskie Mts. Downstream the river breaks through the Polish Uplands. In the gap section the valley is narrow. It has steep, structure-controlled sides consisting of Upper Cretaceous rocks. Lower Cretaceous and Jurassic deposits are exposed only at Rachów. This valley is regarded as being relatable to a valley outlined as far back as pre-Quaternary or Eopleistocene times. The palaeovalley has been repeatedly invaded by the Scandinavian inland ice, on the last occasion around 300 ka years ago at the height of the Middle Polish Glaciation (Odra stage). This part of the Vistula Valley

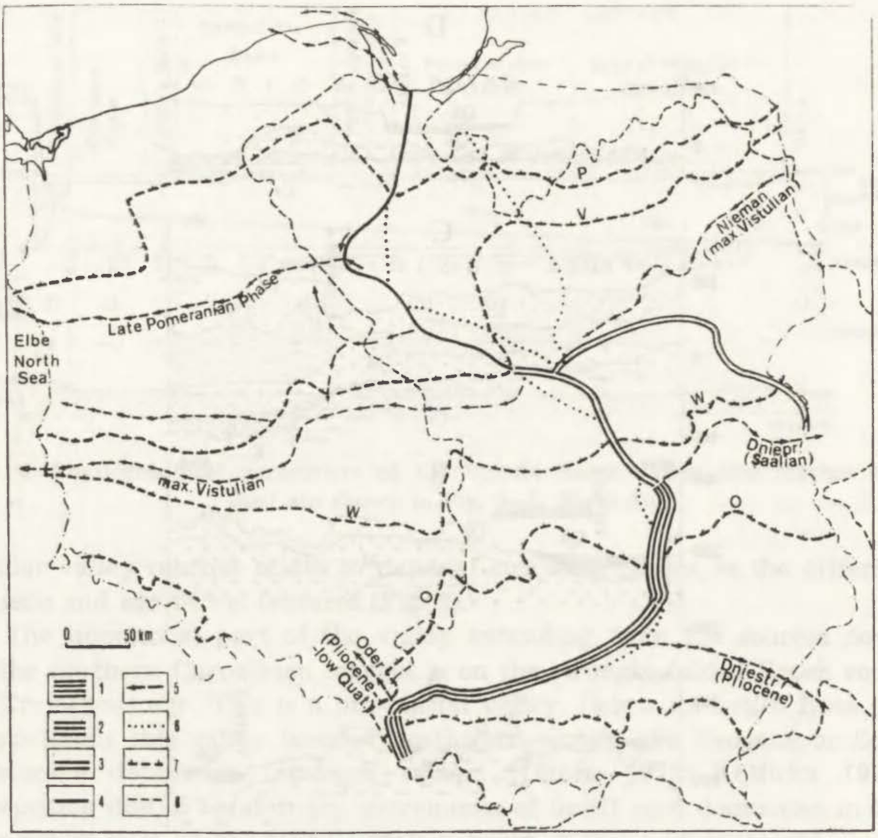

Fig. 8. Ages of various segments of the Vistula River Valley and extent of the Quaternary glaciations (J. E. Mojski, L. Starkel)

1—Pliocene and lower Quaternary valley reaches, 2—valley reaches postdating the Southern Polish Glaciation, 3—valley reaches postdating the Middle Polish Glaciation, 4—valley reaches established after the retreat of the last ice sheet, 5—previous river courses, 6—buried river courses, 7—extent of the ice-sheets (S-Southern Polish, Sanian; Middle Polish: O—Odra, W—Warta, V—greatest extent of the Vistulian, P—Pomeranian Phase), 8—watershed of the Vistula River Basin

is believed to have been fashioned by glacial erosion, although its traces were blurred by subsequent erosion and denudation. The Pleistocene ice blocked the existing drainage outlet toward the north. It also caused the valley to be filled with glaciofluvial and glacial deposits. Glacial record (*eg* Pozaryski 1955) showed that in some places the former Vistula Valley is recognizable to the west of the present valley. The entire gap is of at least 2,000 ka years age. The valley form showed and is still showing strong control by the varying resistance of the Upper Cretaceous rocks to processes of both erosion and deposition. The valley is narrow and deep on the hard limestones and siliceous "opoki", while on the soft, karstified marly rocks, whose age is considered to be Upper Maastrichtian, the valley is broad, *eg* in the Chodel Basin. In the valley reach discussed the tendency to gap formation persisted into the present

-days. Amongst others, evidence of it is provided by positive vertical movements of the earth crust (Fig. 5). Their rate exceeds 0.5 mm/yr there.

Downstream of Puławy, down to Bydgoszcz, the valley clearly follows the marginal depression. Both valley location and spatial variability are related in detail to Neopleistocene and Holocene processes, from the retreat of the Middle Polish and Vistulian ice sheets onwards until present times.

Between Puławy and the Warsaw Basin the Vistula Valley mostly exploited numerous crevasses, glacial channels and end depressions of the Middle Polish (Odra and Warta) ice, 300—200 ka years ago. These features became transformed by subsequent drainage of an ice marginal channel ("pradolina") along the edge of the Warta ice sheet. The sub-Quaternary surface shows buried valleys which trend from SE to NW, *ie* parallel to the present valley. These are the Middle Pleistocene valleys of the rivers Vistula and Bug which have been initiated on the former subglacial channels (Mojski 1981). These became partially filled in earlier times. The drainage of the "pradolina" previously mentioned is clearly discernible in the present relief. In the Wieprz Valley it left an extensive depositional surface which extends eastward *via* the Tyśmienica Valley into the Krzna Valley and then into the sandy Polesie Plains (Zaborski 1927). Thus, drainage was eastward to the Dniepr Valley and to the Black Sea. Subsequent erosion caused the widening of the Vistula Valley, and the reworking of the aquaeo-glacial deposits to fluvial ones. The latter came into existence under favourable conditions prevailing during the Last Glaciation (Vistulian), 20—13 ka years ago (Baraniecka, Konecka-Betley 1987). Those deposits are forming a distinct terrace being most commonly located on the eastern Vistula Valley side.

In the Warsaw Basin the Vistula Valley is somewhat younger than the valley reach just discussed. This basin—independently of an earlier structural control—was probably part of an extensive end depression dating from a younger phase of the Warta ice. During the Eemian interglacial the Vistula flowed across a rather flat surface, with water bodies in which organic sedimentation took place. During the Last Glaciation valley widening by lateral erosion was dominant there.

A characteristic feature of the Warsaw Basin is slope asymmetry. In the surroundings of Warsaw and upvalley the river flows in the immediate vicinity of the morainic plateau. An extensive terrace system is evident on the eastern river bank. Below the River Bug mouth the northern valley side is steeper, whereas on the southern side there are a number of wide terraces. The explanation of this phenomenon is a difficult task. It may be suggested that in the first case there was a braided river the main current of which concentrated into the western-most braid at a critical stage of its development. In the second case the present Vistula may use the former Bug channel. Both rivers must have flowed parallel to each other in a westerly direction in the basin. In the second case differentiated tectonic movements may also be considered to be the cause of faster rise of the southern part of the valley than that of its northern part (Lencewicz 1927). The gradient of the positive movement decreases northward (Fig. 5).

Downstream of the Warsaw Basin the Vistula flows within the young moraine landscape dating from the Last Glaciation. Deposits of Vistulian age are being dissected by the river down to the delta apex. It appears that the Vistula must postdate 18 ka years. Older deposits including Neogene rocks which show glaciotectonic disturbances are exposed in the valley sides (Fig. 7C, the Pliocene top series at Płock).

In this area, down to the River Brda mouth, the Vistula Valley is characterized by two narrow sections alternating with broader basins. The first narrow section, extending above Płock, developed in the area where the valley is incised into the marginal zone of the greatest extent of the Vistulian inland ice. There occur sandy-gravelly deposits forming end moraines, eskers, and outwash plains. Downstream the valley, but especially the supra-flood terraces, broaden in the greater part of the Płock Basin which corresponds to an end depression of the Vistulian ice lobe (Skompski 1969).

Between Włocławek and Nieszawa (Fig. 5), the valley is again narrow, while downstream it passes into the Toruń Basin (Fig. 7D). This corresponds to a wide portion of the Toruń—Eberswalde "pradolina". This broad section is probably due to intensive lateral erosion by water coming from melting ice to the north. The development and present shape of the valley is more and more dependent on the earlier morphogenetic foundations, *ie* the retreat of the last ice sheet, and both direction and evolution of meltwater drainage in the then functioning "pradoliny".

Between the Warsaw Basin and the River Brda mouth, the Vistula Valley crosses at different angles the buried Middle Pleistocene valleys which developed on earlier subglacial channels. In places there may be old ice marginal channels. In this reach, downstream of the Płock Basin, the position of the present valley floor is asymmetrical in relation to the entire valley, so that the river undermines the right valley side. This situation is due to the relative uplift of the Kuyavy—Pomeranian Anticline in the south-west. This causes the north-eastward channel shift along the whole river (Fig. 5).

Between the River Brda mouth and the delta apex, the Vistula Valley also includes two narrow sections (below Fordon and above Chełmno) alternating with two broad sections (the Unisław Basin and the Grudziądz Basin). Such changes in the valley shape depend upon the variability of the glaciogenic relief. The narrow sections correspond to glacial channels that have been modified by the river, whereas the broad sections are extensive thaw basins altered by erosion. These depressions follow the axis of an earlier Pleistocene depression which became invaded by the Eemian Sea. It also was used by the well developed valley network of this age (Makowska 1979). This old depression is located in the central part of the Peribaltic Syneclise. However, the postulated downwarping of the area during the younger Pleistocene (*eg* Brykczyński 1986) is not confirmed by modern studies.

The Vistula River Delta also occupies the former end depression of an ice lobe developed in the Pomeranian phase of the Vistulian Glaciation. The original glaciogenic surface here is very damaged and covered by two Holocene series. During the period of deposition of the older series the Vistula at first flowed north-westward, and then probably in a westerly direction across the shallow bottom of the present southern part of the Baltic Sea toward the Bornholm Deep. The younger series was laid down in the younger part of the Holocene, during the Littorina transgression and in later times. It forms the delta cover proper.

The picture of the geological structure of the Vistula Valley just outlined shows that this valley embraces several different segments of differing age and of differing evolution. These segments were integrated into the present valley in different periods and in different modes. Thus, the Vistula Valley is a polygenetical feature. Within the classification of the European river systems (Starkel 1987c) the Vistula Valley belongs to the river system of the former periglacial zones which was blocked by the successive Scandinavian ice sheets in Central Europe. In the Polish Lowland the age of the successive valley reaches decreases downstream (Fig. 8). However, the location of all of the greater valley reaches is controlled by the overall tectonic structures along the whole valley.

Thus, the morphology of the Vistula Valley which greatly varies from the headwaters down to the outlet is a function of tectonic tendencies, lithology, and hydrological changes (including the glaciations) which took place during the younger Quaternary.

The occurrence of two elevated zones alternating with two depressed zones predisposes the Carpathians and Polish Uplands to dominant degradation, whereas the Subcarpathian basins and the Polish Lowland are predisposed to dominant aggradation in Quaternary times.

THE CLIMATE

The Vistula catchment is in the temperate zone with vigorous westerlies (Schmuck 1959). Maritime-polar air masses (65%) and continental-polar air masses (29%) prevail over Poland. In spring and autumn arctic air masses (4%) frequently move in. In the winter halfyear tropical air masses (2%) do occur occasionally. Mean annual temperatures decrease from 8.5°C in the Subcarpathian basins to 6°C in the north-east (in the mountains the means are lower). The mean temperature of January varies from — 2°C in the west to — 4.5°C in the east. The absolute minimum temperatures range from — 35°C to — 40°C, the absolute maximum temperatures vary from + 35°C to + 40°C. The number of days of air frost increases from 35 in the west to 60 in the east. Spring moving in from the south-west exerts an essential influence on the course of melting of the ice cover on the rivers. It proceeds down-valley so that ice-jam-induced floods may be expected every few years there.

In the Vistula drainage basin the average annual precipitation varies from 460 mm to 800 mm, and it increases from 1200 mm to 1800 mm in the Carpathians. Rainfalls concentrated into the summer months (June—September) are frequently increasing up to 50⁰/₀ of the annual total in the Carpathians. The irregularity coefficient is high. It reaches 200⁰/₀. The snow cover persists for a period of 50—90 days, and even up to 200 days in the high mountains.

THE VEGETATION COVER AND LAND USE

During the upper Vistulian when northern Poland was ice-covered, the polar desert, the tundra zone, and the steppe zone, with small refuges of forest patches on permafrost, extended in the ice foreland (Maruszczak 1968; Starkel, in press). The Late Glacial was characterized by the spread of forests of taiga type. These were replaced by mixed forest communities (Ralska-Jasiewiczowa 1983a). Spatial variations in these communities were due to climate, to soils, and to hydrological conditions. In the Vistula catchment, amongst others, *Fagus* and *Abies* had their northern limit, and *Quercus* had its north-eastern limit. North--eastern Poland was invaded by spruce which also occurs in the Carpathians. Sandy soils being associated with glaciofluvial, fluvial, and aeolian sands are dominated by pine forests (*Vaccinio myrtilli—Pinetum*). The wet "pradoliny" are occupied by alder carr (*Alnetalia glutinosa*), by swampy forests (*Vaccinosa ulginosi Pinetum*), and by forestless swamps.

People began to turn the forests within the Vistula catchment into farmland and pasture from around 6500—6000 years onward. The earliest phase of deforestation began in the loess-covered uplands already during the Neolithic, the Bronze Age, and the Roman period. The lowland areas show evidence of intensive deforestation during the Roman period and in medieval times. Figure 9 (Buczek 1960) shows areas being cleared of forests down to the 10th century. In the mountain areas the continued attack on the forest cover by people began in the 14th—15th

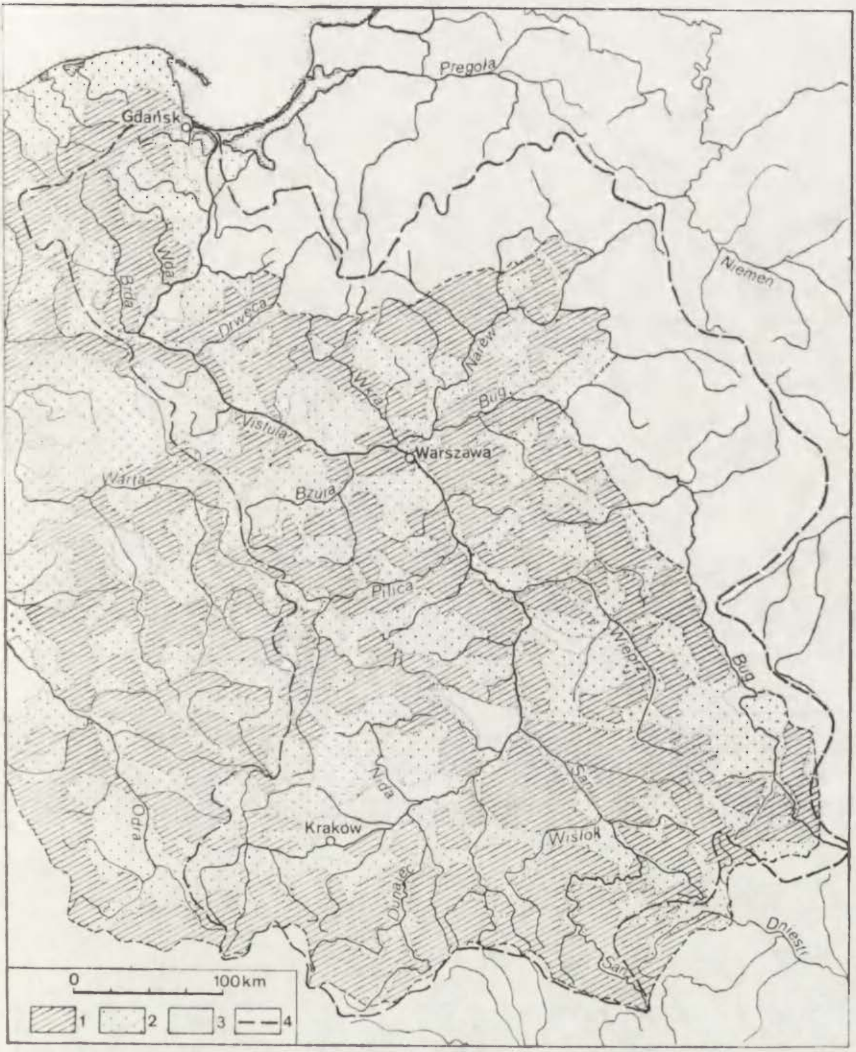

Fig. 9. Reconstruction of land use in the 10th century (Buczek 1960)
1—forests, 2—open (deforested) land with forest patches, 3—cultivated and densely populated areas, 4—watershed

centuries. The present occurrence of large forest complexes is illustrated in Figure 10. Woodland covers less than 25% of the total catchment area. Today woodland within the Vistula drainage basin persisted mostly on the less fertile soils. Woodland does not occur on the meadow- and pasture-dominated flood plains, though with the amelioration and channel correction new arable grounds developed there. The loess-covered uplands and clayey morainic plateaus are nearly forestless. Large forest complexes are restricted to mountain slopes, to the higher dune-

Fig. 10. Woodland (*Narodowy Atlas Polski 1973—1978*)

1—woodland, 2—watershed of the Vistula River

-bearing fluvial terraces, and to the outwash plains. The present land use practices are of prime importance to the contrasting course of both runoff and soil erosion in the periods of flood occurrence.

HYDROLOGICAL CHARACTERISTICS OF THE VISTULA RIVER[4]

The Vistula River belongs to large European rivers. Its position among the rivers of Europe can be determined 6th with respect to the catchment area; 8th with respect to the mean annual discharge and 10th with respect to the length. A characteristic feature of the Vistula catchment is its location in the eastern fringe of those European rivers which originate in mountain areas and then flow throughout the lowlands. The location of the Vistula catchment in the temperate climatic zone, where maritime and continental air masses interact, the intricate geological structure, and the invasion of the area by the Scandinavian ice sheet in Pleistocene times determined the extremely complicated hydrological conditions.

The characteristics of the fundamental hydrological parameters of the Vistula possessing a complex regime is the goal of this chapter. Analysis of the hydrometric material excludes the tributaries, while the main emphasis is on the changes in the hydrological parameters along the Vistula River itself.

HYDROLOGICAL PARAMETERS OF THE RIVER

The Vistula catchment (Fig. 11) occupies an area of 194,424 km^2, and 90% of it is within the Polish territory. The extremely asymmetrical shape of the catchment results from the history of the relief development. The mean altitude of the catchment is only 270 m a.s.l., although more than 100,000 km^2 of the catchment is elevated 100—200 m a.s.l. (Mikulski 1963). The highest spot in the catchment is the summit of Gerlach (2655 m a.s.l.). The flysch Carpathians, where numerous rivers originate, occupy c 9% of the catchment area. The Carpathian ridges rise to 1000—1400 m a.s.l. The springs of the Vistula River are on the slopes of the Mt Barania Góra at 1,067 m a.s.l.

The gradients of both the Vistula and its main tributaries are presented in Figure 12 and Table 1. The mean gradient of the Vistula is 1.04‰, but gradients in the particular river reaches differ significantly from the mean (Fig. 12). The classic division of the river into the upper, middle, and lower reaches being based on the gradient as the main criterion results in an exceptional pattern. According to that criterion, the river section down to the water level gauge in Skoczów (length 27 km, gradient 14.6‰) should be considered as the upper reach. Its northern border is delimited by the geological boundary of the Carpathians. The section Skoczów—Dwory, 55 km long, with a gradient of 0.87‰, can be considered as the middle course. That section is locat-

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[4] Translated by T. Mrozek

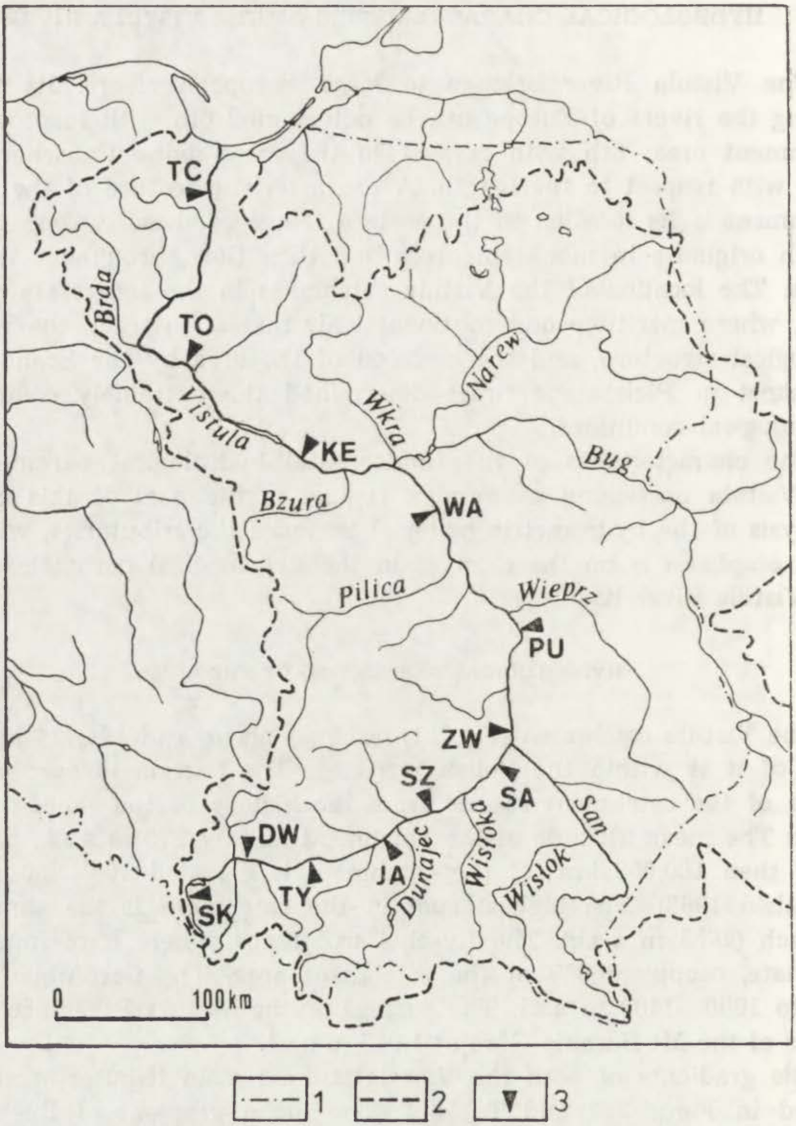

Fig. 11. Map of the Vistula catchment

1—state border, 2—watershed, 3—water level gauges: SK—Skoczów, DW—Dwory, TY—Tyniec-Kraków, JG—Jagodniki, SZ—Szczucin, SN—Sandomierz, ZW—Zawichost, PU—Puławy, WA—Warszawa, KE—Kępa Polska, TO—Toruń, TC—Tczew

ed in the Subcarpathian basins. Downstream of the water level gauge at Dwory to the Vistula outlet, *ie* over 941 km which constitute 90% of the total river length, gradients vary from 0.32‰ to as low as 0.12‰. Most frequently, a simple arbitrary division into three sections is used. The upper Vistula extending to the profile in Zawichost includes the Carpathian basins, and partially the upland drainage basins. The middle Vistula comprises the section downstream of Zawichost to the River

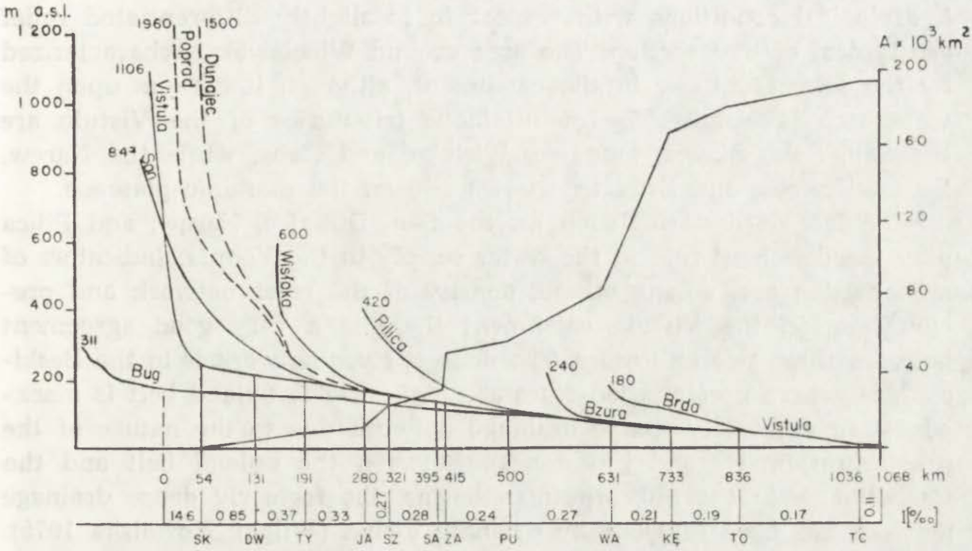

Fig. 12. Longitudinal profile of the Vistula River and its main tributaries
I—river gradient (in[‰]), km—river length from the springs to the mouth, A—increase of the catchment area (in[km^2]); other abbreviations as in Fig. 11

Narew mouth below the city of Warsaw. In the middle section, the Vistula drains the belt of the old uplands. The lower Vistula extends between the Narew mouth and the outlet to the Baltic Sea. Contrasting

Table 1. Hydrological characteristics of the Vistula and its major tributaries

River	Length [km^2]	Gradient [‰]	Area [km^2]	Q^1_{mean} [m^3/s^{-1}]	Precipitation² [mm]	Runoff² [mm]	Outflow index²
Narew	814	0.29	74,808	354	613.0	145.0	0.236
San	444	1.59	16,732	119	687.7	213.7	0.310
Wieprz	328	0.49	10,422	29.8	543.4	91.9	0.171
Pilica	342	0.74	9245	42.0	604.2	153.2	0.254
Bzura	166	1.07	7644	21.4	530.9	105.5	0.197
Dunajec	251	5.29	6798	82.2*	812.3	384.4	0.466
Drwęca	250	0.51	5536	23.9	558.0	158.8	0.290
Brda	217	0.70	4718	18.8	578.4	236.5	0.420
Wisłoka	164	2.72	4096	32.5	733.9	257.6	0.349
Wisła	1060	1.04	194,424	961	590.0	155.0	0.264

[1] For the period of 1951—1965 (*Roczniki hydrologiczne Wisły. Przepływy* ... 1980. In the case of Narew—summarical data calculated for the period of 1971—1975 of the profile Dębe (Narew River) and Cieksyn (Wkra River).

[2] After *Synteza surowego bilansu* ... 1971. Outfow index in the case of Narew — summarical data calculated for the period of 1971—1975 of the profile of Dębe (Narew River) and Cieksyn (Wkra River).

[1] and [2] refer to the gauging profiles and do not include the total catchment areas.
*Period of 1951—1960.

hydrological conditions with respect to so slightly differentiated relief are typical of that section. The area around Włocławek is characterized by the lowest outflow in the catchment, although it borders upon the water-rich lakelands. The mountainous tributaries of the Vistula are the San, Soła, Skawa, Dunajec, Wisłoka, and Raba, while the Narew, Bzura, Drwęca, and Brda tributaries rise on the morainic plateaus.

The large tributaries such as: the San, Dunajec, Narew, and Pilica play the dominant role in the water supply to the Vistula. Indicators of alimentation are, among others, density of the river network and precipitation. In the Vistula catchment there is a very good agreement between those two indicators. The densest river network is in the Beskidy Mts, where precipitation rates are highest. The upland belt is marked by an extremely sparse drainage network due to the nature of the substratum (marls and limestones). Between the upland belt and the Carpathians, in the Subcarpathian basins, the formerly dense drainage network has been replaced by drainage diches (Wilgat, Kowalska 1975). Similar to that in the Sandomierz Basin is the situation in the lower Vistula reach, where the network of small streams in the agricultural areas has been totally modified.

The annual precipitation totals vary from 1000—1300 mm in the Carpathians to *c* 550 mm in the vicinity of Warsaw, and to less than 450 mm in the vicinity of Toruń. In the lakelands the annual precipitation totals increase again to *c* 700 mm. In the entire Vistula catchment, July is the month of the highest precipitation. Precipitation of the hydrological summer (May—October) is larger than that in the winter season. Smallest monthly precipitation totals have been recorded in September, October and February.

RECORDS AND REVIEW OF HYDROLOGICAL INVESTIGATIONS

This chapter is based on printed papers and records published in hydrological yearbooks. The water conditions in the period 1951—1980 have been analysed in detail in 12 water gauging profiles of the Vistula (Fig. 11) by using recorded discharges (*Roczniki hydrologiczne*... 1980). Maximum and minimum water stages in 12 gauging profiles (Table 2) provide information on the water stage amplitude which reaches almost 9 m. So high amplitude results largely from the construction of flood embankments.

Systematic registration of the Vistula water stages originates from 1799, and several water gauges began to operate as early as the beginning of the 19th century. The first discharge measurements were performed in Świecie, in the lower Vistula reach, in 1836 (Mikulski 1963). The partition of the catchment between Russia, Prussia, and Austria

Table 2. Maximum and minimum water stages of the Vistula in the period of 1951–1980

Profile	Maximum [cm]	Minimum [cm]	Amplitude [cm]
Skoczów	430	81	349
Dwory	750	47	703
Tyniec	880	17	863
Jagodniki	878	170	608
Szczucin	892	154	738
Sandomierz	739	115	624
Zawichost	721	239	482
Puławy	675	138	537
Warszawa	624	93	531
Kępa Polska	640	140	500
Toruń	879	151	728
Tczew	1020	184	836

has influenced the quality of the records (different measurement systems, different baselevels *etc*). However, records of water stages have been published systematically since 1867, and hydrological record yearbooks have been known since 1881.

The description of the present-day Vistula, having a non-regulated channel which practically is not suitable for navigation in the majority of its sections, would be incomplete without providing some historical facts determining the stage of today. In 1447, royal bills giving the absolute priority to navigation over the other means of utilization of the river (*eg* fishery, flour milling) were enacted. In the 16th and 17th centuries the Vistula was in prime as a water route and belonged to the ways with the largest traffic in Europe. In the 16th century the river harbour of Włocławek was visited by *c* 1500 vessels *per* navigation season, being limited to maximum eight months on the Vistula River (Gierszewski 1982). Each year about 200,000 tonnes of corn were transported on the Vistula to Gdańsk in the 1640s. Navigation on the Vistula was limited in the 18th and 19th centuries. However, 2200 steamships, 1800 rafts, and 500 other vessels still arrived in Płock in 1902 (*Z biegiem Wisły* 1969). The beginning of the 20th century was the end of a larger navigation on the Vistula. The delays in construction of hydrotechnical structures became larger and larger each year and caused all efforts to restore communication inefficient. This stage is still lasting. In the second half of the 20th century, the role of the river had totally changed. The Vistula receives industrial and municipal sewages. The management of the river is limited to the following large objects: dam reservoirs in Czarna, Goczałkowice, and Włocławek, water gates in the region of Cracow, and flood embankments. The majority of the latter has been constructed several scores of years ago. Navigation, in a small extent, is still under operation on the lower Vistula and in the vicinity of Cracow.

The first hydrological monograph dealing with the Vistula is the work by Keller, entitled *Memel, Pregel und Weichselstrom,* which has been published in Leipzig in 1899. In the 1920s there was another attempt to publish a monograph of the river as a series, but only a few issues had been printed. *Die Weichsel, ihre Bedeutung als Strom und Schiffahrtstrasse und ihre Kulturaufgaben* printed in Leipzig in 1939 is another monograph. Numerous papers dealing with the river were published after 1945. The balance approach was used to present water resources of the Vistula and its tributaries (Dębski 1961). Numerous issues devoted to floods occurring on the Vistula were published as monographs of the particular events: floods of 1960, 1970, 1972. A stimulus to new studies on the water regime of the Vistula was the programme "Wisła" initiated in the 1970s. It assumed a complex management of the catchment (*Wisła...* 1982).

FLOWS IN THE PERIOD 1951—1980 AGAINST THE MULTIYEAR BACKGROUND

The fundamental hydrological material refers to the 30-year period 1951—1980, and there is a need for a comparison with a longer period. Thus, the 80-year period 1901—1980 in the profile of Tczew closing the entire catchment was accepted as a basis. The mean annual discharge and mean discharges of the hydrological half year 1951—1980 are larger than those of the 80-year period. The mean annual discharge of the Vistula in Tczew was by 2% larger (1211 and 1231 $m^3 s^{-1}$ in the absolute values, respectively), the discharge of the winter season was by 3% larger (1055 and 1090 $m^3 s^{-1}$, respectively), and that of the summer season was by 6% larger (900 and 955 $m^3 s^{-1}$). A similar percentage distribution is to be expected in the entire Vistula catchment in both periods compared. Better characteristics of differences and similarities can be obtained by analysing monthly discharges. In order to achieve that, the records in the 53-year period (1921—1937 and 1945—1980) have been used. Mean monthly discharges are larger in the 30-year period, especially from May until July. Minimum monthly discharges are higher as well. The maximum monthly discharges in the 30-year period were smaller only in March and September, while the differences were small in the remaining months. Generally, the period 1951—1980 is characterized by runoff higher than the average. This in turn indicates more intensive channel-forming processes and increased transportation of the stream load from the catchment. That refers mainly to the Vistula channel in which transportation of the sandy material occurs even if the discharge increases slightly.

RUNOFF CHARACTERISTICS

The basic data referring to the Vistula discharges in 12 water gauging profiles are presented in Table 3. The mean annual discharge of the Vistula increases from 6.23 $m^3 s^{-1}$ in Skoczów to 1090 $m^3 s^{-1}$ in Tczew. The increase in the mean annual discharge along the river is of a stepwise nature downstream of the river Dunajec, San, and Narew mouths. These three tributaries are richest in water. The mean annual specific runoff indicating the water resources of the catchment varies from 20.97 $dm^3 s^{-1} km^{-2}$ in Skoczów to 5.39 $dm^3 s^{-1} km^{-2}$ in Tczew. Specific runoff decreases systematically downstream. The most rich in water areas of the Carpathians, with a specific runoff of 10—30 $dm^3 s^{-1} km^{-2}$, are in the south. The upland belt being characterized by smaller water resources and specific runoff of 5—10 $dm^3 s^{-1} km^{-2}$ is found in the middle part of the catchment, while the lowland belt, possessing smallest water resources, is located in the northern part of the catchment. The smallest annual discharges correspond, in general, to the pattern of mean discharges. The lowest discharges of 0.12 $m^3 s^{-1}$ were recorded in the water level gauging profile of Skoczów, of 19.0 $m^3 s^{-1}$ in Cracow (Tyniec profile), and of 253 $m^3 s^{-1}$ in Tczew. Converting the smallest discharges into specific runoff, the appropriate values are as follows: 0.4, 2.52, and 1.30 $dm^3 s^{-1} km^{-2}$. These are very low values when compared to the European rivers having similar catchment areas. According to historical data (*Wyjątki*... 1965), during the last four centuries the total lack of the Vistula discharge was recorded many times in Cracow and in the middle reach of the river. The small retention ability of the catchment resulting from the geological structure causes that in the years with small winter and spring precipitation the water stages are very low and last very long. In such cases, the usually low water stages in the following autumn which are typical of catchments occurring in the continental and temperate climates become catastrophic. Such low water stages occurred prior to the constriction of the river bed, the latter resulting from the channelization performed by the end of the 19th century (Fig. 13).

The pattern of the maximum discharges along the river is different. The maximum discharge in the profile of Skoczów reaches 648 $m^3 s^{-1}$. It then increases very rapidly. Downstream of the Dunajec outlet it exceeds 5000 $m^3 s^{-1}$. The Carpathian tributaries Wisłoka and San cause the rise of the maximum discharges to the value of 7500 $m^3 s^{-1}$ (at the Zawichost water level gauge). The Vistula reach extending between Zawichost and Warsaw is characterized by decreasing maximum discharges, among others, due to significant infiltration. The increase in discharges is relatively small downstream of Warsaw, and in Tczew, near the Vistula mouth, maximum discharges exceed again the values

Table 3. Characteristic discharges in the longitudinal Vistula profile[1]

Profile (Catchment area [km²])	*SQ* (Nov-Oct)	*NWQ* (Nov-Apr)	*NWQ* (May-Oct)	*WQ* (Nov-Apr)	*WQ* (May-Oct)	*NQ* (Nov-Apr)	*NQ* (May-Oct)	*NNQ* (Nov-Apr)	*NNQ* (May-Oct)	*Sq* (Nov-Oct)	*NWq* (Nov-Oct)	*NNq* (Nov-Oct)
Skoczów (297)	6.32	106	648	50.7	153	0.73	0.66	0.20	0.12	21.3	2181	0.40
Dwory (5312)	62.1	461	1490	263	523	25.0	23.5	11.6	13.5	11.7	280	2.18
Tyniec (7524)	91.7	798	2260	392	693	33.5	39.9	19.6	19.0	12.2	300	2.52
Jagodniki (12,058)	138	1190	2800	639	1021	51.2	51.8	30.2	31.5	11.4	232	2.50
Szczucin (23,901)	242	2040	5410	983	1813	81.3	86.4	40.5	66.0	10.1	226	1.69
Sandomierz (31,846)	303	3460	5690	1416	2264	103	108	57.0	66.6	9.51	176	1.79
Zawichot (50,732)	450	5440	7459	2218	2876	150	158	84.0	94.2	8.87	147	1.66
Puławy (57,264)	477	4160	6580	1966	2512	169	184	97.7	111	8.33	115	1.71
Warszawa (84,540)	592	4190	5650	2204	2315	224	254	108	153	7.00	66.8	1.28
Kępa Polska (168,956)	960	5820	6900	3439	2823	390	400	162	234	5.68	40.8	0.96
Toruń (181,033)	1013	5810	6890	3514	2838	391	428	234	262	5.60	38.1	1.29
Tczew (194,376)	1090	7020	7840	3590	2908	478	497	253	300	5.61	40.3	1.30

SQ—mean annual discharge; *NWQ*—absolute maximum discharge; *WQ*—mean maximum discharge; *NQ*—mean minimum discharge; *NNQ*—absolute minimum discharge. Al values of discharges in m^3s^{-1}. *Sq*— mean annual specific runoff; *NWq*—absolute maximum specific runoff; *NNq*—absolute minimum specific runoff. All values of specific runoff in $dm^3s^{-1} km^{-2}$

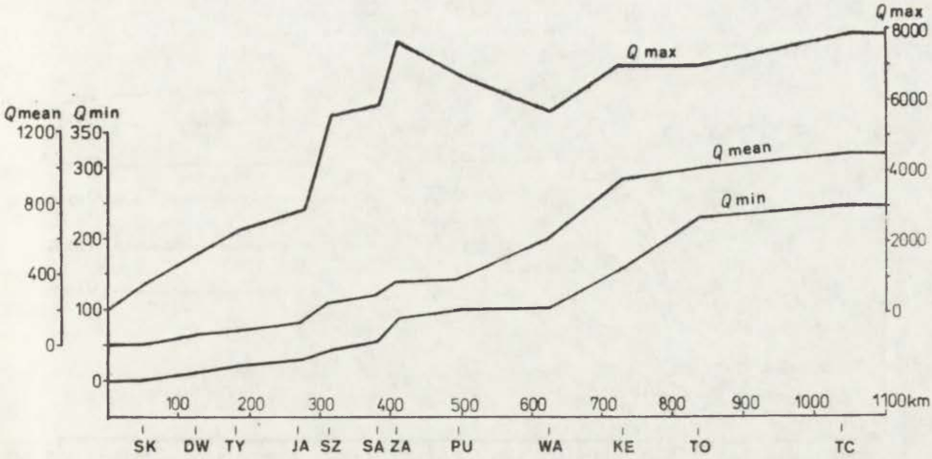

Fig. 13. Maximum, mean, and minimum discharges (Q) in the longitudinal Vistula profile (in[m^3s^{-1}])

Abbreviations as in Fig. 11

recorded in the Carpathian part of the Vistula catchment. The highest discharge in Tczew in the 30-year period was 7849 $m^3 s^{-1}$. It can be assumed to be only slightly lower than the discharges recorded during the last centuries. Characteristic values of the specific runoff of the Vistula are: *c* 2200 $dm^3 s^{-1} km^{-2}$ in Skoczów, 300 $dm^3 s^{-1} km^{-2}$ in Cracow (Tyniec), 121 $dm^3 s^{-1} km^{-2}$ in Zawichost, only 99 $dm^3 s^{-1} km^{-2}$ already in Warsaw, and 40 $dm^3 s^{-1} km^{-2}$ in Tczew. The pattern of the average and extreme discharges in the river longitudinal profile was presented above. A very similar pattern can be obtained from the spatial analysis of the mean values of the maximum (WQ) and minimum (NQ) discharges. This emphasizes the role played by the three large physico-geographical regions previously mentioned in the alimentation of the Vistula. Data presented imply that the Vistula is definitely a transit type river downstream of the River San mouth. The magnitude of the Vistula specific runoff down to the profile of Zawichost is in agreement with that of the Carpathian and upland tributaries. The Vistula specific runoff below Warsaw is 5—7 $dm^3 s^{-1} km^{-2}$, while in the case of its tributaries the specific runoff values are of the order of 2—3 $dm^3 s^{-1} km^{-2}$.

The more detailed characteristics of high water stages of the Vistula is presented in Figure 14. The latter is based on data published in *Roczniki hydrologiczne...* (1980). The mean error of discharge evaluation is 17% in the case of $Q_{1\%}$ and 7% in the case of $Q_{50\%}$ in the profile of Tczew. Errors increase upstream. The corresponding values in Sandomierz are 20% and 10%, respectively. The relation between biennial discharges ($Q_{50\%}$) and centennial discharges ($Q_{1\%}$) changes along the river profile. Downstream of Zawichost to the Vistula mouth the

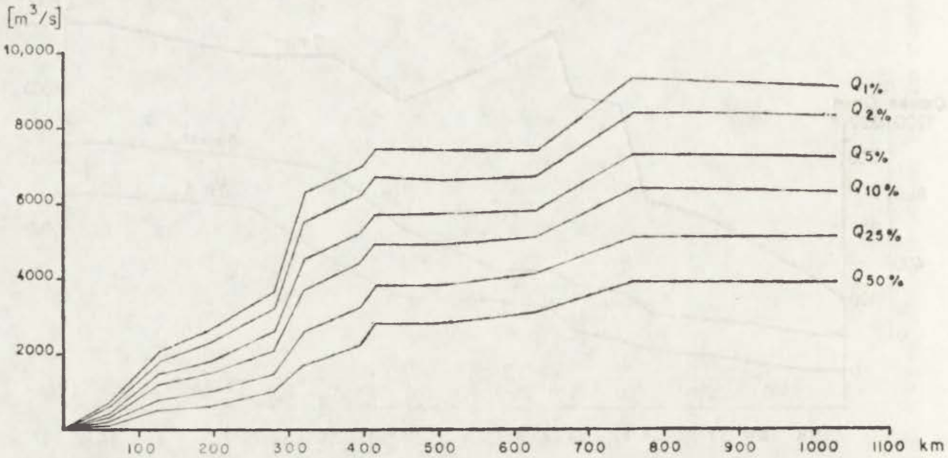

Fig. 14. Maximum discharges (Q_{max}) of a given probability of occurrence in the longitudinal Vistula profile (*Roczniki*... 1980)

centiennial discharges are 3—5 times as great as the biennial ones. A very rapid increase in discharges below the River Dunajec mouth is a very striking feature of the discharge pattern. The 100-year discharge of the Vistula at Szczucin, downstream of the Dunajec mouth, is 6270 $m^3 s^{-1}$, while the Dunajec discharge of the same probability of occurrence is as much as 4870 $m^3 s^{-1}$. Thus, it is significantly higher than $Q_{1\%}$ of the Vistula at the Dunajec mouth. The same is the case of discharges of the probabilities $Q_{1\%}$ and $Q_{50\%}$ being evidence of the dominating role played by the Dunajec River in the formation of high Vistula discharges. The role played by the two large tributaries San and Narew in the formation of high discharges is unproportionally small in relation to the size of their catchments, although both rivers differ with respect to regimes of floods.

FLOODS IN THE VISTULA CATCHMENT

The following types of floods are distinguished (Lambor 1954):

(i) due to heavy downpours occurring in the summer period. These floods are of regional importance. They may occur in the entire Vistula catchment;

(ii) due to long-lasting rains in the hydrological summer season. Such floods occur in the entire Vistula catchment. However, they are most extensive and most frequent in the Carpathian Foreland;

(iii) due to melting which occur each year in the entire Vistula catchment. They depend upon the water capacity of snow and rate of thawing. The snowmelt-induced floods proceed more slowly in the Carpathians than in the lowland part of the catchment due to the diverse relief. When rapid warming is associated with rainfall, such floods become catastrophic events in the northern and middle parts of the catchment;

(iv) storm-induced, causing the water level to rise in the delta area are of a local importance. Floods due to ice-jams also occur locally, but they may appear in any part of the Vistula;

(v) due to ice-jams were notably frequent in strongly meandering sections of the channel (the Carpathian Foreland), and in river reaches containing numerous islands (lower reaches).

Analysis of the spatial flood distribution (Mikulski 1963; Dynowska 1971; Stachy *et al* 1979) indicates that rain-induced floods with high discharges are formed in the Carpathians downstream of the Vistula springs to the Dunajec catchment inclusive. This is the source area of frequently catastrophic floods which shift downstream far to the north. In the present century large rain-induced floods occurred in 1925, 1934, 1960, 1970, and 1972. In historical times the largest flood on the Vistula occurred probably in 1813 (Mikulski 1963). It caused pronounced channel changes in the Vistula River Delta.

In the monograph dealing with rain-induced floods (Langer 1951; Faust 1952; *Powódź*... 1972; *Powódź*... 1975) the mechanism of both flood formation and transformation along the Vistula is documented. The largest three floods of 1934, 1960, and 1970 resulted from rainfall of the order of 3—4 days which has been recorded at precipitation stations located at higher elevations (*Powódź*... 1972). The spatial distribution of precipitation during the 1970 flood (Fig. 15) is typical of the largest floods induced by rainfall in the Vistula catchment. The zone of intensive summer precipitation reaches as far as the Wisłoka catchment, and even the San catchment to the east. The northern border of this zone is delimited either by the Carpathian margin or by the entire upper Vistula catchment to Zawichost. Due to so high precipitation the flood wave is formed. The height of the flood wave reaches 2—3 m in the headwaters, 7 m in Cracow, and 6 m in Zawichost. The maximum discharge then can be as high as 7000 $m^3 s^{-1}$. Downstream of Zawichost it increases only in rare cases. The maximum discharges of the flood waves in the longitudinal profile of the Vistula become disturbed by crevassing of the embankments during the large floods. Consequently, extensive areas become inundated in the Sandomierz Basin (Fig. 16). That was the case of the flood of July, 1934, when more than 1500 km^2 became flooded. Similar events took place in 1970 and 1972. Inundation of areas causes large losses in the economy, but it contributes to the reduction of the flood wave elevation. It also decreases the rate of the flood propagation. Prior to the construction of the flood embankments, the Sandomierz Basin was a sort of a natural retention reservoir. Based

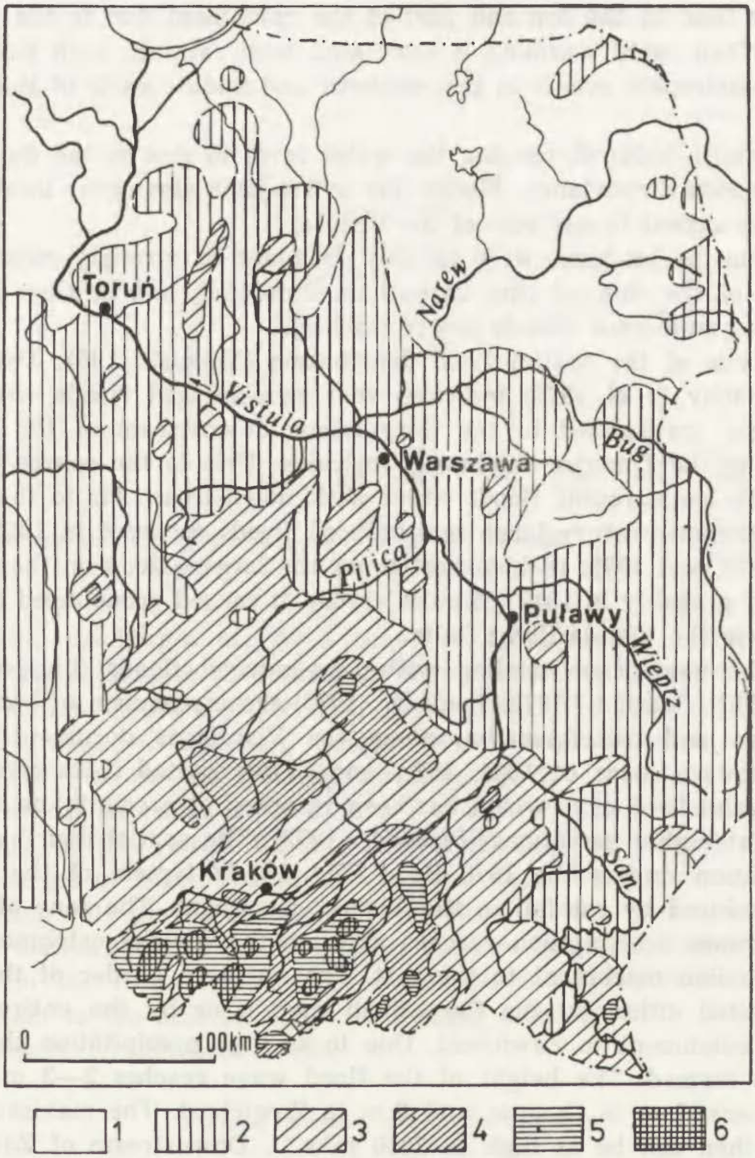

Fig. 15. Precipitation in the Vistula catchment on 15—19 July 1970 (*Powódź*... 1972)

Isohyets (in [mm]): 1—to 50, 2—51-100, 3—101-150, 4—151-200, 5—201-250, 6—251-400

on the cross section of the Vistula channel is the assumption that during the overbank discharges of a probability of $Q_{10\%}$ ponds were formed. The rate of the propagating waves of the largest peak discharges from the sources to the water level gauge in Zawichost is variable. It depends on the channel nature and cross section. Values of 6.8 $m^3 s^{-1}$ were recorded in the source section and of 2.2 $m^3 s^{-1}$ in the Sandomierz Basin. Downstream of Zawichost, in the middle Vistula reach, the na-

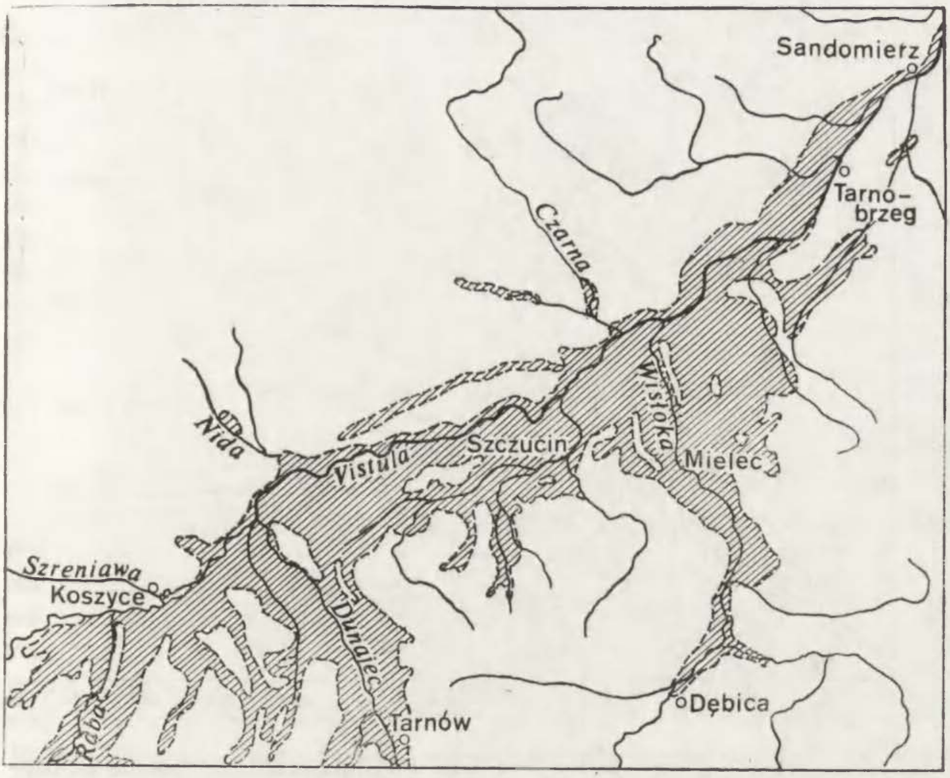

Fig. 16. Inundated areas during the flood of July 1934 in the region of the Sandomierz Basin (*Z biegiem Wisły* 1967)

ture of the flood waves is definitely different. Here a very fast lowering of the peak discharges is most frequent. That lowering averages by 22% over the distance of 150 km of the river reach. The peak of the wave propagates at the rate of 4.8—3.7 km/h (Jankowski, Stolarska 1978). The decrease in the maximum discharge in this section is due to the flattening of the wave and to the strong infiltration of water into the substratum. According to the above authors, the infiltration of large amounts of water is promoted by the long duration of the floods reaching 16—20 days provided the average time of the water rise is 5—7 days. The slow drainage of the flooded areas and the varying time of approach of the waves of the Carpathian tributaries of the Vistula that has been documented by Lambor (1971) promote the elongated duration of a flood. Downstream of Warsaw, peak discharges of the large floods do not change.

Comparison of the patterns of the summer and winter floods (Figs. 17 and 18) indicates fundamental differences. Peak discharges are lower during the floods due to melting, and usually do not exceed 5000 $m^3 s^{-1}$. The area of formation of such floods also is different. Floods due to melting are formed downstream of the River San mouth, *ie* outside the

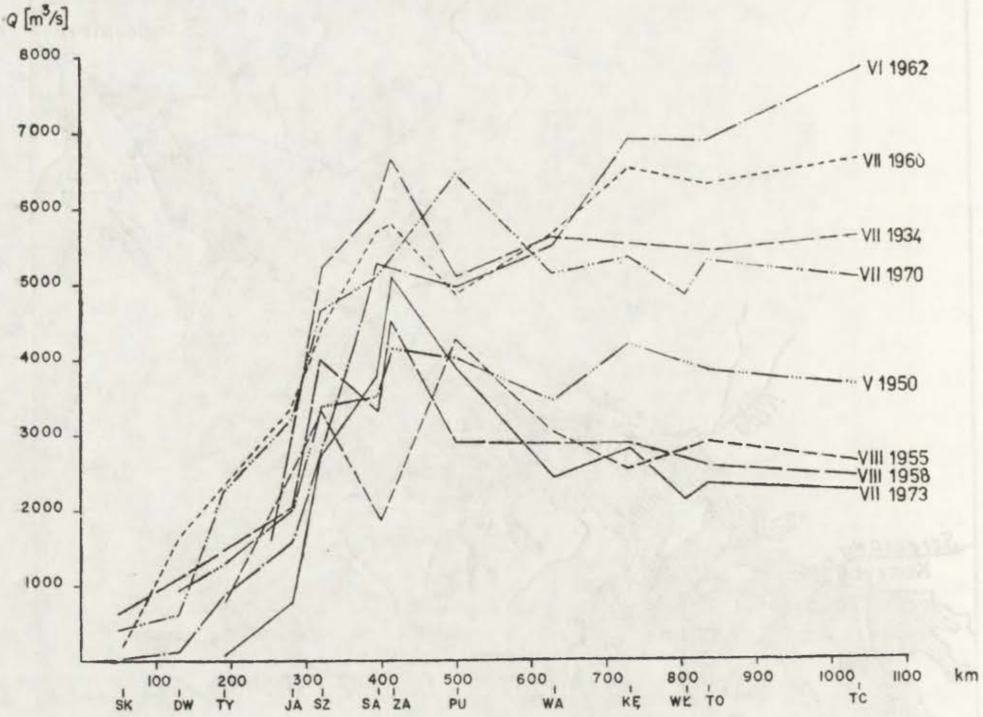

Fig. 17. Maximum discharges in the longitudinal Vistula profile during the summer floods

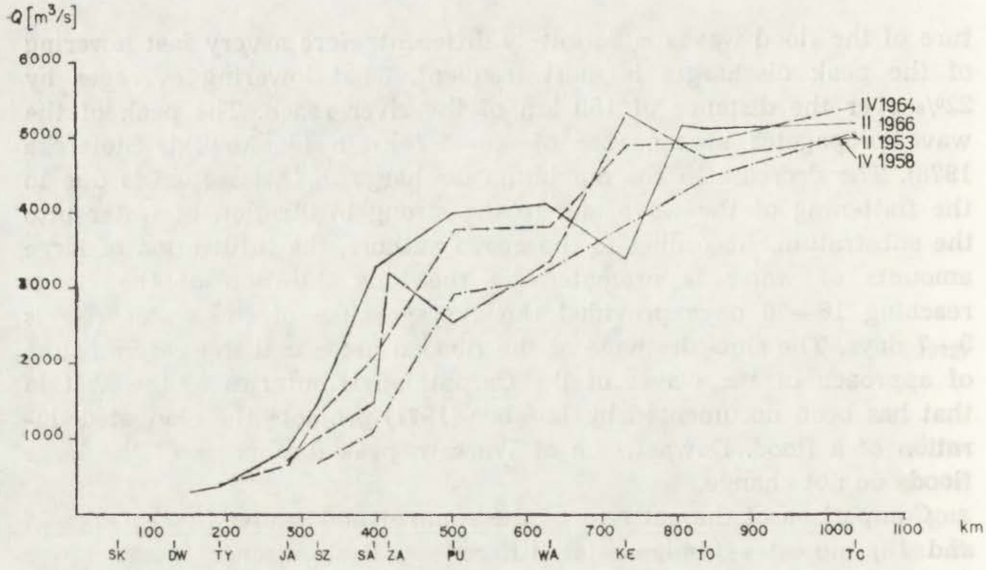

Fig. 18. Maximum discharges in the longitudinal Vistula profile during the snow melt induced floods

Abbreviations as in Fig. 11

Carpathian part of the Vistula catchment. Peak discharges increase in a rather gradual manner down to the Vistula outlet to the Baltic Sea. The velocities of flood wave propagation also are smaller there. The propagation time of the wave peaks of the largest floods due to rainfall in the section Zawichost—Tczew is 160 hrs on the average (*Powódź*... 1972), while that of the floods due to melting reaches 220—240 hours. Floods due to melting are usually twice as long as the rainfall-induced floods of a similar magnitude. The snowmelt-induced floods develop most frequently in one long-lasting cycle. The ice cover does not form after the end of such a cycle.

ICE PHENOMENA

The Vistula is heavily polluted all over its length. The source of pollutants are mining, municipal sewages, and recently agriculture. The contamination of waters strongly affects the occurrence of ice phenomena which in the past were very important in the modelling of the river channel. At the present day, during winters with temperatures corresponding to the multiyear means the Vistula freezes only over short sections in the mountains, in the region of Sandomierz and in the lower reach. The thickness of the ice cover in the freezing sections is 12—30 cm on the average. The ice cover does not form in the section extending between the water level gauge of Dwory and Sandomierz as well as in the vicinity of Warsaw, even during severe winters. Frazil ice, which forms at the abrupt drop of air temperature occurs over the entire reach each year. The dates of the average beginning of ice phenomena (fast ice, frazil ice) occur in the first decade of December. The river becomes frozen in the next 3—4 weeks. The end of the ice phenomena is differentiated along the river. It takes place in the first decade of March in Sandomierz and is delayed by two weeks on the average in the lower river reach. The final stage of the ice phenomena in the lower and middle Vistula is the travel of the ice floes, the latter originating mainly from the tributaries. The average number of days with ice phenomena is 62 in Sandomierz and 82 in the lower Vistula. The process of disappearance of the ice cover is very fast and results from the increase in the flow intensity. The inflow of water from the Carpathian tributaries, where the melting is initiated most early, causes a rapid decay of the ice cover and flow of ice floes downstream. If the ice cover is formed in the lower and middle reaches then the outflow is hindered. This in turn causes ice-jams and frazil ice-jams. The present-day ice-jams are formed in the area of backwater in the Włocławek reservoir on the lower Vistula in spots, where the outflow of ice floes is hindered (Grześ 1985).

Rainfall of the hydrological summer season (May—October) is larger than that of the winter season (November—April) in the entire Vistula catchment. Taking that into account, the comparison of the mean flows of the Vistula in both seasons enables us to infer about the influence of the geographical environment on runoff formation. At Skoczów, *ie* in the source section located entirely in the Carpathians the flow of the winter season is smaller by 12⁰/₀ than the mean summer flow. Downstream of Skoczów to Sandomierz the flows of both seasons are generally balanced. The ratio can change, however, depending on the precipitation totals in the summer season. Below the River San mouth the winter runoff is definitely larger than the summer one by the value of 13⁰/₀. The dominance of the winter season runoff downstream of Warsaw is expressed by the value of 69⁰/₀. Only in the case of years with very low precipitation rates in winter, and if the rain-induced flood occurs in the Carpathians, the role played by both seasons in the Vistula runoff downstream of Warsaw may be balanced. However, that is an unusual phenomenon. The maximum annual discharges are associated with the summer season and are recorded in June and July. From the river source down to the profile of Puławy, the maximum annual flows and average annual maximum flows occur in June and July. Downstream of Puławy, the average annual maximum flows are associated with the winter season and occur in March or April. The possibility of the occurrence of very high discharges during the entire year is one of the more important hydrological features which are typical of the Vistula catchment. The same refers to the minimum flows. The smallest annual flows of the Vistula occur from December until February. However, very low discharges are recorded in summer and from September until February.

The outflow index of Pardé provides the best characteristics of the river regime in the annual runoff cycle. That index is the ratio of the mean monthly flow to the mean annual flow. The plots of the Pardé indices for 12 gauging profiles are presented in Figure 19. The extreme values of the index vary from 0.52—1.69 in Skoczów to 0.67—1.80 in Tczew. The variability of the index in question is between 0.2—2.5 in the case of the Vistula tributaries.

Based on the Pardé index, periods of the intensified alimentation of the river can be distinguished. The period of the intensified alimentation of the Vistula in Skoczów lasts from January until May and there is a characteristic lowering of it in May. The decrease in alimentation in May is noticeable in all profiles down to Warsaw. That decrease separates two more or less pronounced periods of high flows, namely the spring and summer ones. The lowering of alimentation results from a lack of intensified groundwater supply and from increased evapotranspiration. Only in Skoczów the index in question is larger in July than in April. Downstream that index reaches the extreme annual maxima just in April. The plots (Fig. 19) show only one pronounced period of the intensified runoff from March until May downstream of Warsaw. The smallest index, and thus the smallest runoff in the entire catchment is in September. Runoff then increases. This is mainly related to the less intensive evapotranspiration. The low flow period lasts from September until January in the upper and middle Vistula, while a significant decrease in flows below the annual average starts already in August or even in July in the case of the lower Vistula.

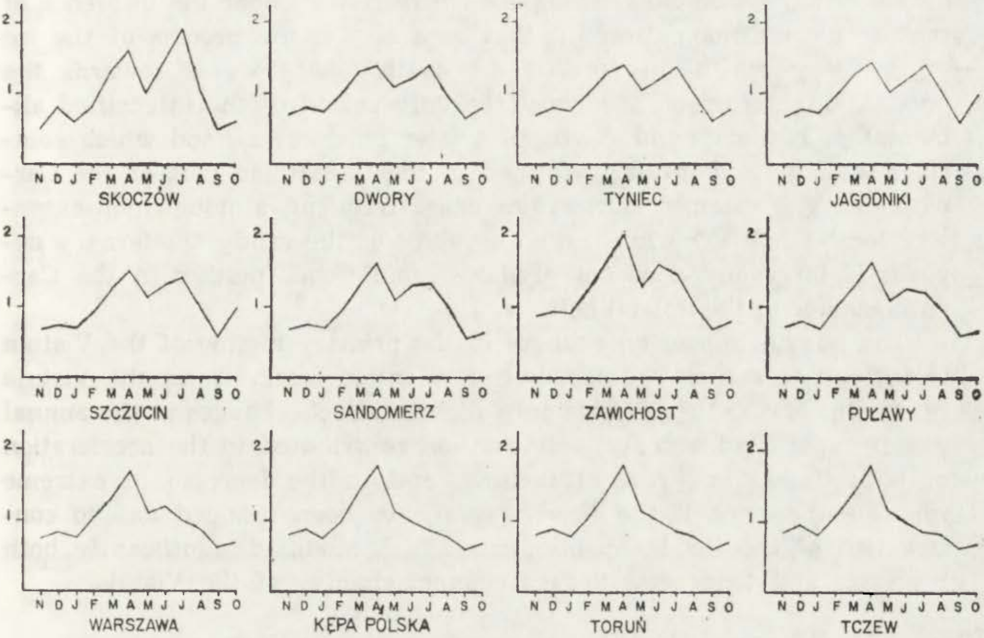

Fig. 19. Indices of the monthly discharges in the gauging profiles of the Vistula

THE HYDROLOGICAL REGIME OF THE VISTULA

According to the typology of Pardé, the Vistula is classified as a river having a complex rainy-nival regime of the continental type of Central Europe. The fundamental role in the formation of the Vistula regime is played by climate. Two areas of various proportions of the rain and nival alimentation can be distinguished in the Vistula catchment. The rain alimentation dominates in the Vistula catchment down to Zawichost, *ie* in an area covering 50,000 km². The remaining part of the catchment covering *c* 145,000 km² is the area of alimentation of nival origin. The Carpathians occupying only 9% of the total catchment area play a special role in the alimentation of the Vistula and in the formation of the hydrological regime. The Carpathians supply over 25% of the total annual runoff of the Vistula at the river mouth. Floods which form in summer in the Carpathians are responsible for the magnitude of maximum flows along the entire river. Under the influence of the ice phenomena pattern in that area also is the process of the ice cover decay which initiates in the south and proceeds towards the north. Downstream of Zawichost the only period of the intensified alimentation is March and April. Meltwater produces a flood which coincides with a flood formerly formed in the Carpathian part of the Carpathians. The summer storm rains cause frequent, although non-extensive local floods. The infiltration capacity of the sandy Quaternary deposits is large and does not promote rapid floods neither in the Carpathians nor in the upland belt.

The human impact on changes in the primary regime of the Vistula is difficult to assess. The capacity of retention reservoirs in the Vistula catchment is c $1 \cdot 10^9$ m^3. This only slightly affects changes in the annual runoff cycle. Undoubtedly, deforestation contributed to the acceleration of both timing and rate of melting, and to the increase in extreme flows. Parameters of the flood waves have been changed due to construction of the flood embankments which modified significantly both processes and tendencies toward channel changes of the Vistula.

THE PRESENT-DAY CHANNEL AND FLOOD-PLAIN OF THE RIVER VISTULA

The short-term, although rather regularly occurring rain- and snowmelt-induced high discharges bring about changes in the topography of both channel and flood-plain that are hardly perceptible in the landscape. On the contrary, extreme floods may cause very large changes in the channel pattern and flood-plain topography.

The rapid growth of fluvial geomorphology in the USA, Sweden and in other countries after the 1950s prompted a number of works in the Vistula Valley (Falkowski 1967; Tomczak 1971; Prószyński 1972; Koc 1972; Mycielska-Dowgiałło 1972; Biernacki 1975; Trafas 1975), and in its major tributary valleys (Falkowski 1970; Klimek, Trafas 1972; Szumański 1972). A further phase of geological-geomorphological enquiry in the Vistula Valley began in the 1980s with increased interest in flood-plain morphology, channel geometry and channel pattern changes which took place over the last centuries (Falkowski 1982; papers in two volumes—Starkel ed. 1982, 1987b, and in *Wisła...* 1982; Klimek 1987a). Despite these studies, much problems of the equilibrium of channel morphology, of hydraulic geometry, and of human-induced channel changes were studied in short reaches of the Vistula.

The Vistula channel, except the short headwaters and some reaches downvalley, is an "alluvial" channel along thee whole river. The channel was cut into the loose fluvial deposits which rest either on other Quaternary sediments or on Tertiary clays. The sinuosity of the present-day Vistula change ranges from 1.40 to 1.59 in its upper regulated reach, whereas in its upper middle non-regulated and lower regulated reaches it diminishes to 1.13—1.03.

River gradient reduction takes place in a relatively systematical manner downstream. Except the short mountainous headwaters, gradients decrease from 0.36 $m \cdot km^{-1}$ in the Oświęcim Basin to 0.11 $m \cdot km^{-1}$ near the valley outlet to the Baltic Sea (Fig. 20). Changes in channel widths are less regular. In the Oświęcim Basin, below the confluence with the Przemsza and the Soła, the average width is 50 m. Below the confluence with the Dunajec the Vistula channel is 200 m wide, in the gap in the Polish uplands the channel ranges in width from 500 to 750 m. In the Mazowshe Lowland the channel is up to 1000 m wide, in places up to 1500 m. In the lower reach, downstream of Toruń, the channel width varies from 400 to 1100 m (Babiński 1982).

Except the headwaters and the Vistula River Delta, the remaining part of the channel lies within the transfer or transportation zone, according to Schumm (1981). However, due to external influences, such as:

— different periods of integration of the particular reaches into the valley system of the Vistula (Starkel ed. 1982),

— local contrasts in the structure of the substratum, mostly of Quaternary age,

— changes in both hydrological regime and relationship between suspended load and bed load below the confluence with the major tributaries (the Dunajec, San, Pilica, Wieprz, Bug, and Drwęca),

different channel types occurred in the Vistula Valley before intensive channel correction was undertaken on the river.

In the Subcarpathian basins, but especially in the Oświęcim Basin and in the surroundings of Cracow, there occurred reaches with a highly sinuous channel (Trafas 1975; Gębica, Starkel 1987; Kalicki, Starkel 1987; Klimek 1987b; Rutkowski 1987). Until now, such a non-regulated channel persisted locally in the Oświęcim Basin upstream of the River Przemsza mouth (Fig. 21). In the Sandomierz Basin sinuosity of the regulated channel gradually decreases. More and more sandy side-bars tend to occur there (Fig. 20A). Above the confluence with the San there appear central bars (Fig. 20B). At intermediate and low water stages these bars emerge above the water level. On the riffles being separated by scour troughs the river is less than 0.9 m deep.

In the gap in the Polish Uplands and in the Mazowshe Lowland

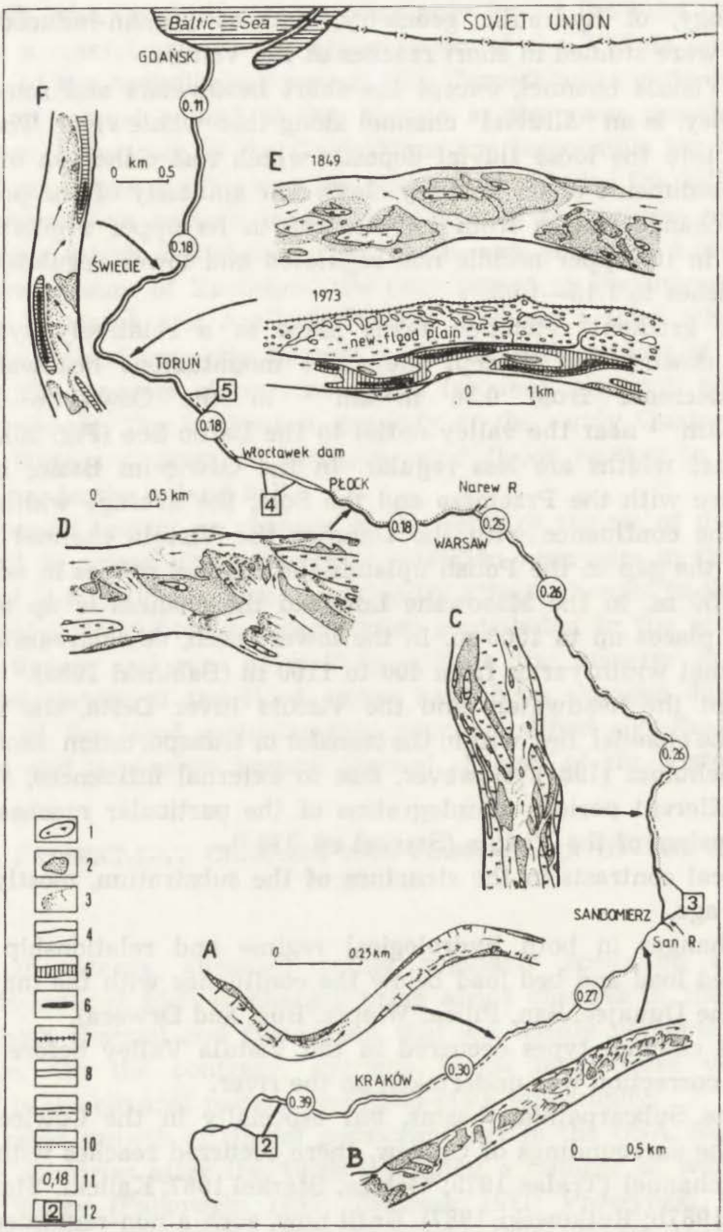

Fig. 20. Types of the present-day Vistula channel (B—acc. to Mycielska-Dowgiałło 1987; C—acc. to Falkowski, Szumański 1975)

1—"kępy" (tree-covered islands and bars), 2—sandy bars emerging during the low water stages, 3—bars extending underwater in the river, 4—depth of up to 2 m, 5—depth of 2—5 m, 6—depth exceeding 5 m, 7—dikes, 8—channel regulated in the 19th century, 9—channel regulated in the 20th century, 10—occasionally regulated channel, 11—mean river gradient [m/km], 12—channel sections shown in Figures 21—24

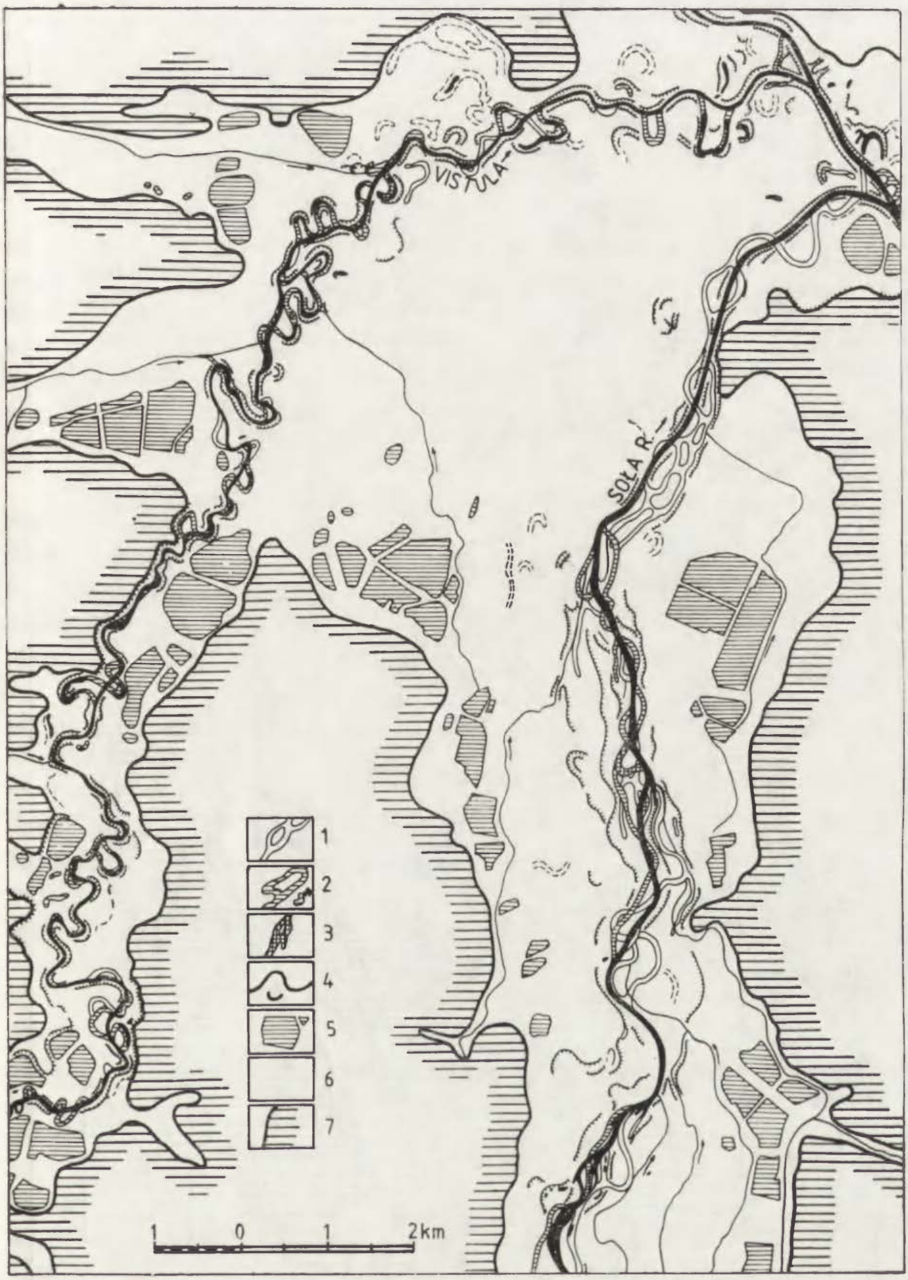

Fig. 21. Channel pattern changes of the Vistula and Soła rivers in the Oświęcim Basin due to channel correction undertaken in the 19th and 20th centuries (acc. to Galarowski 1986)

1—channel in 1855, 2—channel either in 1875 or in 1903, 3—channel either in 1934 or in 1954, 4—channel either in 1974 or in 1975, 5—ponds, 6—Holocene valley floor, 7—edges of Pleistocene plateaus

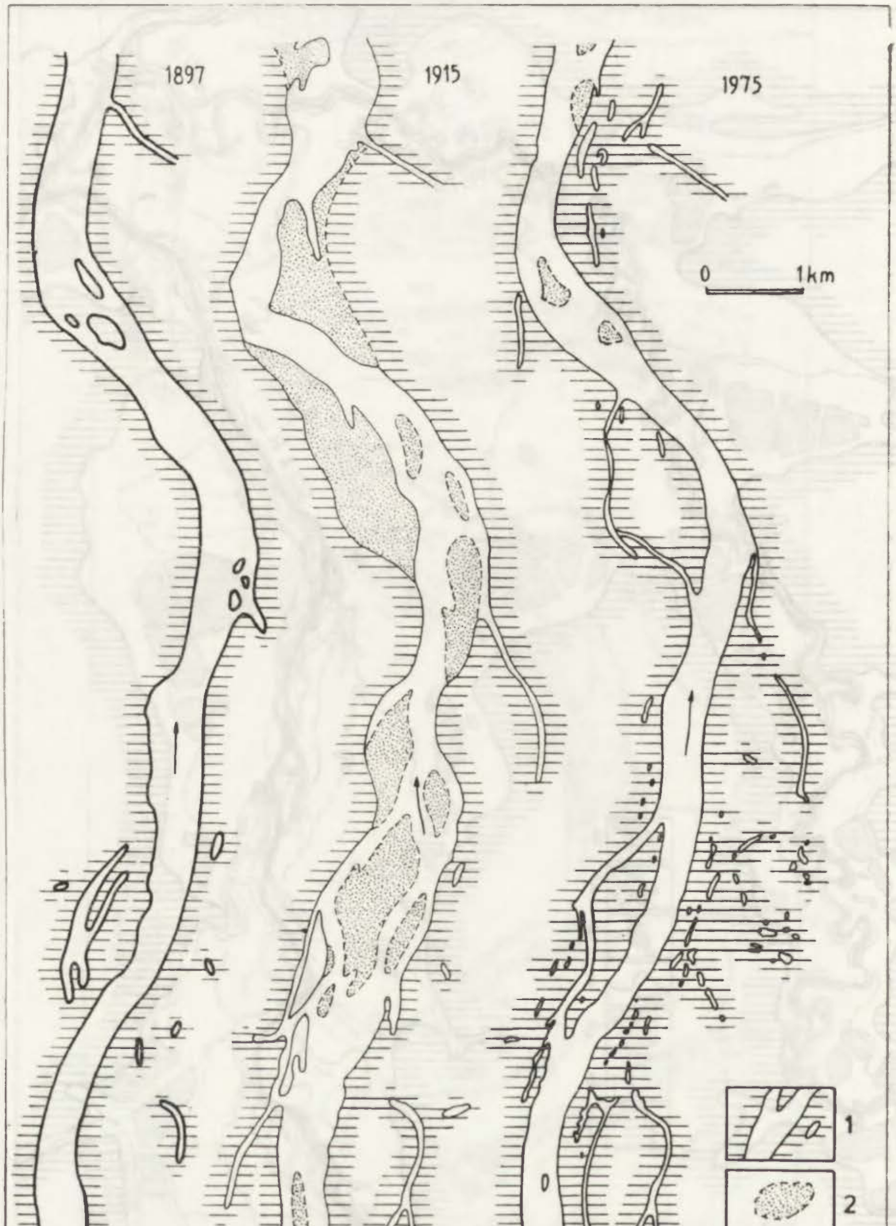

Fig. 22. Changes in the Vistula channel pattern in the gap in the Polish Uplands in the 19th and 20th centuries (acc. to Galarowski 1986)

1—water-filled channel and oxbow lake, 2—sandy bars

down to Włocławek there survived non-regulated or partly regulated channel reaches. Because of the large bed load and suspended load supply by the greatest tributaries: the San, Pilica, Wieprz, and Bug the existing channel pattern changes to a sinuous-braided pattern, with more or less well developed bar-braided sections. In places, even multiple-channel (anastomosing) patterns do exist (Figs. 20C, D and 22).

Sandy bars occurring in this channel section are on the average up to 1 km long and 0.3 km wide. On the air photographs bars extend underwater in the river. The flat bar surfaces rise on the average 0.2 m above the mean water level. As the water level falls, delta-like bars are produced at the outlets of the overflow channels that disrupt the bars (Fig. 20D). In this channel reach there occur many scour troughs which may be as much as 8 m deep below the flood-plain (Falkowski 1967).

Islands or vegetated bars, in Poland commonly known as "kępy", are on the average up to 1 km long and 0.5 m wide (Figs. 20C, D and 22). The great stability of the "kępy" in certain channel sections leads to a multiple channel pattern. Changes in "kępa" size take place only after exceptionally high flows. Some vegetated bars may be scoured away during the catastrophic floods (Falkowski 1967).

In the lower Vistula reach, within the young moraine landscape, the channel pattern of the non-regulated Vistula was similar to the previously mentioned (Figs. 23 and 24). As a consequence of channel correction undertaken on the Vistula since the middle of the 19th century, drastic changes in the primary channel pattern have taken place over long distances (Fig. 20E, F). In the artificial low sinuous channel there developed at 1.2—1.4 km intervals side bars, up to 1 km long and up to 0.3 km wide. Their heights correspond to intermediate and intermediate-low water stages. The steep downcurrent slopes of such bars tend to move 0.4—2.4 m during twenty four hours, with a maximum observed velocity of up to 6.5 m during twenty four hours. The bars are separated by scour troughs, 5—67 m deep at intermediate water stages. On the riffles the shallowest waters are 1.0—1.8 m deep at mean water stages.

There has been permanent human occupance of the Vistula Valley since prehistorical times (Hensel 1982), when the Vistula was becoming a major trade route. River channel changes at specific locations, *eg* in the surroundings of Cracow (Kmietowicz-Drathowa 1964), Toruń (Tomczak 1971), Warsaw (Prószyński 1972), and at many other sites are evident in documentary records and cadastral surveys. It was only in the 19th century that the development of modern cartography and the printing of large-scale maps which show longer valley reaches has made it possible to recognize changes in the Vistula channel pattern which took place in the last 150—200 years. Cartographic data show that chan-

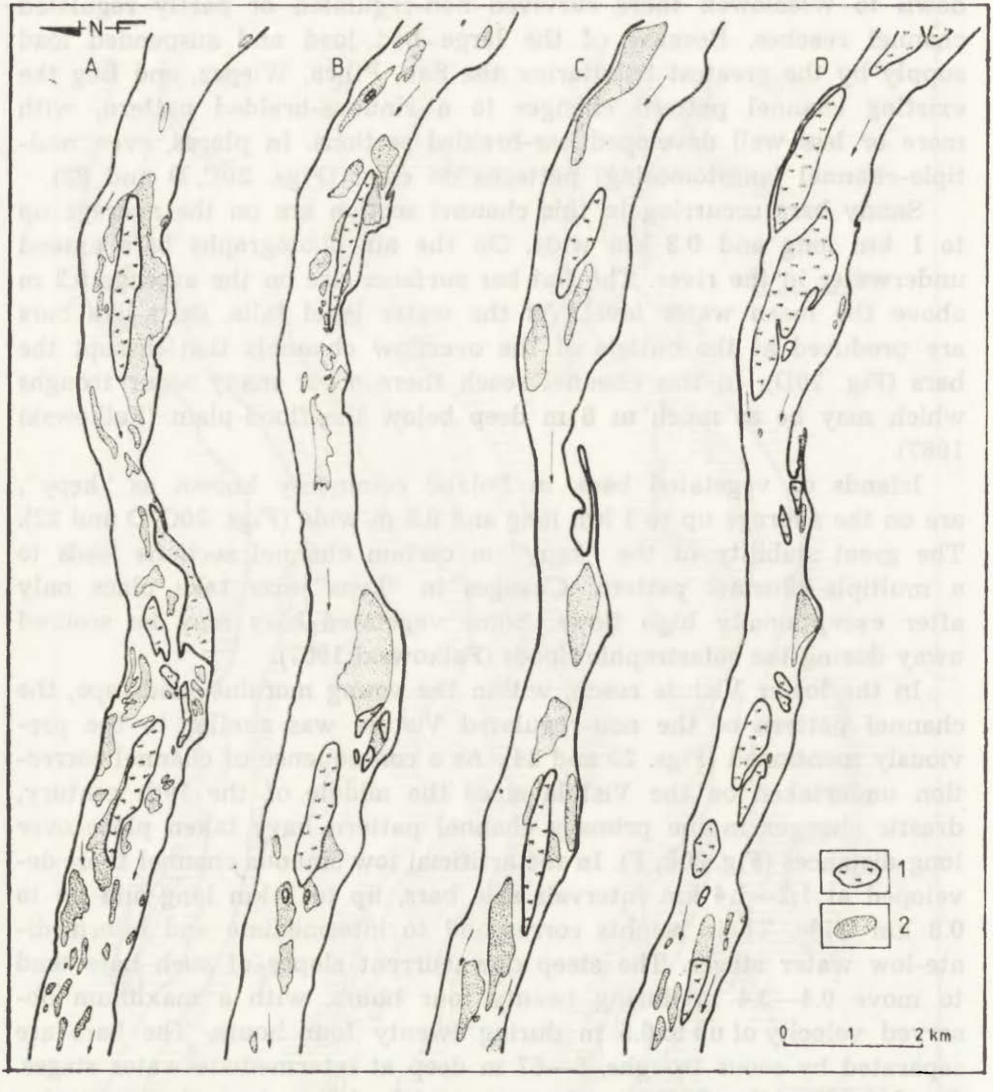

Fig. 23. Changes in the Vistula channel pattern near Dobrzyń in the 19th and 20th centuries (acc. to Koc 1972)

Channel dating from: A—the 1820s, B—the 1860s, C—the early 20th century, D—the 1950s; 1—tree-covered islands ("kępy"), 2—sandy bars

nel changes were both of natural and man-made origin. Engineering changes to channels began already in the early 19th century. The greatest proportion of river regulation has taken place since the second half of the 19th century and in the early decades of the 20th century. Channel correction was first undertaken on the upper Vistula in the surroundings of Cracow and on the lower Vistula downstream of Toruń (Fig. 20). Below the confluence with the Dunajec River regulation was under-

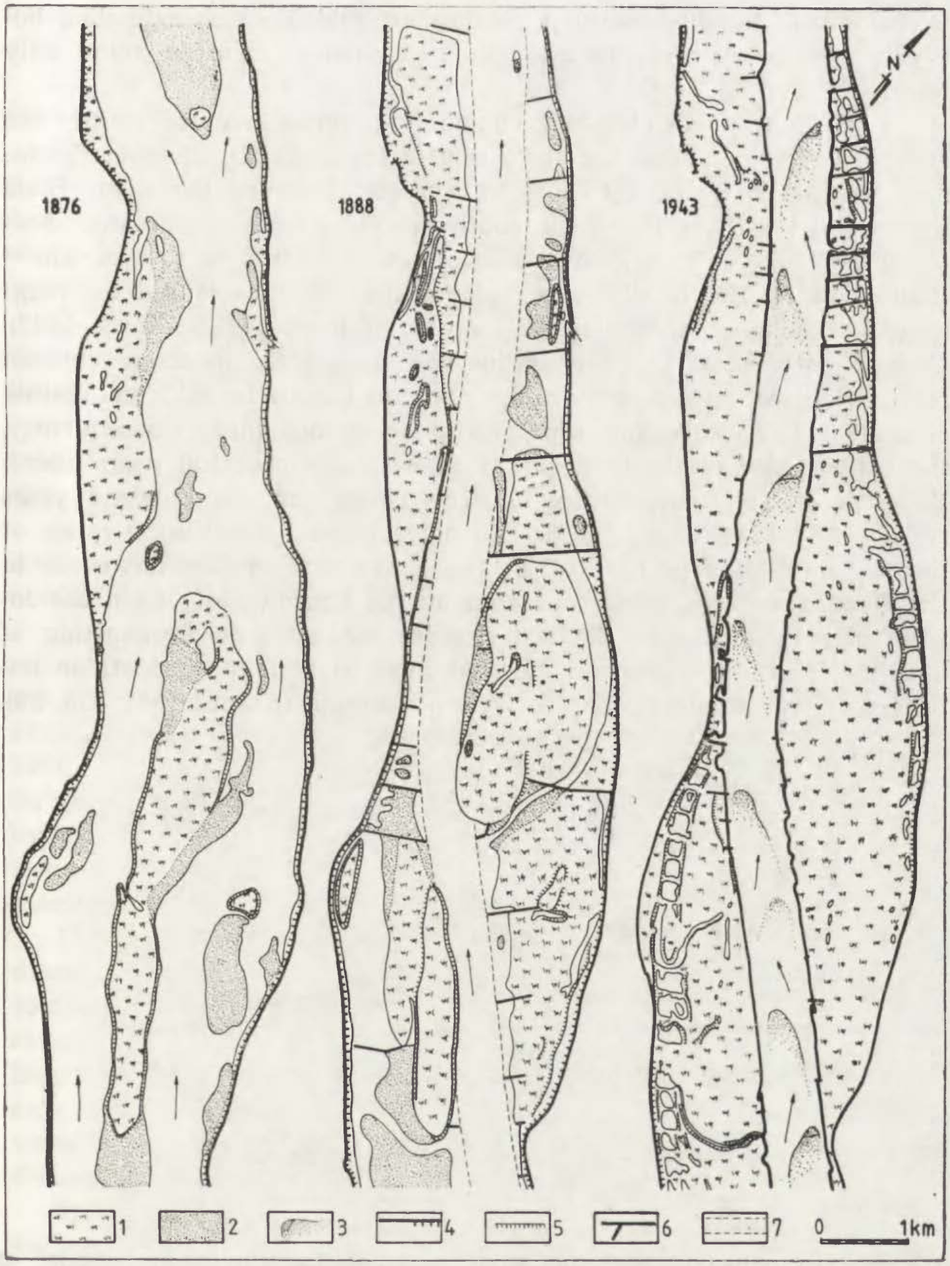

Fig. 24. Changes in the Vistula channel pattern near Toruń in the 19th and 20th centuries (acc. to Koc 1972)

1—tree-covered islands ("kępy") partly connected with the flood plain, 2—sandy bars rising above mean water level, 3—oblique sandy bars (partly extending underwater in the river), 4—river banks prior to the river regulation, 5—erosional edges of the stabilized bars ("kępy"), 6—regulated river banks, transverse dams (spurs), 7—planned zone of river regulation taken only in the 20th century. In the long middle reach extending between Sandomierz and Płock a regulated channel is to be found only locally.

In the Subcarpathian basins engineering works involved mainly the cutting across loops and the erection of dikes (Fig. 21). Channel shortening caused the river gradients to increase. Between the River Biała mouth and the River Przemsza mouth the Vistula channel became shortened by 19 km. Thus, gradients increased from 0.25 to 0.41 $m \cdot km^{-1}$ (Punzet 1981). The locally increased current velocities caused the magnitude of channel deepening to increase (Punzet 1981; Klimek 1983). Censequently, pronounced river incision took place in many channel reaches, but especially in the Subcarpathian basins. In 1813 the Vistula channel in Cracow became confined by stony boulevards. Consequently, the rate of downcutting reached 4 m over the past 150 years there. Rates of channel downcutting of 0.5—0.8 m *per* one hundred years (1870—1970) have been observed in other places in the same reach of the Vistula Valley (Punzet 1981). The above process does not occur in the Oświęcim Basin being separated by the Cracow Gate from the lower valley segment. In the last decades the rates of downcutting of both the Vistula channel and the lowermost parts of the Carpathian tributary valleys accelerated up to 1 cm *per annum* (Klimek 1983; Fig. 25).

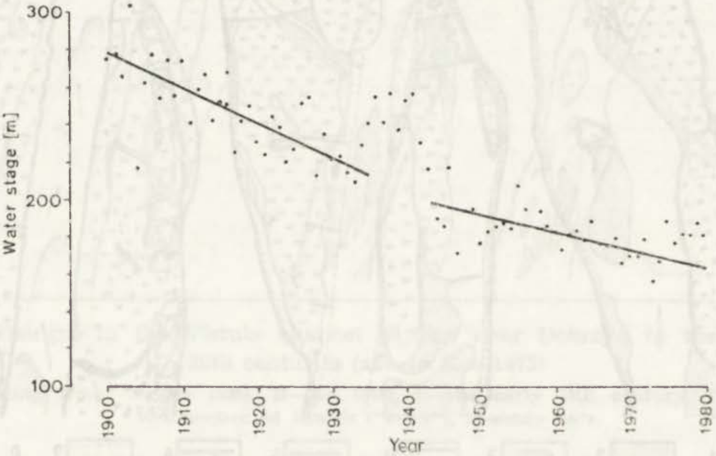

Fig. 25. The course of minimum water stages at Szczucin as an indicator of channel deepening

In the lower Vistula reach river regulation involved channel constriction and formation of one channel of uniform width by constructing low transverse dams (Fig. 24). The concentration of both current and channel downcutting (the rates of which ranged locally from 1.0 to 1.5 m during the last century) was accompanied by deposition of overbank sediments within the former channel bed. As a result, the youngest and lowest flood-plain was created.

Downstream variations in width of the Vistula Valley floor (*ie* the flood-plain) can be explained by:

(i) differences in the geological structure of the sub-Quaternary substratum and in the composition of Quaternary deposits forming the individual regions through which passes the valley: the Subcarpathian basins—the Polish Uplands—the Mazovshe Lowland and the young moraine landscape of Pomerania,

(ii) contrasts in the valley widths in the regions mentioned above, these controlled the more or less easy widening of the youngest valley floor,

(iii) contrasts in ages of the particular valley reaches which became integrated into the present system of the Vistula Valley at different times,

(iv) downvalley changes in the hydrological regime being associated with changes in the transport balance of alluvia, especially below the confluence with the larger tributaries.

The contrasting ages of the Vistula Valley floor and its diversity are reflected in the absence of a specific sequence of cutoffs of differing age which are so typical of some tributary valleys (the San—Szumański 1972; the Wisłoka—Alexandrowicz *et al* 1981; and other—Falkowski 1970). Beside valley reaches showing classical palaeomeanders, *eg* in the Subcarpathian basins (Fig. 26A, B), there occur reaches marked only by the occurrence of braided palaeochannels, *eg* in the wide valley portions that are incised into the morainic plateaus dating form the last glaciation (Fig. 26C, D).

During the earlier half of the 19th century, prior to the erection of dikes and to intensive channel downcutting, the flood-plain corresponded to the extent of the valley floor. In the Subcarpathian basins its widths ranged from 4 to 8 km. The clearly perceptible or even water-filled loops tended to undermine the valley flanks. Along the channel there extended natural levees, up to 2 m high and from some scores to several hundreds of metres in width (Klimek 1987; Kalicki, Starkel 1987; Gębica, Starkel 1987).

In the gap in the Polish Uplands, in many sections without dikes the valley floor is up to 1 km wide. Well preserved palaeomeanders and younger braided channels being partly superimposed on the former one are traceable there (Falkowski 1982). Such channel pattern changes relate to the increased sedimentation rates of both bed material and suspended material since the middle of the 19th century (Maruszczak 1982). In the Mazovshe Plain the valley floor widens locally up to several kilometres. Like in the gap section, there occur semicircular recesses in the valley edge which have been formed by the meandering Vistula.

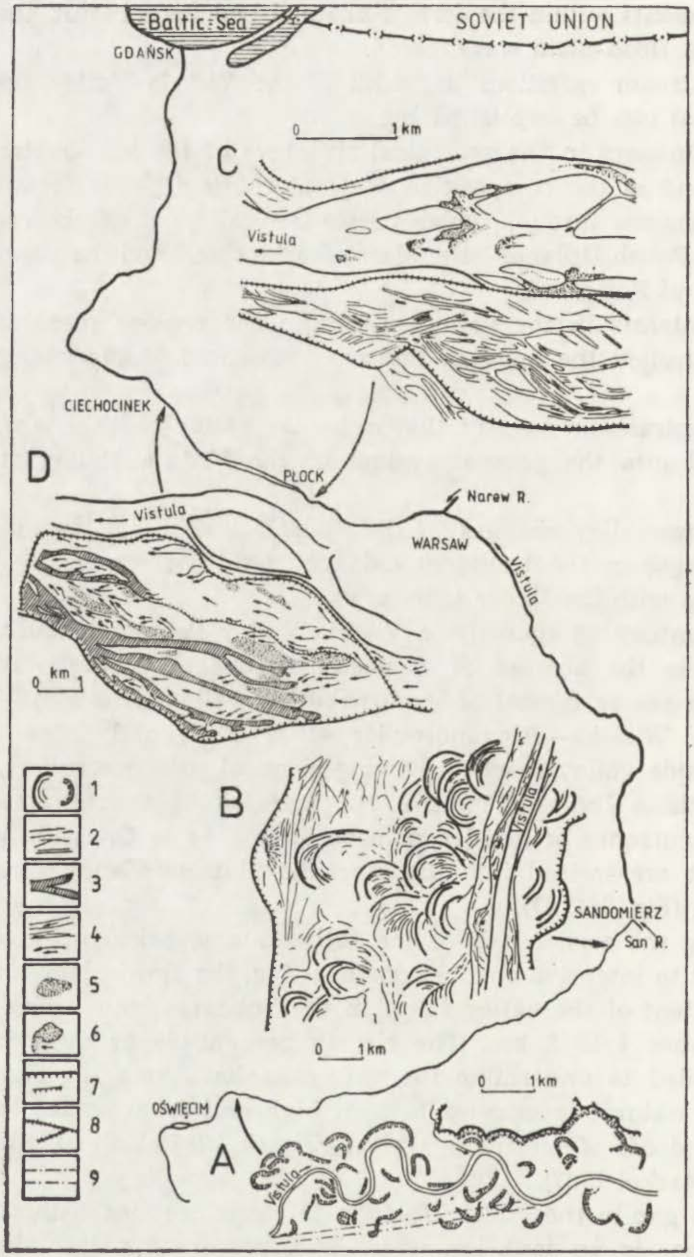

Fig. 26. Flood plain pattern in the Vistula Valley (A,C,D—acc. to the present authors, B—acc. to Mycielska-Dowgiałło 1987)

1—palaeomeanders, 2—traces of braided channels, 3—peatfilled braided channels, 3—traces of water flow, 5—aeolian sand dunes, 6—sandy bars, 7—terrace edges, 8—dikes, 9—canals under construction

Traces of braided channels are also found there, especially close to the modern channel (Falkowski 1982).

In the young moraine landscape the Vistula Valley passes through several basins alternating with narrow valley sections being entrenched into the morainic plateaus. Braided channels, up to 3—4 m deep, which locally contain peat are dominant there (Tomczak 1982).

A characteristic feature of the Vistula flood-plain are natural levees accompanying the present channel and many palaeomeanders. Those landforms occur in the upper reach (Gębica, Starkel 1987; Klimek 1987b), in the middle reach (Falkowski 1967) and in the lower reach of the valley (Tomczak 1982; Niewiarowski 1987b). The levees are 1.5—2 m high and usually hundreds of metres wide (Klimek 1987b; Niewiarowski 1987b).

The earliest evidence of human impact on flood-plain formation comes from remote times (Starkel 1987a). The medieval colonization and continued deforestation of the Vistula catchment showed themselves in the increased sedimentation rates and the upward growth of the flood--plains by deposition of sediments. In the Vistula gap in the Polish Uplands increased aggradation of the flood-plain and change from meandering to braided channel pattern were caused by the cultivation of root crops and the disturbance of water management in the catchment in the middle of the 19th and 20th centuries (Falkowski 1967, 1982; Słupik 1973; Maruszczak 1982).

In the Middle Ages urban growth on the Vistula caused local changes in the morphology of the flood-plain. Ditches, weirs, and dikes prevented part of it from flooding. However, the greatest changes were brought about by channel correction undertaken on long reaches of the river in the 19th century. Channel stabilization procedures are going on in many sections. As a consequence of dike erection, the yearly flooding of the valley floor became confined to the narrow inter-dike area, hundreds of metres wide. The power of flood waters being confined to a narrow path is now greater than that prior to the river regulation. Such waters are able to transport in suspension and deposit much coarser material. The process of increased sedimentation is supported by willow brakes which commonly occur in the inter-dike area. As a result, in many valley sections the gradual growth and levelling of this youngest flood-plain takes place. This process depends in detail on the relief of the initial sedimentary surface, on its width and height above the water level within the channel. Figures published by Dembowski (1984) show that in the Sandomierz Basin, in the inter-dike area downstream of the River Raba mouth, the primary topographical surface has aquired forty years (1937—1976) before attaining a levelled cross profile, and channel constriction took place. Koc's work (1972) demonstrates that in the lower reach of the valley, in the surroundings of Toruń, the construction of low dams being perpendicular to the banks of the island-braided river bed, 2—3 km wide, led to the constriction of the Vistula current to 1 km (Fig. 24). After 55 years, deposition of both suspended material and bed material on the lee side of such a low dam supported by downcutting of the new channel resulted in the generation of a new, lower flood-plain. However, in the lower reach of the Vistula the relief of this youngest flood-plain due to river regulation is still variable, although 100 years passed away. Elevations of the former vegetated islands and water-filled depressions are found there.

Dikes and increased current velocities of the flood waves facilitate both transport and sedimentation of the coarser fractions of bed load and suspended load. Consequently, the youngest overbank deposits are coarser than the corresponding deposits beyond the dikes. This is especially clear in the Oświęcim Basin and in the surroundings of Cracow (Klimek, Zawilińska 1985; Rutkowski 1986). Coal exploitation and industry which have concentrated in the upper Vistula drainage basin have also changed the geochemical composition of the youngest alluvia. In the surroundings of Cracow point bar deposits contain several per cent of coal clasts, whereas the fine-grained intercalations interrupting the present-day alluvia may contain as much as 98% of coal particles (Rutkowski 1986). Concentration of heavy metals, especially of cadmium, zinc, lead, copper, and chromium may be hundreds of times as great as that in the earlier alluvia (Helios-Rybicka 1983; Helios-Rybicka, Rutkowski 1984; Klimek, Zawalińska 1985).

Over the last century the increased flood magnitude causes sometimes crevasse channels to cut across the dikes so that the valley becomes inundated. During the last 20 years the frequency of occurrence of such floods was greater on the lower Vistula in the surroundings of Toruń than in the surroundings of Sandomierz (Fig. 27A). In 1934 the catastrophic rain-induced flood on the upper Vistula in the Carpathians led to the inundation of extensive areas of the Vistula Valley floor in the Sandomierz Basin (Fig. 27B).

Finally man has modified the flood-plains by building large dams and impounding retention reservoirs. Until now, the following dams and water gates have been constructed on the upper Vistula: Goczałkowice—impounded in 1956, capacity of 168 million m^3, Smolice—1988, Łączany—1958, Dąbie—1962, Przewóz—1955, and Włocławek impounded in 1970 on the lower Vistula, capacity of 408 million m^3. In the upper portions of reservoirs increased sedimentation of both bed material and suspended material takes place. This causes bed elevation to increase, and the adjacent flood-plain to grow upward by deposition of sediment, *eg* upstream of Goczałkowice and Włocławek reservoirs. Downstream of the dams both frequency of water level fluctuations and current power have increased. This causes channel deepening immediately below dams and aggradation below this section (Babiński 1982, 1985, 1986, 1987).

Increased sedimentation rates in some reaches of the middle Vistula,

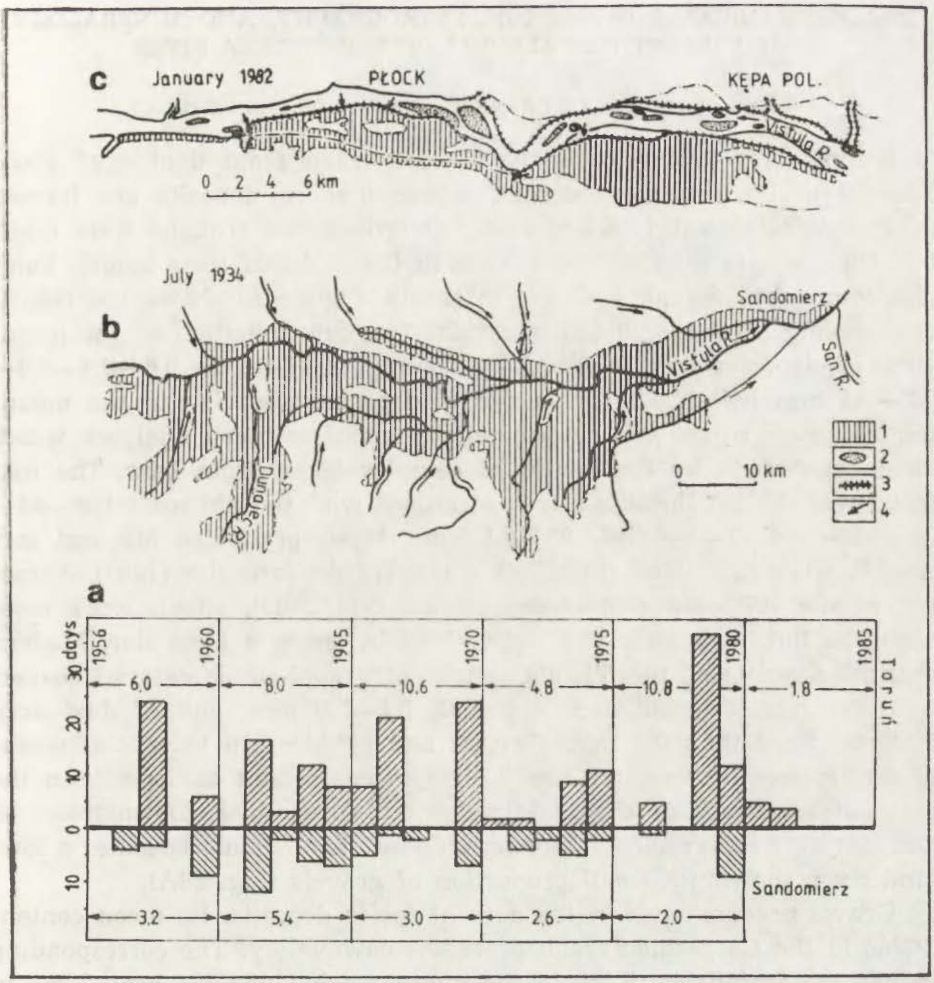

Fig. 27. Extent of: c—the 1982 ice-jam-induced flood near Płock (acc. to Banach 1983), b—the 1934 rain-induced flood in the Sandomierz Basin (based on IMGW data); and frequency and duration of inundation of the flood plains in the middle reach (near Sandomierz) and in the lower reach (near Toruń) of the Vistula—a 1-inundated area, 2-sandy bars and islands in the Vistula Valley near Płock at mean water level, 3-dikes, 4-place, where water spilled over the dikes

where sandy bars, islands and some regulation structures occur, tend to hinder the travel of floes in spring. This favours the formation of ice-jams. Strong currents accompanying the ice-jams produce either erosional troughs or sandy bars on the flood-plain (Karabon 1980).

Retention reservoirs and small dams which hinder the travel of floes may induce ice-jam floods. In January, 1982 a large ice-jam which formed at the Vistula outlet to the Włocławek reservoir caused the rapid rise of the water level and crevassing of the dikes in many places (Grześ, Banach 1983). As a result, an extensive reach of the Vistula Valley floor became flooded (Fig. 27C).

THE MECHANICAL COMPOSITION, PETROGRAPHY, AND MINERALOGY OF PRESENT-DAY ALLUVIA OF THE VISTULA RIVER

THE GRAIN-SIZE OF CHANNEL DEPOSITS OF THE VISTULA

Samples for grain-size analysis were taken from depths of about 1.5—2.5 m in the river current, where modern deposits are formed (Kociszewska-Musial 1969a, b, 1970). Overdeepened troughs were omitted. On the bars samples were taken in the midst of their length. Samples were obtained at 4—5 km intervals. Figure 28 shows the results of sampling at about 20 km intervals. The determination of the grain-size of deposits was achieved by sieving (2—1—1.75—0.6—0.4—0.3—0.2—0.1 mm holes). The grain-size of deposits occurring in the mountainous river reach was determined by supplementary analyses which have been made by Rutkowski of samples taken from bars. The material was shaken through sieves accordant with the *phi* scale 128—64—32—16—8—4—2—1—0.5—0.25—0.1 mm. Mean grain-size *Mz* and sorting P_I were calculated from Folk's and Ward's formulae (1957). Abrasion of the 0.75—0.6 mm quartz grains (Fig. 28D), which work most easily in flowing water, was determined by using a binocular. Modern channel depoists of the Vistula consist of gravel-sized material coarser than 0.2 mm, of sand-sized material, 0.1—2.0 mm, and of dust-sized material finer than 0.1 mm. Gravels and pebbles, up to several scores of centimetres in diameter, are the major component of deposits in the mountainous reach of the Vistula down to Drogomyśl. Downstream of Drogomyśl, river gradients become reduced. The Vistula becomes a lowland river showing a small proportion of gravels (Fig. 28A).

Gravel predominates in the current facies deposits. Its mean content (92%) in the Carpathian reach decreases downvalley. The corresponding values are as follows: 5.0% in the upper reach (106—384 km), 2.3% in the middle reach (384—657 km) and 5.4% in the lower reach of the Vistula (657—1041 km). The value of gravels increases locally up to 27.0% below the River Przemsza mouth, up to 18.2% below the River Raba mouth and up to 17.9% below the River Wisłoka mouth. In the lower reach of the Vistula, which erodes older gravels there, the corresponding values are 32.9% (876 km) and 28.5% (1036 km). The bar facies differs from the current facies by having a lower proportion of gravels in the lower and middle reaches of the Vistula. The dominant value is 0.1—0.5%, the mean value being 0.8%.

In the upper reach of the Vistula the percentage of very coarse-grained sand is 0.9—4.7. Below the River Przemsza mouth down to the River San mouth its percentage is 10—12 in the current facies. Similar values have been obtained for the middle Vistula, especially in the surroundings of Warsaw. The sections previously mentioned are separated by a section extending between the River San mouth and the Ri-

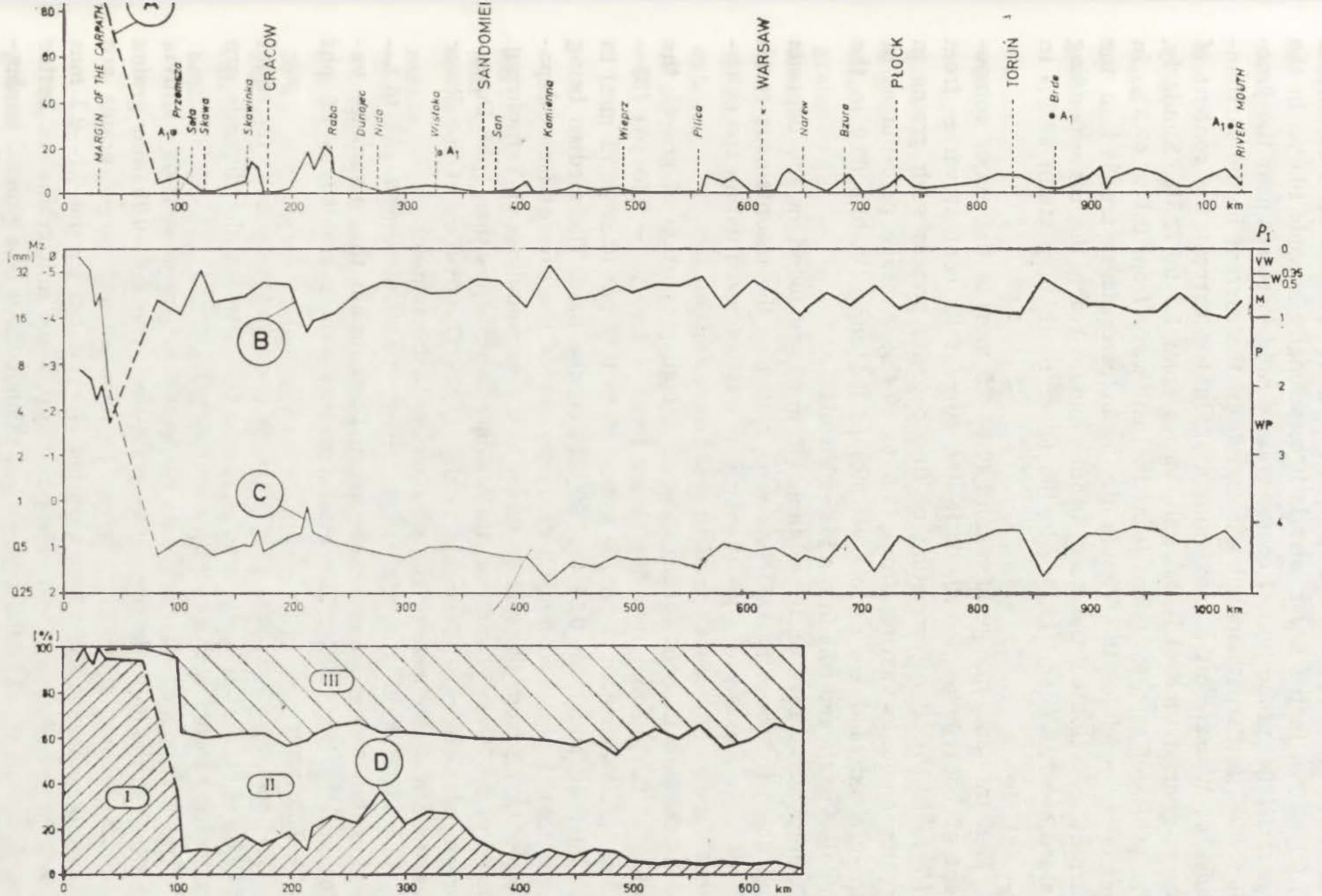

Fig. 28. Grain size of the Vistula channel deposits (acc. to Kociszewska-Musial 1969, 1970, recalculated and suplemented)

A—content of grains coarser than 2 mm, A_1—extreme value, B—sorting δ_1 (VW—very well, W—well, M—moderate; P—poor, VP—very poor), C—mean grain size M_Z, D—abrasion of quartz grains 0.60—0.75 mm fraction (I—angular, II—partly rounded, III—rounded) ver Wieprz mouth, where the content of coarse-grained sand diminishes to 0.1—3.0%. In the lower Vistula it occasionally exceeds 10.0%. In the bar facies the proportion of coarse-grained sand increases near the junction with its Carpathian tributaries, like in the current in the surroundings of Warsaw (at a maximum 6%). In the current the content of coarse-grained sand (0.5—1.0 mm) varies from 1.3 to 72.5%. Similarly, the values of samples taken from the bars vary from 0.3 to 69.3%. In the upper reach of the Vistula the mean percentages are 34.4 in the current and 29.4 on the bars. In the middle reach the corresponding values are 29.0% and 19.1%. In the lower reach they attain 38.0% in the current.

Medium- and fine-grained sand (0.1—0.5 mm) is the major component of both facies described. In the current its content varies from 17.7 to 98.7%. Bars consisting of fine deposits possess such grains in greater amounts varying from 19.5 to 99.4%. Average percentages of fine-grained sand are as follows: 59.5 in the upper Vistula 65.9 in the middle Vistula and 50.9 in the lower Vistula.

Only traces of dust (finer than 0.1 mm) are found in the deposits laid down by the Vistula. Dusts were stated in the mountainous reach of the river marked by a great supply of waste derived within the catchment. Downvalley dusts are transported in suspension.

In the mountainous reach, showing a high proportion of gravel, the value of the median (*phi* 50) varies from − 4.90 to − 5.60 *phi* (30—49 mm). Downstream it ranges from 1.89 to 0.47 *phi* (0.27—0.72 mm) in the current, and from 0.24 to 0.60 mm on the bars. The median being more than 1 *phi* (0.50 mm) is characteristic of the current facies deposits occurring from the springs down to the surroundings of Tarnobrzeg. Down to the River Wieprz mouth this parameter is less than 1*phi*. Downstream of Kozienice it exceeds locally 1 *phi*. Downvalley of the River Bug mouth it is characteristic of about half the samples.

The mean grain-size *Mz* ranges from − 2.65 to − 5.37 *phi* (6.3—41.0 mm) in the mountainous reach. Downstream this parameter varies greatly (Fig. 28C). The most frequent values are 0.5 to 1.5 *phi* (0.7—0.35 mm).

The sorting of deposits (Fig. 28D) is poor and very poor (σ_I equal to 1.75—2.5) in the mountainous reach. Downstream the deposits are moderately sorted, less frequently well sorted.

The abrasion of quartz grains contained in the present-day alluvia of the Vistula depends upon the grain-size. The 0.6—0.75 mm grains exhibit the best abrasion, whereas the smaller and larger grains are less well rounded. The worst abrasion is exhibited by the 0.1—0.2 mm quartz grains. Among the fine sands the 0.3—0.4 mm grains are better rounded than the 0.4—0.5 mm grains, though there is a general tendency to decrease in abrasion with decreasing grain-size. In the present-day alluvia of the Vistula partly rounded grains predominate, while well rounded grains are less numerous. Wear and tear and selection of the angular grains takes place along the river. As a result, those grains decrease in number downstream.

Figure 28D shows the abrasion of the 0.6—0.75 mm grains along the river. In the mountainous section of the Vistula Valley there occur only angular quartz grains (up to 100%). Downstream of the Goczałkowice dam abrasion tends to vary. Rounded material is at first supplied by the Przemsza River. Downstream of its mouth the percentage of well rounded grains in the Vistula increases to c 20.

Angular grains increase in amount below each junction with the Carpathian tributaries. Below the junction with the Soła, Skawa, Skawinka, Raba, and Dunajec the deposits of the Vistula become enriched in angular quartz grains. Downstream such grains occur in smaller quantities due to the selective transport and partly abrasion. The last angular material source along the Vistula is the Wisłoka tributary (Kociszewska-Musiał 1969a). Below its outlet the percentage of angular grains consequently decreases to c 10 toward the River Wieprz mouth, to c 5 toward the River Bug mouth, and to c 1—2 in the lower reach of the Vistula.

Enrichment in well rounded grains is achieved in the Vistula section extending between the river mouths of the San and Wieprz. The value of such grains here exceeds 20% to reach more than 50% downstream.

HEAVY MINERALS

The content of heavy minerals in the deposits of the Vistula is low, particularly in the present-day current. This is due to the greater content of the coarse fraction there which does not favour the co-occurrence of rare minerals. Bar deposits show a higher concentration of minerals of the heavy fraction. The proportion of opaque minerals is high in this fraction ,even 80—95% in the upper Vistula).

The transparent heavy minerals contain mostly garnet (up to c 73%), staurolite (up to 38%), disthene (up to c 32%), epidote (up to 28%), and tourmaline (1.2—23.8%). The latter shows regular variations along the river being influenced by the source material within the catchment. Heavy minerals are represented by minerals resistant to both weathering and transportation.

THE PETROGRAPHICAL VARIABILITY OF GRAVELS WITHIN THE UPPER VISTULA VALLEY

In the upper Vistula Valley there has been observed the mixing of gravels which are from three sources: the Carpathians, the Polish Uplands, and of glacially derived material from Scandinavia and from northern and central Poland (Fig. 29). The Carpathian material consists

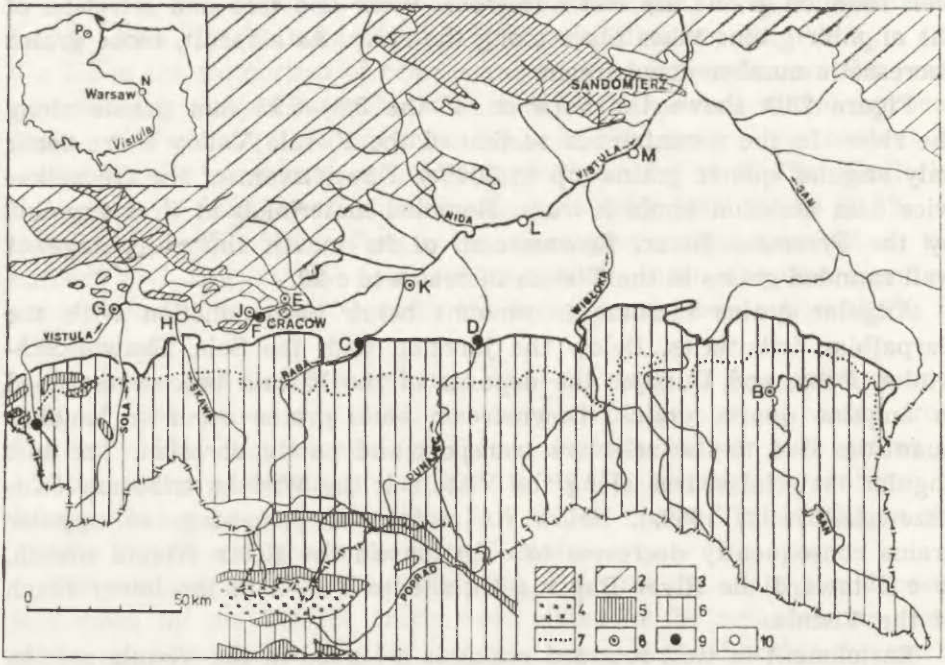

Fig. 29. Sketch showing the exposed geological structure of the upper Vistula catchment and sample sites

Carpathian Foreland: 1—Palaeozoicum, 2—Mesozoicum, 3—Tertiary; the Carpathians: 4—magmatic and metamorphic rocks, together with Werfenian quartzites, 5—limestones, 6—sandstones and shales, 7—limit of the Southern Polish Glaciation; material taken from: terraces—8, bars—9, channel bed—10

of flysch sandstones. The amount of quartz is small, but it gradually increases as the grain-size decreases (Rutkowski 1977). In the southern part of the Polish Carpathians flysch sandstones and quartz are the only gravel components (Fig. 30A). In the west, within the Soła, Skawa, and Raba catchments, associated with the sandstones and quartz may be cherts derived from the Mikoszowice beds. In the east, within the Wisłoka, Wisłok, and San catchments, there occur cherts derived from the menilite beds (Fig. 30B). At the Carpathian margin glacial material is found. Consequently, there appears an admixture of other components (Fig. 30C). In the Dunajec Valley an important component are granites and quartzites of Tatric origin, and limestones derived from the Tatra Mts and the Pieniny Klippen Belt (Fig. 30D; Nawara 1964).

The upland material is represented mainly by flints and silicified limestones (treated in conjunction with flint). The amount of flint is greatest in the coarsest fraction (Fig. 30E—J). The Holocene deposits of the Vistula are practically lacking in limestones because of weathering and dissolution (Rutkowski, Sokołowski 1983). In part, the upland belt also supplied quartz, and some sandstones and quartzites.

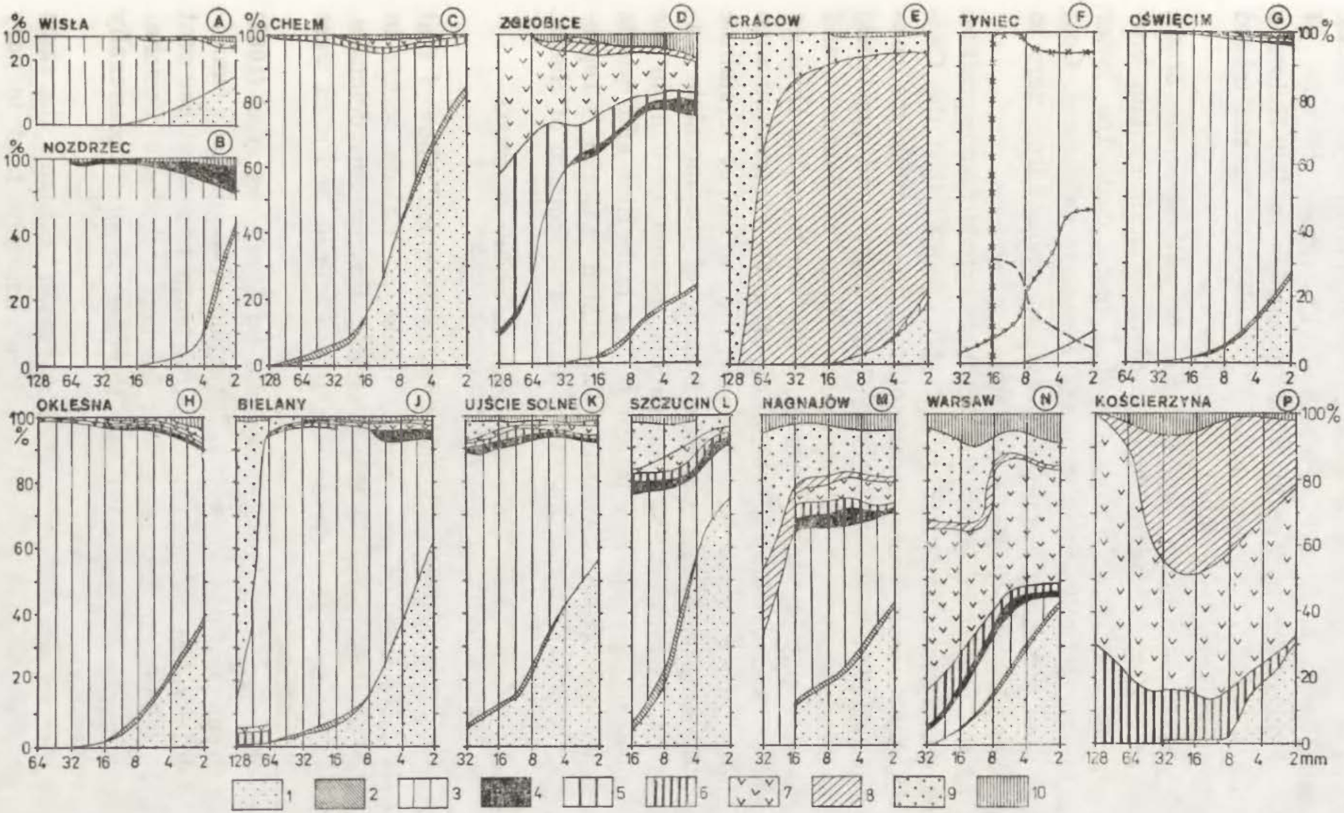

Fig. 30. The petrographical composition of some gravels in the upper Vistula catchment, and their dependence on grain-size (percentage of total gravel amount) (E, J—acc. to Rutkowski, Sokołowski 1983; D, L—acc. to Sokołowski 1987)

A—E—tributaries of the Vistula; F—black coal content in selected samples taken from the surroundings of Tyniec; G—N—Vistula Valley; P—Vistulian Glaciation: 1—quartz, 2—lidytes, 3—sandstones; 4—10—other components: 4—cherts, 5—Tatric quartzites, 6—other quartzites, 7— magmatic and metamorphic rocks, 8—limestones, 9—flints, 10—other rocks

The glacial material of Scandinavian provenance varies greatly in composition (Fig. 30P). It is made up of crystalline rocks (plutonic magmatic rocks, in minor amounts extrusive rocks), metamorphic rocks, quartzites, sandstones, and early Palaeozoic limestones. Because of leaching, these limestones appear in small quantities in the Holocene deposits of the Vistula. There also occur flints (derived by the inland ice from northern and central Poland) and quartz.

Shells of present-day snails and material of anthropogenic origin have not been considered. Modern deposits of the Vistula contain broken glass, pottery, concrete, bricks, slag and black coal. The latter results from mining activity, mainly in the Przemsza catchment. Coal particles finer than 8 mm or 64 mm may vary in amount from zero to nearly 100 per cent (Fig. 30F; Rutkowski 1986).

Analysis of the spatial variability of the petrographical composition of gravels in the Vistula Valley (Fig. 30G—N) revealed that the Carpathian sandstones become consequently eliminated, whereas the content of more resistant components (quartz, flints, cherts, and quartzites) increases. The higher amount of crystalline rocks at Szczucin and Nagnajów is due to an admixture of material derived from the Dunajec catchment, and to the reworking of glacial deposits. On comparison with gravels that have been obtained from Warsaw, the content of crystalline clasts is high there (Fig. 30N). This is a feature of the morainic material, whereas the amount of limestone cobbles is smaller than in the moraines because of abrasion and leaching. The high flint and quartz content is noteworthy. The undisputable Carpathian material is represented by 1/3—2/3 of sandstones, and by a marked proportion of cherts.

THE MINERAL COMPOSITION AND CONCENTRATION OF HEAVY METALS IN THE VISTULA-DEPOSITED ALLUVIAL LOAMS

Analysis of the composition of alluvial loams or “mada” showed that in the fraction finer than 60 μ quartz is dominant. Calcite occurs in minor amounts. In some samples this fraction also contains dolomite. In the fraction finer than 60 μ clayey minerals: kaolinite and mica were found in small amounts.

Studies carried out by Holios-Rybicka and by Myślińska *et al* (1982) revealed that the amount of the clay-sized fraction of the deposits examined in the Vistula Valley ranges from several tenth to several per cent of weight. Beside kaolinite and mica, this fraction includes a dioctahedral heaving mineral belonging to the smectite group. Occasionally chlorite was stated there.

It appears that in the Vistula valley the “mada” contains the same complex of minerals, though their mutual relationships tend to vary locally. The degree of arrangement of the smectite structure also is varied.

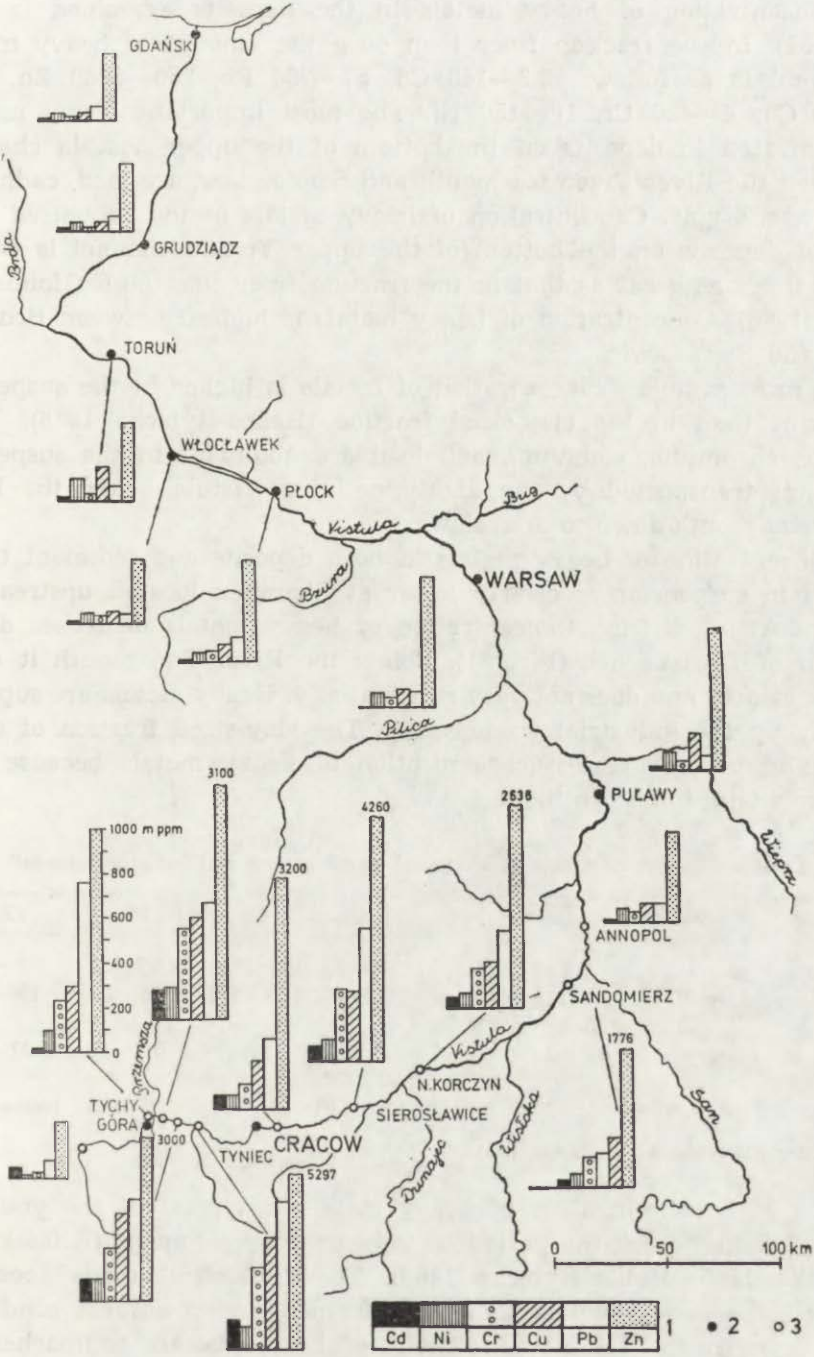

Fig. 31. Concentration of heavy metals in both channel bed deposits and alluvial loams (mada) within the Vistula Valley

1—content of heavy metals (Cd—cadmium, Ni—nickel, Cr—chromium, Cu—copper, Pb—lead, Zn—zinc); sites at which samples were taken from: 2—"mada", 3—channel bed deposits

Concentration of heavy metals in the deposits examined is high (Fig. 31). In the fraction finer than 60 μ the amount of heavy metals (in ppm) is as follows: 3.3—140 Cd, 57—760 Pb, 250—5280 Zn, 25——500 Cu, 4—420 Cr, 10—150 Ni. The most important heavy metals, concentrated in deposits on the bottom of the upper Vistula channel, between the River Przemsza mouth and Sandomierz, are lead, cadmium, copper, and zinc. Concentration of heavy metals in the clay-sized fraction of deposits on the bottom of the upper Vistula channel is two to three times as great as that in the fraction finer than 60 μ (Holios-Rybicka 1986). Concentration of heavy metals is highest between Broszkowice and Sierosławice.

In most samples, concentration of metals is higher in the suspended sediment than in the clay-sized fraction (Helios-Rybicka 1986). Thus, copper, chromium, cadmium, and lead are abundant in the suspended sediment transported by the highly polluted Vistula below the River Przemsza mouth down to Sierosławice.

Concentration of heavy metals in both deposits and sediment transported in suspension is clearly lower at Strumień located upstream of the industrial district. Concentration of heavy metals decreases downstream of Broszkowice (Fig. 31). Below the River San mouth it diminishes clearly and does not vary substantially. Heavy metals are supplied mainly by the industrial waste water. The clay-sized fraction of deposits exhibits the greatest concentration of heavy metals because clay minerals tend to absorb them.

Table 4. Content of heavy metals [ppm] in the natural and industrial „mada"

Site	Mada	Cd	Ni	Cr	Cu	Pb	Zn
Góra[1]	natural	0.4−1	8−13	14−25	3−23.5	14.5−22	9−49
	industrial	1.1−7	10−40	32−325	74−558	16−25	106−610
Tyniec near Cracow	natural	0.2−0.8	4−6	1−22	2−8	0.2−2.0	22−90
	industrial	61−200	80−130	120−130	150−440	220−600	1960−4200

[1] After Klimek and Zawilińska (1985).

The high concentration of heavy metals is typical of the youngest "mada" dating from the period of industrial development (Klimek, Zawilińska 1985; Helios-Rybicka 1986). The "industrial mada" contains much more heavy metals than that formed under natural conditions (Table 4). In the latter the content of heavy metals approaches the values of the geochemical background. Differences in the concentration of heavy metals upstream (at Góra) and downstream of the Przemsza outlet are due to the contamination of this river which drains the Upper Silesian Industrial District.

It appears that the pollution by heavy metals is of anthropogenic origin. Thus, it is an effective stratigraphical indicator. Along the industry-dominated reach of the Vistula more than 99% of both cadmium and lead, and more than 90% of zinc are supplied by the industry (Helios-Rybicka 1986).

SEDIMENT TRANSPORT IN THE VISTULA DRAINAGE BASIN

SUSPENSION TRANSPORT

In 1956—1965 the average rate of suspended sediment output of the Vistula catchment to the sea was 7.0 tonnes/km^2 · yr (Brański 1975).

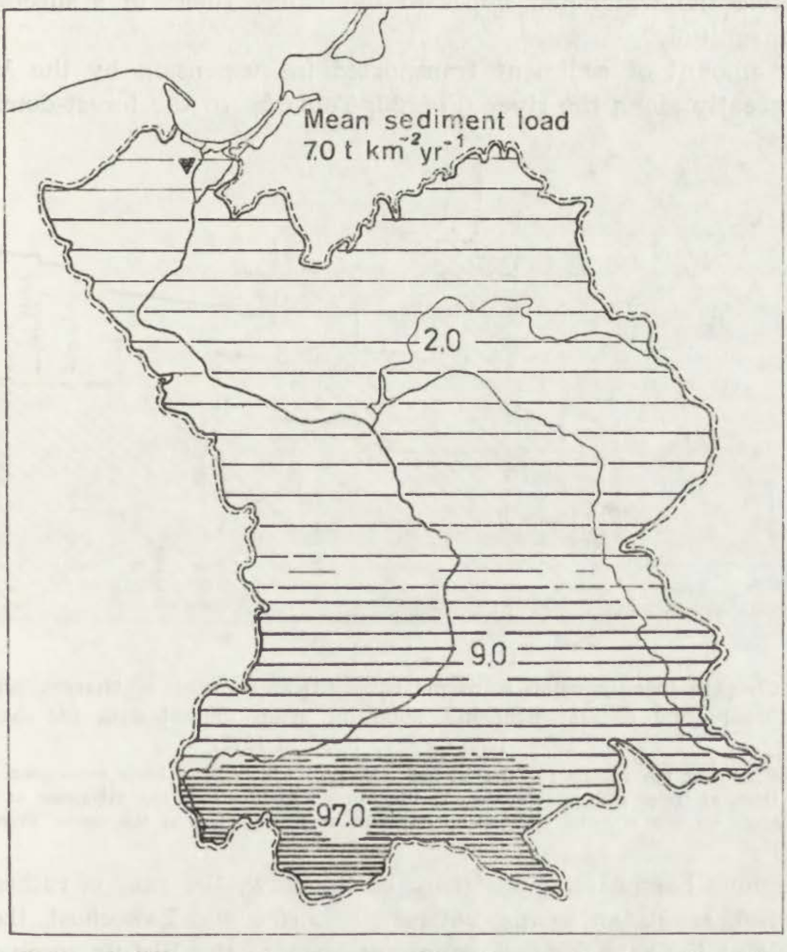

Fig. 32. Regional differences in the suspension transport rate within the Vistula catchment (on the basis of research results 1956—1965 which have been elaborated by Brański, 1975, and compiled by Maruszczak, 1984)

This value constituted only a small proportion of deposits derived by mechanical denudation within the drainage basin. This proportion may be estimated on the basis of data illustrating the suspension transport in the partial catchments. When we take into account lower order catchments covering an area of 1—10,000 km² it appears that the average "weighed" rate of suspended sediment discharge from such catchments was double of the former value, *ie* 14.5 tonnes/km²·yr in the entire Vistula catchment. This rate varied from 97 tonnes/km²·yr in the mountains to 2 tonnes/km²·yr in the lowland areas (Fig. 32). The total amount of the mechanically displaced material in the catchments of successively lower orders has been estimated at *c* 100 tonnes/km²·yr (Maruszczak 1984). It appears that only 7% of the total amount have been removed by the Vistula to the sea. The remaining part was removed *via* the watershed slopes to the valley floors of a successively lower magnitude.

The amount of sediment transported in suspension by the Vistula varies greatly along the river (Fig. 33; Table 5). In the forest-dominated mountainous headwaters, upstream of Skoczów, the rate is rather low. In the Subcarpathian basins, between Skoczów and Zawichost, the rate is double of the rate for the mountains because the Vistula receives tributaries that drain mountains, with less woodland and more cultivated land. In the gap in the Polish Uplands, between Zawichost and Puławy,

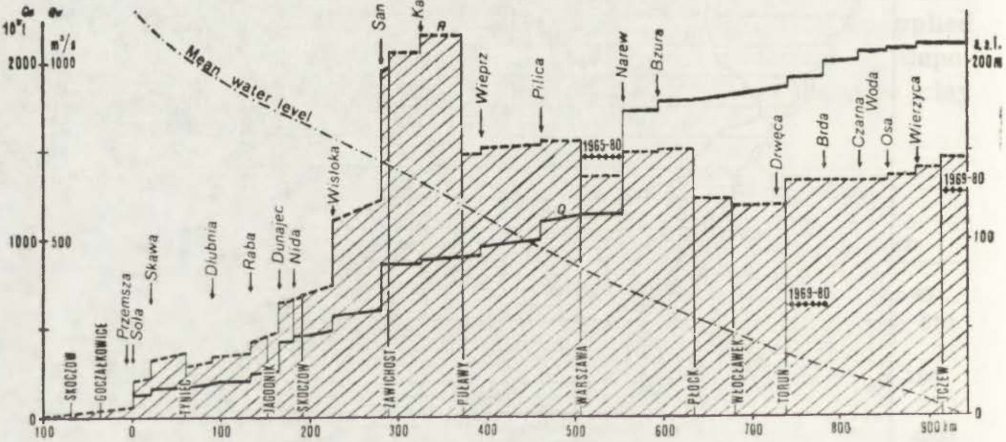

Fig. 33. Changes in suspension transport rates (*R*) and stream discharges (*Q*) along the Vistula plotted against Brański's diagram; mean annual data for the years 1956—1965 (acc. to Brański 1975)

Bold dots indicate the means for the period 1969—1980, which have been calculated by Maruszczak (1988) at three gauges (Warsaw, Toruń, Tczew) to illustrate the influence of Włocławek reservoir on the amount of suspended sediment transported in the lower river reach

Transport of suspended sediment and solutes along the Vistula[1]

Measurement sites	Catchment area [km^2]	Fluvial mechanical denudation (1956–1965)		Mean annual discharges discharges (1951–1975) [m^3/sec]	Rate of mean annual dischare [dm^3/sec·km^2]	Fluvial chemical denudation at the transition of the 1970s and 1980s		
		mean suspended sediment transport [t/km^2·yr]	rate of suspended sediment discharge [t/km^2·yr]			mean annual mineralization[2] (g/m^3)	mean solute transport [t/yr]	rate of solute discharge [t/km^2·yr]
Skoczów	295	5910	20.0	6.2	21.1	164	32,170	109.0
Below River Przemsza mouth (gauge at Pustynia)	3912	154 740	39.6	45.1	11.5	2605	3,705,000	947,0
Below River Dunajec mouth (gauge at Karsy)	19,778	645,380	32.6	(208)*	10.5	1251	8,208,000	415.0
Below River San mouth	50,142	1,889,390	37.7	·	·	·	·	·
Zawichost	50,545	1,990,000	39.4	438	8.7	558	7,708,000	152.5
Puławy	57,088	1,430,000	25.1	469	8.2	·	·	·
Below River Wieprz mouth (gauge at Dęblin)	68,094	1,454,640	21.4	·	·	·	·	·
Below River Pilica mouth (gauge at Gusin)	81,623	1,487,010	18.2	·	·	·	·	·
Warsaw	84,696	1,278,000	15.1	570	6.7	404	7,263,000	85.8
Below River Narew mouth (gauge at Modlin)	159,796	1,400,960	8.8	·	·	·	·	·
Płock	168,857	1,180,000	7.0	898	5.3	·	·	·
Włocławek	171,635	1,140,000	6.6	·	·	·	·	·
Toruń	180,585	1,280,000	7.1	981	5.4	·	·	·
Tczew	193,866	1,360,000	7.0	1050	5.4	342	11.316,000	58.4

[1] Suspended sediment transport and rates of fluvial mechanical denudation (1956—1965) have been elaborated by Brański (1975). Mineralization and rates of fluvial chemical denudation have been calculated by Maruszczak on the basis of data obtained from the voievolship centers of research and environmental control (for yrs 1976—1985) and from discharges (for yrs 1951—1975).

[2] At the centers of research and environmental control mineralization is being assessed by weighing the residue. These results are higher by 11% (Maruszczak 1988). The table lists corrected values.

* Valne refers to 1976—1980.

the Vistula is overloaded with suspended sediment coming from the mountains. Intensive fluvial accumulation occurs there, evidence of which is provided by the numerous, rapidly changing bars within the braided Vistula channel. In this reach the Vistula loses as much as one fourth of the total tonnage of sediment that has been encountered at the gauging station at Zawichost. In the first lowland reach, between Puławy and the River Pilica mouth, a relative stabilization of sediment transported in suspension takes place. Above the confluence with the Pilica, the average rate of suspension transport is about 20 tonnes/ /km^2 • yr. Thus, it is similar to the value of the headwaters. Downstream of the Pilica the rate clearly decreases toward the outlet of the Vistula Valley because of a diminution in the suspended sediment yield from the lowland areas. At least in two valley reaches, *ie* between the River Pilica mouth and Warsaw, and between the River Bzura mouth and Toruń (Fig. 33), overloading and subsequent aggradation due to the low river gradient have been observed.

Until now, those contrasts in the suspended load component for the years 1956—1965 are still important in the upper and middle reaches of the Vistula Valley, whereas in the lower reach drastic changes have been caused by reservoir construction in Włocławek—by closing the dam in autumn, 1968. In Warsaw, *ie* in the non-influenced reach by the effects of the reservoir the average value of the annual rate of suspension transport was 1.4 million tonnes for the years 1969—1980, *ie* it exceeded by *c* 10% the value for the years 1956—1965. In Toruń, lying 55 km below Włocławek, the corresponding value was only 0.57 million tonnes. It comprised as much as 55% of the value for the years 1956— —1967. This set of data indicates the prominent part played by the Włocławek reservoir in controlling the amount of suspended sediment being transported by the Vistula. As a consequence of suspended sediment deposition in the reservoir, the river is clearly "underloaded" downstream of Toruń. In 1969—1980 a tendency toward bed and bank erosion occurred below the dam. Consequently, the average amount of suspended sediment transported between Toruń and Tczew rapidly increased to 1.24 million tonnes *per* year. Thus, it reached almost the values for the years 1956—1965 (Fig. 33).

SOLUTE TRANSPORT

Pertinent data illustrating its magnitude have been available since only the 1970s and 1980s. In comparison with the last two decades, the general mineralization of the stream water increased remarkably (about 25%). This increase was due to the increasing contamination by waste waters. However, the general rules governing the spatial variability of the dissolved load yield did not change. Figure 34 shows conditions prevailing in the cultivated land, *ie* without greater sources of municipal and industrial water pollution. Table 5 lists the total amounts of solutes transported, *ie* together with the polluted water components.

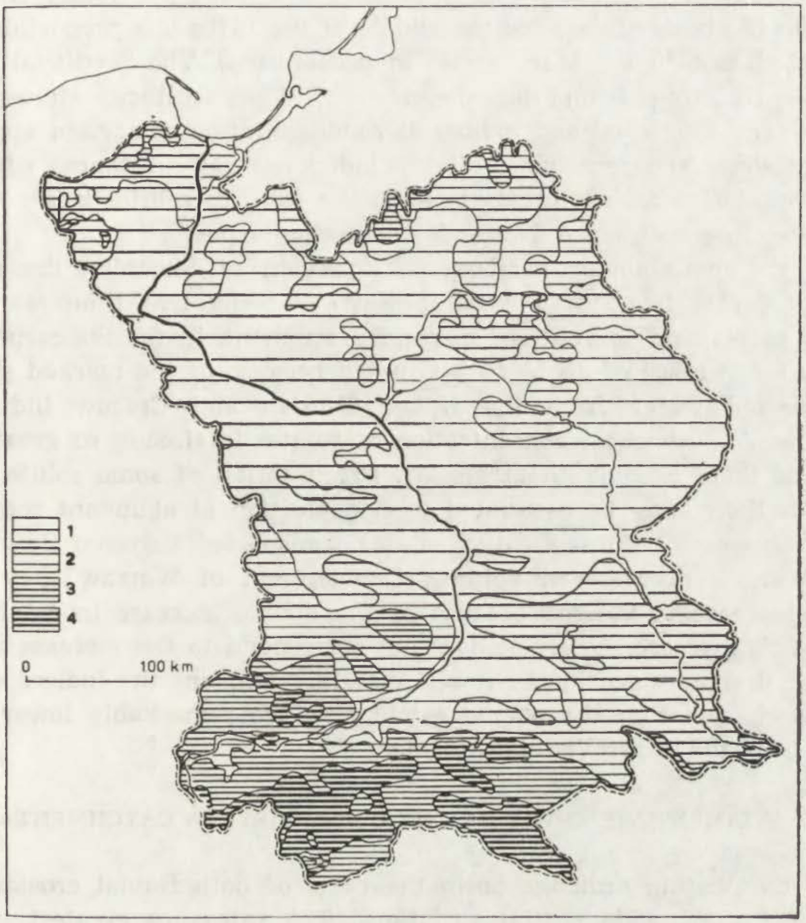

Fig. 34. Spatial variability of solute discharges from cultivated land within the Vistula catchment (by H. Maruszczak and M. Wilgat; the principles *vide* H. Maruszczak, in print)

Assessments of average rates are based upon measurements of the mineralization of stream water, 1976—1985: 1—up to 40 tonnes/km^2 yr, 2—40—60 tonnes/km^2 yr, 3—60—100 tonnes/km^2 yr, 4—in excess of 100 tonnes/km^2 yr. Beyond the boundary of Poland the extrapolated values correspond to both geological structure and relief

On comparison with suspended sediment, the amount of solutes transported by a river is a rather good indicator of the chemical denudation rates. The general solute concentration in the Vistula drainage basin is low. Consequently, the deposition of various types of calcareous tufa takes place sporadically and on a small scale.

It appears that the general rate of solute discharge from the Vistula catchment to the sea is indicative of both natural chemical denudation and contamination by waste water components. At the transition of the 1970s and 1980s this rate reached c 58 tonnes/km^2 • yr. Thus, it was eight times as great as that of suspended sediment. The natural chemical denudation comprised only c 45% of the value previously mentioned. On the basis of data for the middle of the 1970s this proportion was estimated at 48% (H. Maruszczak, in preparation). The "artificial" substances resulting from the chemization of agriculture, atmospheric fallout, and municipal and industrial water pollution comprised approximately 40%. The remaining 15% included natural substances supplied by precipitation and polluted water in the form of solutes being "pumped" together with groundwater for domestic purposes.

In the mountainous headwaters, upstream of Skoczów, the solute transport rate is about 109 tonnes/km^2 • yr being five times as great as the corresponding value of suspended sediment. In the Subcarpathian basins an increase of up to 40% is noted because of the marked supply of polluted water from the Upper Silesian and Cracow industrial districts. At Zawichost concentration of solutes is already so great that some of them become "neutralized". Precipitation of some solute components there may be associated with deposition of abundant sediment from suspension. Consequently, solutes transported between Zawichost and Warsaw decrease in volume. Downstream of Warsaw they once again increase in volume because of the double increase in catchment area. This increase, however, does not correspond to the increase in the surface drained since in the lower Vistula catchment the indices of solute discharge from the partial catchments are remarkably lower than those from the upper Vistula catchment.

SEDIMENT YIELD WITHIN THE UPPER VISTULA CATCHMENT

In the Vistula drainage basin the rates of both fluvial erosion and transport show wide spatial variations. The rates are greatest in the upper part of the catchment, but especially within the Carpathian tributary catchments (Reniger 1959; Dębski 1959; Brański 1975; Maruszczak 1984). Long period records show that in the upper Vistula drainage basin suspension transport predominates. Most of the suspended sediment is derived from the watershed slopes, *ie* from the unprepared roads and the channel. Long-term studies also show that in the Polish Carpathians suspended sediment discharge within a catchment exceeds the rates of solute discharge (Figuła 1966). The rates of chemical denudation of the flysch slopes even exceed 100 tonnes/km • yr (Froehlich 1975, 1982; Welc 1978). On the average, the proportion of both mineral fertilizers and solute content of incoming precipitation comprises 20% of the total solute discharge by rivers. Thus, chemical denudation is three times less than denudation caused by suspended sediment output (cf. Fig. 35).

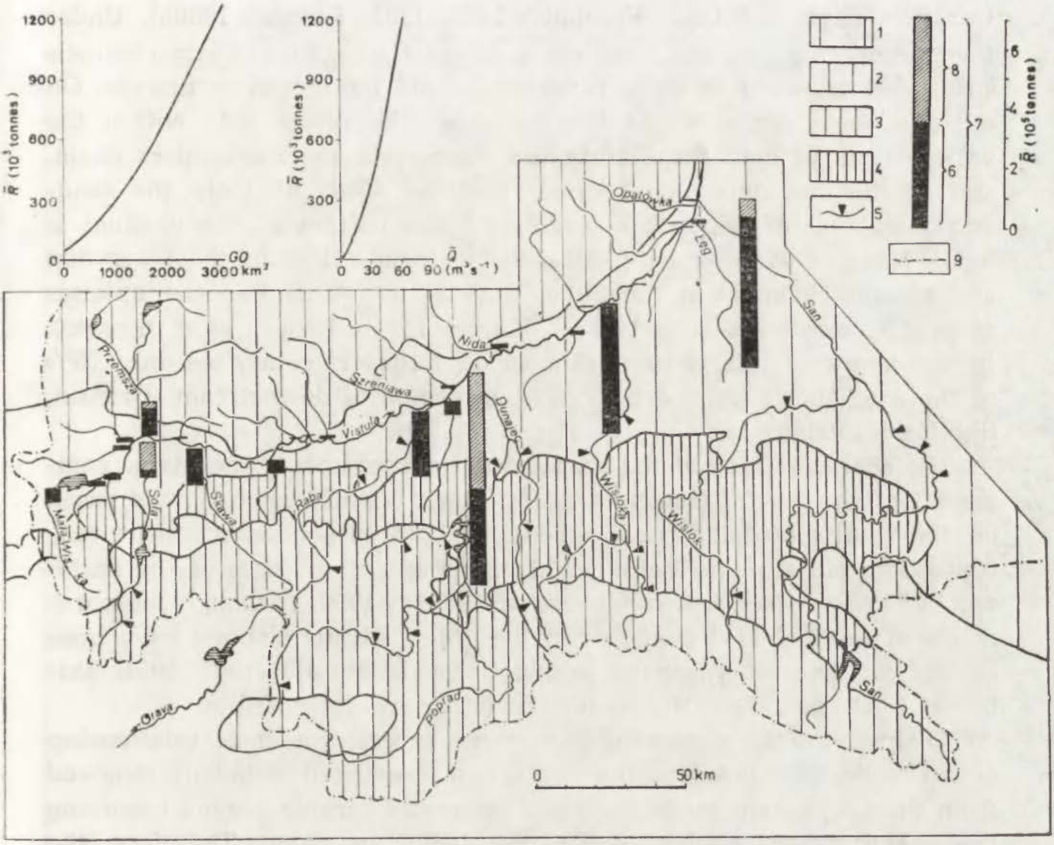

Fig. 35. Spatial variability of denudation rates and sediment supply by tributaries into the upper Vistula

Denudation rates (tonnes·yr^{1}. km^{-2}): 1—< 20, 2—< 90, 3—150—270, 4—200—1000; hydrometric profiles revealing a systematic tendency toward channel downcutting. Rate of suspended sediment supply $\bar{R}$ by tributaries into the Vistula: 6—average value (1961—1980), 7—value of sediment supply by the Carpathian tributaries devoid of dams, 8—sediment supply by the Przemsza River (except coal dust), 9—divide of the Vistula drainage basin. Relationship between average annual volume of suspended sediment derived from the Carpathian catchments $\bar{R}$ and area of arable cultivation within the catchments *GO*, and average annual stream discharges $\bar{Q}$

In years with high flood occurrence the suspended sediment discharge within the Beskidian catchments may be 10 times as great as the solute discharge. In dry years the total rates of fluvial transport become reduced, and the ion transport is dominant (Froehlich 1975, 1982). Similar relations have been stated in the middle reach of the Vistula (Falkowski 1967). In the high-mountain and upland karstic watersheds the ion transport always predominates.

Many years of record of both fluvial processes and sediment deposition in the reservoirs showed that in the Carpathian tributaries of the Vistula suspended sediment comprises 85—95% of the total mechanical transport (Cyberski 1969; Froehlich 1975, 1982; Łajczak 1986b). Under the present conditions of functioning of the Carpathian stream channels suspended sediment is being removed far off the mountain margin. On a larger scale deposition of this material takes place only within the valley floors of both the Vistula and the San in the Sandomierz Basin, and in the mountainous reservoirs (Łajczak 1986a, b). Only the sand--sized fraction of deposits occurring on the bottom of the channel is being transported over long distances to form deltas in the reservoirs and stream channels in the Subcarpathian basins, and in the uplands as well (Kociszewska-Musiał 1969a; Klimek 1987b; Klimek *et al* in press). In the upper Vistula channel suspension transport comprises only 76% of the mechanical transport. This value decreases downstream (Brański, Skibiński 1968).

The characteristics of the suspension transport being the major component of the fluvial transport in the upper Vistula catchment is based on the results of daily measurements of both suspended sediment concentration and stream discharges at all measurement sites of the national hydrological service in the period 1961 to 1980. Although measurements of the bed load transport in the upper Vistula channel have been carried out since 50 years (*eg* Dębski 1939a, 1939b; *Materiał...* 1954; Skibiński 1968), balance estimates of the latter are not possible.

Analysis of the suspension transport revealed a close relationship of parabolic type between the volume of suspended sediment removed from the Carpathian catchments and the area of arable ground occurring there, and stream discharges (Łajczak 1986b, in press). Therefore, the deforested and cultivated Carpathian foothills, the lower portions of the Beskidy Mts and the intramontane basins are most affected by this denudation. Furthermore, in the mountain foreland the rates of channel downcutting are greatest (Klimek 1987a). As a result, both transport and supply of suspended sediment by the Carpathian tributaries into the upper Vistula increase eastward (Fig. 35). Under the present conditions of cultivation the values of suspended sediment yield of the Carpathian, upland and lowland catchments to the Vistula are 89, 10, and 1%. In the reservoirs which have been constructed on the Mała Wisła, Soła, Dunajec and San 0—99% of the total volume of the suspended sediment are being trapped and stored. As a consequence of it, the suspended sediment yield of these rivers to the Vistula becomes reduced by 5, 90, 55, and 10%. If reservoirs were absent from the Carpathians, and if great amounts of coal dust were lacking in the Przemsza River the values of suspended sediment supply by the Carpathian, upland and lowland tributaries to the Vistula were 98, 2, and 0%.

The increased suspended sediment supply by the Carpathian tributaries causes the rapid and stepwise increase of the suspension transport rates along the upper Vistula. General work has been carried out on this

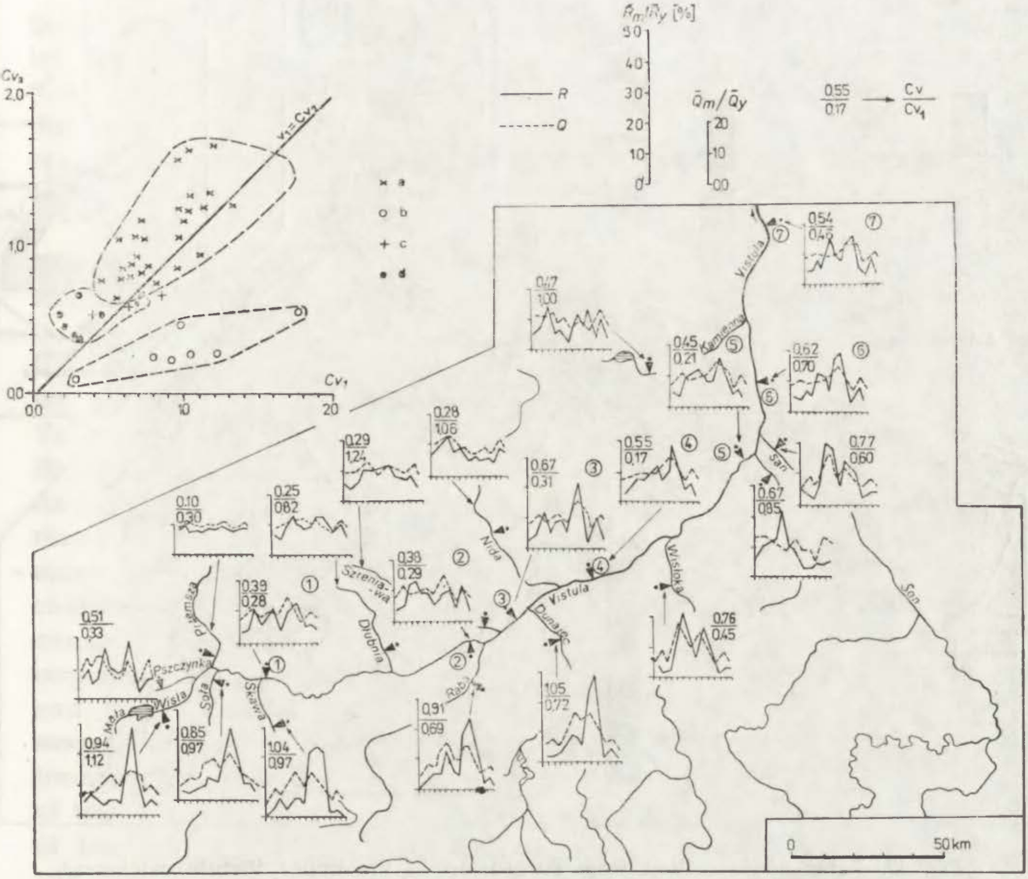

Fig. 36. Seasonal variability of suspended sediment supply *R* into the upper Vistula and discharges *Q* of tributaries on which measurement sites of suspended sediment concentration are located

$R_m/\bar{R}_y$ [%]—quotients of many years' mean monthly transport and annual transport; $\bar{Q}_m/\bar{Q}_y$—quotients of mean monthly discharges and annual discharges; variability coefficients of the suspension transport: Cv_1—many years' variability, Cv_2—seasonal variability. On the horizontal axis of the graph months of the hydrological years (November to November) are indicated. Measurement sites of suspended sediment concentration: 1—Smolice, 2—Sierosławice, 3—Jagodniki, 4—Szczucin, 5—Sandomierz, 6—Annopol, 7—Puławy. Relationship between the variability coefficients of suspension transport Cv_1 and Cv_2 at measurement sites of suspended sediment concentration which are sited on the Carpathian tributaries—a, the upland tributaries—b, the lowland tributaries—c and the upper Vistula—d

theme by Brański, Skibiński (1968), Brański *et al* (1980), and Brański (1975). The suspension transport rates decrease locally in the surroundings of Cracow because of dredging above the weirs constructed on the upper Vistula. Downstream of the River San mouth the peak annual rate of suspended sediment transported $\bar{R} = 1{,}400{,}000$ tonnes at Annopol, $R_{\max} = 3{,}300{,}000$ tonnes) has been noted in the entire Vistula catchment. The transport decreases to 50% in the middle reach of the Vistula.

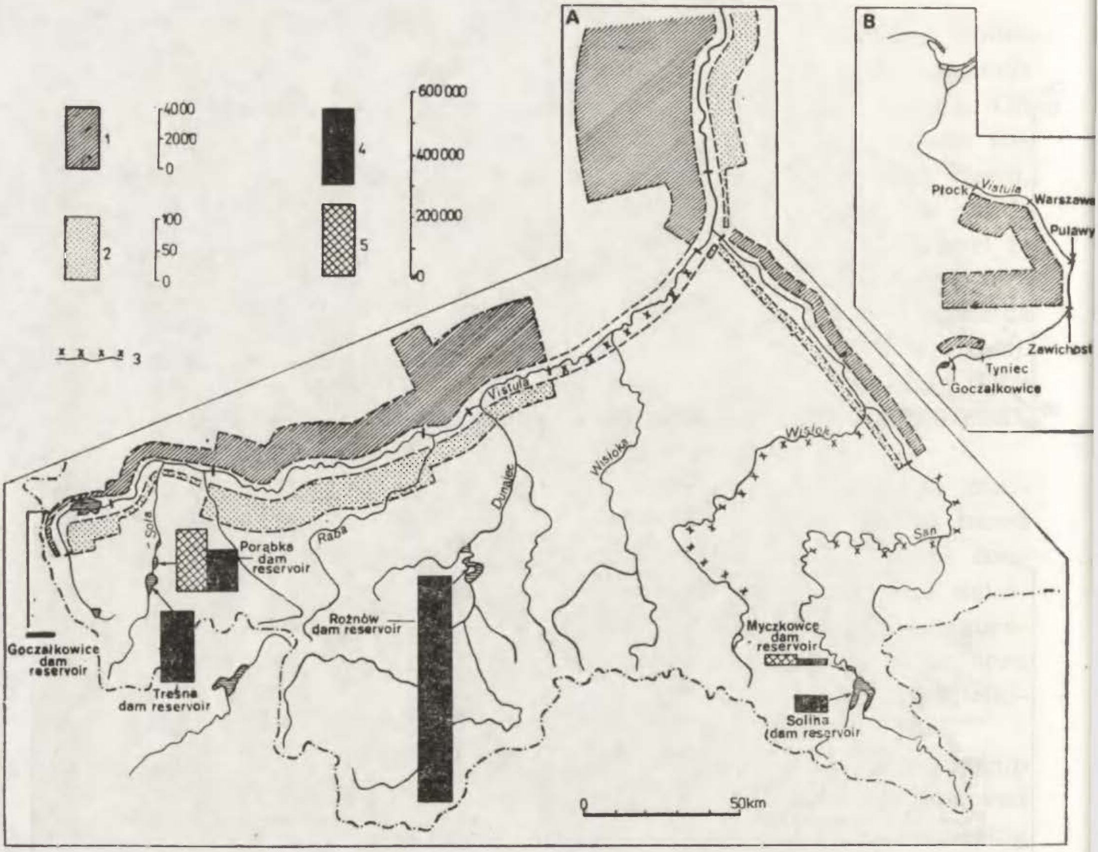

Fig. 37. Rates of deposition from suspension in the upper Vistula catchment

(A): sedimentation rates calculated from the transport equation: 1—(tonnes · yr^{-1} · km^{-2}), 2—percentage of suspended sediment being deposited in the balance valley reach, 3—valley reaches marked by low rates of deposition from suspension which cannot be expressed by numbers. Average annual amount of suspended sediment (tonnes) trapped in reservoirs throughout the period of their functioning (up to 1980): 4—amount of suspended sediment deposited throughout the period of functioning of the reservoir, 5—amount of suspended sediment deposited before the exploitation of the upper deep basin of the cascade marked by a high capacity to retain suspended sediment β; (B) sedimentation rates in the Vistula Valley calculated from data which have been published by Brański (1975)

The Carpathian tributaries also control temporal variations of the suspended sediment transported by the upper Vistula (Maruszczak 1984; Łajczak 1986b). Long period records show that its culmination occurs mostly during the summer rains. Downstream of the Wisłoka River, but especially of the San there increases the role of the spring thaw culmination. Only in the middle reach of the Vistula both culminations are equal. Most of the suspended sediment is brought by the upland and lowland tributaries during the period of snowmelt (Fig. 36). In the upper Vistula drainage basin suspended sediment yield also shows many years' variations. The individual Carpathian tributaries may carry suspended loads exceeding 100 times loads in the successive years. In this group of tributaries the many years' variability of transport (expressed by the variability coefficient Cv_1) is less than the seasonal variability (Cv_2) because of the regular occurrence of high summer rain-induced discharges. A similar relationship was stated in the upper Vistula. The reverse has been the case in the upland and lowland tributaries (Łajczak 1986b, Fig. 36).

Because of overloading with suspended sediment supplied by the tributaries the Vistula shows a natural tendency toward deposition of sediment from suspension in the Subcarpathian basins, but especially in the gap in the Polish Uplands. Up to the critical point of suspension transport by the Vistula, *ie* down to the River San mouth with the greatest material supply, the deposition of suspended sediment in the Vistula Valley devoid of dams comprises 10—30% of the total material yield. Below the San mouth deposition rapidly increases (Fig. 37). Between Annopol and Puławy, deposition of suspended sediment comprises already c 40% of the total material supply. This value corresponds to more than 7700 tonnes of material laid down *per* each kilometer of the channel *per annum* (Łajczak 1986b). Therefore, at Puławy the average annual suspension transport rate comprises only 64% of the value encountered at Annopol. In general, between the sources of the Vistula and Puławy, the mean annual value of deposition of sediment from suspension is at least 1,160,000 tonnes, out of which more than 570,000 tonnes are deposited between Annopol and Puławy. In the lowland reach of the San the rate of deposition from suspension is lower and comprises at least 700 tonnes *per* each kilometer of the channel *per annum*. The varying suspended sediment deposition rates in the valleys of both the Vistula and San in the Subcarpathian basins are confirmed by investigations of the Holocene alluvia there (Starkel 1960, 1977a; Buraczyński, Wojtanowicz 1966; Mycielska-Dowgiałło 1972; Szumański 1977). The present rate of "mada" deposition in the Vistula gap is most excessive throughout the Holocene (Falkowski 1967).

In the reservoirs which have been constructed on the Carpathian tributaries deposition of sediment is intensive. It may comprise up to 99% of the sediment yield. In Rożnów reservoir on the Dunajec c 800,000 tonnes of suspended sediment are deposited *per annum*.

Suspension transport rates in the rivers of the Polish Carpathians increased remarkably over the last 200 years because of man's activity. However, these rates still are lower than those in the remaining peripheral areas of the Carpathians being affected by strong denudation (Łajczak, in press). On the average, in the Carpathian part of the Vistula drainage basin the transfer of suspended sediment from the mountains into the mountain foreland, and the subsequent deposition from suspension in the valleys that extend in the mountain foreland of lowland type is four to twelve times less than in the remaining part of the Carpathians and their foreland.

CHARACTERISTICS OF RELIEF AND SEDIMENTS IN THE VISTULA VALLEY

TERRACE SYSTEM CHARACTERISTICS

PRINCIPLES OF DIFFERENTIATION

Various factors have fashioned the particular reaches of the Vistula Valley. In general, the scheme was adapted that downcutting dominated during the Late Glacial, whereas accumulation prevailed in Holocene times. In the lower valley reach the formation of a series of erosional terraces was controlled by the low base level which in turn was influenced by both glacier retreat and glacial rebound. On the contrary, in the upper valley reach the deposition of the successively lower inserted terrace sheets was climatically controlled. Aggradation in the lower reach, the shortening of which was due to the encroachment of the Litorina transgression, was caused by the increased material supply from the deforested upper part of the catchment. In the latter the effects of forest clearance were modified by both tectonic movements and rhythmical climatic fluctuations.

The occurrence of sinking basins in the immediate mountain foreland caused poor development of the short Vistula headwaters in the Carpathians. Analysis of the terrace systems was, therefore, supported by results which have been obtained from the tributary valleys of the Wisłoka and San having large Carpathian drainage basins.

Wide reaches alternating with narrow reaches of the Vistula Valley have been characterized in a downstream direction. The upper reach extends upstream of the Warsaw Basin, whereas the lower reach extends downvalley of the Warsaw Basin. Detailed information about the particular valley segments is employed from both earlier volumes (Starkel ed. 1982, 1987b), and from the valley map which has been chiefly compiled of the 1 : 500,000 *Geomorphological Map of Poland* (*Przeglądowa mapa*... 1980), and of the synthesizing long and cross profiles (Figs. 38—42).

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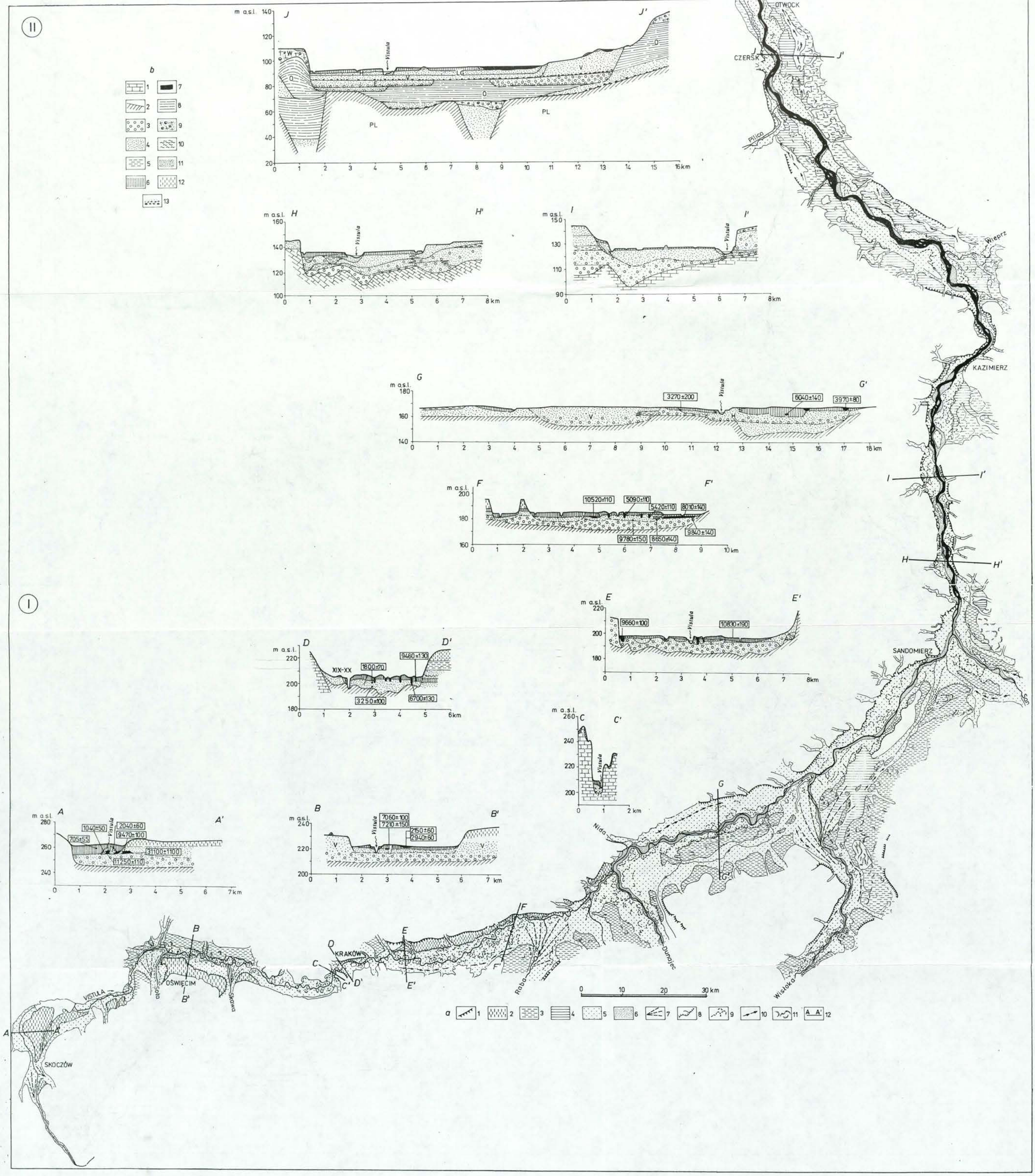

Fig. 38. Geomorphological map and sections across the upper Vistula River Valley (compiled of various data by L. Starkel)

Key of map (a): 1–plateau edges, 2–loess-covered, pre-upper Vistulian terrace, 3–upper Vistulian terrace, 4–Late Glacial terraces, 5–Holocene alluvial plain, 6–lowest flood-plain, 7–alluvial fans, 8–terrace edges, 9–former river courses, 10–palaeochannels, 11–dunes, 12–location of cross-sections

Key of cross-sections (b): 1–resistant bedrock (pre-Neogene), 2–soft bedrock (Neogene), 3–gravels, 4–sands, 5–silt and "mada", 6–alluvial loams ("mada"), 7–peat and other palaeochannel fills, 8–glacio-lacustrine deposits, 9–till, 10–deluvial loams, 11–aeolian sands, 12–loess, 13–gravel horizons

Cross-sections: A-A' (acc. to Niedziałkowska *et al* 1985), B-B' (acc. to Klimek 1987), C-C' and D-D' (acc. to Rutkowski 1987), E-E' (acc. to Kalicki and Starkel 1987), F-F' (acc. to Gębica and Starkel 1987), G-G' (acc. to Sokołowski 1987), H-H' (acc. to Pożaryski 1955), J-J' (acc. to Sarnacka 1987)

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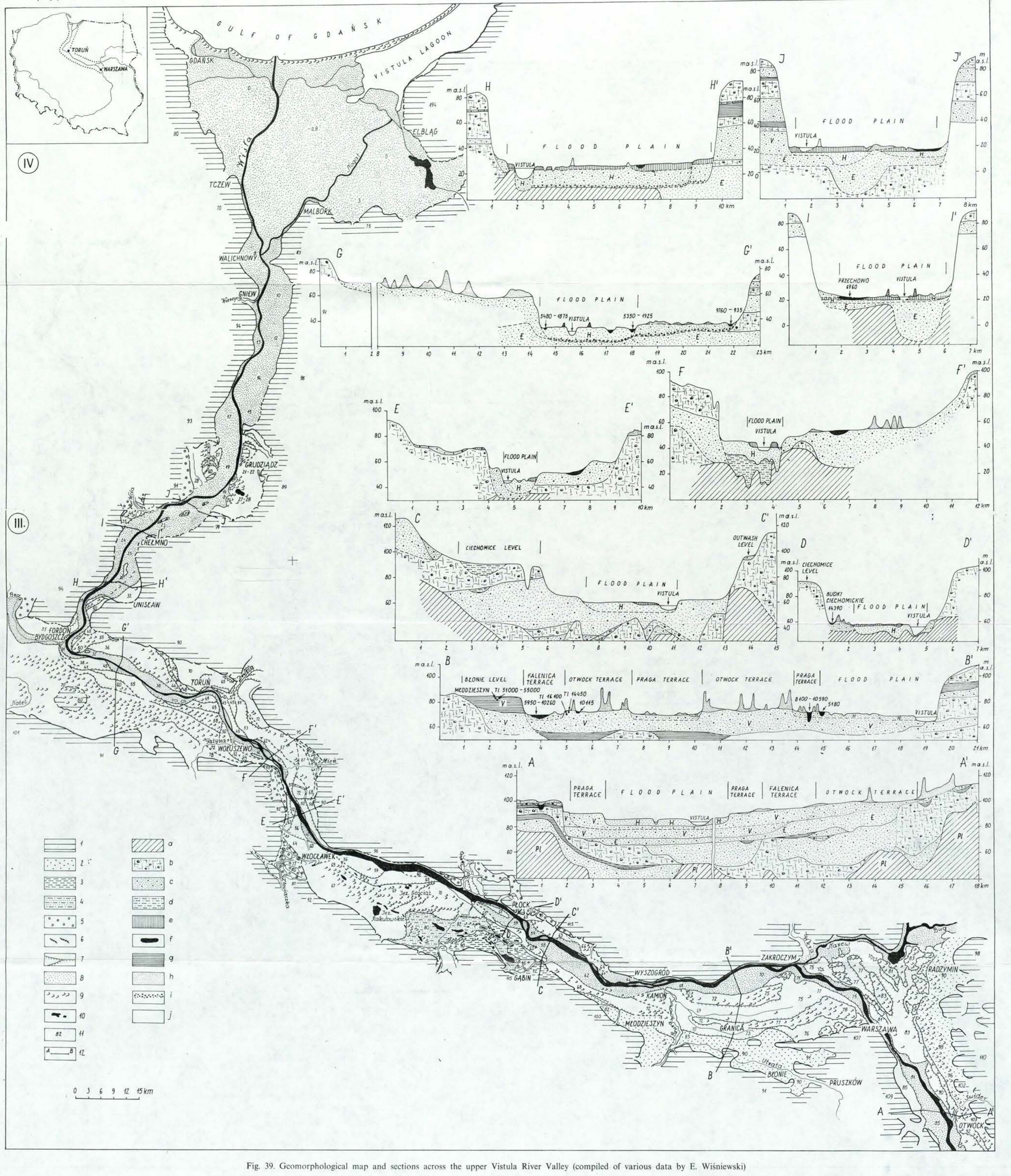

Fig. 39. Geomorphological map and sections across the upper Vistula River Valley (compiled of various data by E. Wiśniewski)

Key of map: 1–morainic plateau, 2–level formed of glacio-lacustrine deposits, 3–Ciechomice level, 4–level formed of sand and silt (deglaciation phase), 5–outwash plain, 6–esker, 7–terrace (*ca* 20–10 ka BP), 8–Holocene alluvial plain, 9–dunes, 10–lakes, 11–terrace heights, m a.s.l., 12–location of cross-sections

Key of cross-sections: a–pre-Quaternary bedrock, b–glacial till, c–sand and gravels, d–silt and muds, e–alluvial loams ("mada"), f–organic deposits, g–glacio-lacustrine clays, h–aeolian sands, i–gravel horizons (lag deposits), j–river; E–Eemian, V–Vistulian, H–Holocene

Cross-sections: A-A' and B-B' (based mainly on Baraniecka and Konecka-Betley 1987), C-C' (acc. to Wiśniewski 1987), D-D' (based on Florek *et al.* 1987), E-E' and F-F' (acc. to Wiśniewski 1982), G-G' (acc. to Niewiarowski and Tomczak 1973), H-H' (acc. to Niewiarowski 1987), I-I' and J-J' (acc. to Drozdowski 1982)

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THE UPPER VISTULA VALLEY

A characteristic feature of the upper Vistula Valley extending upstream of the Warsaw Basin is the occurrence of only 2—3 terrace steps (including the flood-plain) which date from the Vistulian Glaciation and Holocene. Terraces multiply up to 5—6 downstream of the gap in the Polish uplands. The highest terrace occurring in the upland zone and at the Carpathian margin is loess-covered. The other terraces show both dunes and traces of braided channels. Only the 1—2 lower terraces consist of alluvia which were laid down by meandering rivers. Downstream of the gap all higher terraces bear dunes.

The Carpathian reach of the Vistula Valley. The Carpathian segment of the Vistula is only 37 km long, but together with the alluvial fan system built up in the sinking Oświęcim Basin it reaches 60 km. In the mountainous headwaters the 2—4 m terrace, 0.5——1 km wide, is found with an alluvial cover cut across solid rocks. The channel is eroded in bedrock. Downcutting is indicated by both waterfall steps and a Pleniglacial terrace. It is possible to recognize a gravel surface at 15 m and a sub-gravel bench at 5—8 m. Overlying are solifluctional covers (Starkel 1967). In the Carpathian foothills the Holocene valley floor is up to 2—3 km wide. The Vistulian terrace overlain by solifluctional covers lies 12 m above river level. In the mountain foreland the Vistulian alluvial fan, 6—12 m high, is up to 10 km wide. It bears loess-like clays and is interrupted by three channels. The widest western channel into which the modern Vistula channel is cut, 3—6 m deep, contains gravels and sand overlain by alluvial loams ("mada") (Niedziałkowska *et al* 1985). In some places, at the mountain margin, three members of gravels alternating with "mada" are found. These are up to 30 m thick, and they provide evidence of the active sinking of the area. At Drogomyśl there occur at similar heights different inserted alluvia of differing age—from the Allerød (11,250 ± 11 BP) to as late as the Middle Ages (1040 ± 150 BP). The 3—4 m top series of "mada" represents the last millenium.

The Vistulian age of the higher alluvial fan of the Vistula River is indicated by both a buried warm flora at Chybie (45,000 BP) and cool floras that are present immediately below the dusty deluvia in the adjacent alluvial fan of the River Biała (youngest date: 27,470 ± 800 BP——Gilot *et al* 1982).

The eastern part of the Oświęcim Basin. Downstream of the gap in the rising horst near Góra the valley floor is up to 10 km wide. Alluvial fans were built up in the Vistula Valley by the Carpathian rivers Soła and Skawa and by the left-bank Przemsza there. The right-bank, 15—20 m terrace of Early Vistulian or Middle Vistulian age is capped with the younger loess. The left-bank, probably upper Vistulian sandy terrace, 7—10 m high, gradually merges below the Holocene terrace, 4—5 high. Upstream of the River Soła mouth this terrace shows dunes and large (Late Glacial?) palaeomeanders. Downstream of the Sola mouth and in the lower reach of the Soła Valley such palaeomeanders were not recognized. This may suggest that the braided river regime here survived until the Holocene. The overtopping of the organic horizons which have been dated at 2710 ± 70 BP indicates that levee formation began at the beginning of the Subatlantic period there (Klimek 1987b).

The Cracow Gate. The 2—4 km valley floor of the Vistula which winds round the limestone horsts of the Cracow Gate is narrowest at Tyniec (400 m—Rutkowski 1987). The valley floor is accompanied by the loess-capped terrace. Interpleniglacial biogenous deposits are buried beneath the Holocene "mada" there. The Holocene alluvial plain, up to 5 m high, shows palaeomeander systems. Single large palaeomeanders date from pre-Holocene times. The infill of the smaller palaeomeanders which belong to several generations has been dated at 6700 ± 130, 4400—4000 and 2100 ± 80 years BP. Larger and fresh meander loops date from the 17th century. Inserted channel alluvia which reach down to the uneven Miocene clayey bench correspond to a phase of accumulation in the 2nd—4th centuries, evidence of which is provided by several tree trunks. Archaeological sites also bear evidence of the upward growth of the flood-plain by the deposition of "mada" in the 11th century (Radwański 1972).

The western part of the Sandomierz Basin. Near the Raba mouth the Vistula Valley, 5—8 km wide, is bordered by both an erosional scarp and the 15 m terrace. It is possible to recognize Interpleniglacial loess-covered sand at about 10 m. Along the southern border there extend older sandy levels and the dune-bearing alluvial fan built up by the Raba River (Gębica, Starkel 1987; Kalicki, Starkel 1987). The valley floor is made up of inserted fills of differing age. Palaeochannel systems of similar depths also occur there. The oldest palaeochannel includes straight and wide depressions drained by a stream of the pre-Allerød braided river type. In the abandoned channel organic sedimentation began already 11,920 ± 170 years BP. Palaeochannels that have been formed during the Allerød also are deeper than the bed of the present river. Their infill began around 10,920 ± 230 years BP. The large palaeomeanders occurring near the valley-sides were formed during the Younger Dryas period of aggradation, evidence of which is provided by early Holocene fills (the earliest date obtained is 9660 ± 110 BP). The Younger Dryas aggradation brought about a ten-

dency toward peat accumulation in the braids. Several sites show signs of increased flood frequency during the Atlantic period. This is evidenced by "mada" deposition on the organic sediments (7980 ± 70 BP).
The subsequent deposition of alluvia, with systems of smaller palaeomeanders was dated at 6250 and 5400—5200 years BP. At the beginning of the Subboreal period the Vistula channel became straightened in Grobla Forest. Before 5090 ± 110 BP channel avulsion took place there. This phase of reactivation of the fluvial processes well corresponds to a groundwater level rise within the flood-plain, and to peat accumulation in the old channels (between 5380 and 4780 BP; Wasylikowa *et al* 1985). A distinct phase of aggradation followed the deforestation of the alluvial plain in the 1st and 2nd centuries. Sandy deposits also accompany the shallow medieval river channels. Large loops are known from the 11th, 17th, and 18th centuries. Channel correction undertaken on the Vistula in the middle of the 19th century led to channel stabilization and dissection of the flood-plain.

The middle part of the Sandomierz Basin (extending between the rivers Dunajec and San). The Vistula Valley floor, together with a sandy terrace dating from the Last Glacial, is up to 10—15 km wide there. The valley floor passes into the alluvial fans built up by the former tributaries being parallel to the Vistula. These were divided by broad ridges. In the case of the River Dunajec mouth this is the channel of the Breń Creek rising on the Late Glacial—Holocene floor of the Dunajec Valley. Between this channel and the Vistula Valley floor, 7—8 km wide, there extends the 2—3 m Szczucin Ridge, 3—5 km wide. The latter consists of wind-blown sand (Sokołowski 1987). In places, dunes dip below the Holocene alluvia. It is probable that the mountainous River Dunajec, which in many places shows a braided pattern, used the Breń channel by the end of the Pleniglacial. As the Dunajec diverted northward to the Vistula, this segment also became braided. This may explain the lack of large Late Glacial palaeomeanders there. Systems of smaller palaeomeanders have been dated at 6000 ± 4000 years BP.
At the River Wisłoka mouth the Late Glacial step extends east of the Tarnobrzeg Ridge. This step marks the former course of the Wisłoka. The oldest palaeomeander was abandoned 11,640 ± 100 years BP (Mycielska-Dowgiałło 1977). The 20 m Pleniglacial fill of the western channel became dissected. During the Holocene the channel shifted in an easterly direction from 9070 ± 70 BP (in the loop) down to 1850 ± ± 35 BP (in the sandy inserted fill).

The Carpathian tributaries of the Vistula (the Wisłoka and the San). The valleys of the Wisłoka and its tributaries have been examined in detail in the mountains, in the foothills, and in the mountain foreland.

In the mountainous reach of the Ropa Valley the Pleniglacial terrace became dissected. Inserted gravels occurring in the base of the 5 m terrace are interrupted by intercalations of organic matter which has been dated at 2675 ± 60 BP (Dauksza *et al* 1982). This terrace plain was drained by a river during the 18th and 19th centuries. Downcutting to the solid bedrock took place in the present century.

In the lower reach of the Jasiołka Valley, in an intramontane basin, the fills of deep depressions, deeper than the bed of the present river, are composed of Late Glacial freshwater chalk and gyttja (the earliest date is 11,740 ± 150 BP), and of early Holocene peat. Above the date 8650 ± 50 BP the latter is sandy.

In the Carpathian Foreland, near Dębica, the 15 m Pleniglacial terrace of the Wisłoka became dissected. On the lower step out of both Late Glacial steps lying up to 4—6 m above river level there occur large palaeomeanders. Their age has been determined by fills dating from the early Preboreal period (10,100—9900 BP). Superimposed tributary alluvial fans indicate a phase of frequent flood occurrence which began 8400 years BP. The Wisłoka channel, being deeper than the bed of the present river, is filled with alluvia which have been dated at 6500—6000 years BP. Numerous younger fills with tree trunks that are hidden in the 7—9 m Holocene terrace have been dated at 3300—1700 years BP. Dinstinct aggradation marked by the overtopping of the flood-plain by channel deposits took place during the Middle Ages (900—475 years BP). The reactivation of both floods and sediment transport is responsible for the increase in meander parameters and formation of a braided channel pattern during the 18th—19th centuries. As an effect of stream regulation and dissection the braided channel now takes off as a leaf of the lower flood-plain (Alexandrowicz *et al* 1981).

In the adjacent San Valley palaeomeanders occur already in the headwaters on the 4—5 m terrace. At Tarnawa the palaeomeanders are filled with organic deposits dating from the Allerød (Ralska-Jasiewiczowa 1980). Minerogenic intercalations indicate the reactivation of fluvial activity during the Younger Dryas (8700—7800 years BP). Finally, the groundwater table rose around 4400 years BP. In the piedmont reach, near Dubiecko, an abandoned channel being as deep as the modern channel became filled with alluvia from the Allerød onwards. This indicates that Pleniglacial alluvia became dissected already in the Late Glacial (Starkel 1960). It has been found that at the Carpathian margin different elements of the Holocene valley floor are made up of alluvia of differing age—from the beginning of the Holocene onward until the Subatlantic period (Starkel 1966). In the lower reach of the San Valley the dissected and dune-covered Pleniglacial terrace, up to 15 m high, shows traces of braided channels. The lower 8—10 m terrace plain displays a system of large palaeomeanders being filled with Late Glacial peat. Holocene fills showing several generations of smaller palaeomeanders also occur there. The oldest palaeomeanders were abandoned 8560 ± 1000 years BP (Szumański 1982, 1983). The low step of the 3—5 m flood-plain showing traces of braided channels refers to the period before river regulation was undertaken in the middle of the 19th century.

The Vistula gap in the Polish Uplands. The gap, about 90 km long, is entrenched in the Cretaceous marls and siliceous "opoki". Quaternary deposits reach as deep as 30 m below present river level. The Holocene valley floor is 1.5—5 km wide. In the wider reaches containing higher terrace steps its width exceeds 10 km. Below the Pleniglacial high fill at 12—18 m three Late Glacial or earlier erosional benches as well as the 3—5 m flood-plain including two lower steps have been recognized by Pożaryski (1955). The "mada" which reaches at least 3 m below the present Vistula channel, Late Glacial pollen spectra occurring in its base, and archaeological sites (3500—1700 years BP) found at the present water level all indicate a deep Late Glacial incision and subsequent aggradation. The earlier "fat mada" is covered by the historical "meager mada". The upper "mada" is in part synchronous with braided channel development over the last centuries. "Mada" formation is still going on (Falkowski 1975).

The valley reach extending between Puławy and the Warsaw Basin. The Vistula Valley floor, up to 12 km wide, dissects the old morainic plateaus. The valley displays systems of dune-bearing terraces and the Holocene valley floor. For the most part, the latter is interrupted by 2—3 parallel wide ridges which in turn are separated by somewhat higher ridges. Different ages have been ascribed to those terrace systems. They were correlated with the three phases of the Last Glacial (Leszno, Poznań, and Pomeranian—Różycki 1961). Later on the lowest step was assigned to the Late Glacial. Between the River Pilica and the Warsaw Basin, terrace steps on the Vistula rise to 12—15 m, 7.5—12 m, and 5—7 m (Sarnacka 1987). At Całowanie the lowermost step was formed by the river prior to 11,190 ± 65 BP. Afterwards, this step was occupied by the late Palaeolithic man, and subsequently the development of sand dunes took place there during the Younger Dryas (10,650 ± 100 to 10,450 ± 90 BP; Schild 1982). In the abandoned Late Glacial channels occurring on the 5—7 m terrace the last traces of floods were detected in the peat around 8360 ± 75 BP. This indicates downcutting of the Vistula channel. A few palaeomeanders which survived in the marginal part of the flood-plain indicate development of a meandering river during the Mesoholocene periods of stabilization of the hydrological regime.

The higher flood-plain of the Vistula possesses a fossil "mada" which shows traces of settlements prior to 2600—600 years BP. The intensive upward growth of the flood-plain by deposition of sediment began only in the 15th century. Following was braided channel formation. Over the last centuries floods affect even the Late Glacial 5—7 m terrace. Thus, flood water also enters the earlier straight channels. Frequently occurring ice-jam induced floods are favourable for channel avulsions.

THE LOWER VISTULA VALLEY

Downstream of Warsaw the lower Vistula Valley is some 400 km long (Fig. 39). The first part of the valley, 100 km long, is entrenched into the Middle Polish morainic plateaus. Farther north the Vistula flows within the limits of the Last Glaciation.

As the inland-ice retreated by stages, successive deglaciation of the valley dating from the Eemian interglacial took place. Evidence of it is provided by both present shape and different terrace systems present in the particular valley reaches.

Broader basins alternating with narrow sections are characteristic of the lower Vistula Valley. The Warsaw Basin is the first broad reach, 100 km long and up to 25 km wide. Downstream of the River Bzura mouth the valley is narrow (up to 8 km), while beyond this stretch the valley is again broad (up to 20 km). This is the Płock Basin, 60 km long.

Farther north there extends a gap, up to 7 km wide and 20 km long. Downstream the valley broadens into the Toruń Basin, 90 km long and up to 20 km wide. This is the first part of the Noteć—Warta ice marginal channel ("pradolina") extending in a westerly direction. The Vistula is flowing along the eastern side of the basin. At Fordon the river changes rapidly toward north running into a narrow valley (3—8 km) which includes three broad sections of basin type.

The Warsaw Basin. In the broad Warsaw Basin of tectonic origin the following levels and terraces were distinguished by Różycki (1967):

(i) the Radzymin—Błonie level,
(ii) the Otwock terrace (II b),
(iii) the Falenica terrace (II c),
(iv) the Praga terrace (II a).

The Radzymin level is traceable on the right basin side, whereas the corresponding Błonie level is developed on the left side. Both levels are capped with clay.

Analysis of a map showing the Warsaw Basin (Baraniecka, Konecka-Betley 1987) revealed that near Otwock the Radzymin level lies 103 m a.s.l. It gradually descends downstream to 88—90 m a.s.l. To the west of Warsaw, near the River Bzura mouth, the Błonie level lies 85 m a.s.l. It thus appears that both levels lie 19—20 above Vistula level.

In the southern part of the Warsaw Basin, the Otwock terrace lies 100—103 m a.s.l. (16—19 m above Vistula level). It descends to 71—72 m a.s.l. (7—8 m) near the River Bzura mouth. To the south, between Otwock and Warsaw, it is preserved as a bench on the right river bank. In the remaining part of the basin the Otwock terrace forms elongated "islands". The terrace bears dunes, especially in the Kampinos Forest.

The Falenica terrace lying 96—97 m a.s.l. (14—15 m) in the surroundings of Otwock occurs as a bench on the right Vistula bank. Farther downstream it extends into the depressions separating the "islands" of the Otwock terrace (Fig. 39, B-B'). Near the River Bzura mouth it descends to 69—72 m a.s.l. (5—8 m). In the southern part of the basin the Vistula is accompanied by the Praga terrace on both valley sides. In the surroundings of Otwock this terrace lies 90—92 m a.s.l. (7—9 m). Farther north at the River Bzura mouth, it passes into the Falenica terrace. In its lower part the Praga terrace is mantled with a light "mada".

The flood-plain consists of a heavy clayey "mada". At first it is 5—6 km wide. Downstream, toward Warsaw, the flood-plain is narrow, while to the west of Zakroczym it is again 6 km wide. The thin sheet of Holocene deposits occurring on the floor of the Warsaw Basin suggests the absence of a tendency to downcutting of the Vistula in Holocene times (Fig. 39, A-A', B-B').

According to Różycki (1967), varved clays overlying the Radzymin and Błonie levels were deposited in an extensive ice-dammed lake which occupied the Warsaw Basin during the Wkra stage (Middle Polish Glaciation).

However, later investigations showed that on both sides of the Vistula Valley the varved clays rest on Eemian deposits (Janczyk-Kopikowa 1975; Karaszewski 1975; Sarnacka 1982). On the basins of TL datings (51,000 and 53,000 years BP) these clays are believed to correspond to the Middle Vistulian ice advance (Baraniecka, Konecka-Betley 1987), and not to the greatest advance of the last inland ice. There still is disagreement as to whether the Middle Vistulian ice reached so far southward. Baraniecka and Konecka-Betley argued that in the Warsaw Basin the ice-dammed lake existed until the beginning of the upper Vistulian, *ie* during thousands of years. This conclusion is based on results of radiocarbon datings of biogenous deposits that, amongst others, fill in the isolated basins occurring on the adjacent morainic plateau. The deposition of sand, silt, and organic sediments there was caused by the presence of a glacially impounded lake in the Warsaw Basin. Biogenous deposits have been dated at 38,000 ± 3200/2300 and 30,000 ± 2560/1940 years BP.

According to Różycki (1967), the formation of the Otwock terrace sheet was synchronous with blockage of the Vistula Valley during the greatest extent of the Vistulian inland ice (Leszno phase). The infill of the Warsaw Basin with sand and gravels to elevations as high as the lower lake-deposited horizons was due to water coming both from melting ice to the north and extraglacial drainage to the south. Erosion was succeeded by accumulation in the Poznań phase. This resulted in the formation of the lower Falenica terrace sheet. Finally, in the Pomeranian phase the Praga terrace sheet came into existence.

Baraniecka and Konecka-Betley (1987) also postulated that the sedimentation of both fluvial and glaciofluvial deposits in the ice-confined Vistula Valley took place in the Leszno phase. By its end silt, and even clay were deposited. The top series of sands at Wiązowna—Piekiełko, in the southern part of the Warsaw Basin, has been TL dated at 19,500 ± 2900 years BP, and farther north, at Granica, at 16,100 ± 570 and 14,450 ± 300 years BP. It appears that accumulation of deposits under quiet conditions that prevailed in the ice-confined Vistula Valley took place within 8000 years. The formation of the Falenica and Praga terraces is correlated by both authoresses only with the Late Glacial. During the Bølling the sandy series became inserted. Its dissection produced the Falenica terrace. During the Allerød there generated the sheets forming the higher and lower Praga terrace which is distinguished by the local name Nowy Dwór terrace or "mada" terrace. Into these covers the Vistula became incised at the Late Glacial/Holocene transition. The synthesizing geomorphological—geological section across the Warsaw Basin is shown in Figure 41.

The Vistula Valley reach connecting the Warsaw Basin with the Płock Basin. West of Wyszogród, the Vistula Valley is only 8—10 km wide. This gap being about 38 km long (Wiśniewski 1986, 1987) contains five levels and terraces:

(i) the level at 82—83 m a.s.l. which lies 21—22 above river level,
(ii) the level at 73—78 m a.s.l. (17—18 m),
(iii) the terrace at 63—72 m a.s.l. (8—10 m),
(iv) the terrace at 60—69 m a.s.l. (5—6 m),
(v) the flood-plain which lies 58—65 m a.s.l. (2—3 m).

The level at 82—83 m a.s.l. being distinguished by the name "iłowski" is preserved on the left bank of the Vistula. This level consist of Pleistocene clays and fine sand, to the west. The level discussed stretches back to the Błonie level (made up of glacial lake deposits) which occurs east of the River Bzura. At Młodzieszyn near Wyszogród the top series of clay forming the "ilowski" level has been TL dated at 53,000—51,000 years BP (Baraniecka, Konecka-Betley 1987).

The "iłowski" level is bordered by a bench at 78 m a.s.l., 7 km long and 0.5 km wide. It is built of fine sand, like the "ilowski" level. This bench may correspond to the level at 73 m a.s.l. evident on the right bank of the Vistula. The latter level is composed of fine sand showing a horizontal lamination.

The first typical fluvial terrace is clearly developed along the left bank. Near the River Bzura mouth it lies 72 m a.s.l., and in the vicinity of Płock it stands at 63—64 m a.s.l. Ruszczyńska-Szenajch (1964) regarded this terrace sheet as the result of fluvial accumulation in the ice-confined Vistula Valley during the Vistulian Glaciation. It is probable that the terrace discussed corresponds to the Otwock terrace recognizable in the Warsaw Basin. The terrace is formed of fine and medium sand, and in some cases also of gravels.

Next above the flood-plain is the terrace at 60—69 m a.s.l. which probably corresponds to the joint Falenica and Praga terraces. Between Wyszogród and Płock the supra-flood terrace is preserved on the left river bank and on both valley sides in the eastern part of the Płock Basin. In many places dunes developed on the terrace, with traces of cutoffs which contain organic fills.

Radiocarbon datings on organic deposits underlying a dune at Kamion to the south of Wyszogród revealed an age of 14,590 ± 270 years BP (Fig. 39; Manikowska 1982). Similarly, organic abandoned channel deposits, which have been described from the same terrace south of Płock, were dated at 14,390 ± 270 years BP (E. Florek, W. Florek, Mycielska-Dowgiałło 1987; Figs. 39, D-D' and 41).

Between Wyszogród and Płock the extensive flood-plain is 2—6 km broad. The above cited new datings on biogenous deposits found on the supra-flood terrace indicate that after the Vistula Valley had been opened and led northward, the river reached the level of the present flood-plain already before the Late Glacial. In later times no essential downcutting was stated near Wyszogród and Płock. The river flows almost immediately on till or Pliocene deposits there.

Organic abandoned channel fills found on the flood-plain were shown by numerous radiocarbon datings to be 8450 ± 105—990 years old (Wiśniewski 1985; E. Florek *et al* 1987). It appears that only valley widening and alluvia reworking took place during the Late Glacial and Holocene there.

The Płock Basin. Downstream of Płock the Vistula flows along the northern border of the Płock Basin. Here it undermines the steep slopes of the morainic Płock Plateau, and farther north those of the Dobrzyń Plateau, though the stream power has been reduced by the construction of a dam near Włocławek. As its result, the system of both levels and terraces survived entirely on the left bank.

During the Vistulian Glaciation the Płock Basin was completely ice-covered. For this reason its complex relief shows both glacial and fluvial features (Lencewicz 1927; Domosławska-Baraniecka, Mojski 1960; Mojski 1960; Skompski 1969).

Below the morainic plateau (90—115 m a.s.l.) there occur in the Płock Basin levels which do not generate from the activity of the Vistula River, and fluvial terraces as well. Their heights are as follows:

(i) the sandur level at 98 m a.s.l.,
(ii) the Ciechomice level at 90—92 m a.s.l.,
(iii) the level at 80—82 m a.s.l.,
(iv) the terrace at 65—70 m a.s.l.,
(v) the terrace at 60—65 m a.s.l.,
(vi) the supra-flood terrace at 56—62 m a.s.l.,
(vii) the flood-plain at 57—59 m a.s.l.

The sandur level, lying 98 m a.s.l., forms a bench on the right side of the Płock Basin, east of Płock. This bench is 10 km long and 1—1.5 km wide. Analysis of the texture of the bench-forming deposits revealed that these were laid down by meltwater flowing in an easterly direction, *ie* toward the Warsaw Basin (Fig. 39, C—C' and 41).

On the lower Ciechomice level (90—92 m a.s.l.) eskers, kames, small hills formed of sandy and clayey deposits and till are found. This landform complex is due to deglaciation of the area discussed (Skompski 1963). In its western, more sandy part kames often co-exist with dunes.

In its southern part the Ciechomice level is confined by a higher (2—3 m) small pitted outwash plain which originated on ice.

The next lower level lies 80—82 m a.s.l. It consists of fine sand and silt. It also bears eskers.

The terrace at 65—75 m a.s.l. is best developed in the Płock Basin. South-east of Lake Rakutowskie its surface is flat and decreases downstream (near Włocławek it lies 65 m a.s.l.) and in a northerly direction *ie* towards the valley axis (69—70 m a.s.l.). The terrace surface bears dunes. It also shows numerous subglacial chutes and thaw basins. Amongst others, there occur Lake Rakutowskie and Lake Gościąż. The latter lake basin is filled with a 15 m series of deposits showing a rhythmical lamination. Their accumulation began some 12,600 years ago (Ralska-Jasiewiczowa *et al* 1987). Organic deposits gave a similar radiocarbon date there (Pazdur *et al* 1987).

In the Płock Basin, below the terrace at 65—70 m a.s.l., other terrace remnants lie 60—65 m a.s.l. and 56—62 m a.s.l. (supra-flood terrace). The narrow flood-plain (57—59 m a.s.l.) became inundated by reservoir construction in Włocławek.

The Vistula Valley section connecting the Płock Basin with the Toruń Basin. The reach of the Vistula Valley extending between Włocławek and the River Drwęca mouth, c 40 km long and 7 km wide, which postdates the retreat of the Vistulian ice is a typical lowland gap. Before this event took place this part of the Vistula Valley was fashioned by meltwaters (Wiśniewski 1976a, b, 1982). The evidence of it is provided by levels at 88—89 m a.s.l., 80—84 m a.s.l. and 78 m a.s.l. on the right bank, and at 80 m a.s.l. and 75—77 m a.s.l. on the right bank, at the outlet of the Mienia Valley. In the gap fluvial terraces lie:

(i) 72 m a.s.l. (30 m above stream level),
(ii) 67—69 m a.s.l. (25 m),
(iii) 62—63 m a.s.l. (18—19 m),
(iv) 57—59 m a.s.l. (13—16 m),
(v) 51—52 m a.s.l. (8—11 m),
(vi) 45—47 m a.s.l. (7 m),
(vii) 43—45 m a.s.l (5 m).

The flood-plain lies 40—42 m a.s.l. (cf. Fig. 40). The highest levels at 88—89 m a.s.l. and 80—84 m a.s.l. which descend southward are erosional steps cut into the ground moraine of the Kuyavy Plateau. At these levels, west of Włocławek, meltwaters at first connected with meltwaters draining the Płock Basin; thence the waters drained westward *via* the Bachorza Valley (Wiśniewski 1974). The levels discussed are made up of till overlain by 1 m of sand.

The first fluvial terrace which is believed to serve as a connecting link (transfluency) between the Płock Basin and the Toruń Basin lies 70—72 m a.s.l. This is a typical erosional terrace without gradient (Fig. 40). The thickness of the sandy capping of the till varies from 0 to 2 m (Fig. 39, E—E').

The terrace at 67—69 m a.s.l. occurs as broad troughs corresponding in height to the terrace at 70—72 m a.s.l. Lower erosional terrace benches are found at 62—63 m a.s.l., 57—59 m a.s.l. and 51—52 m a.s.l.

South of the Drwęca Valley the lowest terrace plain is pitted with deep thaw basins which may have been drilled by former meltwater streams. The beginning of organic sedimentation in the Dzikowo thaw basin was radiocarbon dated at 13,080 ± 170 years BP (Tomczak 1987).

The successively lower terraces which are preserved as benches and "islands" at 45—47 m a.s.l. and 43—45 m a.s.l. are already supra-flood terraces. The higher terrace is an erosional feature, whereas the lower one is an accumulational terrace.

In the gap discussed the flood-plain occurs as narrow stripes, in some places up to 1.5 km wide. Down to 4 m it is composed of overbank "mada" and fine sand which often rest on peat, up to 2 m thick. At Wołuszewo peat accumulation continued from 8,940 ± 160 to as late as

2730 ± 70 years BP (Tomczak 1987; Fig. 41). The present author is of the opinion that the cutoff at Wołoszewo is not a feature of the supra-flood terrace. Other datings on deposits taken by Tomczak from both the supra-flood terrace and the flood-plain indicate that their accumulation only began 6200 ± 120 years BP there.

Upstream of Płock the small thickness of the flood-plain forming alluvia suggests the lack of pronounced downcutting. On the contrary, downstream of Włocławek alluvia become thicker and thicker. In Włocławek alluvia which rest on Pliocene deposits attain a thickness of 12 m. In the eastern part of the Toruń Basin the youngest sandy-gravelly alluvia are 17 m thick (Fig. 39, F—F').

The Toruń Basin. In the Toruń Basin the Vistula is flowing along its eastern and north-eastern sides. Investigation carried out by Galon (1953) and Mrózek (1958) in the Toruń Basin and the Brda Valley eastablished the occurrence of eleven terraces. These were first fashioned by meltwaters and then by rivers. According to Galon, at the XI terrace (78—80 m a.s.l.) and X terrace levels (75—77 m a.s.l.) the escape route of meltwater in the Pomeranian phase has been, amongst others, *via* the Brda outwash plain and the Drwęca "pradolina" into the Toruń Basin. Then the meltwater escaped westward by the way of the Noteć—Warta "pradolina". It is believed that this drainage system also collected extraglacial water of the Vistula.

According to Galon, at the IX terrace level (72 m a.s.l.) bifurcation took place. Some water still discharged in a westerly direction, while some water discharged northward into the Baltic Glacial Lake at this time. In the bifurcation phase four terraces came into existence, *ie* the IX, VIII, VII, and VI ones. At 52—55 m a.s.l. (V terrace), in the surroundings of Toruń, the Vistula diverted northward.

In the analysed part of the Toruń Basin the following terraces may be distinguished (Niewiarowski, Tomczak 1973; Tomczak 1987):

(i) at 77—79 m a.s.l (42—43 m above river level),

(ii) at 70—71 m a.s.l. (37—38 m),
(iii) at 60—66 m a.s.l. (27—29 m),
(iv) at 51—58 m a.s.l. (20—22 m),
(v) at 52—55 m a.s.l. (18—19 m),
(vi) at 41—49 m a.s.l. (12—13 m),
(vii) at 36—44 m a.s.l. (7—9 m),
(viii) the flood-plain at 31—38 m a.s.l.

All terraces previously mentioned are erosional features. As a rule the thickness of fluvial deposits is small, and the surfaces cut across till. The right-bank erosional-accumulational supra-flood terrace lying 36—44 m a.s.l. frequently shows numerous cutoffs. One of them contains peat which has been radiocarbon dated at 9700 ± 260 years BP (Tomczak 1987; Fig. 39, G—G').

The flood-plain, up to 5 km wide, possessing numerous cutoffs is formed of overbank deposits interrupted by peaty intercalations. Underlying are sandy-gravelly deposits and channel lag deposits, more than ten metres deep. The infill of the cutoffs began at least around 5480 ± ± 60 years BP (Tomczak 1987; Fig. 39, G—G').

The Vistula Valley section extending between Fordon and the Żuławy. The Vistula Valley section extending between Fordon and the Żuławy, *ie* the Vistula River Delta is the youngest reach of the lower Vistula Valley. It is 115 km long. At Fordon, near Bydgoszcz, it attains a width of only 3 km. The average width varies from 7 to 10 km. This valley section is characterized by three widenings known as the Unisław Basin, the Chełmno Basin, and the Grudziądz Basin. Galon (1934) expressed the view that this part of the Vistula Valley was created only after the joint meltwaters from the north and the fluvial waters from the south had discharged northward through the Fordon gap into the developing Baltic. The bifurcation of these waters took place at 70—72 m a.s.l. (IX terrace) in the Toruń Basin.

In the valley reach discussed terrace remants survived only between Fordon and the Unisław Basin, and in the Grudziądz Basin.

Downstream of Fordon, in the narrowest valley reach, terraces lie 50 m a.s.l. (25 m), 40—43 m a.s.l. (15—18 m) and 34 m a.s.l. (*ie* the supra-flood terrace rising 9 m above river level). The flood-plain lies 27—28 m a.s.l. In the Unisław Basin, next above the flood-plain is only the supra-flood terrace at 32—33 m a.s.l. According to Galon (1934), both the Unisław Basin and the less well developed Chełmno Basin at the confluence with the River Wda formed through the downstream translatory movement of the Vistula bends and undermining of the adjacent morainic Chełmno and Świecie Plateaus.

In the Grudziądz Basin, small remnants of the high terrace border the three morainic islands distinguished by the local name "kępy". These are found on the bottom of the basin. The highest terrace remnant lies 60—61 m a.s.l. (44—45 m above river level). It borders the Kępa Górnej Grupy to the north. According to Galon, this terrace corresponds to the IX terrace at 70—72 m a.s.l. occurring in the Toruń Basin. At this level waters first breached this reach in a northerly direction. Below the above mentioned terrace remnant eight lower steps have been recognized. The flood-plain here lies 19—20 m a.s.l. Galon postulated that the creation of the Grudziądz Basin postdates the Vistula breach in a northerly direction. According to Drozdowski (1974), the Grudziądz Basin is of an older foundation. On the earlier glacial features dating from the Middle Vistulian ice advance, which subsequently were conserved by dead ice, the Late Glacial and Holocene fluvial relief due to activity of the Vistula here became superimposed.

As would be expected, in the lower Vistula Valley segment all terraces rising above the supra-flood plain are erosional features overlain by 1—2 m of sand and gravels.

Alluvia are thicker on the supra-flood terrace and the flood-plain. In the Grudziądz Basin, 6—7 m of alluvia consisting mostly of fine sand have been found on the supra-flood terrace (Drozdowski 1982).

In the Unisław Basin, the flood-plain is composed of a 15 m series of channel facies deposits (sand and gravels, with cobbles), of overbank deposits (silt and fine sand), and of organic deposits (Fig. 39, H—H'; Niewiarowski 1987b).

Niewiarowski also noted that the present dune-bearing supra-flood terrace includes both older, Late Glacial features, and younger, Holocene features. A radiocarbon dating on the substratum of peat disclosed on the flood-plain gave an age of 10,050 ± 150 years BP, *ie* the Late Glacial age of the supra-flood terrace. According to Niewiarowski, at the Subboreal/Subatlantic transition peak flows reached as high as the highest parts of the flood-plain. Because of the upward growth of the flood-plain by deposition of both overbank sediments and peat the surface of this youngest depositional feature is at the same level as that of the Late Glacial supra-flood terrace today. In the Grudziądz Basin, the Late Glacial age of the supra-flood terrace is also inferred from a radiocarbon date (11,630 ± 265 years BP) obtained from the basis of peat that fills a thaw basin being partly occupied by Lake Rudnickie Małe (Drozdowski, Berglund 1976).

Organic deposits taken from two places on the flood-plain were dated by Drozdowski and Berglund at 6960 ± 75 years BP and 4940 ± 65 years BP (Fig. 39, I—I'). In the Grudziądz Basin, the Holocene alluvia of the Vistula are 16—19.5 m thick (Fig. 39, J—J').

Analysis of the long profile of the lower Vistula Valley reveals the multiplication of the terraces downstream (Fig. 40), especially in the gap connecting the Płock Basin with the Toruń Basin, and in the Toruń Basin itself. The cause of it were impulses which induced downcutting upvalley. Therefore, it is difficult to correlate terraces occurring in the surroundings of Wyszogród and Warsaw with the particular terrace steps downvalley. Attention should be drawn to the fact that it is extremely difficult to correlate the highest terrace at 70—72 m a.s.l. with any terrace upstream. In the valley reach connecting the Warsaw Basin with the Płock Basin the highest terrace is below the terrace at 70—72 m a.s.l. that occurs between Włocławek and Toruń. This problem is still a matter for debate. It will be discussed in the chapter devoted to the geomorphological evolution of the Vistula Valley.

LITHOLOGY AND FACIES OF FLUVIAL DEPOSITS

INTRODUCTION

The nature of deposits forming fluvial landforms of differing age is reflected in the different structural and textural properties of the various facies. These are an important sources of information on the functioning of the fluvial environment and its variability along the river.

According to the present authors, the last 15,000 years during which the evolution of the existing Vistula Valley took place may be subdivided into four main periods, including:

(i) the functioning of a Pleniglacial and partly Late Glacial braided channel ("bed-load" river),

(ii) the formation of large palaeomeanders, and mixed load ("mixed--load" river),

(iii) the development of a meandering or sinuous channel of the Holocene river, and the dominance of suspended load over bed load ("suspended-load" river),

(iv) the historical period marked by rivers overloaded with suspended sediment due to anthropic pressure; the increasing competence of the river caused the bed load to be set in motion; consequently, the Vistula channel pattern reverted to a braided one ("mixed-load" river).

In each of the periods quoted above there occurred deposition of sediments of the channel facies (channel lag deposits, central bar deposits, point bar deposits), of the overbank facies (flood basin deposits, abandoned channel deposits, natural levee deposits, crevasse splay deposits *etc*), and of associated facies such as alluvial fan deposits laid down by the tributaries of the Vistula, slope deposits and aeolian ones.

In this chapter, structure, grain-size distribution, abrasion of quartz grains of the medium sand-sized fractions, concentration of heavy minerals in the fine sand-sized fractions, petrographical features of both sand and gravels *etc* are considered in the individual sections across the Vistula Valley along the river.

The properties of valley fills of some tributaries, but especially of the Carpathian rivers Wisłoka, Ropa, and San being important to the development of the major valley have also been considered.

DEPOSITS OF BOTH "BED-LOAD" AND "MIXED-LOAD" RIVERS BY THE END OF THE VISTULIAN

By the end of the Vistulian Glaciation in many valley reaches of the Vistula and some tributaries (*eg* the San) the braided channel defined by Schumm (1981) as the "bed-load" type changed to a sinuous channel, and even to a meandering channel of the "mixed-load" type. This change was due to the increasing stability of the channel pattern. This in turn responded to the smoothing of the annual discharges and to the development of the vegetation cover.

In the upper Vistula reach, upstream of Cracow, the sinuous Late Glacial channel of "mixed-load" type became filled with sand and gravels showing a cross-bedding. The beds varied in thickness from several to more than 30 cm (Rutkowski 1987). Cobbles coarser than 64 mm occur occasionally. The proportion of fine-grained sediment (below 0.12 mm) is insignificant. This deposit is bimodal, the modes occur in the classes 0.25—1.0 mm and 8—64 mm. In the lower coarse-grained sediment the mean grain diameter (*Mz*) varies from — 0.45 to — 2.69 *phi*, the value of the standard daviation (σ_1) ranges from 1.99 to 2.78, whereas in the upper sandy series *Mz* varies from 1.48 to 2.46 *phi*, and standard deviation is between 0.36 and 0.99.

In the coarse-grained material there predominate sandstones brought in from the Carpathians. In the gravels the proportion of quartzites, and of both magmatic and metamorphic rocks derived from the glacial deposits is small (Fig. 30). Silex also is present there. The latter probably is a weathering residue of the Jurassic limestones. The lack of limestone cobbles is explained by their rapid destruction and small supply from the side valleys (Rutkowski 1987). The quartz content increases with the gradual fining of the deposit.

In the valleys of the Carpathian tributaries Wisłoka and San the Late Vistulian deposits are rather less thick, *eg* 1—2 m in the Wisłoka Valley. Channel fills are composed of sand and gravels which show either a cross-bedding or a horizontal bedding. Sorting varies from 0.5 to 3.6 Gravels are usually poorly and very poorly sorted, whereas sands are poorly and medium sorted (Alexandrowicz *et al* 1981).

In the lower San Valley, the Late Glacial channel fill consists of well sorted sands overlain either by finer aeolian sands or by overbank deposits (Szumański 1982).

In the Vistula Valley, near Sandomierz, the bottom of Late Glacial deposits is formed of gravels and sands which gradually pass into sands. These are overlain by flood deposits and alluvial fan deposits laid down by the small tributaries of the Vistula (Mycielska-Dowgiałło 1977, 1978, 1987).

The Late Vistulian gravelly deposits are characterized by a marked proportion (35—60%) of grains coarser than 2 mm, with a low mode between 0.3 and 0.7 mm. The mean grain diameter (*Mz*) varies from — 1.78 to — 0.29 *phi*. Sorting is poor (σ_I is between 1.27 and 2.38). The sediment is positively skewed (SK_I). In the base of this series, far off the valley side, sporadic erratic blocks, up to 2.5 m in diameter, are found. These were transported by thick floes.

Zał. do pozycji "Evolution of the Vistula River Valley..."

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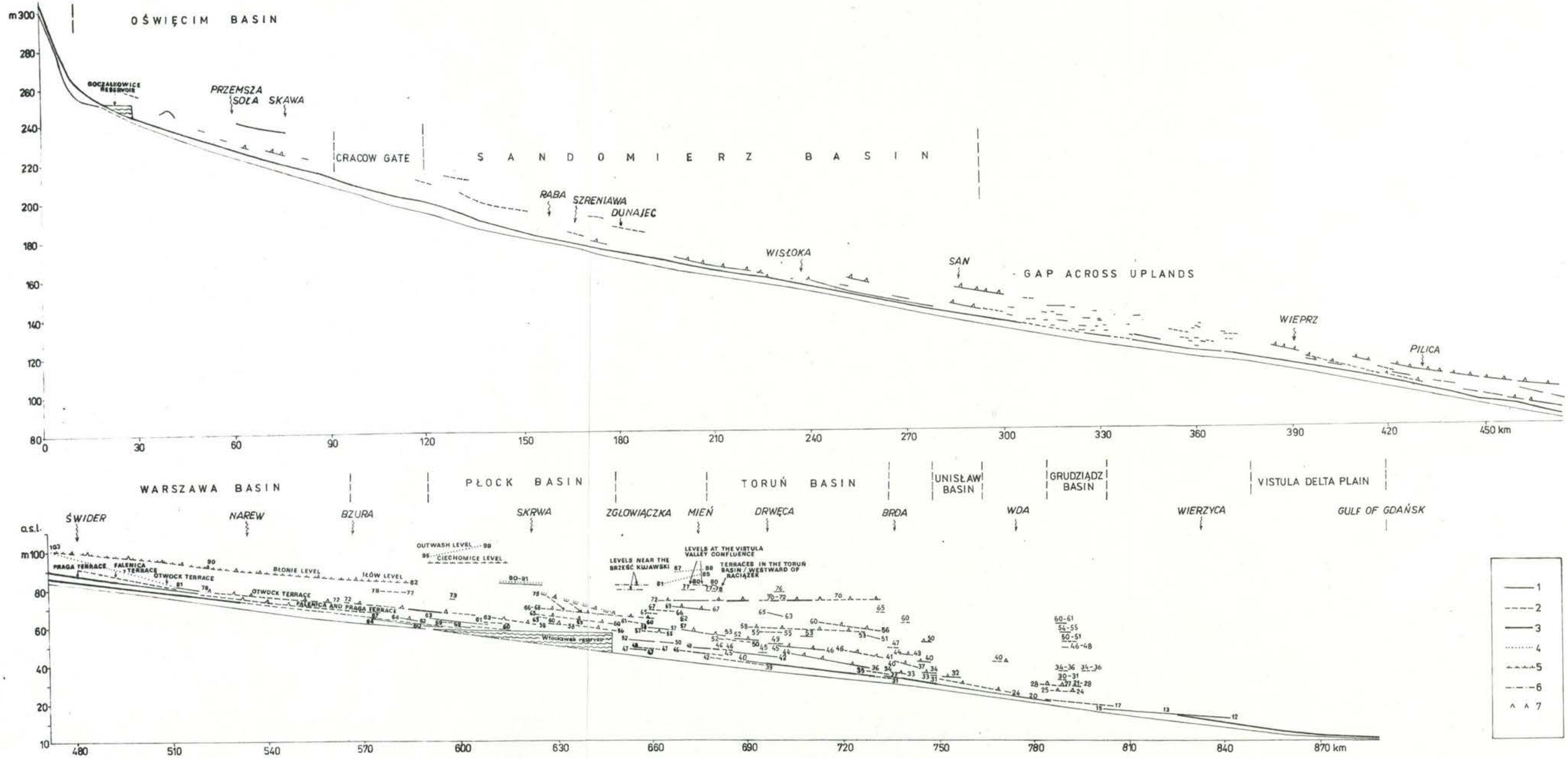

Fig. 40. Longitudinal terrace profiles in the Vistula River Valley (L. Starkel and E. Wiśniewski)

1-**right-bank** terrace, 2 left-bank terrace, 3-terrace on both banks, 4-outwash plain, 5-glaciolacustrine level, 6-transitional glaciofluvial-fluvial level, 7 dune

Zakład Narodowy im. Ossolińskich – Wydawnictwo PAN, Wrocław 1990

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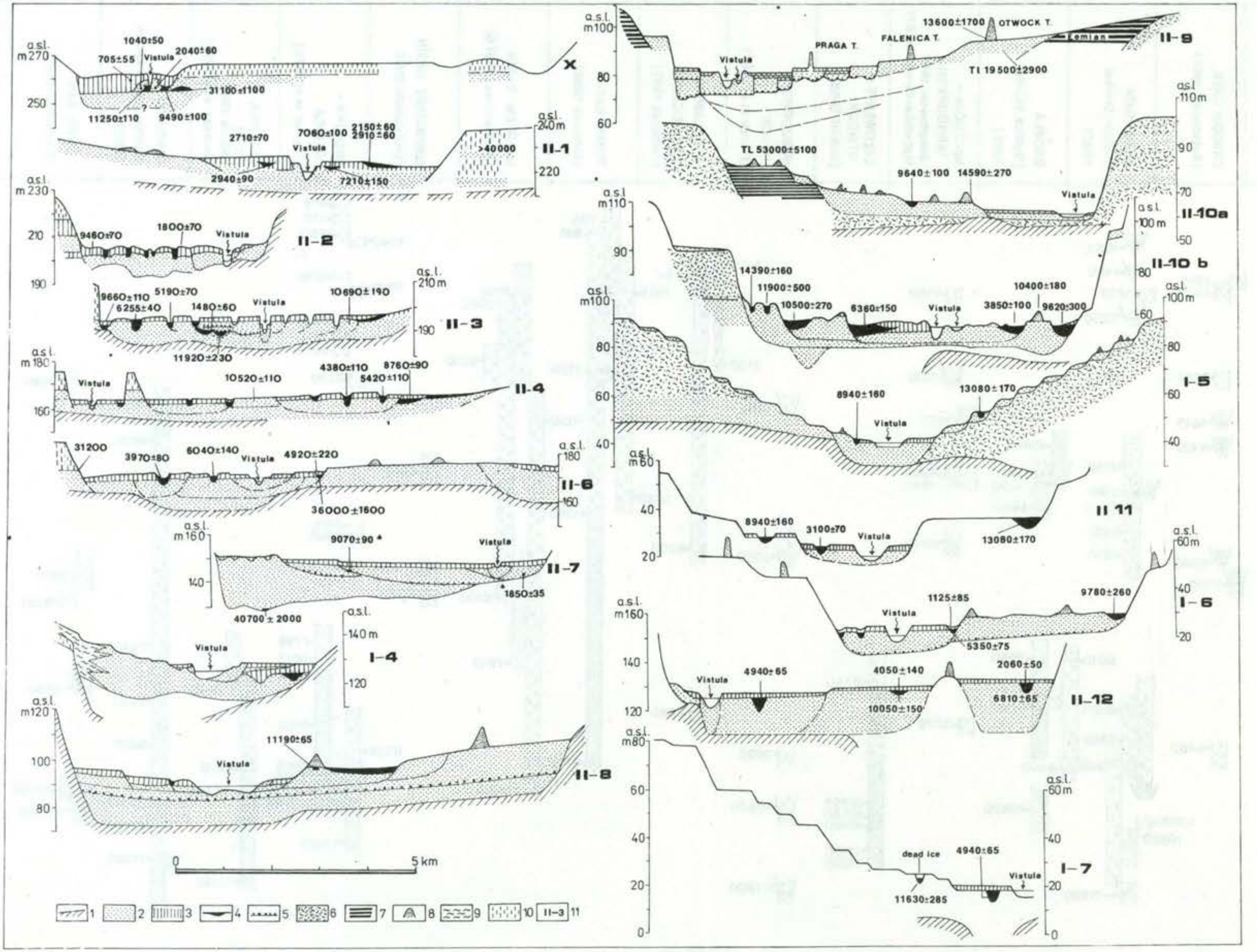


Fig. 41. Synthetical sections across the Vistula Valley floor (the reaches are shown in Fig. 3)

X–acc. to Niedziałkowska *et al* (1985), II-1–acc. to Klimek (1985) and unpublished data, II-2 acc. to Rutkowski (1987), II-3 acc. to Kalicki and Starkel (1987), II-4–acc. to Gębica and Starkel (1987), II-6–based on Sokołowski (1987), II-7–acc. to Mycielska-Dowgiałło (1977), I-4–acc. to Pożaryski (1955), II-8 acc. to Sarnacka (1987), II-9 based on Baraniecka and Konecka-Betley (1987) and Biernacki (1975), II-10a–acc. to Wiśniewski (1987), II-10b–acc. to Florek *et al.* (1987), I-5–acc. to Wiśniewski (1982) publ. in Starkel (1983), II-11–acc. to Tomczak (1987), I-6–acc. to Tomczak (1982), II-12–based on Niewiarowski (1987), I-7–acc. to Drozdowski (1982)

1–bedrock, 2–gravels and sands (channel facies), 3–alluvial loams (overbank facies), 4–oxbow-lake facies and their organic deposits, 5–lag subfacies, 6–till, 7–varved clays, 8–aeolian sand, 9–slope deposits, 10–loess-like silt, 11–number of valley reach (*cf* Figs. 3 and 6)

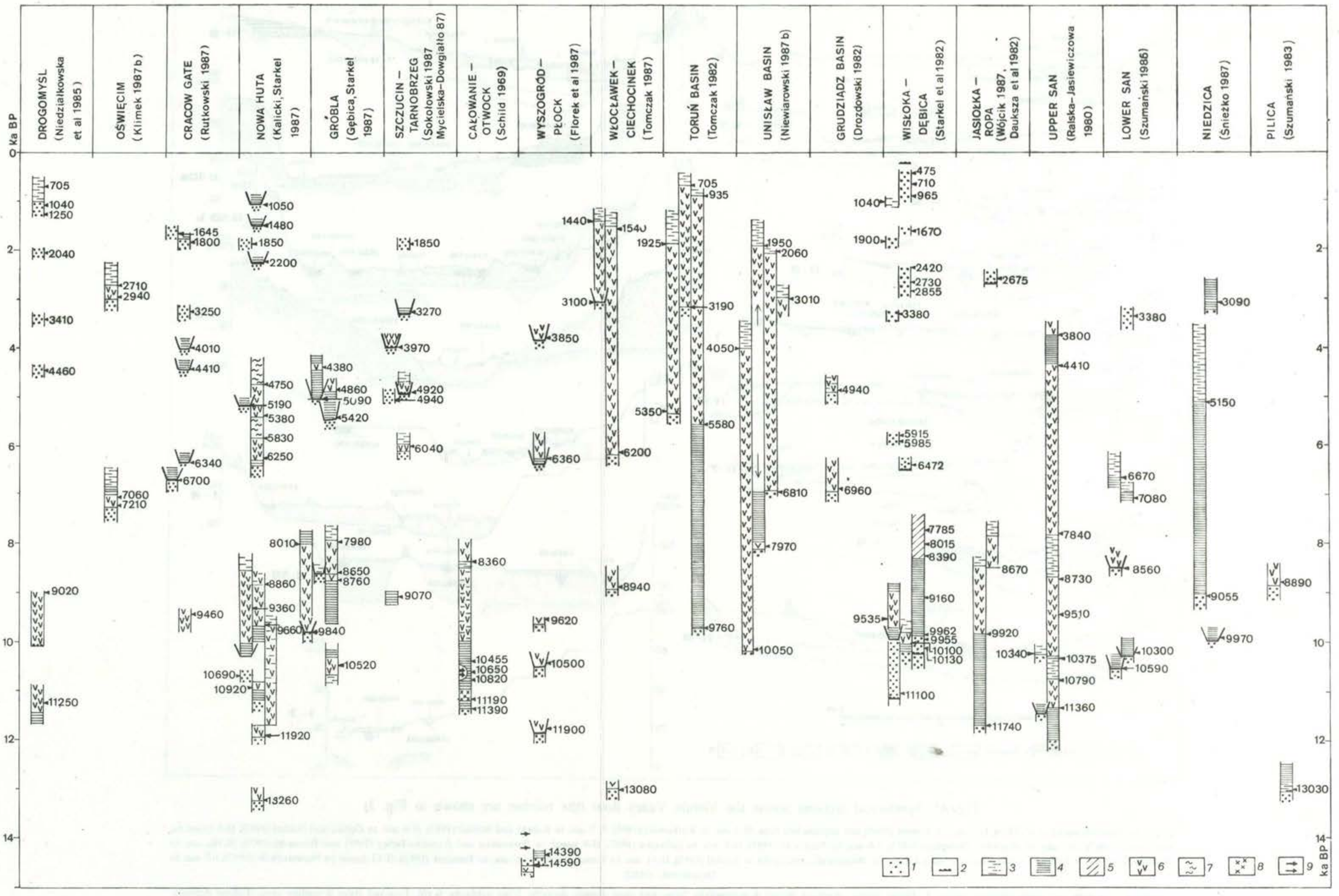


Fig. 42. Radiocarbon dated sequences of the Late Glacial and Holocene fluvial deposits in various valley reaches of the Vistula and its tributaries (compiled by L. Starkel)

1–channel facies, 2–lag subfacies, 3–overbank lacies, 4–palaeochannel fill ("mada"), 5–tributary fan facies, 6–peat, 7–slope deposits, 8–fossil soils, 9–aeolian deposits

Abrasion of the 0.5—0.8 mm quartz grains is expressed by the abrasion index (*Wo*) which varies from 954 to 1212. The corresponding histograms are flat, and the values of the heterogeneity index *Nm* are high (8.0—12.7).

The petrographical composition of the 0.5—0.8 mm sand grains varies slightly. The value of quartz is high (on the average 83%). Feldspars and particles of crystalline rocks, mostly gneisses and crystalline schists (on the average 14%), also occur there. Deposits contained in the braided Vistula channel, near Tarnobrzeg, show an upward decrease in the amount of crystalline rock particles (Mycielska-Dowgiałło 1978).

In the zone of large palaeomeander occurrence, the channel facies deposits are medium and fine sand. Layers showing a cross-bedding are 5—10 cm thick. On the surface of fluvial deposits there developed small dunes. The aeolian sands are well sorted ($\sigma_1 = 0.45—0.33$), better than the fluvial sands ($\sigma_1 = 0.49—0.72$). In the dune sands coarser grains tend to dominate.

Between Zawichost and Solec (Falkowski 1967, 1975, 1982), the Late Vistulian channel fills consist of poorly sorted medium and coarse sand, with gravels showing both a trough-bedding and a tabular cross-bedding. Their structure is similar to that of the modern channel bars. The series discussed is 8 m thick, *ie* being double of that in the Vistula reach near Tarnobrzeg.

South of Warsaw the presence of fluvial deposits probably dating from the Older Dryas has been stated by Schild (1982). These are thin channel gravels overlain by sands and dusty sands of the bar facies. During the Younger Dryas dunes developed on their surface. At the same time, a thin series of overbank alluvial loams ("mada") was laid down. Schild (1982) expressed the view that these are sediments of a braided river. However, the palaeochannel which has been dated to the Allerød is a large meander loop.

In the surroundings of Warsaw, the Late Vistulian deposits are preserved as sandy bars within a braided channel. They are overlain by a twofold "mada" (Biernacki 1975).

Downstream of Warsaw, near Wyszogród, stony channel lag deposits are succeeded by gravels and sands of the channel facies. These were laid down before 14,590 ± 270 years BP (Manikowska 1982).

Between Kępa Polska and Płock, the Late Glacial channel deposits are mostly thick-bedded medium sands showing both a tabular bedding and a trough cross-bedding. A distinct feature is the great variability in sorting and mean grain-sive from bed to bed. The content of well rounded quartz (γ type) is greatest in the fraction 0.75—1.02 mm. The average value of the 0.6—0.75 mm grains of γ type is 22.3%, in the fraction 0.75—1.02 mm (27.4%), and in the fraction 1.02—1.5 mm it reaches 19.6%. The same phenomenon is reflected in the values of the abrasion index (*Wo*) varying from 960 to 1468. The 0.75—1.02 mm grains are best rounded (Cichosz-Kostecka *et al* 1986; E. Florek *et al* 1987). Similar values have been obtained by Wiśniewski (personal communication, 1987).

The grain-size distribution in the late Plenivistulian sandur deposits being one of the sources for alluvia in the valley reach near Płock also varies considerably from bed to bed. These form aggrading cyclothems. The sand-sized grains are less rounded than those of alluvia (the average percentage of the best rounded grains of γ type is 11.6, the average abrasion index is 1017 (Ostrowski 1982). The coarser fractions are better rounded than the finer ones.

In the Vistula gap between Włocławek and Ciechocinek (Wiśniewski 1976a,b, 1982) fine- and medium-sized bar sands showing a cross-bedding as well as coarse sand and gravels which rest on coarse channel lag deposits constitute the major part of horizons dating from the Vistulian decline time. Channel deposits are usually 2—2.5 m thick.

Conditions change in the Toruń Basin (Tomczak 1982, 1987). Late Glacial fluvial deposits forming the supra-flood plain vary in thickness from 20 m to 30 m. As a rule, channel lag deposits consist of coarse, weathered and poorly rounded material. A common occurrence are stony--gravelly beds with boulders. Crystalline rocks predominate there. In places, limestones are present.

Channel lag deposits are overlain by medium sands, with single cobbles. The sand-sized fraction (0.25—0.8 mm) including 11—21% of the very fine sand-sized fraction (0.1—0.25 mm) is dominant. Quartz grains are frosted and well rounded. Cobbles contain poorly rounded limestone, silex, and crystalline rock particles.

Finally, fine and medium sans predominate in the top series in which polished quartz grains predominate. Overlying is the Late Vistulian "mada" capped with aeolian deposits dating from the Younger Dryas.

In the Unisław Basin, alluvia are only 10 m thick (Niewiarowski 1987b). Channel facies deposits are dominant. The lower unit of these deposits are coarse sands and gravels. The upper unit is formed of medium sand including some gravels. The upper unit is marked by the dominance (50—70%) of the fraction 0.25 to 0.5 mm, whereas the clay--sized fractions are lacking. The average value of the mean grain diameter is 1.57 *phi*, whereas *Mz* of the overlying aeolian sands is 1.69 *phi*. The mean value of the abrasion index (*Wo*) of the terrace-forming sands is 1125, and that of the terrace-derived wind-blown sands is 1063.

On the Late Vistulian terrace flats extending between Chełmno and Grudziądz alluvia gradually increase in thickness from 1—2 m on the upper flats to 6—7 m on the lowermost ones (Drozdowski 1982).

In the Vistula Delta area the Late Vistulian sediments are buried

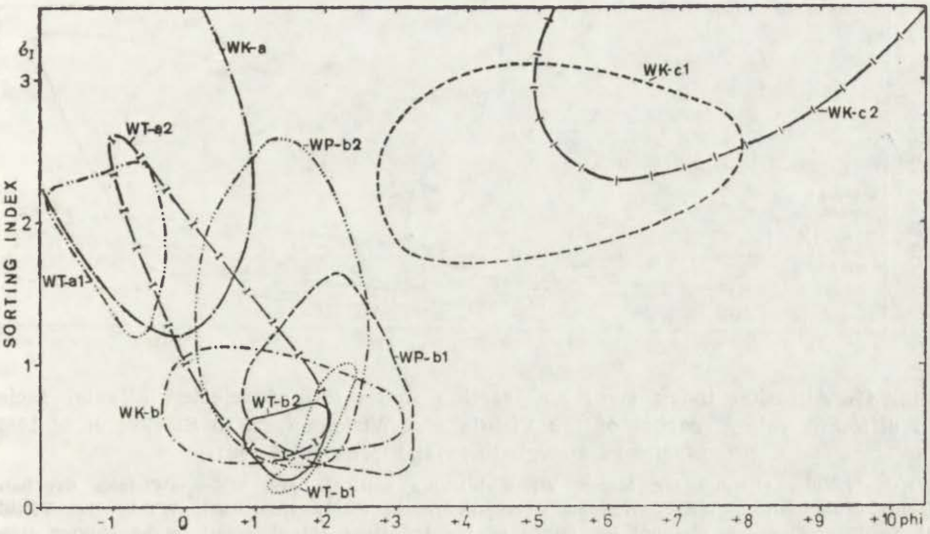


Fig. 43. Mean grain-size and standard deviation of selected alluvial facies in different valley reaches of the Vistula and Wisłoka (acc. to Starkel 1982; Mycielska-Dowgiałło 1978; Florek *et al* 1987)

For explanations see Fig. 44

beneath a veneer of younger deposits (Mojski 1982). The former differ from the younger deposits by the $CaCO_3$ content and by the lack of plant remains, amongst others, of wood particles. These are sands, with gravels in the lower part, which show an upward decrease in both grain-size and $CaCO_3$ content. The total thickness of deposits varies from several metres to 22 m.

In general, the fills of the late Pleniglacial braided channels ("bed-load" type) and of the Late Glacial large palaeomeanders ("mixed-load" type) possess the following characteristics:

(i) the occurrence of relatively coarse and poorly sorted (Fig. 43) channel deposits which show a fining both upward and downstream,

(ii) the dominance of bar facies deposits over the channel lag deposits; on the lower Vistula the sandur deposits are marked by a relative quantitative equilibrium of both subfacies; changes in the general thickness of deposits reaching its maximum in subsidence zones (such as the Carpathian basins and near the river mouth); thicknesses are least in the gap reaches,

(iii) the dominance of horizontal bedding in the channel lag deposits and of cross-bedding in the bar deposits; the proportion of tabular cross-bedding decreases in favour of trough cross-bedding with both increasing distance and fining of the material,

(iv) downstream the proportion of Carpathian material decreases in favour of material of Scandinavian provenance (Fig. 30); deposits show

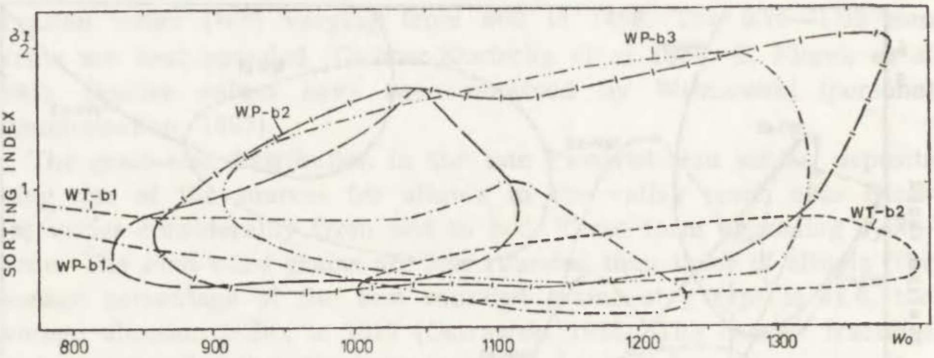
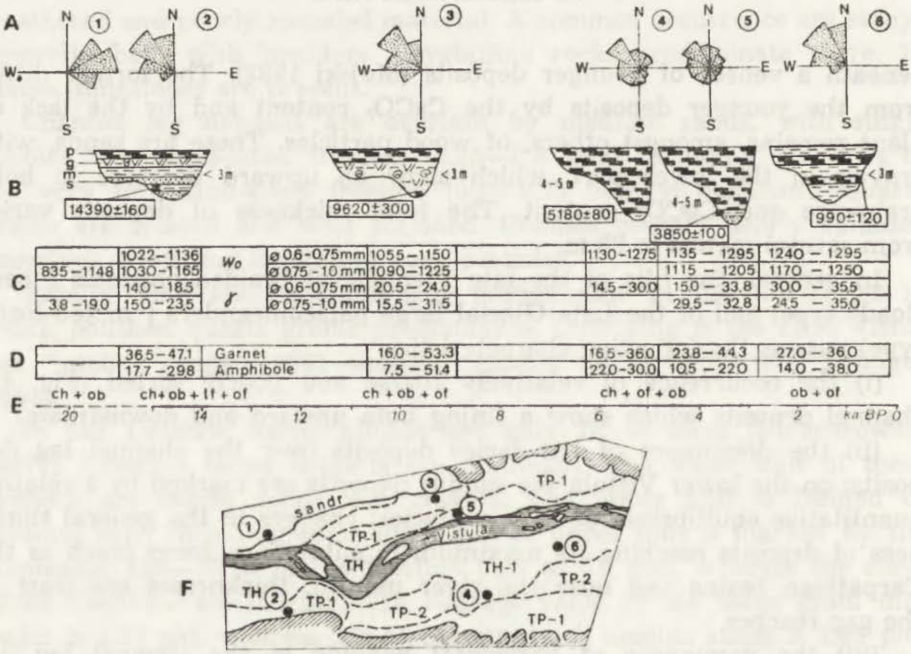


Fig. 44. Abrasion index (*Wo*) and sorting index (δ_I) of selected alluvial facies in different valley reaches of the Vistula and Wisłoka (acc. to Starkel *et al* 1982; Mycielska-Dowgiałło 1978; Florek *et al* 1987)

WK-a—Wisłoka channel lag facies, WK-b—Wisłoka central bars, WK-c_1—Wisłoka overbank facies (Subatlantic), WK-c_2—Wisłoka overbank facies (early Holocene), WT-a_1—the Vistula at Tarnobrzeg—either channel lag facies or braided river (Pleniglacial), WT-a_2—above site—channel lag facies of the meandering river (Holocene), WT-b_1—above site—central bars of the braided river, WT-b_2—above site—central bars of the meandering river, WP-b_1—Płock Basin—central bars of the meltwater-built sandur plains, WP-b_2—above site—central bars of the Late Glacial braided river, WP-b_3—above site—central bars of the Holocene river



	1022–1136	*Wo*	ø 0.6-0.75 mm	1055–1150		1130-1275	1135 – 1295	1240 – 1295
835–1148	1030–1165		ø 0.75 - 1.0 mm	1090–1225			1115 – 1205	1170 – 1250
	14.0 - 18.5	γ	ø 0.6-0.75 mm	20.5 – 24.0		14.5–30.0	15.0 – 33.8	30.0 – 35.5
3.8 –19.0	15.0 –23.5		ø 0.75–1.0 mm	15.5 – 31.5			29.5 – 32.8	24.5 – 35.0

	36.5 – 47.1	Garnet	16.0 – 53.3		16.5-36.0	23.8 – 44.3	27.0 – 36.0
	17.7 –29.8	Amphibole	7.5 – 51.4		22.0-30.0	10.5 – 22.0	14.0 – 38.0

Fig. 45. Changes in sedimentological parameters of the Vistulian and Holocene fluvial deposits in the Płock reach of the Vistula Valley (acc. to Florek *et al* 1987)

A—transport directions in the cross-bedded central bar deposits; B—depths and sequence of palaeochannel fills of differing age (s—sand, m—mud, g—gyttja, p—peat); C—abrasion index (*Wo*) and percentage of the well rounded grains (γ); D—heavy minerals; E—dominant facies in different periods (ch—channel, ob—overbank, cf—channel fills, tf—tributary fan); F—location of various deposits examined

no selection of heavy minerals from the bottom toward the top series (Fig. 45) because of the abundant supply of fresh material into the channels; the other cause is the violent and disarranged character of sedimentation,

(v) the rather high degree of quartz grain abrasion being higher than that of the sandur material, especially that of the fraction 0.75 to 1.00 mm (Fig. 44); this depends on the proportion of ancient wind-worn grains in the deposit,

(vi) the overbank facies includes a thin, fine-sandy and silty "mada" as well as shallow (up to 4 m) palaeochannel fills composed of silt, sandy silt, and gyttja which may contain a malacofauna,

(vii) frequent occurrences are associated facies of both aeolian deposits and alluvial fan deposits.

The Late Glacial "mada" is fine sand (*eg* in the Vistula Valley passing through the Cracow Gate, and in the Wisłoka Valley). However, silt, 0.5—1.0 m thick, predominates there. Downstream of Niepołomice the "mada" is intercalated with organic deposits which represent the Younger Dryas (Gębica, Starkel 1987). In places, the top series of the "mada" shows hydroplastic deformations (*eg* near Warsaw, cf. Biernacki 1975). In the tributary valleys, *eg* in the Nidzica valley silt contains organic substance (Śnieszko 1987).

In the lower reach of the Vistula Valley, near Płock and in the Toruń Basin, Late Vistulian natural levees have been recognized. These are formed of poorly sorted dusty sands showing low values of skewness (Tomczak 1982, 1987); Cichosz-Kostecka *et al* 1986; E. Florek *et al* 1987; Kamińska *et al* 1987). Levees bear dunes. In the successively younger aeolian deposits sorting improves upward.

In places, the "mada"-covered flats also are wind-affected and dune-covered.

The Late Glacial palaeochannel fills are rather thin. Deposits vary in thickness along the river. Many palaeochannels are poorly preserved. Thus, it is very difficult to reconstruct both the original channel shape and the sequence of channel fills.

On the alluvial fan built up by the Vistula in the Oświęcim Basin remnants of fossil palaeochannels are filled with Allerød silt and peat (Niedziałkowska *et al* 1985). Upstream of Cracow large palaeomeanders dating from the Allerød contain sandy silt devoid of organic matter (Rutkowski 1987). Downstream of Cracow the deep and large palaeomeanders dating from the Younger Dryas are filled with silt (2.2 m in the base) which was laid down during the Younger Dryas. They also contain a Preboreal peat, 2—5 m thick (Kalicki, Starkel 1987). Fossil palaeochannels dating from the Allerød display peaty silts.

Similar deposits have been record from the Late Glacial palaeochannels within the Carpathian tributary valleys of the Vistula. In the

Wisłoka Valley these are poorly sorted clayey silts (Starkel *et al* 1982). In the San Valley large palaeomeanders are filled with gyttja and peat which locally rest on thin beds of silty biogenous deposits. The total thickness of the deposits discussed ranges from 1 to 4 m to a peak of 6 m (Szumański 1982).

In the surroundings of Płock several palaeochannels dating from the Vistulian decline time and the beginning of the Holocene have been examined. This has opened up possibilities for comparing palaeochannels of differing age. The oldest palaeochannel (14,390 ± 160 years BP), up to 3 m deep, contains silty-sandy sediments, with intercalations of gyttja and peat. The palaeochannel at Bończa, which was abandoned 11,900 ± 500 years BP, is equally deep (up to 2.96 m). Its fill consists of gyttja containing a malacofauna, and of peat (Fig. 45). The younger palaeochannel at Juliszewo (10,500 ± 270 years BP) is filled with gyttja occurring in the base, and with peat (down to 2.8 m). In a still younger palaeochannel the Holocene sequence includes gyttja, with a malacofauna—peat—sand—peat and silt down to 2.28 m (Cichosz-Kostecka *et al* 1986; E. Florek *et al* 1987).

In the Toruń Basin palaeochannels dating from the Allerød are up to 3.8 m deep (on the average 1—2 m). Their fill is composed of gyttja and peat (Tomczak 1987) overlying fine sand. The peat is capped with a 20—30 cm layer of silty sediments.

It thus appears that the Vistula channel shows no increase in depth steadily downcurrent. The hydrological regime became stabilized, evidence of which is provided by biogenous palaeochannel fills dating from the Allerød. These fills included calcareous and freshwater marl. Calcium carbonate was supplied by water leaching the rocks in the surroundings of the valleys. Similar deposits appeared in the palaeochannels of the middle Warta River during the Allerød (Kozarski 1983), and in the lakes of Greater Poland (Wielkopolska) and Pomerania.

DEPOSITS OF THE HOLOCENE "SUSPENDED-LOAD" MEANDERING RIVER

It is probable that at the mouths of rivers which carried coarse bed material (the Soła, Dunajec) braided channel patterns have survived until the Holocene. However, smaller cutoff loops are known already from the Preboreal (Mycielska-Dowgiałło 1978; Szumański 1983). The distribution of fractions is typical of the Holocene meandering rivers. Alluvia of the meandering rivers are up to 10—15 m thick. They mostly include inserted series of deposits of differing age (Mycielska-Dowgiałło 1978; Kalicki, Starkel 1987; Klimek 1987b; Rutkowski 1987). The lower part of deposits consists of gravels and sand (channel lag deposits). The upper part is composed of sands forming both point bars and natural levees. The thickness of gravels decreases downstream in favour of the sandy members. Furthermore, grain-size of channel lag deposits also decreases downstream. Gravels become replaced by sandy-gravelly sediments.

In the upper Vistula Valley, earlier washed alluvia dominate in the channel lag deposits, evidence of which is provided by numerous residuals of the earlier Vistulian series. Residuals have also been recorded from other valleys (Klimaszewski 1948; Starkel 1960; Mamakowa, Starkel 1974). The lack of detailed data from the mountainous reach of the Vistula Valley may be replaced by values that have been obtained from the Wisłoka Valley, at the Carpathian margin (Alexandrowicz *et al* 1981). At Brzeźnica the mean grain diameter (*Mz*) is between — 4.6 and 1.7 *phi*. In the surroundings of Cracow this parameter of the gravel series most often varies from — 2.69 to — 0.45 *phi* (Rutkowski 1987), whereas between the mouths of the rivers Dunajec and Breń *Mz* is between — 0.9 and 1.9 *phi* (Sokołowski 1987). Identical values have been obtained from such deposits at Tarnobrzeg (Mycielska-Dowgiałło 1978).

Sandy deposits of the bar subfacies, the thickness of which increases downvalley, show a somewhat coarser mean fraction in the Vistula Valley, in the surroundings of Tarnobrzeg. Deposits here are better sorted (*Mz* varies from 1.17 to 1.92 *phi*) than those in the surroundings of Cracow, where *Mz* is between 1.48 and 2.46 *phi*.

Quartz grain abrasion has been examined in the Vistula Valley in the northern part of the Sandomierz Basin (Mycielska-Dowgiałło 1978). In the gravelly member the Krygowski abrasion index *Wo* (1964) of the fraction 0.5—0.8 mm ranges from 1058 to 1292. The value of grains of γ type (showing the best abrasion is 12—27%. In the overlying sandy member the *Wo* index for the same fraction varies from 1009 to 1390, and the value of grains falling into the γ group is 12—50%.

At the Carpathian margin, abrasion of the 0.5—0.8 mm quartz grains contained in the gravelly channel deposits of the Wisłoka was examined by Alexandrowicz *et al* (1981). The *Wo* values are between 809 and 1048, the value of grains of γ type varies from 0.5 to 3.5% (Niedziałkowska *et al* 1977). The proportion of aeolian deposits increases and the supply of fresh material into the alluvia decreases with increasing distance from the Carpathian margin as compared with the Tarnobrzeg region.

In the surroundings of Cracow, studies of the petrographical composition of the gravelly channel lag deposits revealed that the latter are similar to the pre-Quaternary substratum. This indicates washing of the older sediments (Rutkowski 1987; Fig. 30). In the coarse gravel-sized fraction Carpathian sandstones are most numerous. Finer fractions contain more quartz grains. Quartzites, and both magmatic and metamorphic rocks derived from the glacial deposits occur less frequently. Silex also is present. The latter may come from the weathered

Jurassic limestones. There was no supply of Jurassic limestone cobbles from the upland valleys.

Petrographical analyses of deposits occurring between the mouths of the rivers Dunajec and Breń revealed contrasts in the gravel composition in the northern and southern parts of the valley. This indicates the lack of both mixing and homogeneity of the petrographical composition of the deposit (Sokołowski 1987). This may be a specific feature of the meandering river deposits, whereas through the braids the river simultaneously strayed across the entire valley bottom.

For the most part, the gravelly and sandy-gravelly channel deposits described show a cross-bedding. Trough cross-bedding predominates. In the gravelly member the beds are 25—30 cm thick, whereas in the sandy member they attain a thickness of 5—10 cm (Mycielska-Dowgiałło 1978). The dispersion of the dip of laminae is high (Mycielska-Dowgiałło 1978; Rutkowski 1987) being typical of alluvia laid down by the meandering rivers.

Abandoned channel deposits dating from the entire earlier half of the Holocene are characterized by sandy and silty fills overlain by peat, up to 4—5 m thick (Starkel, Kalicki 1984; Sokołowski 1987). Until 3000 years BP in the Oświęcim Basin (Klimek 1987b) and until 1500 years BP in the surroundings of Cracow (Kalicki, Starkel 1987) the Holocene cutoffs of differing age developed at nearly one level. At this time, neither distinct aggradation nor erosion did occur in the Vistula Valley in the Subcarpathian basins.

At the Boreal/Atlantic transition increased humidity of climate was accompanied by the first distinct change in the character of alluvial deposits interfingering with slope-derived sediments. In the Wisłoka Valley a thick series of alluvial fan deposits then overtopped the abandoned channel fills. Alluvial fan deposits interfinger with overbank deposits. The multiple recurrence of the latter indicates increased flood frequency (Niedziałkowska *et al* 1977; Alexandrowicz *et al* 1981; Starkel *et al* 1982). At the same time, accumulation of biogenous sediments occurring in the Vistula Valley downstream of Cracow became interrupted by floods and increased alluvia deposition. Dusty sheets (Kalicki, Starkel 1987) and clayey beds (Gębica, Starkel 1987) then came into existence.

In the Oświęcim Basin overbank deposits, dating from the early half of the Holocene, include sandy clays, very clayey silt, and clay (Klimek 1987b). In the surroundings of Cracow the “mada” meander fills belonging to the earlier generations mostly consist of clayey dust (Rutkowski 1987). In the Sandomierz Basin, a common occurrence is the twofold “mada” which sometimes displays a fossil soil (Mycielska-Dowgiałło 1978; Szumański 1982; Gębica, Starkel 1987; Sokołowski 1987). The “mada” is clayey below and dusty above. The grain-size distribution in the earlier dusty "mada", which probably dates from the Atlantic period, was analysed at several sites on the middle and lower Vistula. For the most part, this "mada" includes 15—40% of clay-sized particles and 5—30% of sand-sized particles (Myślińska 1980).

From the decline of the Subboreal onwards throughout the Subatlantic period reactivation of the fluvial processes took place in the upper Vistula catchment. Erosion in the mountains was associated with aggradation in the mountain foreland. In the middle and lower reaches of the Vistula Valley the sandy "mada" which often rests on a fossil soil was deposited by the braided river during floods. This "mada" was analysed by Myślińska (1980). It contains clay-sized particles (5—10%), dust-sized particles (20—60%), and sand-sized particles (30—70%). In the Ropa Valley this period is represented by 1.5—4.5 m of channel facies deposits including boulders, cobbles, gravels, and clay (Dauksza *et al* 1982b). These became buried by clayey and sandy-dusty overbank deposits. Abandoned channel deposits are developed as vari-grained, stratified sands being inserted into gravels and clays. In the Wisłoka Valley this period is represented by complete profiles of alluvia consisting of poorly sorted channel deposits (sand and gravels), of well sorted sandy side-bar deposits, and of flood-deposited silt being again poorly sorted (Alexandrowicz *et al* 1981).

The process of a similar channel migration can be traced in the Vistula Valley in the Subcarpathian basins. Large palaeomeanders then came into being (Mycielska-Dowgiałło 1978; Kalicki, Starkel 1987). In the channel deposits, especially at the toe of slopes, numerous oak trunks and slope-derived boulders are found (Mycielska-Dowgiałło 1978). Alluvia reworking reaches down to 5—7 m. Both textural and structural properties of the channel deposits are similar to those of the earlier meander generation.

Studies made by Falkowski (1967, 1982) in the Vistula gap in the Polish Uplands revealed that the "mada" did not accumulate in the Subboreal and Subatlantic periods. Evidence of it is provided by numerous archaeological sites found on top of the Atlantic "mada". In the surroundings of Cracow a phase of pronounced aggradation was stated in the Vistula Valley already 1500 years BP.

Like in the upper reach of the Vistula Valley, the major phase of erosion in the middle and lower reaches occurred at the Vistulian/Holocene transition (Biernacki 1975; Wiśniewski 1982; Drozdowski 1982; Mojski 1982; Tomczak 1982, 1987; E. Florek *et al* 1987; Niewiarowski 1987b). The braided channel pattern which prevailed by the end of the Last Glacial period was still common in the middle and lower valley sections at the beginning of the Holocene. Shallow (2.5—3 m) stream channels then were dominant. At the toe of slopes alluvial fans developed. These modified the channel courses.

During the Atlantic period increased moisture of climate caused both concentration of waters and channel downcutting. This in turn induced the fall of the groundwater table and changes in the type of abandoned channel deposits which developed on the higher terraces. Accumulation of gyttja gave way to peat formation (Tomczak 1982; E. Florek *et al* 1987). It is probable that this change took place around 6000 years BP.

Like in the upper Vistula Valley, the vertical extent of alluvia reworking at this developmental stage is marked by channel lag deposits which occur at depths of 10—15 m in the surroundings of Warsaw (Biernacki 1975), and at depths of 10—12 m in the Płock Basin (E. Florek *et al* 1987) and in the Toruń Basin (Tomczak 1987).

In the Holocene alluvia the sand-sized fraction predominates. In the surroundings of Płock the mean grain diameter varies from 0.8 to 2.5 *phi*. The complete characteristics of this series was given by Tomczak (1982). Five sedimentary members were distinguished there. They correspond to three facies: the channel, the overbank, and the abandoned channel facies. According to Tomczak, the channel facies includes 1 m of channel lag deposits occurring in the base of the alluvial series. Alluvia consist of cobbles, finer than 10 cm, of single large blocks, and of coarse sands with gravels, 1.5—6 m thick. Overlying is fine sand which contains a small proportion of coarse sand. Overbank deposits are made up of fine and very fine sands alternating with clayey deposits. The abandoned channel facies is represented by peaty sediments. In some cases these are overlain by younger Holocene overbank deposits, c 0.8 m thick.

In the surroundings of Płock the Vistula Valley shows Middle Holocene meandering channels. Sorting of channel deposits improves upward (standard deviation σ_1 decreases from 1.1 in the base to 0.6 at the top). The composition of heavy minerals also changes upward. The proportion of the 0.1—0.2 mm garnet increases, whereas that of amphibole decreases (the percentages are as follows: *eg* at Białobrzegi near Płock at a depth of 3.5 m—garnet 24 and amphibole 17.5; at a depth of 1.7 m—garnet 44.3 and amphibole 12.5; at Wyszków near Płock at a depth of 4.5 m—garnet 18.2 and amphibole 24.4, at a depth of 2.9 m—garnet 40 and amphibole 15).

The above changes in the nature of deposits show that these have been affected by much washing and redeposition. This causes sorting to improve. Consequently, heavy minerals become enriched in minerals resistant to mechanical abrasion on the expense of the less resistant minerals. The process of repeated washing of the deposits is characteristic of rivers having a stable channel pattern (*eg* meandering and stable regime).

The abrasion of quartz grains of the sand-sized fraction of alluvia is similar to that of the dune horizons which acclmulated during the

Holocene. In both sediments of differing genesis grains are best rounded in the fraction 0.6—0.75 mm. The second maximum occurs in the fraction 0.75—1.0 mm (*Wo* varies from 1119 to 1311). The percentage of grains of γ type is high (19—36).

At the same time textural features of the channel deposits may reflect local conditions. In the case of eroded morainic and sandur deposits the nature of alluvia is similar to that of deposits previously mentioned (*eg* the abrasion of grains is worse). In the case of a higher dune-bearing terrace plain that is undermined by the river abrasion of grains improves in the alluvia.

Overbank deposits forming the flood-plain near Płock frequently show a twofold division. They are very clayey below and dusty-sandy above. In both the Unisław Basin and the Vistula gap north of Bydgoszcz—Fordon (Niewiarowski 1987b) overbank deposits vary in thickness (0.5—3 m) and composition. Near the modern stream channel fine sand and silt (1—3 m thick) tend to dominate. Farther off there occur silty-sandy and silty-clayey sediments, up to 0.5—1 m thick.

In the lowermost reach of the Vistula Valley (Mojski 1982), aggradation prevailed throughout the Holocene. Prior to the Littorina transgression and its initial phase sandy and sandy-silty deposits with clayey and peaty intercalations were laid down by the river. This series is up to 20 m thick. The rising sea level caused the successively younger members to be deposited there. From the culmination of the Littorina transgression onwards, biogenous deposits containing a small proportion of fine sand are dominant. The latter series is only a few metres thick.

In summary, characteristic features of the Holocene meandering river deposits in the Vistula drainage basin are as follows:

(i) thicknesses generally range from 19 to 15 m: the gravelly channel lag deposits are 7—10 m thick, sandy bar deposits—3—8 m, the silty--clayey "mada"—1—4 m,

(ii) the dominance of trough cross-bedding with a high dispersion of the dip of laminae,

(iii) the proportion of more resistant minerals contained in the channel deposits increases upwards; this indicates both selection and limitation of fresh material supply into the channel (Fig. 45),

(iv) in general, a rather well abrasion of the quartz grains, especially in the fraction 0.5—0.75 mm (Fig. 44),

(v) in the overbank facies an essential role is played by "mada". Generally, the latter is twofold: clayey below and dusty above. Coarse, even sandy intercalations represent periods of increased river activity,

(vi) marked thicknesses of the palaeochannel fills (4—6 m) containing abundant peat,

(vii) from the Atlantic period onward the associated facies include alluvial fan deposits and deluvial deposits. These either interfinger with the flood-plain deposits or cause the upward growth of the flood-plain; in areas made up of carbonate rocks there developed calcareous tufa (from 9 ka down to 3 ka years BP).

DEPOSITS OF THE "MIXED-LOAD" RIVER SHOWING A TENDENCY TOWARD BRAIDING IN HISTORICAL TIMES

Though the historical period in the Vistula evolution is only a small part of the Holocene, the hydrological changes then occurring caused such a marked change in the river-laid deposits that they gave reason for discussion of this period and its sedimentological consequences.

The fundamental change in the development of the fluvial processes expresses itself in a tendency to the increase in bed elevation by aggradation. Consequently, the channel becomes shallower and wider. In most of the valley reaches of the Vistula and its tributaries examined this process was initiated in the 10th century. In some places it started earlier, *eg* downstream of Cracow after 1480 years BP. Near Oświęcim and Warsaw it began even in the Middle Subboreal period.

In the 18th century (at the River Breń mouth) and in the 17th century (in the Vistula Valley between Zawichost and Solec) there began the second important period of the man-induced channel transformation. The existing Vistula channel overloaded with material reverted to a braided channel.

Few data available for characterizing the textural properties of the then formed channel deposits make any comparison with the remaining Holocene deposits difficult. Petrographical analyses (Rutkowski 1987) revealed the gradual increase in anthropogenic components: broken pottery (mostly bricks), rock fragments used for hydrotechnical purposes (*eg* Jurassic limestones in the upper river reach), and coal clasts (since the earlier half of the 19th century). According to Falkowski (1967), the sorting of channel deposits laid down after AD 1600 is less well than that of the earlier deposits.

Cutoffs dating from the historical period are filled either with "mada" (in the Cracow Gate—Rutkowski 1987) or with gyttja and peat overlain by a silty "mada" (Kalicki, Starkel 1987).

In the historical period the overbank facies is becoming significant in both a quantitative and qualitative sense. This facies is an essential indicator of transformations of both fluvial processes and the catchment area.

The most important fact is the encroachment of flood deposits on the earlier Holocene deposits, and even on the late-Pleistocene terrace plains. Both increasing accumulation rates (cf. Falkowski 1967, 1982) and increasing grain-sizes are associated with a worsening of sorting (Falkowski 1967; Kalicki, Starkel 1987). The latter remark also concerns the Carpathian tributaries of the Vistula: the Wisłoka (Alexandrowicz *et al* 1981; Starkel *et al* 1982) and the San (Szumański 1982).

Alongside the lower Vistula channel natural levees (Niewiarowski 1987b) are forming, together with crevasse, splay deposits extending in large tongues. These also overtop the early Holocene alluvia (E. Florek *et al* 1987). The deposits discussed are medium sand. Their mean grain diameter (*Mz*) varies from 1 to 1.5 *phi*. Crevasse splay deposits gently slope away from the channel. They may cap the series of clayey "mada". Around Ciechocinek 3.5 m of fine sand and sandy "mada" rest on a dark-grey clay, 0.7 m thick (Wiśniewski 1982). The whole series overlies organic sediments, 2 m thick, which have been deposited since the beginning of the Atlantic period (also cf. Tomczak 1982). Peat occurring deeper than the bed of the present river indicates pronounced aggradation along the entire lower reach of the Vistula.

The "mada" that was laid down during the last millenium shows either a rhythmical bedding (Falkowski 1967; Klimek 1974, 1987b; Mycielska-Dowgiałło 1978) or lack of bedding (Falkowski 1967). Drifted plant material (4—6%, acc. to Klimek 1987b), coal dust, municipal and industrial pollutants may be concentrated into it (Klimek, Zawilińska 1986; Rutkowski 1987).

Over the past century processes of flood-plain transformation are confined to the inter-dike area (Dembowski 1984). Only during catastrophic floods large quantities of flood water and sediment are diverted onto the flood-plain. Such flood-deposited sediments contain a higher proportion of the coarse fractions due to greater current velocities between the dikes. Today accretion rates are still higher than previously: in the Oświęcim Basin and in the Vistula Valley they reached 2—3 m over the last 100 years (Alexandrowicz *et al* 1981; Klimek 1987b), 0.5—3 m at the Raba mouth (Dembowski 1984), and 1 m since 1914 at Basonia in the Vistula gap in the Polish Uplands (Falkowski 1967). In the inter-dike area regular flat sheets occur occasionally. Most frequently the relief of the accumulational surface is varied. Common features are sharp edges (Cichosz-Kostecka *et al* 1986; E. Florek *et al* 1987). This accumulation owes a great deal to channel correction. The dominant sandy deposits were derived from the stream channel. They occupy large areas extending upstream of Włocławek reservoir.

Deposits laid down during the historical period possess the following characteristics:

(i) generally, rather small thicknesses (3—4.3 m), though locally they may exceed 10 m,

(ii) the poor sorting of the channel facies deposits,

(iii) the dominance of overbank facies deposits, with a maximum observed thickness of 10 m,

(iv) in some cases the channel facies deposits may overtop the overbank deposits,

(v) for the most part the overbank facies deposits ("mada", natural levee deposits, and crevasse splay deposits) consist of sand and sandy dust; palaeochannel fills are made up of silt, gyttja, and peat,

(vi) the marked concentration of organic matter, heavy metals, and broken pottery; pollution with municipal and industrial waste water, especially of the overbank deposits.

THE VISTULA RIVER DELTA

The Vistula River Delta (Fig. 46) is a unique morphogenetic feature in Poland because of its geological structure and correlation with the history of the Baltic Sea in Holocene times.

Although the survey of the Vistula River Delta started nearly a hundred years ago, an important qualitative progress has been made in the last decade. This progress is due to both general and detailed geological surveys of the delta (Makowska 1977, 1987; Mojski, Sylwestrzak 1977; Mojski 1978, 1979, 1984, 1985, in press). Furthermore, results of the many years' lithostratigraphical and biostratigraphical studies, along with abundant data on the ages of deposits, have been published by Mojski (1982, 1983), Bogaczewicz-Adamczak, Miotk (1985), Zachowicz (1985), Zachowicz *et al* (1982), and others.

THE CONFIGURATION OF THE SUB-HOLOCENE SURFACE

In order to understand both origin and evolution of the Vistula River Delta, it is necessary to characterize the sub-Holocene surface of this area. This surface owes a great deal to erosion. In some instances little modified glaciogenic landforms may be discerned. The lowest places due to erosion occur more than thirty metres below the present sea level. In the glacial "islands" the glaciogenic surface rises several metres above sea level. Thus, the local relief of the sub-Holocene surface reaches about 40 m.

Erosional landforms include narrow depressions trending nearly northwards. They begin at the delta apex and continue in a northerly direction as far as the seashore. These are the former Vistula channels corresponding to different stages in the formation of the valley and later on of the delta. These are (perhaps mostly) Middle Holocene palaeochannels and not only pre-Holocene features.

In the south-eastern part of the delta similar depressions are due to channel downcutting by smaller rivers draining away from the morainic plateau in a northerly direction. The palaeochannels attain an

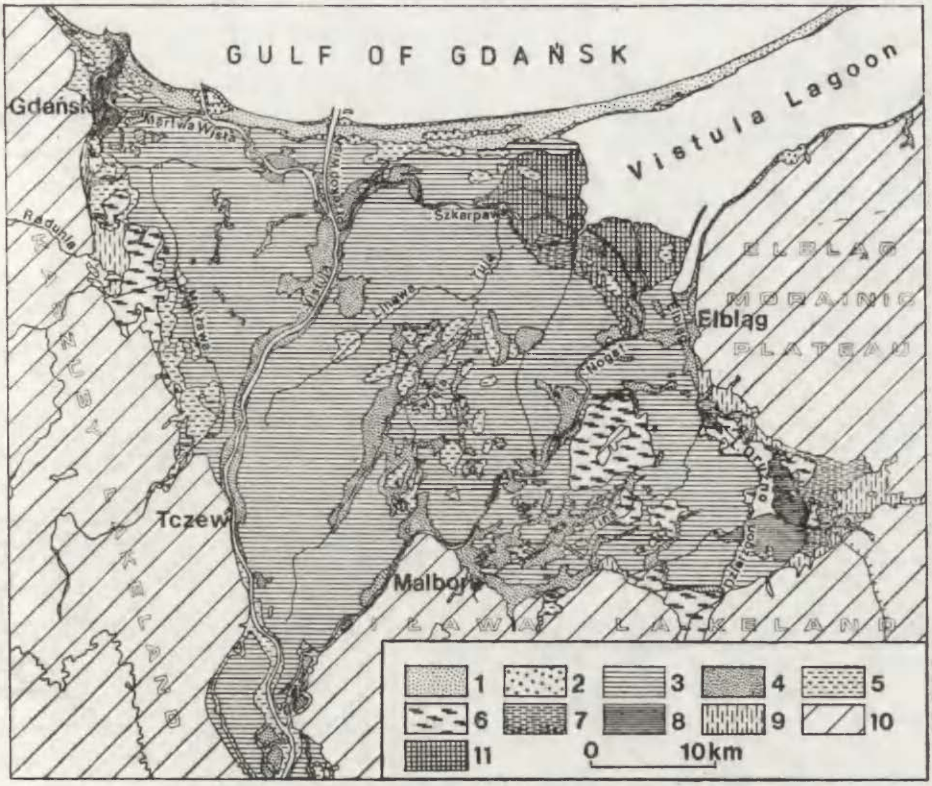


Fig. 46. Geological sketch map showing the Vistula River Delta

1—dune sand building up the Vistula Spit, 2—sand forming the Vistula Spit, 3—"mada", 4—sandy channel facies deposits, 5—loamy-peaty deposits, 6—peat, 7—lacustrine deposits, 8—gyttja, 9—fan-forming sand, 10—morainic plateau, 11—deltaic sediments deposited over the last century

average depth of 5—15 m. In places they are up to 20 m deep, *eg* in the vicinity of the present Vistula mouth. This depth, however, has been calculated from the sub-Holocene surface upwards. The real depth must have exceeded the above values because the palaeochannels are often carved into a cover of Holocene deposits, 5—10 m thick.

The sub-Holocene surface which shows a little transformed glaciogenic relief is found in two relatively high areas. One of these lies on the north-eastern side of the delta apex at several metres below sea level. Holocene deposits are less than 10 m thick there. The other is perpendicular to the former area and extends at a somewhat greater depth. In both areas the Holocene series is directly underlain by till dating from the Vistulian. Furthermore, deposits belonging to this stage are generally forming the sub-Holocene surface. In places Holocene sediments rest on the Eemian marine deposits. It is probable that the

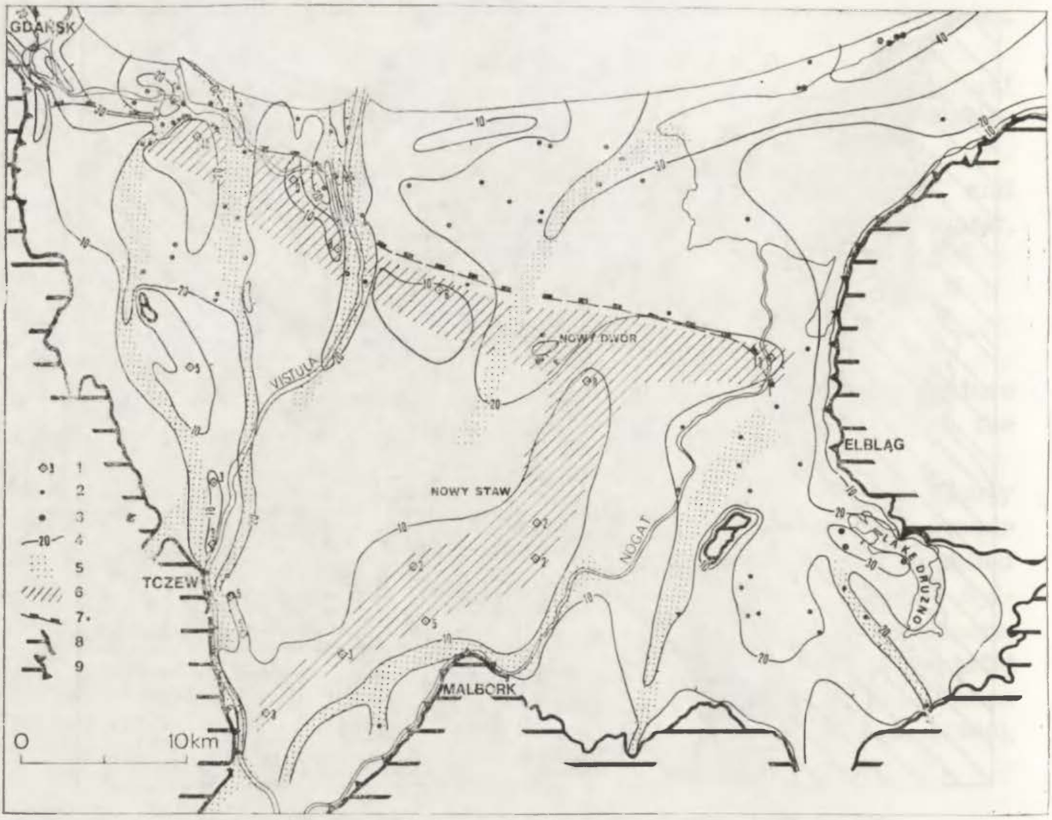


Fig. 47. The sub-Holocene surface of the Vistula River Delta
1—bore-holes displaying Holocene deposits less than 10 m thick, 2—selected bore-holes displaying Holocene deposits, 10—30 m thick, 3—selected bore-holes displaying Holocene deposits more than 30 m thick, 4—contour-lines [m] showing the sub-Holocene surface, 5—main palaeochannels, 6—eminences of the sub-Holocene surface, 7—fossil cliff (?) corresponding to the greatest extent of the Baltic Sea in Holocene times, 8—boundary of morainic plateau, 9—erosional boundary of morainic plateau

first eminence is forming the major palaeowatershed in the delta area. This watershed divided the present delta into two parts. The western part was occupied by the Vistula Valley. The eastern part and its floor were more irregularly shaped.

The second eminence extends between Gdańsk and Elbląg. Its surface also consists mostly of glaciogenic deposits. The origin of this landform is not certain. It seems, however, that its northern border is formed by a fossil cliff (Fig. 47) which marks the greatest extent of the marine transgression in the delta area. Such a cliff also appears in the buried relief in the vicinity of Gdańsk. Between Gdańsk and Sopot the higher part of the cliff is a relief element of the present day (Mojski 1983).

The palaeowatershed dividing the delta into two parts was the most important feature amongst the sub-Holocene landforms described that controlled the evolution of the delta. This watershed existed for a long time. In the youngest phase of the delta evolution it became covered only with alluvia of the Vistula.

THE STRATIGRAPHY OF HOLOCENE DEPOSITS WITHIN THE DELTA AREA

The lithostratigraphical profile of Holocene deposits forming the Vistula River Delta has been discussed by the present author in his earlier works (Mojski 1982, 1983, in press). This paper provides dates and the chronostratigraphy.

The Holocene cover may be subdivided into two lithostratigraphical units, namely, a lower and an upper ones (Figs. 48—50). The lower unit consists of fine gravel in its lower part. These sediments are often interbedded with fluvial "mada", clay and biogenous deposits which include abundant pieces of wood and other plant remains. Molluscan schells of *Monachoides rubiginosa* (A. Schm.), *Valvata piscinalis* (Müll.), *Bithynia tentaculata* L., *Theodoxus fluviatilis* L., *Limnea peregra* (Müll.), *Armiger crista* f. *cristatus* Drap., *Pisidium henslovanum* (Shepp.), *P. subtruncatum* Malm. and *P. personatum* Malm. (determinations were made by Dr. Aurelia Makowska, Geological Institute, Warsaw) were also found there. A similar assemblage occurs in the whole Holocene cover beyond the reach of the sea.

On this basis the sediments described are interpreted as the channel facies. These contain in small quantities deposits of the overbank and abandoned channel facies.

On this basis the sediments described are interpreted as the channel cene deposits there lie directly either biogenous or minero-biogenous deposits consisting of more or less humic clay, peaty loam, "mada" and peats. This highly variable upper part of the lower cover indicates essential changes in the hydrological regime, gradient reduction and increase in the amount of material supplied by lateral erosion of the flood-plains. The lower cover is usually from several to more than ten metres thick.

In the southern and central parts of the delta the composition of the upper cover is similar to that of the lower one. In the lower part fine sands of the channel facies tend to dominate. These are interbedded with biogenous deposits. In the upper part there occurs "mada" which shows a highly varied composition and different properties (Witek 1965, 1976). Pieces of wood and other macroscopic plant remains as well as a freshwater fauna being similar to that in the lower cover commonly occur there. Sediments which form the upper cover, up to 12 m thick, are building the delta surface.

In the northern and eastern parts of the delta the fluvial sediments that compose the upper cover are replaced by marine deposits. Their

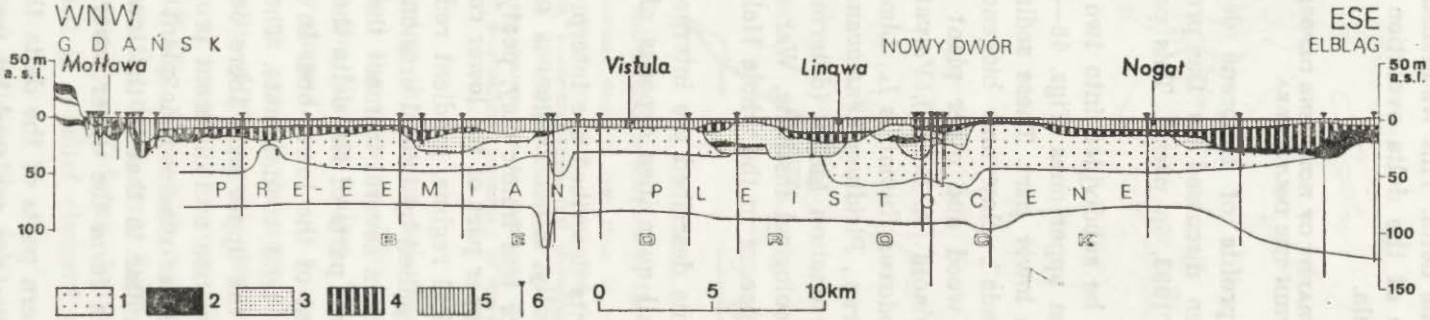


Fig. 48. Gdańsk—Elbląg geological cross-section

1—Eemian marine deposits, 2—till of Vistulian age, 3—fluvioglacial and limnoglacial deposits of Vistulian age, 4—lower lithostratigraphical unit of the Holocene, 5—upper lithostratigraphical unit of the Holocene, 6—selected bore-holes

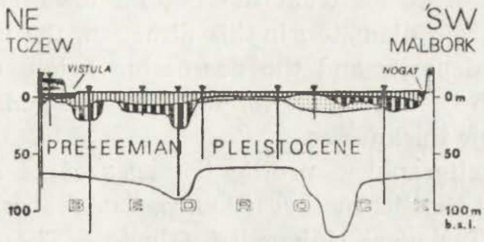


Fig. 49. Tczew—Malbork geological cross-section

For explanations see Fig. 48

profile includes lag deposits being represented by a 0.3 m sand-and-gravel bed. It contains biogenous sediment balls which were derived from the higher part of the lower cover. Compact macroscopic plant remains, abundant molluscan shells and pieces of amber also occur there. Overlying are marine shallow-water sands with a fauna being typical of the present-day Baltic Sea (unfinished study by Mrs Jarmila Kamińska, Geological Institute).

In the zone of the Vistula Spit (Mierzeja Wiślana) marine deposits became covered by dune-forming aeolian sands.

The above described lithostratigraphical profile of the delta-forming Holocene sediments is valid for the whole area discussed. In some regions where there numerous borings and studies were made, *eg* in the surroundings of Gdańsk, strata of local importance may be distinguished in both units (Mojski 1983).

Common features of both lithostratigraphical units are as follows:

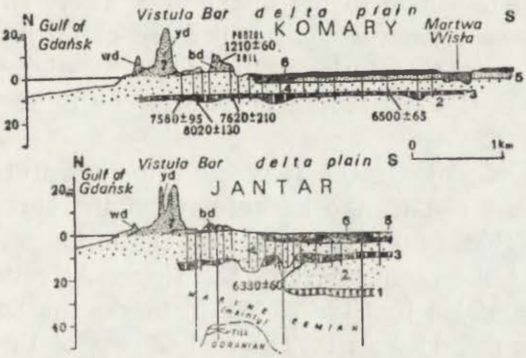


Fig. 50. Geological cross-section at Komary (2 km to the west of Przekop Wisły = present Vistula outlet) and at Jantar (4 km to the east of Przekop Wisły)

1—dominant biogenous deposits of Preboreal age, 2—lower part of the lower lithostratigraphical unit (mostly sand), 3—upper part of the lower lithostratigraphical unit (biogenous deposits), with ^{14}C dates BP, 4—lower part of the upper lithostratigraphical unit (mostly sand of fluvial and marine origin), 5—upper part of the upper lithostratigraphical unit (sandy channel facies), 6—upper part of the upper lithostratigraphical unit-peat and "mada" (overbank facies), 7—aeolian sand: bd—brown dunes, yd—yellow dunes, wd—white dunes similar sequences of strata from the bottom towards the top, the decrease of median grain diameters in this direction, the increasing proportion of biogenous deposits and the decreasing height differences of the fluvial relief. Both sections (Fig. 48, 49) show the general occurrence of both units and their thicknesses.

In the lithostratigraphical profile the ages of 24 samples were determined by using the ^{14}C method (Radiocarbon Laboratory, Institute of Physics, Silesian Technical University, Gliwice). The results of datings (Fig. 51) fall into three groups. The first group includes two dates greater than 9 ka BP: 9690 ± 150 years BP (Gd-539) and 9130 ± 90 years BP (Gd-1414). The first date refers to a peaty soil, the second to peat. Both deposits form part of the biogenous intercalations which were found in the lower part of the lower cover. The first date indicates that the deposit developed during the Preboreal, the second date refers to the Lower Boreal. It is probable that these deposits accumulated on the then flooded valley floor as a thin mineral sheet of the early Holocene.

The second group comprises 16 dates. All of them fall within 8020 ± ± 130 years BP (Gd-1405) and 6330 ± 60 years BP (Gd-1408). These are dates of the biogenous deposits forming the higher part of the lower unit. All datings indicate an Atlantic age. Most of them refer to the Middle Atlantic period (AT_2—AT_3), *ie.* 7.7—6.0 ka, according to the subdivision of the Holocene by Starkel (1977b). The geological situation of such dated deposits is shown on two geological sections being perpendicular to the present shoreline, at Komary and Jantar (Fig. 50).

The third group comprises 6 dates covering a long span of time, from 5415 ± 105 years BP (Gd-540) onwards until 1210 ± 60 years BP (Gd--1661). These are dates of deposits of differing origin, peats, "mada", and fossil soils. All belong to the upper unit. These single dates which have been obtained from various profiles are of no greater importance to the discussion of the evolution of the delta. Stratigraphically they refer to the decline of the Atlantic period, to the Subboreal, and to the Subatlantic.

The existing ^{14}C dates make it possible to interpret the ages of the geological processes against the background of the chronostratigraphical division of the Holocene (Fig. 51). Datings of the top series of the upper unit indicate that the higher part of the Upper Atlantic period (AT_3 in the fourfold subdivision by Starkel 1977b) marks the boundary between both units, *ie* around 6.3 ka BP. The earlier part of the Atlantic period is represented by peats, "mada", gyttja, and loams making up the higher part of the lower unit. This came into existence 8 ka—6.3 ka years BP. Thus, the formation of the lower part of the above unit has taken place from the beginning of the Holocene onwards until 8 ka years BP.

The upper unit includes the upper part of the Holocene (from AT_3 to as late as the present time), *ie* the last 6.3 ka years BP. Hence, it follows

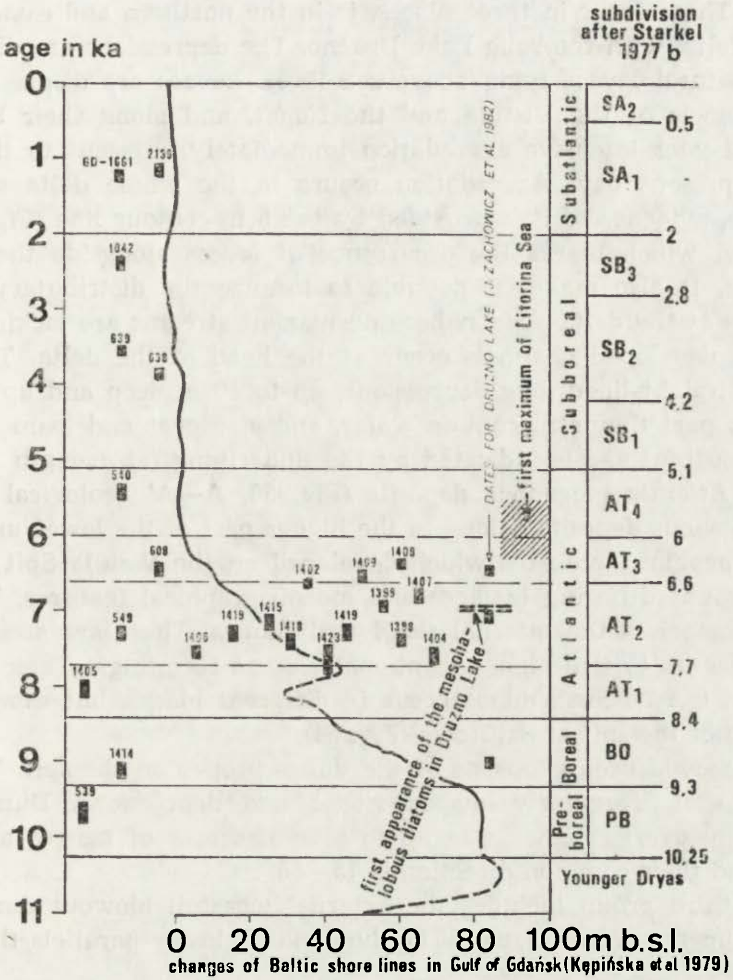


Fig. 51. The position of ^{14}C dated deposits within the study area in the Holocene subdivision, and sea-level changes in the Gulf of Gdańsk

that the marine deposits which built up the delta are younger than 6.3 ka years. Furthermore, in the Lake Druzno lacustrine deposits the mesohalobous diatoms appear as early as 7 ka years ago (Zachowicz *et al* 1982). Such evidence points toward the periodical occurrence of marine ingressions into this lake basin.

THE DELTA CONFIGURATION

In order to recognize the morphogenesis of the delta, analyses of the morphometry, and the location of both abandoned channels and aeolian landforms occurring on the Vistula Spit have been made.

On the hypsometrical map the location of depressed areas is clearly visible. These occur in three places, *ie* in the northern and eastern parts of the delta, with the relic Lake Drużno. The depressions are divided by broad natural levees lying above sea level. Levees are displayed along the channels of the Vistula and the Nogat, and along their branches. This indicates intensive aggradation immediately adjacent to the rivers of the present day. Aggradation occurs in the whole delta area. For example, evidence of it is provided by the 5 m contour line (Fig. 52) the course of which marks the occurrence of levees alongside the present channels. It also makes it possible to localize the distributary palaeochannels at the delta apex, where permanent streams are lacking today.

Well developed channels occur at the head of the delta. These are nearly straight-lined long depressions, up to 10 m deep and up to 80 m wide. In part they still contain water, and also peat and loam (Fig. 53). Their youthful age is indicated by the underlying (at a depth of 10 m) Middle Atlantic biogenous deposits (Fig. 53, A—A' geological section). The biogenous deposits belong to the higher part of the lower unit there.

The aeolian landforms which developed on the Vistula Spit fall into three groups differing by ages and morphographical features. The first group comprises the internal (landward) dunes. These are straight and flat ridges up to 4 m high, exceptionally up to 10 m high. Their common direction is 90°. Such dunes occur in different places, but especially at the head of the spit at Sztutowo (Fig. 54).

The second group consists of the dunes proper on the spit. They are made up of irregularly shaped ridges and depressions. Dune ridges frequently overlap. They rise up to several scores of metres above sea level, and their common direction is 75—85°.

The third group includes the external (coastal) blowout dune ridge. It rises up to several metres. The dune ridge closely parallels the shoreline.

The threefold morphological division of the dune zone corresponds to the threefold age division which in turn is reflected in the different degree of soil profile development. The internal dunes belong to the so called brown dunes having a very well developed podzolic soil. This soil is preserved only locally. The second group comprises yellow dunes, with a young and poorly developed soil. Finally, the external dune is a white dune possessing an undeveloped soil profile.

The humic substance in the zone of accumulation of the podzolic soil that developed on a brown dune at Komary has been dated at 1210 ± 60 years BP (Gd-1661). This soil (Fig. 50) is covered with a younger aeolian sheet up to 1 m thick. However, the stratigraphical position of all dune types indicates that all of them are younger Holocene in age. On the basis of comparison with similar dunes occurring on the Świna Spit (Mierzeja Świny) (Plichta 1970) it appears that dune formation took place during the last 4.5 ka years.

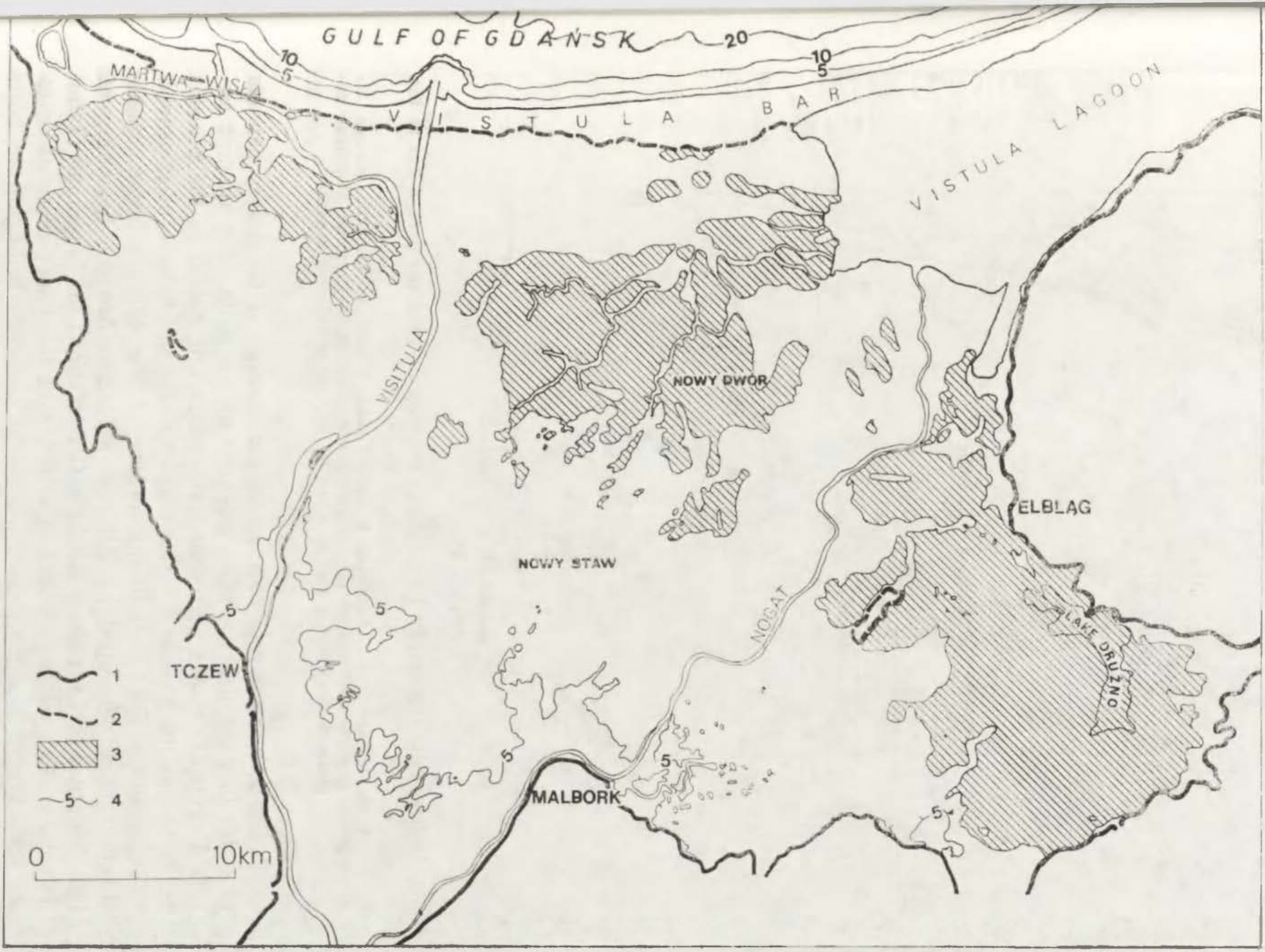


Fig. 52. Outline of the Vistula River Delta hypsometry
1—delta boundary, 2—boundaries of the Vistula spit and the Pleistocene "islands" occurring in the delta area, 3—area below 0 m, 4—5 m contour line (elevation above sea level)

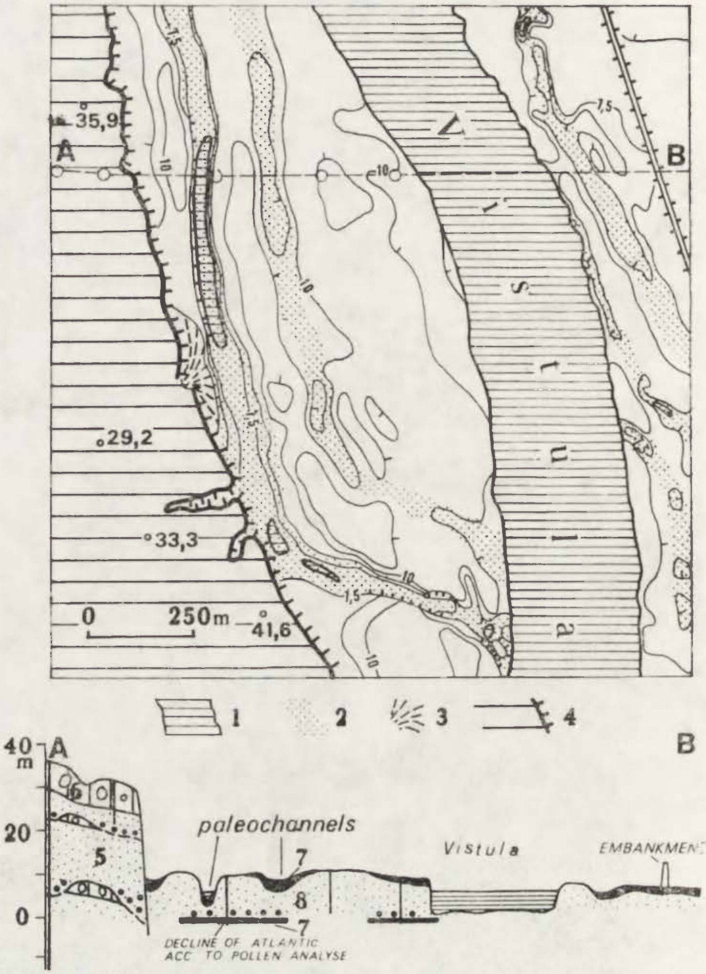


Fig. 53. The delta topography by taking as example its southern part, 5 km to the south of Tczew

1—Vistula channel, 2—morainic plateau, 3—alluvial fans, 4—edge of morainic plateau, 5—fluvioglacial deposits of Vistulian age, 6—till of Vistulian age, 7—Holocene biogenous deposits, 8—sand with gravel occurring in the base of Holocene deposits

It also is necessary to reconstruct the location of the palaeochannels in order to recognize the morphogenesis of the delta. The attempt enclosed (Fig. 55) shows palaeochannels which are visible in the present relief and in the stream courses, and channels which have been proved to occur within the sub-Holocene surface (cf. Fig. 47). The latter palaeochannels have developed in different periods—since the beginning of the Holocene, perhaps since the Late Glacial, until the beginning of the Atlantic period. At that time accumulation of the lower cover came to an end. There is a discrepancy between channels belonging to both generations.

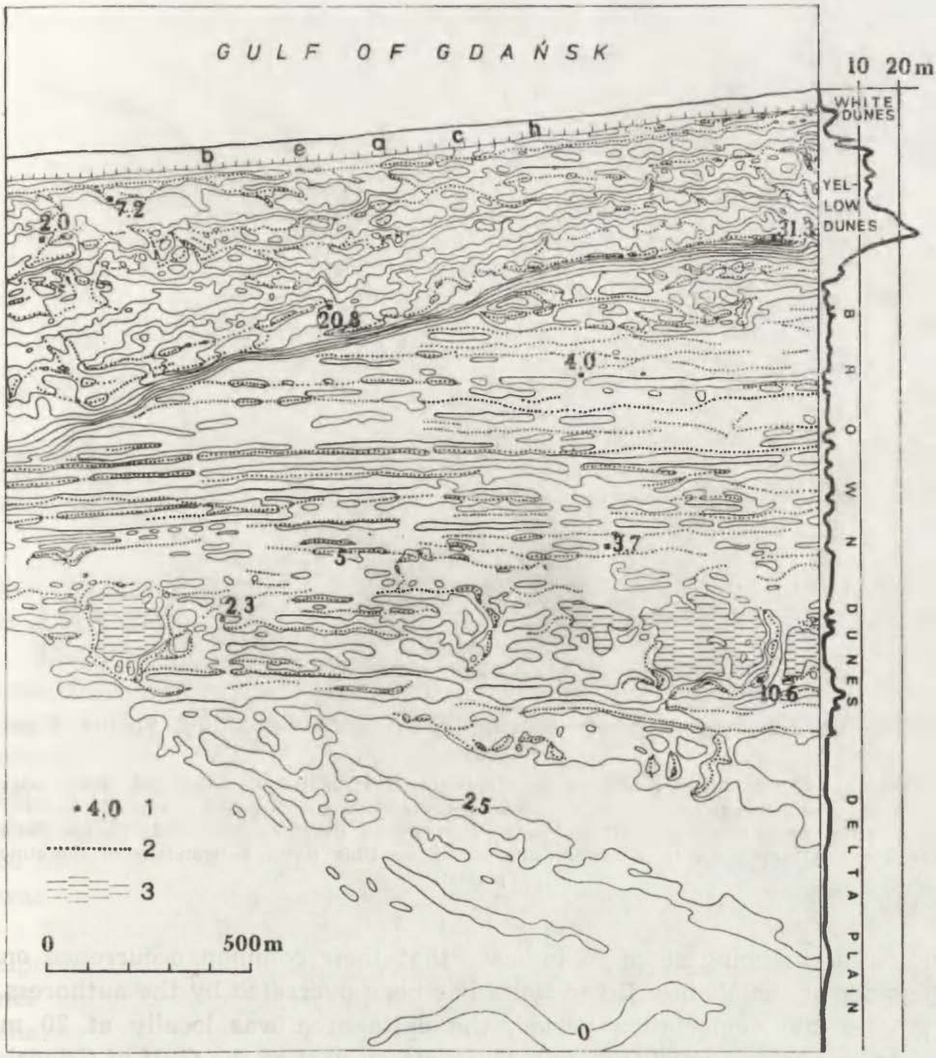


Fig. 54. An example of the Vistula Spit topography including aeolian features
1—metres above sea level, 2—selected dune ridges, 3—closed kettles

AN OUTLINE OF THE DELTA AREA EVOLUTION

As the Scandinavian inland ice wasted down by the end of the Pomeranian phase, a glaciogenic relief came into existence in the delta area. This relief was similar to that of the adjacent morainic plateau. Among the deposits then forming a certain role was played by the loamy-clayey sediments. These represent shallow depression fills and thaw moraines. The deposits discussed have been long recognized and examined in detail by Roszko (1969). However, results of the new detailed

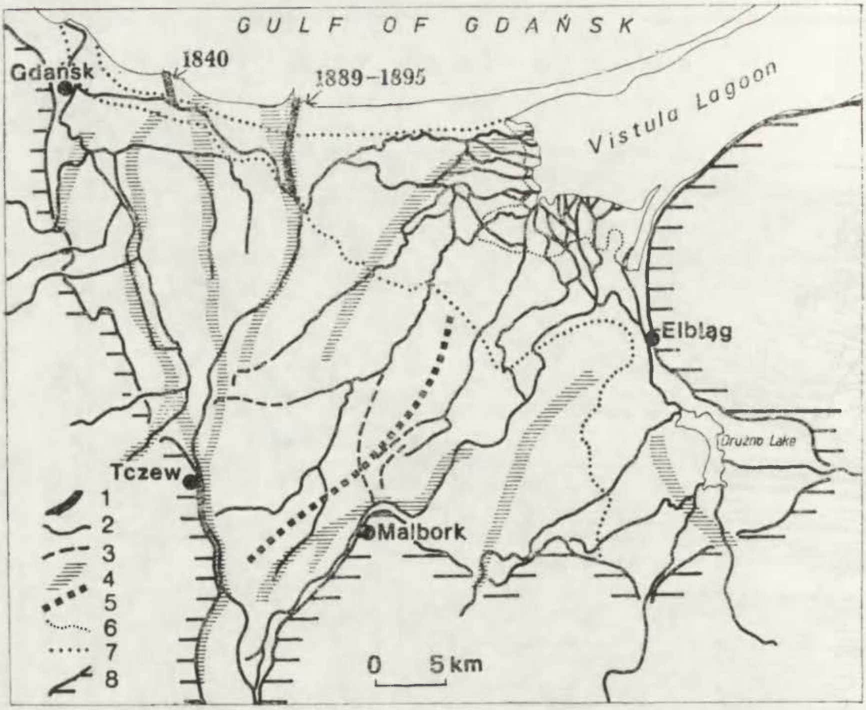


Fig. 55. Palaeohydrography and present-day hydrography of the Vistula River Delta

1—historical Vistula River mouths (years indicate their activity), 2—selected present-day channels, 3—present-day periodical channels, 4—palaeochannels, 5—palaeowatershed, 6—water body in the delta area until AD 1900, acc. to Majewski (1969), 7—water body in the delta area about AD 890, acc. to Wulfstan, interpreted by Uhle (1942), 8—boundary of morainic plateau

geological mapping seem to indicate that their common occurrence on the sides of the Vistula River Delta has been overrated by the authoress.

After the deglaciation period, the delta area was locally at 20 m below present sea level (Fig. 56). The western part of the Gulf of Gdańsk and most of the southern Baltic Sea displayed similar heights. Such a low position of the delta area must have been controlled by the pre-existing relief features. Evidence of it is provided by the transgression of the Eemian sea which reached far toward the south in the present lower Vistula Valley (Makowska 1979). Only the Gdańsk Deep was occupied by stagnant ice, and later on by dead ice. It is probable that in the latest part of the Late Glacial the Vistula drained the western part of the present delta to the east of Gdańsk. Hence, the river continued to the north-west to the head of the Hel Peninsula by a system of depressions being still recognizable on the floor of the Baltic Sea (Rosa 1967; *Mapa form...* 1979). The Vistula then flowed off a parallel running ice marginal channel ("pradolina") far to the west. In the

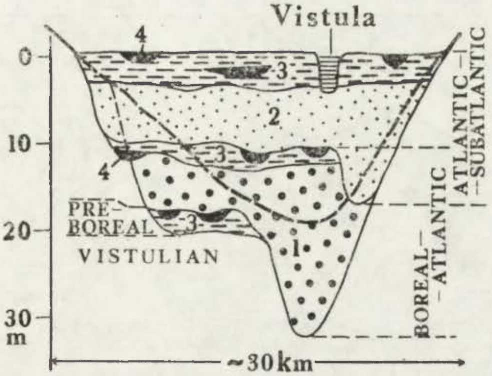


Fig. 56. Diagram showing the main trends of activity of the Vistula in the delta area during the Holocene

1—mainly channel deposits of the lower Holocene unit, 2—mainly channel deposits of the upper Holocene unit, 3—mainly palaeochannel non-biogenous deposits, 4—palaeochannel and lacustrine biogenous deposits of both lower and upper Holocene units; the broken line shows the primary glaciogenic surface by the end of the Vistulian Stage

Bornholm Basin it emptied out and built up a fan (Fig. 57). This fan is shown on both maps previously mentioned.

During the time which elapsed since the deglaciation of the delta area until the onset of the Holocene, *ie* in the Preboreal, deposits making up the lower part of the lower cover were laid down. The river which drained a young moraine landscape connected with each other depressions of differing genesis. The river also built up the thin sandy sheets forming the accumulational terrace. The Vistula channel was at 30 m below present sea level. In places the valley which varied in depth was clearly incised.

The further warming in the Boreal and subsequent increase in precipitation rates was associated with increasing stream discharges. Channel aggradation took place. The proportion of overbank and abandoned channel facies deposits also increased. The rise of the Baltic Sea level brought about gradient reduction and baselevel rise. This was favourable for the formation of biogenous deposits.

The sea gradually encroached upon the whole southern Baltic Sea. In the Gulf of Gdańsk the shoreline was farther westward and southward than today. The Vistula Valley became shortened and the river mouth found itself in the present place.

At this stage in the history the Vistula drained the western part of the delta. The river used various palaeochannels which have been recognized within the sub-Holocene surface (Figs. 47 and 55). This western part was confined by the palaeowatershed. The area to the east showed a little transformed glaciogenic relief which included young and rather deep valleys largely running towards the north. There also occurred thaw basins being occupied by lakes. The major one, *ie* Lake Drużno,

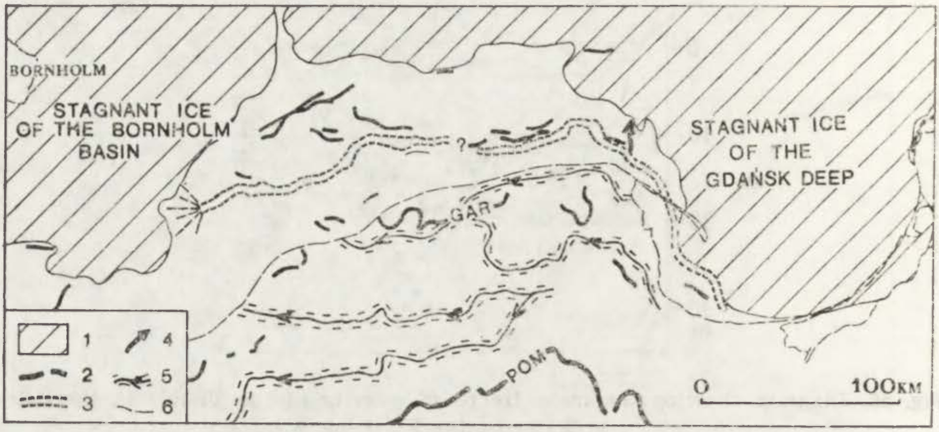


Fig. 57. Outline of relief during the earliest Late Glacial in the southern Baltic area
1—stagnant ice sheet, 2—main end moraines, POM—Pomeranian Phase, GAR—Gardno Phase, 3—main southern Baltic "pradolina", perhaps the Vistula Valley, with a fan in the western part, 4—later Vistula River mouth (postdating the decay of the ice sheet), 5—main older "pradoliny", 6—present-day shoreline

has been functioning since the Late Glacial (Zachowicz *et al* 1982).

The results obtained show that the formation of the Vistula Delta was contemporaneous with that of the widespread biogenous deposits belonging to the lower unit, *ie* 8 ka—6.3 ka years BP. It is likely that this process at first proceeded at a low rate. Later on it became violent and rapidly expanded, especially in the northern and western parts of the area discussed.

At the beginning of the greatest extent of the Baltic Sea transgression the further expansion of the flooded areas has caused the increasing dominance of the biogenous and biogenous-mineral accumulation. Conditions were most favourable at the height of the first transgression of the Littorina Sea, *ie* 6.3 ka—5.5 ka years BP (Fig. 51) until nearly the Atlantic decline time. This transgression reached as high as the present sea level. No marked changes took place afterwards. According to Rosa, the greatest extent of the marine transgression occurred in the upper Subboreal, 2.5 ka years BP.

Continued forest clearance in early historical times and growth of the Vistula Spit (which hindered the removal of flood sediments into the sea) led to increased "mada" deposition. The spit developed by the joining of several islands. These became built up by dunes belonging to three generations. As the shoreline retreated, this zone of islands generally migrated in a northerly direction. The last changes in the shoreline were repeatedly treated by Majewski (1969) and the present author (1982). The position of two earlier shorelines is shown in Figure 55.

Since 90 years the Vistula has carried its water and sediment load by an artificial channel known as the Przekop Wisly. Since 1914 only this channel has been used. At the channel outlet the river is building up a new fan. During the first 16 hours immediately following the opening of the artificial channel 2 milions cubic metres of deposits were laid down there (Łomniewski 1963). This caused accumulation to a depth of at least 10 m. Since that time the fan has increased in area including the subaerial part.

THE EVOLUTION OF THE VISTULA VALLEY

A review of both terrace systems and terrace-forming deposits found along the present Vistula Valley show that this valley embraces several significantly different sections of differing genesis and age. During the last 18—20 ka years valley evolution was related not only to changes in the hydrological regime and sediment transport, but also was controlled by deglaciation, baselevel lowering, and sudden changes in stream discharges in the lower river reach (Figs. 58 and 59). This is elucidated by a map showing the Proto-Vistula (Fig. 60) which once constituted the main river flowing along the ice edge into the North Sea. This river collected both meltwaters and waters of the rivers Nieman, Odra, and Elbe, together with many lesser streams. In the Pomeranian phase the Toruń—Eberswalde ice marginal channel ("pradolina") also carried the Neris (Viliya) River, a tributary of the Nieman. The evolution of the Vistula Valley will be discussed in two parts. The first includes the upper valley section extending upstream of the Warsaw Basin. The lower valley section extends downstream of the Warsaw Basin to the valley outlet.

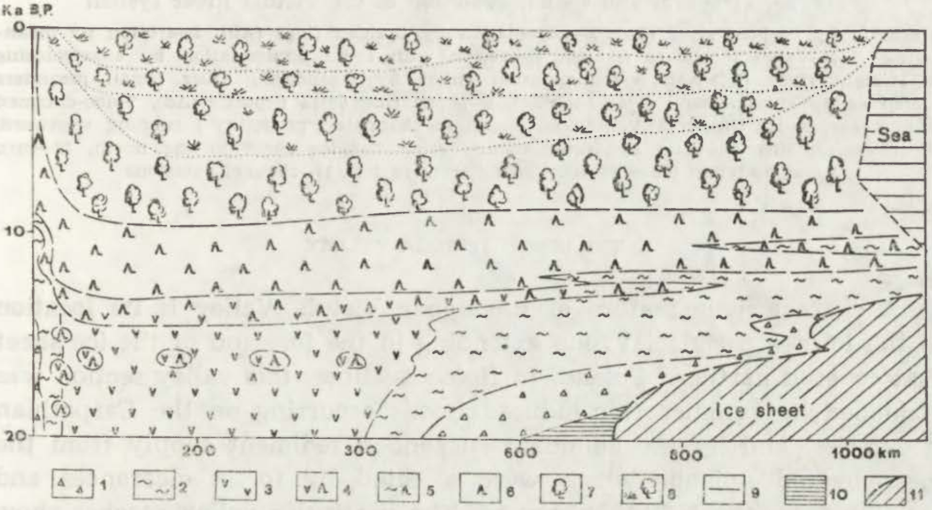


Fig. 58. Palaeogeographical transect along the Vistula River Valley

1—arctic desert, 2—tundra, 3—steppe, 4—forest steppe, 5—forest tundra, 6—boreal forest, 7—deciduous forest, 8—stages of deforestation, 9—sea, 10—ice-dammed lake, 11—ice sheet

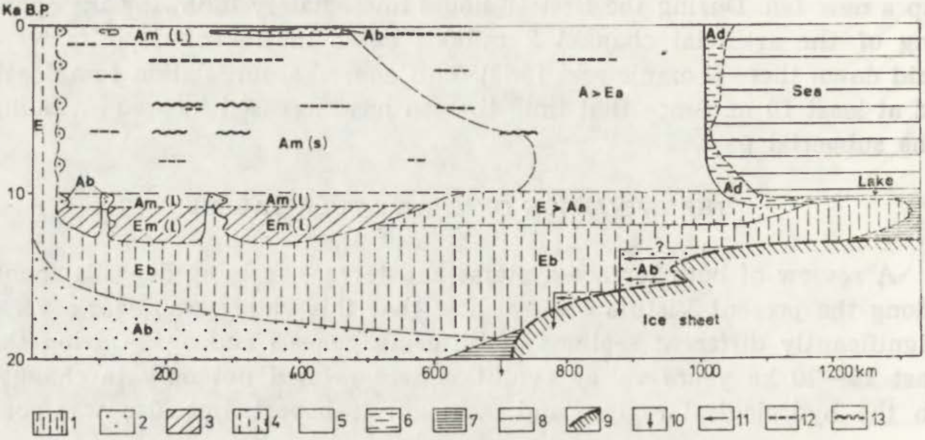


Fig. 59. Temporal and spatial evolution of the Vistula River system

1—erosion by braided river (Eb), 2—aggradation by braided river (Ab), 3—erosion by meandering river—large meanders (Em(l)), 4—erosion with some accumulation by anastomosing or straight river (E > Aa), 5—accumulation either by meandering river (small meanders Am(s)) or by anastomosing river (A > Ea), 6—perimarine delta deposits (Ad), 7—ice-dammed lake, 8—sea, 9—ice sheet, 10—Vistula ice marginal channels ("pradoliny") running westward, 11—outwash plains built up by water coming from the ice sheet to the north, 12—turn aggradation (superposition of different facies), 13—channel avulsions

THE UPPER VISTULA VALLEY

A characteristic feature of the upper Vistula Valley is its location in the former periglacial zone extending in the foreland of the ice sheet that covered northern Poland. In Holocene times this valley section was fashioned by summer rain-induced floods occurring on the Carpathian tributaries, and by the abundant suspended sediment supply from the loess-covered uplands which were affected by forest clearances and farming from the Neolithic onward. The particular valley reaches show striking differences in valley floor widths, in the occurrence of large tributaries, and in the intricate tectonic tendencies.

In the morphology of the upper Vistula Valley changes in the climatic regime are reflected. These caused erosion and aggradation. Superimposed on the climatic changes were baselevel changes associated with the disappearance of an ice-dammed lake which occupied the Warsaw Basin, and with the deglaciation of the Polish Lowland.

In the valleys of the rivers Vistula, Dunajec, Wisloka, and San—draining the eastern part of the Sandomierz Basin—Pleniglacial accumulation led to the formation of a system of sandy plains and alluvial fans lying 2—5 m above the Holocene plains. This level is best developed in the uppermost reach, where the loess-capped 10 m terrace consisting of Interpleniglacial alluvia (cf. Fig. 40) lies immediately above the Late Glacial and Holocene plains. The disappearance of an ice-dammed lake in the Warsaw Basin caused increased dowcutting, evidence of which

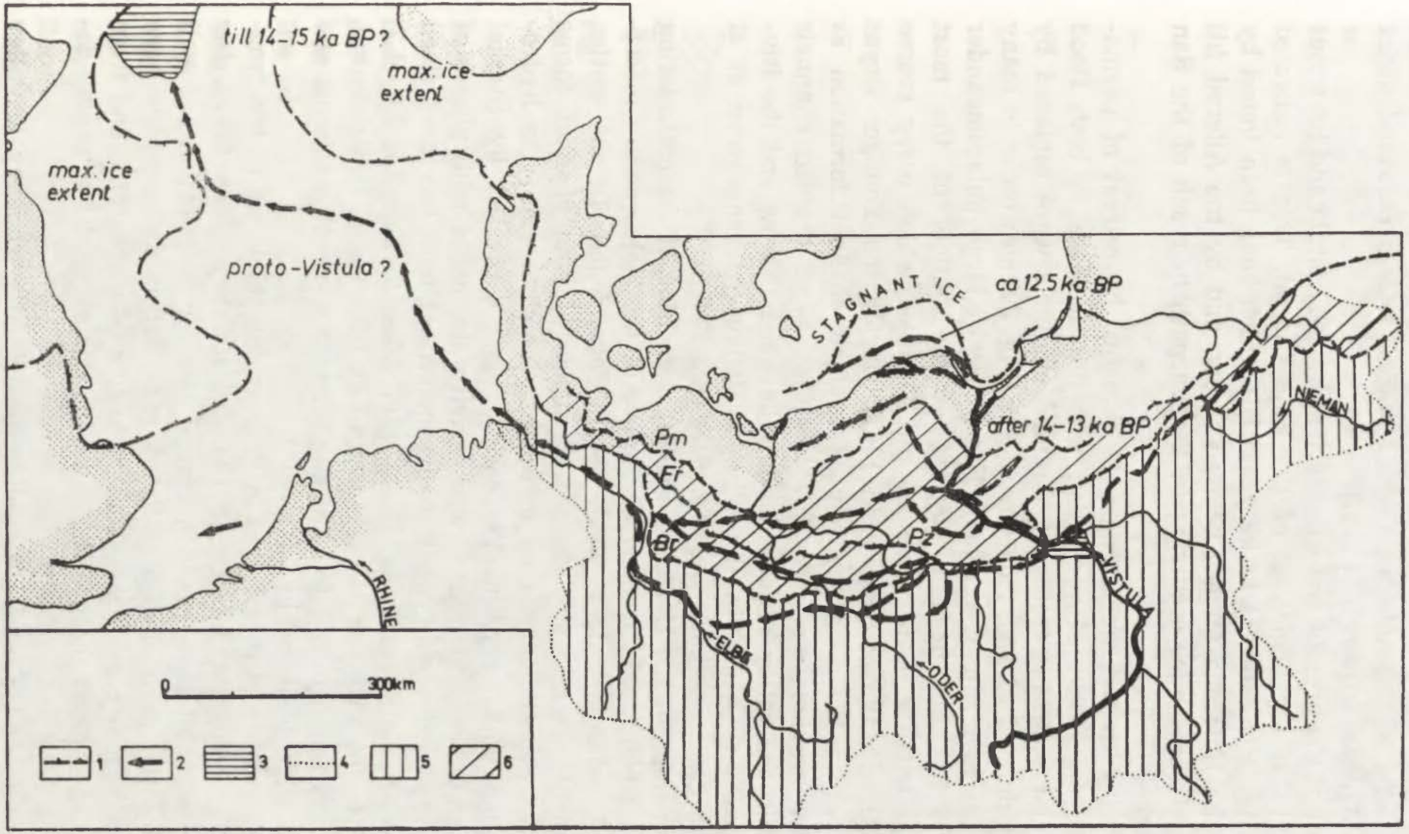


Fig. 60. Changes in river courses and catchment basin of the Proto-Vistula (L. Starkel)

1—extent of the last Scandinavian ice sheet in various phases, 2—meltwater drainage and the Proto-Vistula in various phase of the ice retreat, 3—proglacial lake in the Warsaw Basin, 4—watershed of the Proto-Vistula drainage basin (20—14 ka BP), 5—catchment of the Proto-Vistula in the Leszno (Brandenburg) Phase, 6-additional cartch ment of the Proto-Vistula in the Pomeranian Phase is provided by a distinct staircase of terrace remnants which dominate the Vistula gap in the Polish uplands (Pożaryski 1955). A braided channel pattern is traceable on these terrace surfaces (Alexandrowicz *et al* 1981; Mycielska-Dowgiałło 1987).

The level of the present bed was reached by the Vistula and its tributaries already at the beginning of the Late Glacial. This is indicated by organic deposits dated at 13 ka years BP which have been found by Nalepa on the Holocene terrace below Cracow, and by the Allerød fill of a deep palaeomeander occurring in the Carpathian reach of the San Valley (Starkel 1960).

Associated with the amelioration of climate, the retreat of permafrost, and the invasion of vegetation was the decrease in both flood frequency and sediment transport. Braided channels were replaced by meandering channels. Large palaeomeanders (Fig. 59) also occur in many tributary valleys (Szumański 1983). The phase of large palaeomeander development has not been recognized at the outlets of the most mountainous tributaries, *ie* the Soła and Dunajec which carry coarse sediment (Klimek 1987b; Sokołowski 1987). During the Younger Dryas there reappeared the tendency toward braided channel formation as predicted by previous work (Falkowski 1975). Such braided channels were dated in the valley reach extending between Cracow and the River Raba mouth (Fig. 50), in the Wisłoka Valley (Alexandrowicz *et al* 1981), and at Całowań above Warsaw (Sarnacka 1987).

At the opening of the Holocene a slight deepening of the meandering channels took place. A characteristic feature of the Holocene are inserted fills and palaeomeanders which became abandoned. In the wetter phases channels became straightened. Analysis of both channel forms and facies of deposits allows us to reconstruct changes in the hydrological regime which confirm the earlier view expressed by Starkel (1983a) that phases of increased river activity alternated with phases of decreased river activity (cf. next chapters). Phases with increased flood frequency were dated to 8.5—7.7, 6.5—6.0, 5.0—4.5, 2.8—2.5, 2.0—1.7, *c* 1.0, and 0.4—0.1 ka years BP. Prior to 3.0 ka BP channel straightening, widening, and downcutting took place, whereas channel widening and aggradation were dominant in later times.

These phases are also reflected in the varying thickness of the "mada". On the contrary, phases of channel stability were favourable for organic accumulation (Fig. 61). Phases of river reactivation are well indicated by the chronologically listed radiocarbon dates which have been obtained from black oaks, from basic fills of the cutoffs, and from the top series of peats the growth of which was stopped by "mada" deposition (Fig. 42).

The tectonic factor tends to modify the climatic tendency to valley development. In the headwaters of the Carpathian rivers and in the antecedent gaps as well the sequence of cut and fill shows itself in the slow incision into the solid bedrock (Froehlich *et al* 1972; Starkel *et al* 1982). In the Subcarpathian basins subsidence shows itself in a tendency toward aggradation and many channel avulsions (Niedziałkowska *et al* 1985; Gębica, Starkel 1987).

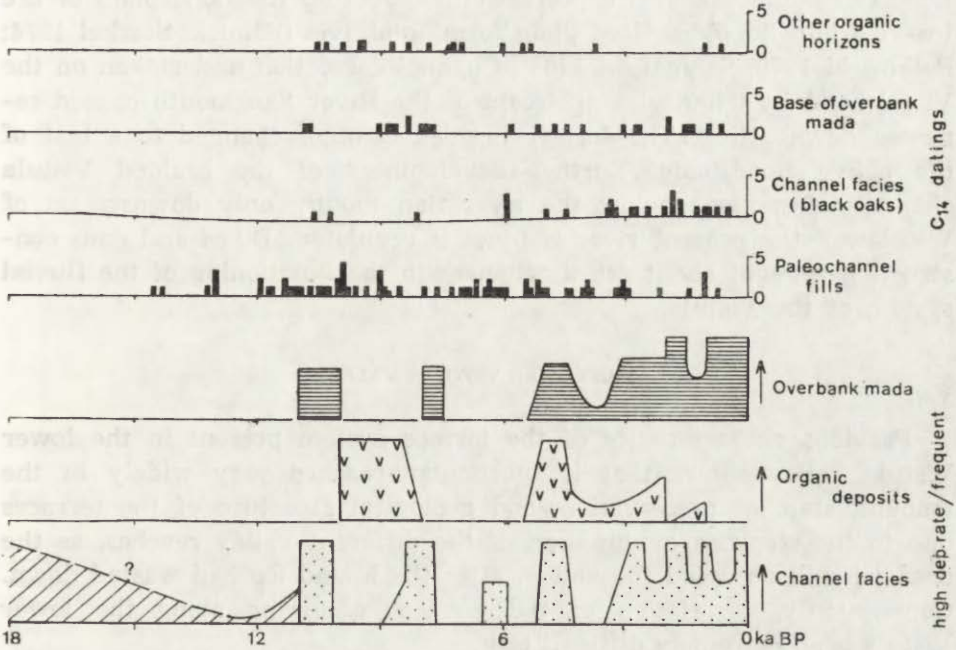


Fig. 61. Phases of increased deposition of various facies within the Vistula River Basin and radiocarbon datings on alluvial sediments supporting them (L. Starkel)

During the Neoholocene superimposed on the natural evolution of both river channels and flood-plains is the anthropogenic factor. Its early influence is visible in the accumulation of loessic deluvia at the foot of a loess-capped terrace edge already 5900 years BP, and of "mada" in the Vistula gap in the Polish uplands (Falkowski 1975). Slopewash also took place within the valleys of the loess-covered uplands at the beginning of the Subboreal period (Śnieszko 1985, 1987).

In the surroundings of Oświęcim (Klimek 1987b), and in the Ropa Valley (Dauksza *et al* 1982) "mada" was deposited by the end of the Bronze Age. Both aggradation and extensive clearance of flood-plain woodlands took place during the late Roman period, 2000—1700 years BP (Tomczak 1987; Kalicki, Starkel 1987). These were associated with increase in bed elevation. The phases of both aggradation and frequent flood occurrence, being related to man's activity, recurred from the 10th—11th centuries onward in the Oświęcim Basin (Niedziałkowska *et al* 1985) and in the Wisłoka Valley (Alexandrowicz *et al* 1981). In the

Vistula catchment deforestation in medieval times has encouraged the reactivation of soil erosion (*eg* Kosmowska-Suffczyńska 1983; Starkel 1987a). Overpopulation and potato cultivation in the upper Vistula drainage basin, together with the deterioration in climate during the Little Ice Age, have had dramatic consequences, with braided channel formation. The sediments then deposited either overtop the flood-plain or are inserted into the older flood-plain forming alluvia (Klimek, Starkel 1974; Falkowski 1975; Szumański 1983). Channel correction undertaken on the Vistula and its tributaries upstream of the River San mouth caused renewed downcutting. The former braided channel changed to a leaf of the active flood-plain. Further development of the braided Vistula channel takes place below the river San mouth, only downstream of Włocławek the present river channel is regulated. Dikes and dam construction brought about drastic changes in the functioning of the fluvial system of the Vistula.

THE LOWER VISTULA VALLEY

Previous characteristics of the terrace system present in the lower Vistula valley shows that its particular reaches vary widely in the amount, state of preservation, and geological structure of the terraces due to the stepwise exhumation of the different valley reaches, as the dead ice still occupied the valley, after the inland ice had wasted down. Consequently, correlation of the terraces occurring along the lower Vistula is an extremely difficult task.

Earlier work by Wiśniewski (1976b) confirms the similarity of the present course of the Vistula to that before the Last Glacial between the line of the greatest extent of the Vistulian Glaciation and the Toruń Basin. Only north of this basin the present Vistula does not follow the Eemian valley. Niewiarowski (1984) argued that the buried valley is situated to the east of the present valley. The former river discharged into a bay of the Eemian sea, south of Grudziądz.

The inland ice blocked the existing drainage outlet. In the Vistula Valley there took place intensive accumulation of deposits of the gravel- and sand-sized fractions being overlain by clay or silt. Those deposits are evident in the Vistula Valley and below till on the adjacent morainic plateaus extending between the Płock Basin and the Toruń Basin. Both genesis and age of the clay were discussed by many authors (Wiśniewski 1976b). In the area examined ice-dammed lake deposits occur at different heights. It appears that the floor of the ice-dammed lake basin then existing was irregular so that the advancing ice did not cause the complete infill of the valley. This concave landform favoured the survival of dead ice there under a covering of glacial and fluvioglacial sediments.

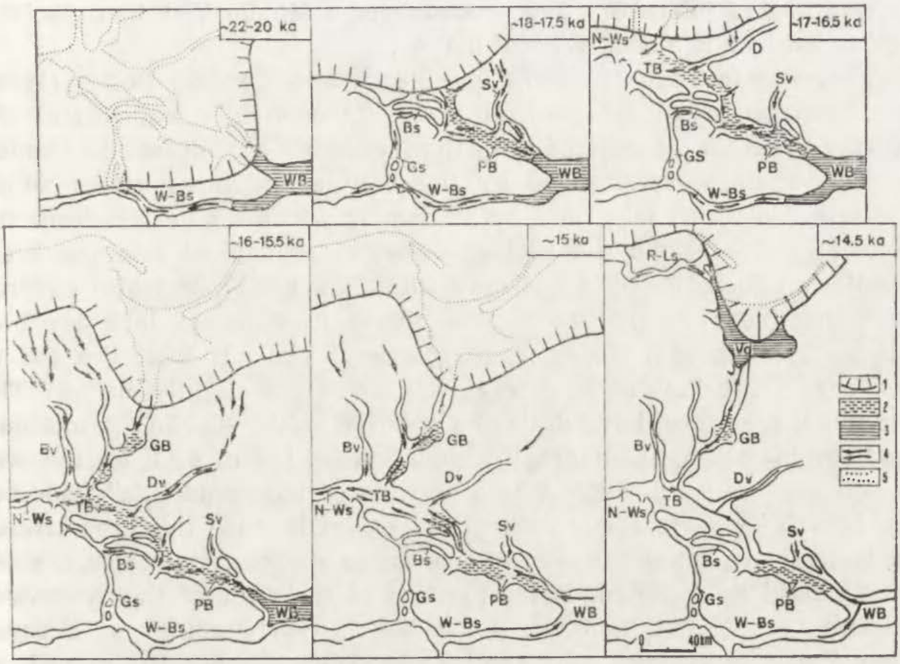


Fig. 62. Various stages of river pattern changes which took place during the deglaciation of the lower Vistula Valley (E. Wiśniewski)

1—ice-margin, 2—dead ice occurring in the Vistula Valley, 3—ice-dammed lakes, 4—drainage directions, 5—present-day contours of the Vistula Valley and the Baltic Sea; WB—Warsaw Basin, W-Bs—Warsaw-Berlin ice marginal channel ("pradolina"), PB—Płock Basin, SV—Skrwa Valley, Bs—Bachorza Valley, Gs—Gopło "pradolina", TB—Toruń Basin, Dv—Drwęca Valley, N-Ws—Noteć-Warta "pradolina", Bv—Brda Valley, GB—Grudziądz Basin, Vd—Vistula Delta, R-Łs—Reda-Łeba "pradolina"

At times of the greatest extent of the last ice-sheet, which reached as far south as the eastern part of the Płock Basin, a lake must have been impounded by ice blocking the existing Vistula Valley. The ice-dammed lake extended into the Warsaw Basin (Fig. 62A). According to Różycki (1967), a glacially impounded lake existed there already during the Wkra stage of the Middle Polish Glaciation. Confirmation of the presence of an ice-dammed lake in the Warsaw Basin also during the Vistulian Glaciation comes from Eemian deposits underlying the clays. However, Baraniecka and Konecka-Betley (1987) relying on TL datings ascribed a Middle Vistulian age to the top series of clays which rest on the Eemian deposits. It thus appears that the Warsaw Basin was twice occupied by ice-dammed lakes. The first lake is believed to have been impounded there by the Middle Vistulian ice. Its extent is not known. The second lake was formed around 22—20 ka years BP. According to Baraniecka and Konecka-Betley, the Middle Vistulian glacially impounded lake has functioned over an extended period, until the Hengelo and Denekamp interstadials. However, at that time even Scandinavia was free of inland ice. The existence of a Middle Vistulian glacially impounded lake is a controversial matter.

According to Różycki (1967), Baraniecka and Konecka-Betley (1987), the formation of an ice-dammed lake in the Vistula Valley and the Warsaw Basin was associated with the increasing accumulation of sandy deposits. These were supplied by the Vistula and other rivers which discharged into this lake, and by meltwater which discharged from the Nieman catchment *via* the Biebrza—Narew "pradolina" into the Warsaw Basin. Those deposits not only filled the valley, but also covered the lower parts of the Radzymin—Błonie ice-dammed lake level of Middle Vistulian age. However, the clayey Radzymin level lies 103 m a.s.l. near Otwock. The lake level was no doubt slightly higher. The lake must, therefore, have drained *via* the Warsaw—Berlin "pradolina", the floor of which has a present elevation of 102 m a.s.l. on the watershed near Łęczyca. Such a high position of the "pradolina" floor before 22—20 ka years BP is difficult to accept because this area crosses the tectonically active Kuyavy—Pomeranian Anticlinorium. Thus, some uplift should be accepted. If the position of the floor of the Warsaw—Berlin "pradolina" then was lower in the surroundings of Łęczyca it is difficult to explain why the lake level stood above 103 m a.s.l.

The last ice sheet at its maximum position covered the whole Płock Basin having a fluvial relief. The latter was probably blurred by sedimentation of sandy deposits due to a shortening of the Vistula during the ice advance. The ice halt in the Płock Basin showed itself in the creation of a small outwash plain in the eastern part of the basin which lies 2—3 m above the Ciechomice level, at 90—92 m a.s.l. (Fig. 39). This outwash plain, with a steep proximal side, was formed on the ice snout, with a gentle dip. The melting out of ice caused a strong modification of the sandur surface and the disturbance of the original stratification of the plain-forming fluvioglacial deposits.

Stagnant ice occupying the Płock Basin was associated with the intensive activity of both subglacial and subaerial meltwaters. These built up numerous channels, eskers, and kames (Skompski 1963) which indicate the existence of many ice tunnels and caves there.

The Płock Basin has long been regarded (Domosławska-Baraniecka, Mojski 1960; Mojski 1960) as having been occupied by dead ice which was mantled either with ablation material or with fluvioglacial deposits over an extended period. The morainic plateau rises 110—115 m a.s.l. adjacent to the eastern part of the Płock Basin. Thus, the surface of the mantled dead ice may have reached as high as that of the morainic plateau. This retarded the opening of an outlet which led from the ice-dammed lake in the valley through the Płock Basin.

In the Kuyavy subphase meltwaters discharged *via* the Skrwa outwash plain into this basin (Kotarbiński, Urbaniak-Biernacka 1975) east and west of Płock (Fig. 62B). East of Płock meltwaters discharged into the Warsaw ice-dammed lake formed between the edge of the dead ice which occupied the Płock Basin and that of the morainic plateau. Evidence of it is provided by a sandur leaf at 95—98 m a.s.l., 10 km long and up to 1.5 km wide, which extended as far as the ice margin. Today this leaf is evident up to 5—6 m above the Ciechomice level, showing many eskers and kames.

The position of the sandur leaf suggests that in this phase of ice withdrawal the ice-dammed lake stood below the fill of the Warsaw Basin—up to 103 m a.s.l.

In the Kuyavian subphase the Vistula Valley reach connecting the Płock Basin with the Toruń Basin was already uncovered from beneath the ice. On the left valley side, at the dead ice/Kuyavy plateau contact, there functioned a short-lived meltwater channel. It trended southward at 88—89 m a.s.l. and 80—84 m a.s.l. In the surroundings of Brześć Kujawski meltwater escaped westward as a result of blockage of the escape route by a high dead ice surface. Thus, the Bachorza Valley came into existence.

The Bachorza Valley, 42 km long, joins the so-called Gopło Valley in the surroundings of Kruszwica. The further escape route of meltwaters either southward *via* the Gopło Valley into the Warsaw—Berlin "pradolina" or northward *via* the Noteć Valley into the forming Noteć—Warta "pradolina" is most difficult to recognize. The second outlet did not come into operation until after the ice withdrew from the moraines of the Kuyavian subphase to the north of the Noteć—Warta "pradolina". The original gradient of the escape routes became disturbed probably by crustal movement due to uplift of the Kuyavy—Pomeranian Anticlinorium, to glacial rebound (Wiśniewski 1974), and to halokinetics (Niewiarowski 1983). In the surroundings of Brześć Kujawski meltwater activity resulted in the formation of levels hanging at 80 m and 77 m a.s.l. above the Vistula Valley floor.

Studies made in the surroundings of Brześć Kujawski also show that at the levels of previously mentioned meltwaters, which discharged *via* the Bachorza Valley, came both from the north and from the Płock Basin to the south-east. Meltwaters were supplied probably by melting dead ice and by the Skrwa outwash plain, a branch of which reached the Płock Basin, north-west of Płock. It is likely that in the Kuyavian subphase the Warsaw ice-dammed lake was drained through subglacial and subaerial tunnels in the dead ice to the western part of the Płock Basin. The surface of the dead ice here lay lower than that in the eastern part of the basin. The morainic plateaus in the west lie 90—92 m a.s.l., whereas those in the surroundings of Płock and Gąbin rise 110—115 m a.s.l. These meltwaters also may have discharged *via* the Bachorza Valley.

The short-lived southward drainage along the margin of the Vistula Valley in the Kuyavian subphase came to an end, as the inland ice retreated northward. It is possible that some meltwater once again discharged southward *via* the Drwęca Valley to the east into the Toruń Basin in the Krajno subphase (Fig. 62C). Niewiarowski postulated that meltwaters continued southward, *ie* toward Brześć Kujawski, while dead ice existed in the Vistula Valley. Drainage of the Płock Basin (where the dead ice became reduced in area) *via* the Bachorza Valley was still going on. The ice-free areas were immediately flooded by an ice-dammed lake. Thus, the 80—82 m a.s.l. level in the Płock Basin might have been formed. This level consists of fine sand and silt in which an esker is buried. The edge of this level to the west is an ice-contact feature.

Waters were forced to spill over into the Toruń Basin by the disappearance of dead ice in the Vistula Valley and by normal catchment drainage. Between the Płock and Toruń basins this event took place at 70—72 m a.s.l. (Fig. 62E) at the beginning of ice retreat from moraines of the Pomeranian phase, evidence of which is provided by the occurrence of terrace remnants on both banks of the Vistula in this gap section. In the Toruń Basin the erosional terrace is extensively developed and dune-covered.

Between the Warsaw Basin and the Płock Basin, the highest Vistula terrace lies 72 m a.s.l. near the River Bzura mouth and 63—64 m a.s.l. in the surroundings of Płock. Thus, between the Płock Basin and the Toruń Basin, the terrace at 70—72 m a.s.l. formed prior to the terrace mentioned above. This relationship is traceable along the terrace long profile (Fig. 40). However, the introduction of water which arrived from the Warsaw Basin allowed the separate Płock and Toruń basins to connect one with another. The ice-dammed lake drained *via* the narrow valley section in the eastern part of the Płock Basin. In this phase of drainage of the glacially impounded lake conditions were unfavourable for fluvial terrace formation above Płock.

Previous work has suggested water escaped at 78—80 m a.s.l. and 75—77 m a.s.l. from the Toruń Basin westward to the Noteć—Warta "pradolina" in the Pomeranian phase (Fig. 62D). It is believed that at these levels water also came from the Vistula to the south. However, such high terraces have not been found upstream of the Toruń Basin. On the contrary, the southward escape of meltwater has been documented.

According to Galon (1934, 1961), bifurcation of riverine waters took place at the IX level, *ie* the terrace at 70—72 m a.s.l. Some water escaped westward, while some water already escaped northward to the Baltic Glacial Lake. As the Vistula dissected the terrace at 55 m a.s.l. (Galon's VI terrace) near Fordon in the Toruń Basin, the river finally diverted to the north. The above concept is based entirely on the occurrence of small level remnants (the highest lies 60—61 m a.s.l.) in the Grudziądz Basin, situated 60 km to the north. Bifurcation of waters in the Toruń Basin is open to doubt because all higher terraces, together with the terrace at 55 m a.s.l. found near Fordon which constitutes the floor of the Noteć—Warta "pradolina", are traceable in a westerly direction. It is, thus, probable that the Vistula divertion to the north took place only at this level (Fig. 62F).

The narrow 3 km valley section at Fordon may indicate that river divertion was favoured by the presence of earlier depressions there. Most probably these were glacial channels. The Grudziądz Basin also follows such depressions.

Subsequently, the Vistula first escaped westward *via* the Noteć—Warta "pradolina" and then northward. This change in the river course below Fordon caused increased downcutting. The best example is the valley reach previously covered by the Vistulian ice sheet. The exhumation of the former valley between the Płock and Toruń basins was facilitated by incision into the rapidly decaying dead ice which occupied the valley. The stages of incision are reflected in the formation of seven erosional terrace steps and of the flood-plain. As already has been mentioned, the highest terrace here lies 60—72 m a.s.l. (Fig. 40). In the valley reach of the former periglacial zone, *ie* between the Warsaw and Płock basins only two terraces are evident above the flood-plain: the terrace at 72 m a.s.l., near the River Bzura mouth, which decreases to 63—64 m a.s.l., near Płock, and the supra-flood terrace which slopes from 69 m a.s.l. to 60 m a.s.l. between Wyszogród and Płock. The higher terrace passes into the Otwock terrace, and the supra-flood terrace continues on into the Falenica and Praga terrace in the Warsaw Basin.

After the Warsaw ice-dammed lake had disappeared and river erosion reactivated, the formation of the terrace at 63—72 m a.s.l. took place. Hence, the three or four highest terraces (at 70—72, 67—69, 62—63, and 57—59 m a.s.l.) occurring between the Płock and Toruń basins may have formed during the drainage of the ice-dammed lake.

Downstream of Płock the multiplication of the terraces may have been caused by intensive downcutting upvalley due to baselevel changes supported by glacial rebound. Although clear evidence of the latter is absent from the Vistula Valley, it cannot be denied. Data from the Dvina and Nieman valleys (Mieshcheriakov 1961; Voznyachuk, Valchik 1978) do show evidence of glacial rebound which caused terrace deformation. In the lower Vistula Valley its occurrence may be suggested by the lack of inclination of the terrace at 70—72 m a.s.l. occurring downstream of the Płock Basin. The lower terraces are preserved mostly as short leafs. Therefore, a most difficult problem lies in attempting to correlate terrace fragments along the river and to identify eventual disturbances of the terrace gradients due to glacial rebound.

Datings on organic fills of both cutoffs and thaw basins occurring on the lower terraces allow us to state that the Vistula reached the level of the present flood-plain between the Warsaw and Płock basins as early as around 14.5 ka years BP. Such a low position of the Vistula channel in the deglaciation period cannot be explained without the influence of glacial rebound. As the Vistula gap was formed near Fordon, the baselevel was probably very low in the present Baltic depression. Rapid uplift in response to glacial rebound may have increased downcutting upvalley. By 1934 Galon already argued that the Vistula Valley outlet was raised by 70 m. Further investigation is required to support the theory of the influence of glacio-isostasy on terrace formation.

Datings on organic sediments taken from the supra-flood plain in the surroundings of Wyszogród and Płock (E. Florek *et al* 1987; Manikowska 1982) gave an age of 14.5 ka years BP. This shows that the Vistula reached the level of the present flood-plain already before the Late Glacial. Thus, there is no evidence for the presence of three inserted terrace sheets in the Warsaw Basin being related to the Leszno, Poznań, and Pomeranian phases (Różycki 1967), and for the correlation of formation of the Falenice and Praga terrace with phases of both erosion and accumulation (Baraniecka, Konecka-Betley 1987). However, the authors mentioned above rightly observed that the increasing accumulation of sandy deposits in the Warsaw Basin was caused by the Vistulian ice blocking the existing Vistula Valley. The present author is of the opinion that in those sediments there were eroded probably the terraces which lie above the flood-plain in the Warsaw Basin. It is likely that in this basin accumulation continued throughout the period of existence of the ice-dammed lake.

As the Vistula reached the level of the present flood-plain between the Warsaw and Płock basins, further downcutting came to an end. The Vistula frequently flows across till or Tertiary rocks there. Downstream of the Płock Basin alluvia are mostly about 15 m thick. In places, *eg* in the surroundings of Ciechocinek, Toruń, Unisław, and Grudziądz (Drozdowski 1982; Wiśniewski 1982; Niewiarowski 1987b; Tomczak 1987) alluvia have a thickness of 20 m or more. During the Late Glacial, and from the Late Glacial decline time onwards throughout the Holocene river activity in the gap section below Fordon showed itself in both lateral channel migrations and alluvia reworking.

Periods of the upward growth of the flood-plain by deposition of sediment that have been noted during the Holocene can hardly be related to changes in the Baltic Sea level (Tomczak 1987). For example, the Littorina transgression could not influence the river activity upstream since the long profile of the valley was already well developed. Thus, Holocene changes in the morphology of the Vistula Valley were caused by fluctuations of the hydrological regime.

Below the confluence with the Tążyna, 15 km to the south-east of Toruń, channel correction was undertaken on the Vistula in the 19th century. The Vistula channel is also regulated downstream of the Włocławek reservoir. However, engineering works have not been finished there.

In the surroundings of Włocławek a dam was constructed on the Vistula in 1963—1970. As a consequence of water level rise by 10.7 m, a remarkable reach of the valley floor became inundated. Below the dam bed scour occurs (Babiński 1982).

RECONSTRUCTION OF BOTH PALAEOHYDROLOGICAL ELEMENTS AND PALAEOCLIMATE BASED ON ENVIRONMENTAL FEATURES

CHANNEL PATTERN CHANGES AND ATTEMPT TO RECONSTRUCT THE HYDROLOGICAL CHANGES

Changes in the fluvial activity of the Vistula and its tributaries which occurred in the last 15,000 years are manifested through the morphology of the present valley floors. Detailed analysis was made of selected valley reaches of the Vistula and its tributaries that approach in character the present lowland rivers. The segments examined include the entire Vistula Valley downstream of Oświęcim, the lower Vistula Valley, the lower San Valley and the middle Pilica Valley near Przedbórz. Results of research which was completed on the valleys of the rivers Wieprz, Bug, Narew, and Pisa were also employed.

Periglacial conditions prevailing in the upper Vistula catchment during the Upper Vistulian favoured the formation of a sand and gravel sheet by the braided rivers within the valley floors. Braided river patterns are traceable only on some of the youngest Pleniglacial terrace remnants. They are mostly masked by Late Glacial aeolian deposits there. The present relief of the valley floors and composition of the alluvial fills show similarities which were conditioned by the basin-wide sequence of climatic and hydrological changes. Contrasts are due to different deglaciation periods, to different distances to the sinking base-level of the particular valley reaches, to the influence of both tectonical and orographical conditions (valley width and depth), to shallowly occurring resistant deposits underlying the alluvia, to variable tectonical movements, to different sediment supply by the tributaries, to different periods of both deforestation and man-induced channel changes, and to the regime of both runoff and sediment transport. A rather complete sequence of Late Glacial and Holocene events was documented in the valley of the lower San which easily reworked its alluvia. The San Valley floor, up to 8 km wide, contains more than 20 m of alluvia. It is mostly bordered by the middle terrace plain of Pleniglacial age.

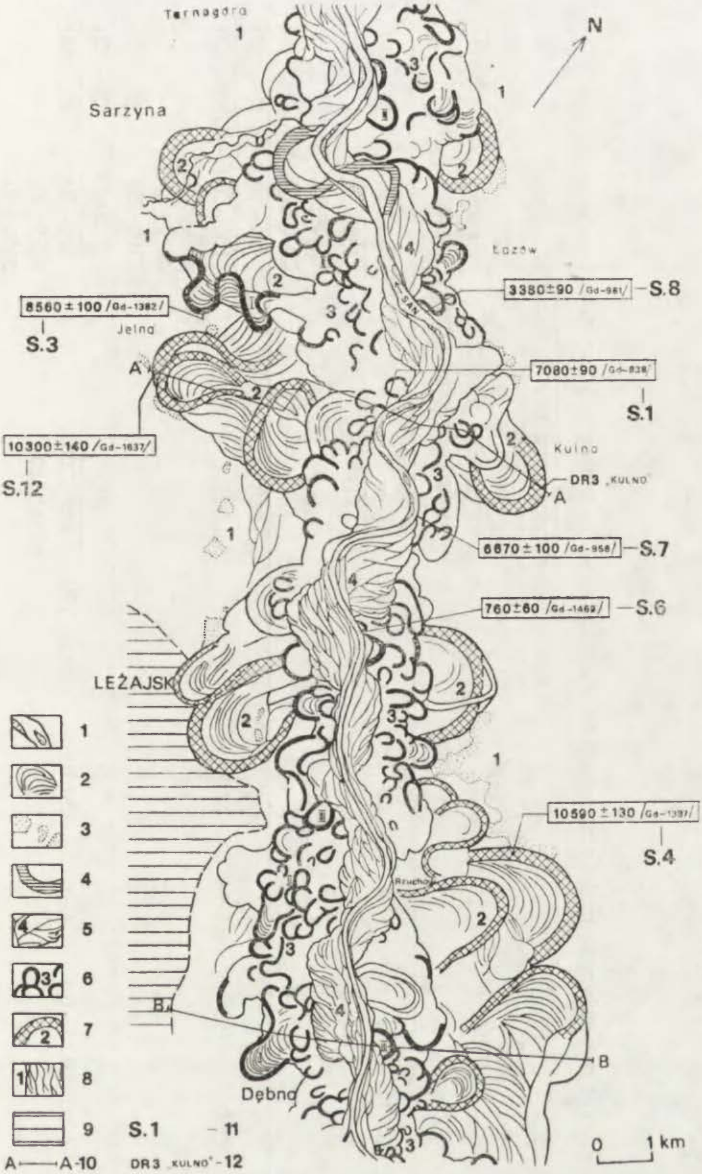


Fig. 63. Photo interpretation sketch showing the San Valley floor between Dębno and Tarnogóra — based on air photos taken during 1962 on the scale of 1 : 12,000 and during 1965 on the scale of 1 : 12,000 (by Szumański)

1—sandy channel bars, 2—traces of point bars, 3—aeolian sand, dunes, 4—meanders of the San near Sarzyna, cut across by a canal in 1903, 5—terrace 4, with traces of a present-day braided channel pattern, 6—terrace 3, with traces of small palaeomeanders (Holocene), 7—terrace 2, with traces of large palaeomeanders (Late Vistulian), 8—terrace 1 (middle), with traces of a braided channel pattern (Vistulian), 9—interfluve, 10—geological section, 11—sample number and radiocarbon date, 12—pollen dating; I, II, III-generations of small palaeomeanders on terrace 3

Table 6. Parameters of palaeochannels in different reaches of the Vistula and its tributaries (after various authors)

River valley reach	Catchment area [km²]	River gradient [‰]	Alluvial plain width [km]	19th century and present-day channel	Palaeochannel parameters *W*/*R* [m] and ¹⁴C datings				Medium-sized meanders (historical)
					braided/ straight (Late Glacial)	large meanders (Late Glacial)	medium meanders (Eoholocene)	small meanders (Holocene)	
Vistula – Oświęcim (II-1)	5000	0.4	3–4	M–B/R		$\frac{-}{640}$		$\frac{-}{130-300}$ 7210±150 2940±70	
Vistula – Cracow Gate (II-2)	7500	0.4	0.4–4	M/R		$\frac{170}{490}$		$\frac{50-100}{100-300}$ 6700±130 4410±180 2100±80	$\frac{120-200}{300-420}$ (till 18th c.)
Vistula – Nowa Huta (II-3)	8500	0.25–0.3	4–6	M/R	11920±170	$\frac{100}{600-700}$ 9660±110		$\frac{50}{200-300}$ 6255±40 5190±70	$\frac{70-120}{400-500}$
Vistula – Grobla Forest (II-4)	8800	0.1–0.4	6–8	M/R	9840±140	$\frac{135}{740}$ 8760±90		$\frac{30-65}{120-240}$ 5420±110 5090±110	$\frac{45-80}{175-390}$

Vistula – dowstream of Dunajec mouth (11-6)	24000	0.28	2.5 – 6.5	B/R				$\frac{40-160}{150-630}$ 6400±140 3270±200	$\frac{300}{700}$ 17th c.
Vistula – Tarnobrzeg (11-7)	31000		6 – 7	B/R	11640±100		9070±90	1795±35	
Vistula-gap (1-4)	50000	0.24	2 – 5	B				(AT±SA)	
Wisłoka – Dębica (I-2)	3200	0.63	4 – 6	B/R		$\frac{100-120}{400-700}$ 11100±125 10130±115		$\frac{30-60}{80-180}$ 1040±95	$\frac{100}{240-360}$ 18th c.
San – lower reach (1-3)	16000	0.28	2 – 8	B/R		$\frac{130\pm350}{320-1100}$ 10800±100 10590±130 10300±140	$\frac{80-120}{200-300}$ 9090±100 8560±100	$\frac{30\pm70}{80-180}$ 7080±90 6670±100 5170±50 3380±90 760±60	$\frac{120}{300}$ (till 18th c.)
Pilica – Przedbórz	2500	0.5	0.7 – 2.7	B		$\frac{90}{500}$ 13030±200	$\frac{10-30}{30-100}$ 8890±60		

There occur three low terrace steps showing traces of river channels of different types (Szumański 1982). On the middle terrace which may be attributed to the upper Pleniglacial (Laskowska-Wysoczańska 1971; Mamakowa, Starkel 1974) distinct traces of braided channels are visible (Szumański 1977).

Low terraces found in the marginal zone of the present valley floor show sandy point bar remnants within the well developed large palaeomeanders of the San. These palaeomeanders are incised in the middle terrace and filled with organic deposits. Datings on the basic peat or gyttja indicate that those channels were active during the Late Glacial (Figs. 42 and 63, Table 6).

Adjacent to the zone of large palaeomeander occurrence there lies a plain being by 0.5—1 m lower. It consists of sand capped with a clayey-dusty "mada" varying in thickness. Its surface shows many palaeomeanders which date from different periods of the Holocene (Table 6). These palaeomeanders contain at least three generations which differ by parameters and the state of preservation. The first generation includes large meanders, with distinct traces of point bars and a peaty fill. These meanders undermine the higher steps. One of the palaeomeanders discussed is inserted into another large palaeomeander (Fig. 63). This indicates that the first generation came into existence already in the Preboreal phase of reduced stream discharges. The fill has been dated at 8560 ± 100 years BP (Table 6). In the second generation there prevail meanders showing the smallest parameters. These loops being covered by "mada" point to a long period of stabilization of the horizontal channel pattern (Fig. 63). Such channels functioned in different parts of the Atlantic, Subboreal, and Subatlantic periods, but continued down to the 13th century (Table 6). The third generation of palaeomeanders contains larger and well preserved cutoffs which occur at the border of the present low flood-plain. Their development was especially intensive during the 17th and 18th centuries. The formation of those loops was associated with increased deposition of the loess-like "mada" on the earlier patches of the valley floor.

The third zone of the San Valley floor showing height differences is occupied by the flood-plain which extends along the San River channel. Traces of meanders are not present there (Fig. 63).

Archival data (Szumański 1977) indicate that from the beginning of the 19th century onwards the lower San was a braided river which tended to widen and straighten its channel in response to the rapid erosion of the Holocene terrace.

During the 20th century partial channel correction was undertaken on the San. The channel became confined, dikes were erected, and the channel pattern became stabilized. Engineering works determine the modern channel parameters.

Research on the upper Vistula Valley (Falkowski 1967; Mycielska-Dowgiałło 1987; Gębica, Starkel 1987; Kalicki, Starkel 1987; Klimek 1987b; Rutkowski 1987; Sokołowski 1987) revealed numerous similarities to the San Valley, but it does contain remarkable contrasts. In the Vistula Valley the development of free meanders is hindered in the Cracow Gate, where the valley floor is only 0.4—2.0 km wide, and in the Vistula gap, between Zawichost and Puławy, up to 2 km wide.

In the Vistula Valley the alluvial fills are up to 10—20 m thick in the Oświęcim and Sandomierz basins. The thickness of alluvia decreases to several metres in the Cracow Gate and locally below the River Dunajec mouth, where there shallowly occur the Krakowiec clays. In the Oświęcim Basin and in the reach extending between Cracow and Sandomierz the Vistula Valley is bordered by the sandy-gravelly or sandy middle terrace. In places this terrace is loess-capped. The Vistula Valley floor made up of sand, and of sand with gravels overlain by a clayey "mada" shows many generations of small palaeomeanders (Fig. 38, Table 6). The earliest descernible system includes wide and flat, probably pre-Allerød, plains and braided river channels of Younger Dryas age. The latter extend along the southern border of the Vistula Valley downstream of Cracow (Kalicki, Starkel 1987) and to the east of the lower reaches of the rivers Dunajec (Sokołowski 1987) and Wisłoka (Mycielska-Dowgiałło 1987).

The phase of large palaeomeander occurrence is represented by some meanders, the fills of which have been dated to the Younger Dryas and Preboreal. The latter survived in the surroundings of Cracow (Gębica, Starkel 1987; Kalicki, Starkel 1987; Rutkowski 1987). Until now, traces of large palaeomeanders have not been disclosed neither below the River Soła mouth (Klimek 1987b) nor immediately below the River Dunajec mouth (Sokołowski 1987), nor between Zawichost and Solec (Falkowski 1967) and downvalley to the River Narew mouth. In the Wisłoka Valley, near Dębica the phase of large palaeomeander formation is documented by several large meanders being filled with channel deposits which have been dated to the Allerød decline time and the Younger Dryas (Alexandrowicz *et al* 1981; Starkel *et al* 1982). Both large palaeomeanders and sandy point bars persisted on the valley floors of the Nida, Pilica, Wieprz, Bug, Narew, and Pisa (Szumański 1981, 1983, 1986), and in the adjacent valleys of the rivers Warta (Kozarski 1983) and Prosna (Rotnicki 1983, in press). All large palaeomeanders are attributed to the period that elapsed between the Bølling and the Preboreal.

In the Vistula Valley the small palaeomeanders represent mostly the Meso- and Neoholocene. In some cases their parameters vary clearly (Table 7). In the Oświęcim Basin most of the visible palaeomeanders postdate 300 years BP. In the Cracow Gate and downstream of Cracow there occur several meander generations. The smaller ones developed far from the present river channel. The larger meanders were active until the 17th or 18th century. These meanders were abandoned by the Vistula in different periods: c 6500—6200 years BP (Wasylikowa *et al* 1985), c 5000 years BP (Gębica, Starkel 1987) and in later times. Between Niepołomice and the River Raba mouth, there occur two palaeochannel systems indicating channel avulsions. The older system whose basic fill has been dated at 5000—4300 years BP, includes a sinuous channel with slightly mature meanders and single abandoned older, well developed meanders. The system discussed provides evidence of increasing flood frequency. This at first caused channel straightening and subsequent channel avulsion. The younger palaeochannel system accompanies the river. It includes two to three generations showing different parameters. A few meandering channels which are traceable on the Vistula Valley floor below the River San mouth and also in the valleys of the rivers Bug and Narew have been interpreted by Falkowski (1967, 1975) as indicators of the culmination of channel constriction due to the dense vegetation cover. Channel constriction began during the Atlantic period and persisted into the early Subatlantic period.

On the lower Wisłoka River (Alexandrowicz *et al* 1981) the system of small palaeomeanders, being clearly discernible on the valley floor, was formed prior to 1000 years BP. Medium-sized meanders due to aggradation developed until the 17th century (Table 6). The older small palaeomeanders often became buried or destroyed by laterally migrating rivers with time.

It thus appears, that the occurrence of numerous small palaeomeanders on the valley floors is a common feature in the Vistula catchment. Datings (Figs. 41 and 42) show that within the valleys the younger meanders are mostly preserved. Older palaeochannels, especially those dating from the early Holocene, became subsequently destroyed. The sinuous pattern of the majority of river channels survived down to the middle of 17th or 18th century, exceptionally down to the middle of 19th or 20th century (*eg* in the Vistula Valley near Oświęcim and Cracow, in the Wieprz Valley near Kock and in the lower Pisa Valley). The decline of the phase of meandering rivers is everywhere documented by the youngest generation of medium-sized palaeomeanders showing greater parameters (Table 6).

The majority of valley floors occurring in the Vistula catchment, but especially at the Carpathian margin and downstream of the River San mouth exhibit distinct signs of braided river formation. This tendency is manifested through channel widening and shallowing, the increasing and irregular sinuosity, the subsequent channel straightening and appearance of numerous central bars and "kępy" (islands) within the channels. Later erosion which destroyed the deforested alluvial plain promoted formation of a new flood-plain devoid of traces of meanders.

This flood plain consists of coarser deposits. The changee of the 19th century features to braided channels was mostly blurred by the later channel correction undertaken in the upper Vistula catchment by the former Austrian partitioners.

According to Falkowski (1967), the typical braided river channel which has been formed 200—300 years ago survived in the Vistula Valley below the River San mouth into the present day. The very young flood plain shows a typical braided pattern of the bedforms and a typical composition of alluvia. Above the River San mouth engineering changes to channels of both the Vistula and its tributaries occur. The former braided channel beds are now forming a step of the lower flood plain. Braided channels still persisted in many valley reaches of the Pilica, Świder, Bug, and Narew tributaries.

In the middle Vistula Valley, the Late Glacial stage of large palaeomeander formation has not been observed because of shallowly occurring resistant deposits. Furthermore, it is possible that palaeomeanders were destroyed by the laterally migrating river, or even by channel avulsion.

In the lower Vistula Valley, which was ice-covered during the Last Glacial, and immediately upvalley (the Warsaw Basin) an important influence of both glaciation and sinking baselevel has been exhumed by stages and downcutting. Channels which are traceable on the Late Glacial terraces are of the braided type there. Two to three braids with varying levels of activity may have shifted mostly during the ice-jam-induced floods (cf. Karabon 1980). It is likely that by the end of the Late Glacial and in early Holocene times the low baselevel was favourable for the construction of both the lower Vistula channel and active zone, and for incision as well (Tomczak 1982, 1987). The small valley width hindered the formation of large, even constrained palaeomeanders.

It is probable that the Vistula reworking its sandy alluvia within a straight or slightly sinuous channel approached in character an anastomosing river throughout the Holocene. In the historical period increased sediment supply promoted aggradation and changes to braided river formation. The latter process was disturbed by channel correction undertaken on the lower Vistula by the former Prussian partitioners (Tomczak 1987).

The exact knowledge of the temporal sequence of changes in both channel patterns and parameters allows us to reconstruct the type of the hydrological regime and characteristic discharges (mean annual discharge, bankfull discharge, channel-forming discharge). In the Vistula Valley less detailed analyses have been made of the palaeochannels than in the middle Warta Valley (Kozarski 1983; Antczak 1986) and in the Prosna Valley (Rotnicki 1983). Only in the Carpathian Wisloka tributary valley attempts were made to reconstruct the channel-forming peak discharges. During the Late Glacial peak discharges were four times as great as peak discharges prior to the channel correction, and nine to fourteen times as great as those in the prehistorical period, *ie* before the deforestation.

Trafas (1975) stated that in the Vistula Valley downstream of Cracow channel-forming discharges increased from c 268 m^3/sec in the prehistorical period when the area was almost in its natural state to 762 m^3/sec at the beginning of the 19th century before channel correction was undertaken, *ie* three times.

Unquestionable traces of a pre-Late Glacial braided river found in the San Valley provide evidence of both increased sediment yield during the high annual spring discharges and absence of a dense vegetation cover. The occurrence of Late Glacial broad and large palaeomeanders either above the present channels (in the lower San Valley—Szumański 1982) or at the level of the bed of the present river (*eg* the Vistula downstream of Cracow—Kalicki, Starkel 1987; the middle San Valley—Starkel 1960) indicate a slow adjustment of discharges and reduced sediment supply from the mountains and vegetated channel banks (except the alluvial fans built up by the Carpathian rivers Sola and Dunajec). Falkowski (1967) suggested in the Vistula Valley and in the Carpathian tributary valleys there reappeared a tendency toward channel braiding and lateral planation during the Younger Dryas. Evidence of it is provided by the occurrence of meanders of Younger Dryas age (being incised into the pre-Quaternary bedrock) close to the valley sides (Alexandrowicz *et al* 1981; Kalicki 1987). The other evidence are the broad braided channels occurring upstream of the River Raba mouth (Gębica, Starkel 1987).

In the Vistula Valley, downstream of the Warsaw Basin, the gradual constriction of the valley floor during the deglaciation period and the Late Glacial indicates both reduced channel-forming discharges and the more and more difficult erosion of the vegetated channel banks.

The survival of whole channel systems which date either from the early Holocene (lower San—Szumański 1983) or from the Atlantic decline time (upstream of the River Raba mouth—Gębica, Starkel 1987) indicates the occurrence of phases of channel avulsions, straightening and downcutting. These provide evidence of both frequent high discharge occurrence and increased river activity. Similar events have been noted during the last 300 years, during the so-called Little Ice Age. These phases are synchronous with facies changes in the alluvia and with increased sedimentation rates (Starkel 1983a). The above changes are dated at 8500—8000 years BP and 5000—4500 years BP. In the Vistula Valley, downstream of Cracow (Kalicki, Starkel 1987), and in the Wisłoka Valley (Alexandrowicz *et al* 1981) there also occur fossil channels which have been dated at 2200—1500 years BP. These channels are now buried beneath channel facies deposits.

The conclusion is that in the upper and middle Vistula catchment *Qw* decreased at the transition from periglacial to forest climatic conditions, and channel stabilization took place during the Holocene. This stability became interrupted in the phases of higher discharge occurrence and increased human activity. Their reflection in both channel and flood-plain morphology depends either upon downcutting or upon aggradation. In the Subcarpathian basins the latter is locally influenced by tendencies toward subsidence. From the Roman period onwards aggradation is controlled by the anthropogenic factor.

CHANGES IN THE HYDROLOGICAL REGIME INFERRED FROM FACIES CHANGES IN THE FLUVIAL DEPOSITS

Systematical research has not been completed along the whole Vistula Valley to focus upon the palaeohydrological aspect of alluvia laid down during the last 15,000 years. Therefore, attempts to reconstruct the palaeohydrological events give only an apparent picture. In the Vistula Valley reconstructions are less advanced than those, in the adjacent Warta Valley (Kozarski 1983; Antczak 1986). At the same time, it is possible to infer the discharge regime from the properties of alluvial deposits such as sorting, mean grain diameter, petrographical and mineralogical composition, thickness of series, and character of the palaeochannels that have been defined in several reaches of the Vistula. It should be stressed that during the period discussed—irrespective of the flood frequency and magnitude—the Vistula and its tributaries have changed from aggrading rivers to eroding ones and *vice versa* in response to the changing conditions of sediment yield (among others, the density of vegetation), and to changes in both gradients and baselevel.

The past 15,000 years can be divided into four periods (see p. 111). During the period 15—13 ka years BP slow degradation of permafrost took place. A dense vegetation cover was absent at least from the Polish Lowland. This period was characterized by rivers showing a positive alluvial balance. Poorly sorted channel deposits containing much gravels, the poor petrographical and mineral segregation, the predominance of a tabular cross-bedding, all indicate highly variable and dynamic stream discharges and the overloading with sediment.

In the upper river reach the processes of erosion led to the formation of broad channels which are buried below the Holocene plain today. Subsequently, some abandoned channels became filled with biogenous deposits.

In the lower river reach both Vistula waters and glacial meltwaters eroded broad ice marginal channels ("pradoliny") carrying the rivers

Narew and Noteć. In these "pradoliny" poorly sorted deposits which contain a rather high proportion of the coarse fraction were laid down. During the period 13—10 ka years BP channel facies deposits showing a varying sorting were dominant. Typical bar deposits and channel lag deposits may be related to a phase of laterally migrating channels during the Younger Dryas. The proportion of overbank "mada" is insignificant. For the most part, "mada" occurs on the 1—2 m plain rising above the present channels (Gębica, Starkel 1987).

The Holocene is marked by a variable hydrological regime. Phases of a low flood frequency altered with phases of a high one (Starkel 1983a), evidence of which is provided by the nature of deposits. Periods of a metastable equilibrium are characterized by well sorted channel deposits and a well petrographical and mineralogical selection. The proportion of garnet increases upward, whereas the proportion of crystalline rock particles decreases in favour of quartz. These properties point to a repeated washing and redeposition of the sediments.

On the contrary, periods of a high flood frequency are marked by heterogeneous channel deposits.

A few point bars occurring within the meandering channels have been dated at 10—8.5 ka years BP. Thin clayey and organic fills of depressions located on the flood plain indicate diminishing sedimentation rates. The phase 8.5—7.7 ka years BP is marked by the deposition of both inserted channel deposits and alluvial fan deposits, 5—7 m thick, built up by the tributaries (the Wisłoka Valley). These indicate a high flood frequency and intensive sedimentation (Starkel 1984b). In the upper Vistula catchment "mada" was laid down on gyttja and peaty oxbow fills (cf. the Vistula Valley reach downstream of Cracow, Starkel ed. 1987b). Accumulation rates were low throughout the Atlantic period, except the phase 6.5—5.9 ka years BP when distinct falls of trees took place.

During the period 5.0—4.5 ka years BP both moister conditions and forest clearance promoted the general increase in sedimentation rates. This is documented by dated series of new alluvial fills, and by the superposition of "mada" on the earlier alluvia. The latter processes have also been noted in the upland valleys (Śnieszko 1987). In the middle reach of the Vistula, in the surroundings of Płock, the channels then are represented by two types: the deep and sinuous channels which were drained at low and intermediate flows and the straight, shallow channels carrying flood water which encroached on the lower levels of the Pleistocene supra-flood terrace (Florek *et al* 1987).

From 2800 years BP onwards the channel facies deposits once again contain numerous tree trunks and other organic remains (Mycielska-Dowgiałło 1978; Alexandrowicz *et al* 1981; Dauksza *et al* 1982). There also appears "mada" building the natural levees (Klimek 1987b). A distinct phase of accumulation of the channel facies deposits which initiated a period of aggradation, *ie* the upbuilding of the flood-plain and increase in bed elevation, began in the first and second centuries. This phase has been documented in the upper Vistula Valley (Rutkowski 1987; Kalicki, Starkel 1987) and in the lower Vistula Valley (Tomczak 1987). The general upward growth of the flood-plain by deposition of both "mada" and crevasse splay deposits took place in the 10th—11th centuries and in later times. This process is observed in the entire Vistula drainage basin (Radwański 1972; Alexandrowicz *et al* 1981; Niedziałkowska *et al* 1985; Florek *et al* 1987; Kalicki, Krąpiec 1988). Channels were straightened and cut wider in response to continued forest clearance and increasing flood frequency in the 15th—16th centuries. At this time, "mada" deposition took place along the channels (Biernacki 1975; Falkowski 1975). The river regime changed to a "mixed load" type. Over the last 200—300 years 2—3 m of "mada" were deposited due to channel migrations (Klimek 1974).

Greater fractions of the alluvia and increased sedimentation rates are typical of the last two centuries, with a high flood frequency. Such deposits differ from the earlier ones by the greater concentration of both heavy metals (Klimek, Zawilińska 1985) and coal clasts (Rutkowski 1986).

Figure 61 shows periods of increased accumulation of channel facies deposits, of overbank deposits, and of alluvial fan deposits as well as periods of stabilization marked by the accumulation of organic deposits. Periods of the reactivation of accumulation correspond to periods of channel avulsions and abandonment, and of the beginning of channel infill. Phases of reactivation of the hydrological regime, being associated with moister climate and a higher flood frequency, were dated as: the Younger Dryas, 8.5—7.7 ka, 6.5—5.9 ka, and 5.0—4.5 ka years BP. From 3 ka years BP onwards, but especially during the late Roman period (1st—5th centuries), in the Middle Ages (10th—11th centuries), and from the 15th or 17th centuries onwards phases of both increased flood occurrence and aggradation are clearly related to phases of deforestation, though the influence of the climatic factor cannot be neglected (cf. fluctuations of the Alpine glaciers—Patzelt 1977; Bortenschlager 1982).

HYDROLOGICAL CHANGES IN THE LIGHT OF SOIL STUDIES

The soil-forming processes act in concert, though their action shows quantitative and qualitative variations in space and time (Jenny 1983; Kowalkowski 1988). In the Vistula Valley the principal factors that determined the type of processes are as follows:

(i) the degree of pedogenical alterations of the top series of the terrace-forming alluvia and deluvia which in turn depends on both genesis and age of the parent soils,

(ii) the differing grain-size of alluvial and deluvial deposits, and the content of both organic matter and $CaCO_3$ due to origin, fluvial transport, and sedimentation,

(iii) the duration of the soil-forming process being controlled by the age of deposits and location in the river valley,

(iv) the dynamics of surface water flow, and both depths and amplitude of groundwater table fluctuations which in turn depend on climatic changes and man's activity,

(v) the sequence of plant communities being controlled by both climate and dynamics of the hydrological conditions.

Among the factors previously mentioned only water and plant communities show dynamic changes with passage of time. Thus, the resulting soil mosaics are stable indicators of the dynamics of their activity in the Vistula Valley environment (cf. p. 24).

Old soils profiles of which correspond to the climato- and phytogenic soils evolved from alluvia forming the Pleistocene terraces (Strzemski 1955; Rytelewski 1965; *Systematyka gleb Polski* 1974). However, in the Holocene alluvial and deluvial deposits the typical properties are absent. That's why they are known as fluvial soils which in the Polish typological nomenclature correspond to "mada". The subdivision of the young alluvia and deluvia depends on the stable pedogenic properties that developed at the place of their alimentation, and on hydrological conditions prevailing at the place of their deposition, except the swampy alluvia and deluvia. Without respect to their age, such deposits may be assigned to the hydrogenic bog soils. Under favourable hydrological conditions the boggy process tends to affect rapidly new deposits. In a short span of time those deposits show characteristic properties of processes of gleization and of accumulation of the peaty organic matter (Strzemski 1955).

FACIES OF SOIL MOSAICS AND HYDROLOGICAL REGIMES

Within the Vistula Valley four age facies of the soil mosaics may be distinguished in the soil development. Those facies are controlled by the sequence of dynamics of changes in both the hydrological regime and deposit balance which took place during the last 15,000 years. According to Starkel (1983a), such changes were characteristic of the Central European valleys. The facies are as follows:

— the Pleniglacial—Allerød facies which came to an end around 10,900 years BP,

— the Late Glacial—Eoholocene facies (10,900—8500 years BP),

— the Mesoholocene—early Subboreal facies (8500—2800 years BP),

— the Subboreal—Subatlantic facies (from 2800 years BP onwards until the present time).

In the Pleniglacial valley carrying a braided, intensively accumulating river which replaced by a meandering one during the Allerød cryogenic glacial soils and interglacial soils at the initial stage of development were dominant on the terraces then existing. Those soils combined into mosaic with the authogenic rusty soils and parabrown soils. In the moister parts of the valley there developed hydrogenic ground-gley soils and gley podzols as well as pseudogley and peat soils (Strzemski 1955; Kowalkowski, Starkel 1977; Zawadzki 1980; Kowalkowski, Mycielska-Dowgiałło 1983; Baraniecka, Konecka-Betley 1987; Kowalkowski 1988). Those soil profiles became disturbed by cryogenic processes (Kowalkowski 1988).

From the Younger Dryas to as late as the Boreal/Atlantic transition (10,900—8500 years BP) the reversion to a braided river under cold and dry climatic conditions which subsequently changed to a warmer and moister ones favoured the further development of cryogenic peat soils. At that time peat accretion took place in the depressions occurring on the Pleistocene terraces. Peat accumulated on the gley podzols and ground gley soils there. On the higher terraces and elevations, where water did not influence directly the zone of pedogenesis, both rusty soils and parabrown ones continued to develop. Chernozem also formed there.

The most typical cryogenic rusty soils are found on the light alluvia and aeolian sands, amongst others, in the upper and middle Vistula Valley (Strzemski 1955; Baraniecka, Konecka-Betley 1987). The distribution of both parabrown soils and chernozems was related to similar soils being associated with the surrounding plateaus. This relationship is most distinct in the narrow valleys (Zawadzki 1980). In the Vistula Valley typical parabrown soils are found between the River Nida mouth and Puławy, in the Warsaw Basin and in the Żuławy Wysokie (Vistula River Delta) (Krzyszkowski 1952; Strzemski 1955; Witek 1965; Nowak, Nipanicz 1967; Baraniecka, Konecka-Betley 1987). Thick authogenic chernozems showing properties of deluvial soils which may have been renewed in the following periods occur in the Vistula Valley between Brzesko Nowe and the River Nidzica mouth, in the Nidzica and Szreniawa tributary valleys and in the Lublin Upland (Strzemski 1955; Zawadzki 1980). Numerous authors draw attention to the great extent of black earths, being frequently carbonate rich, on the higher Pleistocene terraces (Strzemski 1955; Zawadzki, Guz 1961; Witek 1965). These post-bog soils are frequently accompanied by gyttja, and by freshwater and meadow chalk which may contain a cold-climate malacofauna (Krzyszkowski 1952; Kowalkowski, Hoffmann 1961; Kowalkowski, Berger 1966; Kowalkowski 1968; Stasiak 1971; Konecka-Betley, Stefaniak 1983). Thus, during the Late Glacial and early Holocene period of high intensity soil formation leaching of carbonates was associated with the formation of authogenic soils on the acid plateaus, and of hydromorphic soils in the river valleys (Kern 1985; Kowalkowski 1988). The leaching of carbonates led to the development of rusty soils from deposits poor in mineral colloids, and of parabrown soils from deposits rich in these fractions (Kowalkowski 1988).

The third period of soil mosaic formation under dense Atlantic and Subboreal forests included three cycles of river activity. Phases of braided rivers that intensively reworked the earlier terrace deposits around 8500—7500, 6500—5900, and 5100—4500 years BP alternated with phases with meandering rivers, increasing aggradation and peat accretion in the valleys. At that time hydrogenic mud soils and bog soils were produced (Okruszko 1969; Żurek 1975; Baraniecka, Konecka-Betley 1987). On the youngest Holocene terraces there developed initial alluvial soils, weakly developed humus soils and alluvial podzolized ones. Incision into the lower Holocene terraces caused groundwater table lowering. Consequently, some bog soils were affected by muck processes which produced muck soils. Under a forest vegetation much rusty soils and parabrown ones were affected by podzolization being manifested through the formation of rusty podzolized and parabrown podzolized soils.

During the last 2000—3000 years forest clearance, farming, and pasture have increased soil erosion rates in the elevated areas. This in turn caused "mada" deposition in the river valleys. The meandering rivers reverted to braided ones during the last 200—400 years (Starkel 1983a), and the higher groundwater table favoured the development of mires on the lower Holocene terraces. Widespread drainage ditches caused the desiccation of both mires and gley soils. This in turn resulted in the common formation of peat-muck soils, and the desiccation of both ground-gley soils and gley podzols showing relic gley properties today. At the same time, initial alluvial soils and weakly developed alluvial humus soils spread widely in the Vistula catchment, and dunes and terrace sand became blown by wind. Today there is a threat of markedly increased denudation rates. In the urban and industrial areas these are expected to be 20,000—40,000 times as great as those in areas which are more or less in their natural state (Becker, Muthern 1975). Threat formers are (Okruszko 1976; Marcinek 1976):

(i) the general reduction of the humus content in the organic and mineral soils,

(ii) the pulverization of the soils due to excessive desiccation,

(iii) the unreasonable usage of mineral fertilizers and other chemical substances.

The latter factors, together with strong gas emissions and industrial wastes produce soil deserts. The toxic material which has been washed

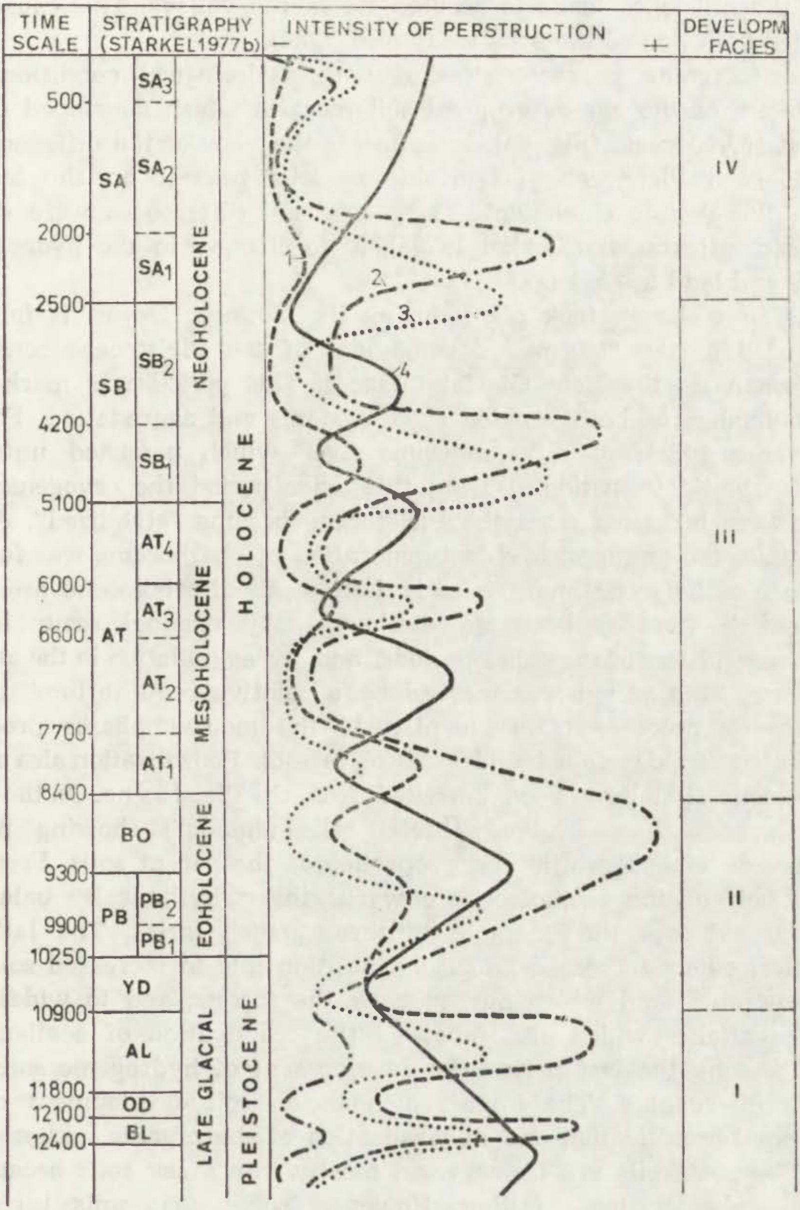


Fig. 64. Relationship between sequences of changes in both hydrological regime and deposit balance in the Central European river valleys, and some pedogenic processes occurring during the last 15,000 years (acc. to Starkel 1983a and Kowalkowski 1988)

1—intensity of leaching, 2—intensity of humus accumulation, 3—rate of peat accumulation, 4—intensity of fluvial activity down the hillslopes tends to accumulate in the valleys. This causes the localized pollution of the soils today (see p. 24).

The foregoing characteristics of both hydrological conditions and four facies of the age-determined soil mosaics which developed during the last 15,000 years (Fig. 64) drew nearer the view of the differing genesis of both Pleistocene and Holocene soils present on the terraces within the Vistula catchment. These essential differences were due to threshold adjustment (Starkel 1979a), *ie* to changes in the hydrological factors and land use changes.

The first change took place during the Younger Dryas. It followed the period of the "stormy" development of the Pleistocene soils that are present on the Late Glacial terraces. This period was marked by the dominance of both braided river systems and aggradation. Following was a phase of a meandering river which persisted until the Boreal/Atlantic transition. During this drier period the cryogenic soils which were inherited from the Pleistocene became "stabilized". At the same time, the youngest and last generation of chernozems was formed.

The Mesoholocene and the early half of the Neoholocene are characterized by increased stream discharges, by channel scour in the descending phases of the moist periods, and by aggradation in the ascending phase. This period was marked by a relative "equilibrium" of the soil-forming processes. Consequently, in the moister phases processes of podzolization developed under dense forests. Podzolization also affected the soils that have been inherited from the Pleistocene. On the Holocene terraces there evolved fluvial soils ("mada") showing mostly a poorly developed profile and properties of the parent soils. From the second half of the Neoholocene onwards this "rhythmically balanced" cycle passed into the unstable "anthropogenic" facies. The latter is characterized by increased "mada" deposition due to increased soil erosion of arable land which pushed back the forests, and to widespread draining ditches which also favoured the reactivation of aeolian processes. During the last period the development of hydrogenic soils also became interrupted. The impact of man on soil development causes accelerated humification and mineralization of the organic matter in all soils. The peat soils are transformed mostly into muck soils because of the groundwater table falling. However, some peat soils turn into deserts (Okruszko 1976; Marcinek 1976).

HYDROLOGICAL CHANGES IN THE LIGHT OF PALAEOLAKE STUDIES

Lakes covering more than 1 hectare occupy 1293 km², *ie* 0.735% of the entire Vistula catchment (Majdanowski 1954). The distribution of lakes is irregular. More than 90% of the lakes are found in northern Poland which was occupied by the last Scandinavian ice sheet. Here lakes cover 2.5% of the young moraine landscape, in places even more than 15$^{0}/_{0}$. Beyond the limits of the last glaciation lakes occur in the Łęczna—Włodawa Lakeland and in the Tatra Mts.

Both origin and age of the lake basins should be distinguished from that of the lakes, since the date of initiation of lakes could vary thousands of years. Lake basins occurring in the Vistula drainage basin are of differing genesis (Table 7).

In northern Poland there dominate lake basins due to glacial and aqueoglacial erosion which took place between 20 ka and 13.2 ka years BP (Kozarski 1986). These basins were not filled with water soon after they came into existence because they were occupied either by glacier ice or by winter ice for a long period. This ice—like the buried ice blocks—melted out mostly during the warm periods of the Late Glacial, and probably at the beginning of the Holocene. Although the future lake basins differed widely in ages, the melting out of the buried ice masses took place during similar periods. Analogically, in the ice-free areas the blow-outs were formed during the cold periods of the Late Glacial, whereas the thermokarst depressions developed mostly during periods of climatic amelioration. Thus, in Poland most of the basins holding lakes were established during the Late Glacial, except the Late Glacial and Holocene oxbow lakes and the man-made depressions.

Table 7. Main genetic types of lake basins occurring in the Vistula drainage basin

Geomorphological factors	Types of lake basins	Occurrence
Glacial erosion	glacial cirques and depressions glacial channels	Tatra Mts northern Poland
Aqueoglacial erosion	various types of sub - and englacial channels	northern Poland
Irregular glacial accumulation	depressions on the morainic plateaus showing a varied relief	northern Poland
Karst processes	karstic depressions	Łęczno-Włodawa Lakeland
Thermokarst processes	shallow depressions	central and southern Poland
Deflation	blow-outs	dune fields
Fluvial erosion	abandoned channels oxbows	river valleys
Man's activity	pits, dammed-up lakes on the rivers	over the whole of Poland

In Poland several palaeolake generations may be distinguished. The oldest ones are proglacial lakes which formed in the glacier foreland. These were short-lived features which did not survive to as late as the Holocene.

The second generation includes shallow lakes which occupied depressions developing above the buried ice masses within the limits of the last glaciation during periods of warming preceding the end of the Allerød. This is documented by minerogenic lake deposits, with a molluscan fauna and scant pollen. The occurrence of dated raised beaches (Lamparski 1979; Niewiarowski 1987a) contradicts the opinion expressed by Stasiak (1967) that in northern Poland the Allerød was preceded by a long lake-free period. Beyond the limits of the last glaciation the formation of such tundra lakes was due to degradation of many years' permafrost (thermokarst). Summer temperatures were the major factor responsible for the melting out of shallowly buried ice masses and for the degradation of permafrost. Therefore, such lakes indicate a warming of climate and not its humidity. The existence of lakes during the Bølling is evidenced by the results of palynological investigations (Ralska-Jasiewiczowa, Starkel 1988).

The next generation includes lakes that were established after the buried ice had finally melted out. Many lakes survived until present times. Numerous authors (Kozarski 1962; Więckowski 1966; Niewiarowski 1978, 1987a, and others) expressed the view that the final melting out of the buried ice masses took place already by the end of the Allerød. However, Stasiak (1967, 1971) and others believe that this process lasted until the climatic optimum of the Holocene. It seems that in northern Poland these were exceptional cases. Even in the higher glacial cirques of the Tatra Mts lakes were established already during the Late Glacial. Only the morainic lakes due to melting out of the buried ice masses were formed during the climatic optimum of the Holocene (Kondracki 1984). Investigation of many lake deposits (Więckowski 1978) revealed that the majority of the Polish lakes belonging to the younger generation was established between 12 ka and 10 ka years BP.

Lake level fluctuations in Poland caused changes in the lake extent, depth, and volume. Because of the falling water level, the shallow lakes became grown over and disappeared. At high groundwater tables the lakes reappeared, even in the formerly dry depressions.

The lake level is determined by the water balance of the lake catchment, *ie* the input (precipitation to the lake area and groundwater flow), and outflow losses (evaporation from the lake area and runoff). Generally, lake level fluctuations are controlled chiefly by climatic factors, by the vegetation cover within the lake catchment, and by the possibility of water outflow (Skarżyńska 1965).

However, lake levels depended not only on the climatic conditions. In areas, where there occurred buried ice masses the falling lake level owed a great deal to the process of melting out of the ice. This led to the deepening of the lake basins. The magnitude of lowering was often overrated. It could reach at a maximum 9%, *ie* the difference between the volume of ice and that of meltwater. A similar process was likely to occur in the actively developing karst and thermokarst depressions. For the most part, such depressions occurred in Late Glacial times.

In the lake basins marked by an irregular topography of the basin floor, and above all in the throughflow ribbon (furrow) lakes, a major role was played by the formation of overflow gaps and downcutting of the barriers. This process may cause both the shallowing and complete disappearance of the lakes. In this case the increasing humidity of climate was associated with high lake levels and increased stream erosion in the overflow gaps. This in turn resulted in low lake levels. All throughflow lakes are sensitive to changes in stream levels, but especially those situated on the valley floors (cutoffs).

Levels of the coastal lakes (*eg* Lake Drużno) were affected by fluctuations of the Baltic Sea level. According to Zachowicz *et al* (1982), Lake Drużno existed as early as the Late Glacial. Subsequently, peat accretion took place there to be followed by inundation by the Vistula Lagoon waters around 7.0 ka years BP. The mire was completely flooded around 6.5 ka years BP. Subsequent water level changes were controlled by the eustatic fluctuations of the Baltic Sea level which are not synchronous with the inland lake level fluctuations.

Few investigations have been made into the indirect impact of man (forest clearance) on lake level fluctuations. The view generally accepted that deforestation couses a lake level rise. However, Pennington (1981) showed that deforestation brought about dramatic changes in the small closed lakes, whereas in the large throughflow lakes it operated with less effect.

The above review revealed that local factors (*eg* erosion of barriers, artificial impounding and lake level fall, forest clearance, and melting out of the buried ice masses), regional factors (*eg* influence of the Baltic Sea on some coastal lakes) and overall factors (climate) can all induce lake level fluctuations in Poland. It appears that on an overall scale considerations of hydrological changes should eliminate changes caused by local factors.

The "Handbook of Holocene Palaeoecology and Palaeohydrology" edited by Berglund (1986) shows that different methods are used to examine lake level fluctuations. The best approach is to conduct various complex researches. In Poland investigations have been carried out to recognize lake level fluctuations. Progress has been made within the IGCP Subproject 158-B being co-ordinated and summarized by Ralska-Jasiewiczowa (1987). Relative lake level fluctuations are indicated by cores taken from the deepest parts of both lakes and mires. However, it is difficult to reconstruct palaeolake levels in metres in relation to the present water level above sea level. Until now, little work has been carried out on the detailed reconstruction of lake levels over a longer period (12 ka) (Kondracki 1969; Stasiak 1971; Czeczuga 1975; Hjelmroos-Ericsson 1981; Niewiarowski 1987a).

Despite the diverse geographical environment of Poland, *ie* the zonal arrangement of mountains, uplands and lowlands it is likely that the tendencies to climatically controlled hydrological changes were similar and synchronous in both fluvial and lacustrine environments because of the rather small area of Poland (Ralska-Jasiewiczowa, Starkel 1988).

Data on the age of lake basins indicate that tundra lakes which were established before the end of the Allerød, during the warmer periods of the Late Glacial, were shallow water bodies, up to several metres deep. Their depth was controlled by permafrost occurrence. This refers to lakes occupying shallow thaw basins, blow-outs, thermokarst depressions, and depressions located on the valley floors, since the braided channels also were rather shallow. It is likely that lake level fluctuations were rather small. Lake depths rapidly decreased at first by the accumulation of minerogenic deposits, and then by peat accretion during the Bølling and Allerød.

During the Late Glacial hydrological changes due to the Allerød warming of climate were most important. This warming caused a marked retreat of permafrost and the deep, even complete melting out of the buried ice masses. Thus, lakes including the deep ribbon lakes were

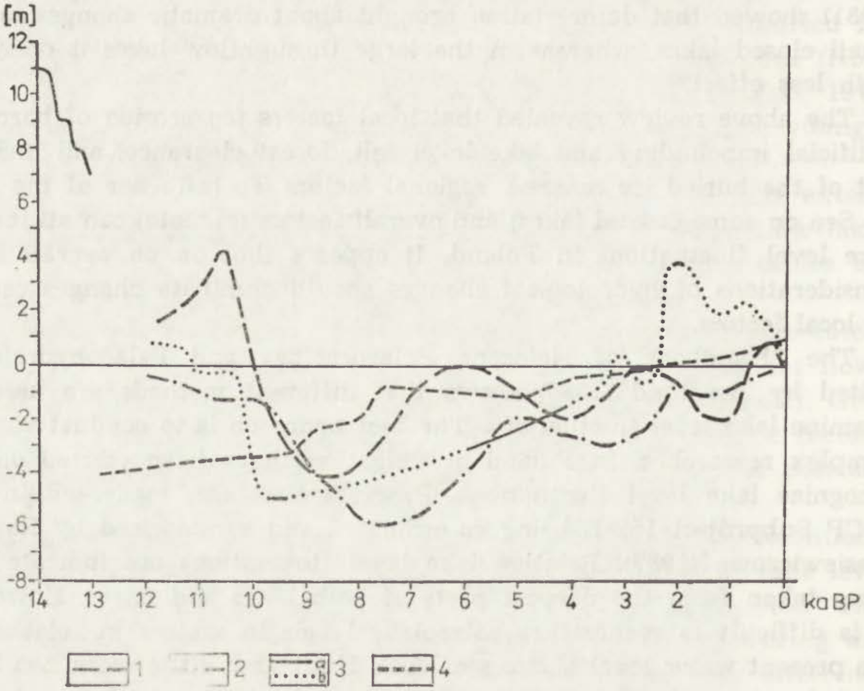


Fig. 65. Curves showing lake level fluctuations

1—Great Mazurian Lakes (Kondracki 1969), 2—lakes in the Mazurian Lakeland (Stasiak 1971), 3—Lake Strażym and Kuyavian lakes: a) established, b) presumed (Niewiarowski 1976, 1978, 1987a), 4—the Wizna mire (Balwierz, Żurek 1987)

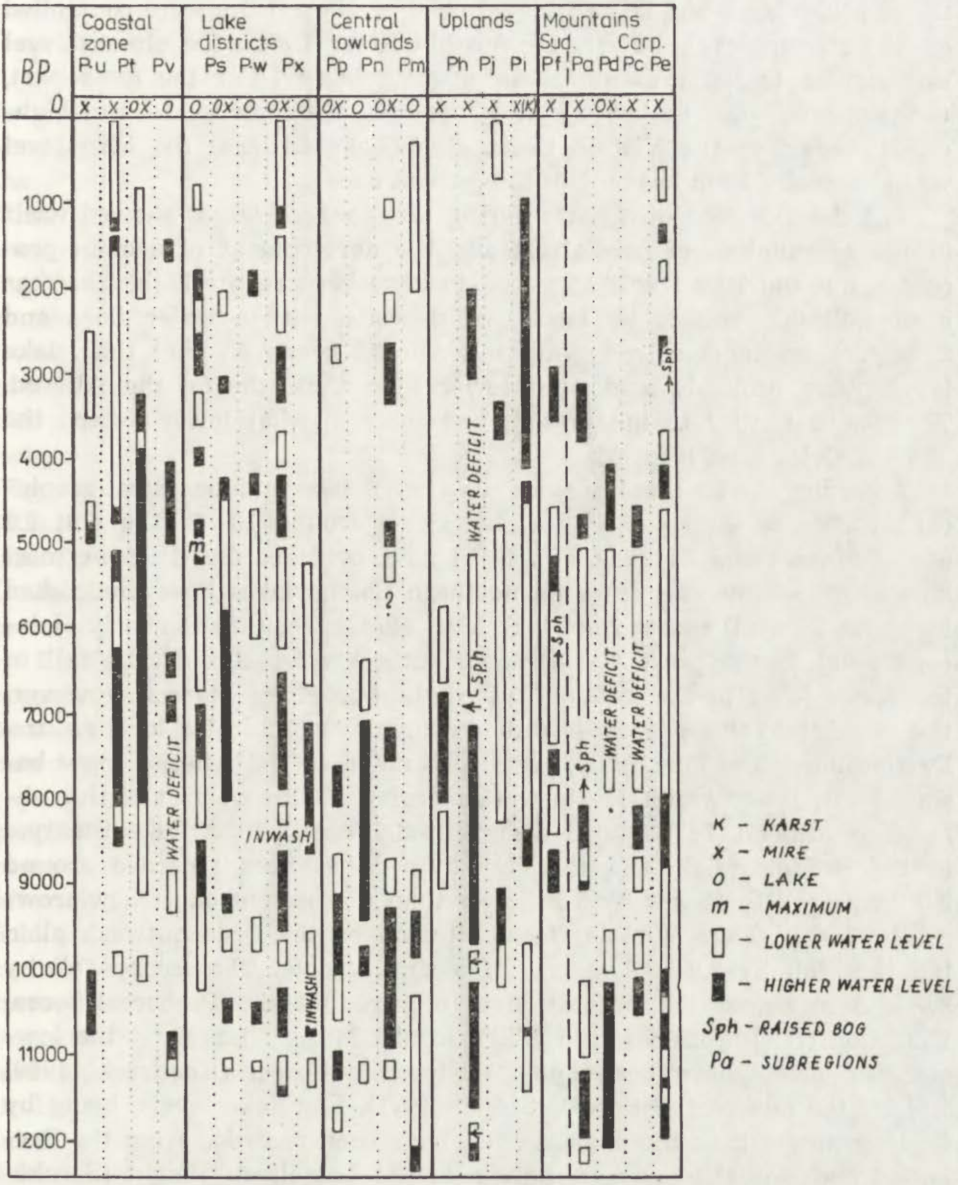


Fig. 66. The palaeohydrology of Polish lakes and mires during the last 12,000 years (Ralska-Jasiewiczowa 1987)

established in masses. At that time, the density of lake occurrence in Poland was greatest, being similar to that of Finland. Ever since 2/3 of the former lake surface in Poland has already diminished (Kalinowska 1961). During the Late Glacial lakes were nourished by both precipitation and water resulting from the melting out of both ground ice and buried ice. At that time, lake levels varied in height. Levels of both throughflow lakes and lakes situated on the valley floors were controlled by the stream level. Except the Vistula River Delta, the stream level was similar to the present one or slightly higher. For the most part, the lake level was similar to that of the present-day or by 1—2 m higher. However, in the Vistula Delta area (Lake Drużno) the lake level was at least by 10 m lower than the present one.

The deterioration of climate during the Younger Dryas showed itself in the aggradation of permafrost and the development of aeolian processes, but the lake levels appeared to have been rather high. This has been well documented by lacustrine deposits, with a water flora and *Cladocera* assemblages overlying the Allerød peats. At that time, lake levels were probably somewhat lower than those during the Allerød. They were similar to the present ones or somewhat lower except the Vistula Delta area (Fig. 65).

According to Ralska-Jasiewiczowa (1987), lake and bog stratigraphical data are evidence of low water levels around 10—9.5 ka and 9.2 (9.0—8.5) ka years BP (Fig. 66). Until now, evidence for the lowermost lake level in Holocene times (in northern Poland lakes have diminished by about 3—6 m) comes from lake level studies relating the early Holocene level to the present one. Some authors refer this drastic fall in the water level to the melting out of the buried ice masses. However, the fall due to this process is rather insignificant and of a local nature. Furthermore, low lake levels were also noted in the Allerød thaw basins. Thus, lower water levels were associated with warm and dry climatic conditions. In the well documented lakes such as Lake Strażym in the Brodnica Lakeland the lowest level has been recorded around 9.5 ka years BP. It was by 5 m lower than the present one (Niewiarowski 1987a). In Lake Wielkie Gacno situated on the Brda outwash plain the first fall by 2.8—3.0 m was of a similar date. The second fall by 2.7—2.8 m below the present level occurred at the Preboreal/Boreal transition (Hjelmroos-Ericsson 1981). In the Mazury Lakeland the lowest lake levels have been noted during the Boreal (Kondracki 1969) and by the end of the Boreal (Stasiak 1971). Low lake levels, being by 4—10 m lower than the present ones, have been recorded from the Preboreal and Boreal in eastern Latvia, in the Latgaliyan Height (Sorokin ed. 1983). Gaillard (1985) argued that synchronous, climatically controlled falls in the lake level over the whole of Europe occurred around 10—9.5 ka and 8.5—8.0 ka years BP. Berglund (1983) found that in southern Sweden the lowest lake levels have been reached around 9.0 ka years BP. Such a fall in the water level in early Holocene times must have remarkably reduced the density of lakes. Consequently, shallow lakes either became grown over or disappeared, whereas the deeper lakes became reduced in area. Palaeoclimatic variations apparent in the Preboreal—Boreal periods (Starkel 1977b) must have caused lake level fluctuations (Fig. 66). However, detailed data on the magnitude of the lake level rises are lacking.

Until now, views on the water levels during the Atlantic period are varying. Higher lake levels (being similar to the present ones) have been shown to occur in the Great Mazurian Lakes (Kondracki 1969) and in the Suwałki Lakeland (Czeczuga 1975). In Subboreal times lakes have diminished by 1—2 m there. However, Stasiak (1971) suggests that in the Mazurian Lakeland the lake level was by 4 m higher than that during the Boreal period (Fig. 65), although this level was still by 2 m lower than the present level. Lake Strażym level was higher by 1.5 m between 6 ka and 4 ka years BP, though it was lower by 1.8 m than the present level. Very important is the statement (Ralska-Jasiewiczowa 1987) that in Poland all sites that have been examined within the IGCP Subproject 158-B provide good evidence for a phase of water level fall (Fig. 66) in the Atlantic decline time, and in some areas throughout the Atlantic period. Evidence for both drier climatic conditions and lower lake levels in Europe between 7.0 ka and 5.0 ka years BP comes from Gaillard's studies (1985). This does not refer to the coastal lakes which were affected by fluctuations of the Baltic Sea level.

From *c* 5.0 ka years BP onwards both deterioration and increased oceanization of climate (Pennington 1981) caused the general rise of the average lake level (Berglund 1983). This period was increasingly dominated by human forest clearance activity in Central and Northern Europe. It brought about changes in the small and closed lakes. The superposition of both natural and man-induced changes caused a complex nature of water level fluctuations (Fig. 65 and 66). It is probable that after the local causes had been eliminated, the higher lake levels 5.0 ka —4.4 ka years BP, 2.8 ka —2.4 ka years BP, and in the 14th—19th centuries were due to overall climatic changes. Falls in the lake levels have been noted between 4.0 ka and 3.0 ka and between 1.8 ka and 1.0 ka years BP. In southern Sweden the fall in the lake level between 3.5 ka and 3.0 ka years BP appears to have been the second major lowering in Holocene times (Digerfeldt 1972; Gaillard 1985). The diminishing of lakes by 1.6 m in north-eastern Poland between 1970 and 1200 years BP is known as the Neoboreal period (Czeczuga 1975).

In northern Poland a fall in the lake level has been noted by the end of the Subboreal period. At that time, lakes diminished by 1—2 m, *ie* less than in Preboreal and Boreal times. In Poland higher lake levels following the Hallstatt period (*c* 2.4 ka years BP) down to *c* 1.8 ka years BP have been fairly well documented. In the Kuyavy and Brodnica Lakeland (Niewiarowski 1976, 1978, 1987a) this rise by 2—4.5 m above present level is acknowledged to be the culmination in Holocene times. In Lake Mikołajskie there also is evidence for a 2 m higher lake level (above the present one) in the Subatlantic period (Korolec 1968).

In the light of palaeolake studies marked and intricate paleohydrological changes took place in the Vistula catchment during the Late Glacial and Holocene. There is still a need for further complex studies.

THE MALACOFAUNA PRESERVED IN LATE GLACIAL AND HOLOCENE DEPOSITS WITHIN THE VISTULA CATCHMENT

In the Vistula catchment marked changes in the malacocoenoses took place during the last 15,000 years. These changes were controlled by the evolution of both climatical and palaeogeographical conditions, and by the increasing influence of man's activity over the last millenia. Molluscan assemblages are incorporated in the different genetic types of deposits dating from different phases of the Late Glacial and Holocene (Fig. 67). In profiles representative of long spans of time those assemblages are forming malacological sequences which allow us to reconstruct both types and development of the habitats, the nature of the vegetation cover and the course of sedimentation on the valley floors, on the hill slopes and at the toe of slopes.

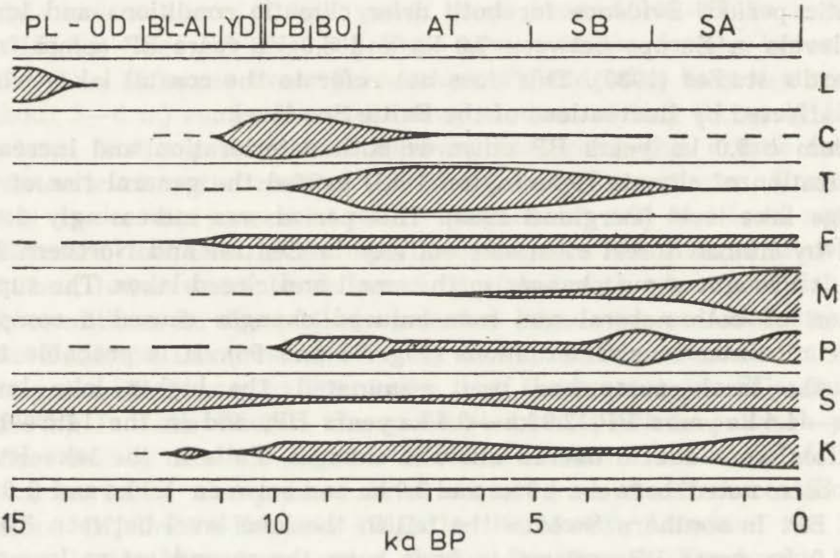


Fig. 67. Stratigraphical ranges of the main types of deposits containing a malacofauna

PL-OD—Pleniglacial—Oldest Dryas, BL-AL—Bølling—Allerød, YD—Younger Dryas; Holocene phases: PB—Preboreal, BO—Boreal, AT—Atlantic, SB—Subboreal, SA—Subatlantic; types of deposits: L—loess, C—freshwater chalk, T—calcareous tufa and travertines, F—fluvial deposits (channel facies deposits and abandoned channel fills), M—"mada", P—fossil soils, S—slope deposits, K—landslide deposits; ka BP—age, thousand years

During the period preceding the phase of warming that characterized the Late Glacial (Bølling—Allerød) loess sedimentation came to an end in the Miechów Upland. Loesses which were laid down under periglacial conditions include molluscan assemblages indicative of open country, and, locally, of aquatic habitats (Alexandrowicz 1985). In the youngest loesses *Succinea oblonga elongata* was dominant. This lived in moderately moist habitats. Faunas with *Pupilla loessica*, which preferred drier habitats, played a minor part. *Succinea* shells preserved in the loesses at Bibice (northern suburb of Cracow) have been radiocarbon dated by Dr. J. Evin at 14,800 ± 300 years BP (Ly-3513). In the Vistula Valley, between Cracow and the River Dunajec mouth, the presence of a water fauna with *Gyraulus laevis* has been noted in two loess profiles. In the first profile at Opatowiec the loess is overlain by silt and sand containing *Pisidium stewarti* and *P. obtusale lapponicum*. This assemblage is characteristic of pools occurring in the periglacial zone. Such pools existed in the Vistula Valley by the end of loess sedimentation (Fig. 67).

Calcareous deposits are represented by freshwater chalk and gyttja as well as by calcareous tufa and travertines. Deposits at first mentioned formed mostly beyond the river valleys, in different thaw basins, often in glacial channels being concentrated in the northern part of the Vistula catchment. Chalk and gyttja began to accumulate in the Late Glacial phase of warming. Their maximum deposition coincides with the Lower Holocene. During the Boreal and Atlantic periods most of these water bodies disappeared giving way to mires. Only some lakes persisted until the present time. Late Glacial deposits contain poor and little variable molluscan assemblages. Species such as *Gyraulus acronicus*, *G. laevis*, *Lymnea peregra ovata*, *Valvata piscinales*, *Pisidium nitidum*, *P. milium* and *Sphaerium corneum* had a wide ecological valence. They were adapted to life under cold conditions. At several sites there were found boreal-arctic faunas, with *Pisidium stewarti*, *P. obtusale lapponicum* and *P. lillieborgi*. The opening of the Holocene shows itself in a change in the lake fauna and the successive expansion of such species as: *Bithynia tentaculata*, *Gyraulus albus* and *Planorbis corneus*. The phase of infill and growing up of the water bodies is marked by the presence of amphibiotic and hygrophilous snails. This phase was preceded by the concentration of *Valvata piscinalis* and *V. piscinalis antiqua* shells in mass. Such shell beds represent secondary enriched thanatocoenoses (Alexandrowicz 1988b). Isolated Late Glacial freshwater chalk sites, with *Pisidium stewarti*, *P. lillieborgi*, *Gyraulus laevis* and *Vertigo genesii* occur in the Jasło—Sanok Depression, within the Wisłok and Wisłoka tributary catchments (Alexandrowicz 1981, 1984).

Tufa and travertines originated throughout the Holocene. Such deposits occur mostly in the Carpathians and in the Cracow Upland. A few occurrences are known from the Świętokrzyskie Mts, and from the middle and lower reaches of the Vistula Valley (Fig. 68). In the Carpathians three phases of calcareous tufa deposition may be distinguished (Alexan-

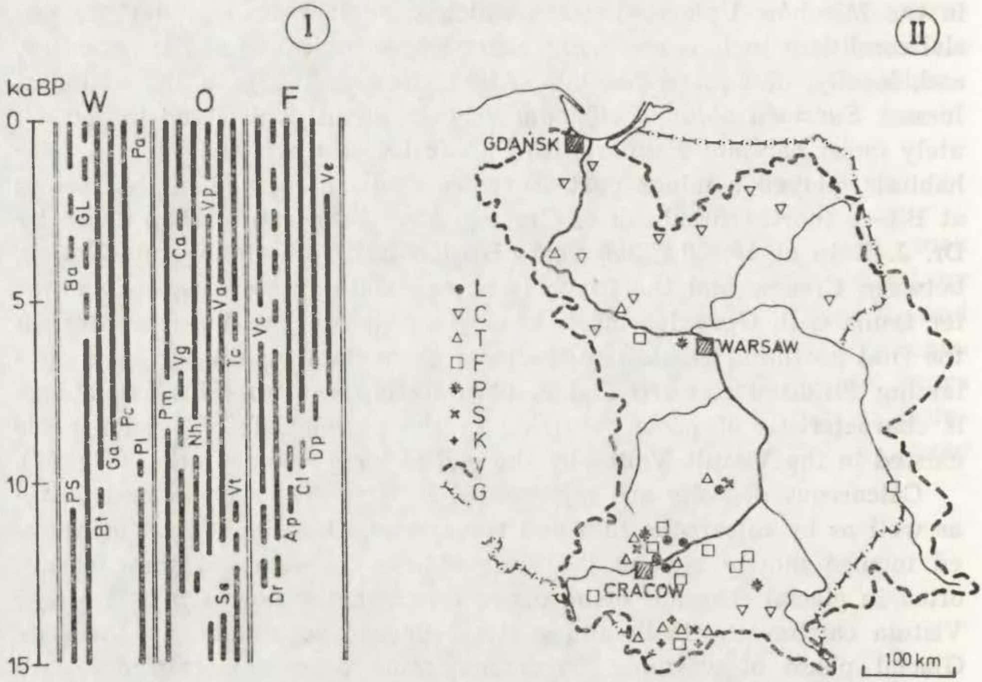


Fig. 68. Main *Mollusca* sites within the Vistula catchment

I—Stratigraphical ranges of selected species of *Mollusca* in the Late Glacial and Holocene profiles. Key: ka BP—age, thousand years, W—water environments, O—open and partly shadowed environments, F—forest environment; species: Ps—*Pisidium stewarti*, PL—*P. obtusale lapponicum*, Gl—*Gyraulus laevis*, Ga—*G, albus*, Bt—*Bithynia tentaculata*, Pi—*Planorbis corneus*, Ba—*Bythinella austriaca*, Pa—*Physa acuta*, Pm—*Pupilla muscorum*, Pl—*P. loessica*, Vg—*Vertigo genesii*, Va—*V. angustior*, Ca—*Cecilioides acicula*, Vp—*Vallonia pulchella*, Vt—*V. tenuilabris*, Se—*Succinea oblonga elongata*, Nh—*Nesovitrea hammonis*, Tc—*Truncatellina cylindrica*, Vc—*Vitrea crystallina*, Dr—*Discus ruderatus*, Dp—*Discus perspectivus*, Ap—*Aegopinella pura*, Cl—*Cochlodina laminata*, Ve—*Vestia elata*

II—Distribution of subfossil malacofauna sites. Types of fauna containing deposits: L—loesses, C—freshwater chalk and gyttja, T—calcareous tufa and travertine, F—fluvial deposits, P—fossil soils, S—slope-derived deposits, K—landslide deposits; V—watershed of the Vistula catchment, G—state boundary

drowicz 1984). Evidence for the first phase at the beginning of the Holocene is available mostly in the Podhale (at Gliczarów and Ostrysz). Calcareous deposits of this age contain molluscan assemblages, with a high proportion of euryecologic species being typical of open environment. Taxa adapted to life under cold conditions include *Columella columella, Vertigo genesii, V. geyerii* and *Semilimax kotulai* as well as the boreal species *Discus ruderatus*. The second phase of tufa sedimentation corresponds to the climatic optimum of the Holocene. It is characterized by a rich malacofauna and a high proportion of forest snails, amongst others: *Discus perspectivus, Aegopinella pura, Vitrea diaphana, V. crystallina, Iphigena plicatula, Vestia gulo,* and *Isognomostoma isognomostoma*. The third and youngest phase is shown in the late Holocene, and even in present-day tufa and travertines. Their fauna corresponds to modern habitats. A characteristic species may be *Bythinella austriaca.*

In the Cracow Upland and Świętokrzyskie Mts two types of sequences of molluscan assemblages may be distinguished in the calcareous tufa profiles (Alexandrowicz 1983b, 1987). The first type has been described from the narrow and deep valleys. The second type has been recognized in the wide and flat-floored valleys. These sequences differ from each other by the proportion of forest species. In the first type forest species are abundant, whereas in the second type they are an accessory component. The Lower Holocene deposits include poor assemblages, with *Discus ruderatus, Vallonia pulchella, Nesovitrea hammonis,* and *Lymnea truncatula.* Taxa increase in number in Middle Holocene times. There occur either forest snails (*Acanthinula aculeata, Discus rotundatus, D. perspectivus, Orcula doliolum, Vitrea crystallina,* and *Clausillidae*) or mesophilous snails (*Cochlicopa lubrica, Punctum pygmaeum, Vitrina pellucida, Euconulus fulvus,* and *Carychium tridentatum*). The Upper Holocene fauna indicates the continued forest clearance which led to the arrival of snails. These are typical of open environment and xerothermical habitats, amongst others: *Vallonia costata, Pupilla muscorum, Cochlicopa lubricella,* and *Truncatellina cylindrica.* The above assemblages are found locally replaced by a water fauna. The profiles discussed do not embrace the historical period.

In the fluvial deposits different molluscan assemblages are embedded. In the channel deposits the malacofauna is scant and poorly preserved. These are usually allochthonous thanatocoenoses including both land snails and rheophilous water molluscs which occur in silt, sand, and sand with gravels containing abundant plant remains. Characteristic sequences of such assemblages have been described from cutoff fills occurring, *eg* in the Wisłoka Valley near Dębica, in the Prądnik Valley near Cracow, in the Sancygniówka Valley near Działoszyce, in the Bug Valley near Hrubieszów, and in the Vistula Valley near Kępa Polska (Alexandrowicz 1980, 1984, 1987). The first member of such a sequence includes usually water faunas, with *Lymnaeidae* and *Planorbidae.* These correspond to a period when closed water basins existed there. In the higher parts of the profiles the proportion of both amphibiotic and hygrophilous species tends to increase. There occur *Anisus leucostomus, Planorbis planorbis, Lymnea truncata, Vertigo antivertigo, Succinea putris,* and *Zonitioides nitidus.* The phase of infill and growing up of the oxbow is marked by the complete disappearance of the water fauna and the high proportions of both mesophilous snails and snails being typical of open environment: *Vertigo angustior, Punctum pygmaeum, Euconulus fulvus, Vallonia pulchella, Pupilla muscorum,* and *Perforatella bidentata.* The type of the malacological sequence described may occur in deposits of differing age.

Overbank deposits are represented mostly by mineral and organic "mada" which contains shells of hydrophilous, mesophilous, and meadow snails. Water molluscs play a minor part there. In the malacofauna assemblages *Vallonia pulchella, V. costata, V. enniensis, Pupilla muscorum, Cochlicopa lubrica, Vertigo angustior, Succinea oblonga, Valvata cristata,* and *Lymnea truncatula* are dominant. A characteristic feature is the absence of forest snails. "Mada" containing such a fauna was laid down on the valley bottoms being dominated by moist, and even wet open habitats. The major phases of "mada" deposition were associated with clearance and farming episodes from the Neolithic onward until the rapid development of potato plantations (Alexandrowicz 1987, 1988a). "Mada" containing a Middle and Upper Holocene molluscan fauna has been reported from many fluvial valleys dissecting the Cracow Upland, the Miechów Upland, and the Świętokrzyskie Mts (Fig. 68).

In the soil profiles well preserved molluscan shells are found sporadically. Special attention should be paid to a site located in the Kampinos Forest near Warsaw (Baraniecka, Konecka-Betley 1987). On calcareous tufa that precipitated near the springs there developed a thin organic-carbonate soil which represents the last millenia. This deposit contains a very rich malacofauna, with dominant mesophilous and meadow species: *Vertigo angustior, V. antivertigo, V. pygmaea, Pupilla muscorum, Vallonia pulchella,* and *Succinea oblonga.* In the lower part of the profile water species are important. These are typical of both flooded areas and periodically drying up water bodies: *Lymnaea truncatula, Planorbis planorbis, Anisus leucostomus,* and *Segmentina nitida.* The malacological sequence indicates the gradual desiccation of the environment due to channel downcutting and drainage of the valley floor (Alexandrowicz 1983a).

Other fauna occurrences in soil environment are known from Jerzmanowice near Ojców and from Olimpów near Rzeszów (Fig. 68). The molluscan assemblage found at Jerzmanowice has been dated at c 1500 years BP. This fauna consists of forest and mesophilous snails which lived in the Cracow Upland before the major phase of forest clearance. The second site is marked by the presence of a steppe fauna which developed already in a forestless country.

Slope-derived deposits comprising subfossil snail shells include limestone debris, clay with limestone and marly particles, and dusty clays. These are separated by fossil soil horizons and beds being especially rich in humus and plant remains. Malacofauna is less frequently found there. Its occurrences are known from the Pieniny Mts, the Cracow and Miechów Uplands, and from the Świętokrzyskie Mts (Fig. 68). In the lower part of such molluscan sequences the species are cold climate types. In the middle part of the sequences there occur assemblages with forest snails, whereas in the upper part the assemblages are characteristic of forestless dry, and even xerothermic habitats. The three phases of fauna development previously mentioned correspond to the Pleniglacial and Late Glacial, to the Lower and Middle Holocene, and to the Late Holocene, together with the historical period.

Rich and characteristic molluscan assemblages have been found in the fills of pools being confined by slipped masses. In the Carpathians such fills developed in the surroundings of Czorsztyn, Krościenko, Szczawnica, Piwniczna, and Krynica (Alexandrowicz 1988a). They date mostly from the Lower and Middle Holocene, and from historical times. The malacofauna includes species living in habitats which existed around the landslides at the time of their formation. These are forest, mesophilous and hydrophilous snails being characteristic of hill slopes and valley floors. Water molluscs which indicate the kind of the basin of deposition also occur there. Sites grouped in the surroundings of Krościenko on the Dunajec River have been dated to the last millenium. They suggest that in the mountainous reaches of the side valleys changes in the natural environment are less evident than in the other areas, though the fauna became impoverished during the last century.

Changes in both climate and natural environment which took place in Late Glacial and Holocene times may be inferred from malacological record (Fig. 68). In the aquatic environments a climatic amelioration is most evident at the boundary of the Vistulian and Holocene. This led to the diminution in some boreal—arctic species which were replaced by more warmth-demanding taxa. In Upper Holocene times, but especially in the historical period both drainage and desiccation of the valley floors favoured the development of molluscs being well adapted to life in the periodically disappearing water bodies. As a result of increased contamination of water in the second half of this century some species such as *Physa acuta* are migrating in habitats associated with industrial development (Alexandrowicz 1986).

Changes in land snail assemblages are more marked (Fig. 68). The Late Glacial fauna contains more taxa than the Pleniglacial fauna. During the Late Glacial there arrived species which extend as far north as the 63 parallel, and even the Polar Circle today. In contrast to some species being typical of loesses which disappeared in Poland at the beginning of the Holocene, the species previously mentioned live in our country today. The expansion of deciduous forests in Boreal and Middle Holocene times favoured the arrival of rich assemblages including taxa of a limited ecological valence. The majority of them persisted until the present days in zones containing little modified habitats, chiefly in the national parks and nature reserves. The degradation of the natural environment due to human activites, but especially the deforestation of large areas throughout the upper Holocene led to the impoverishment of the malacocoenoses, and to the expansion of species that prefer forestless and less shadowed habitats. At the same time, the development of farming favoured the arrival of species living underground such as *Cecilioides acicula*. In the present century a remarkable expansion of the synanthropic fauna takes place. The latter is a characteristic feature of the youngest deposits (Alexandrowicz 1988a).

CHANGES IN CLIMATE AND HYDROLOGICAL REGIME INFERRED FROM ISOTOPIC AND SEDIMENTOLOGICAL STUDIES OF CALCAREOUS TUFA[5]

Calcareous tufa precipitated from normal surface water appear to be highly significant indicator of the past changes in both climate and hydrological regime because of their direct relation to the environment of deposition. The presented reconstruction of the course of calcareous deposition, of fluvial activity, and of changes in palaeotemperatures during the Holocene is based on results of sedimentological and isotopic studies which were made of four calcareous tufa sites in southern Poland (Racławka, Rzerzuśnia, Trzebienice, Sieradowice). The first three sites were studied in detail by Szulc (1984, 1986). Calcareous sediments occurring at Sieradowice were described by Jersak *et al* (1983). All ^{13}C and ^{18}O measurements were performed on samples which have been dated by using the ^{14}C method (Pazdur 1987, 1988; Pazdur *et al* 1988, in press). This provides a precise time scale for reconstructing the environmental changes. High values of the isotopic concentration of oxygen ^{18}O (higher values of $\delta\ ^{18}O$) in spring calcareous tufa indicate relatively warm phases. Smaller values correspond to cold phases. Both warm and cold periods are reflected in the isotopic concentration of carbon ^{13}C ($\delta\ ^{13}C$) because of a positive correlation between $\delta\ ^{18}O$ and $\delta\ ^{13}C$ at most of the sites studied (Pazdur 1987; Pazdur *et al*, in press).

COURSE OF THE CARBONATE DEPOSITION AND FLUVIAL ACTIVITY

The Racławka site. This site has a relatively great number of ^{14}C dates obtained on tufaceous sediments and three dates on organic sediments. Radiocarbon dates were complemented by pollen analysis of the basal part of the profile (Madeyska, ms, unpublished). Sedimentological studies, together with the ^{14}C and pollen data, lead to the following reconstruction of events: the oldest sediments resting on the bottom of the Racławka Valley are represented by a fossil soil belonging to the Younger Dryas (10,630 ± 80 BP). This soil developed immediately on the limestone bedrock. The fossil soil level is overlain by calcareous tufa. This indicates that carbonate deposition started just before the beginning

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[5] Translated by A. Pazdur

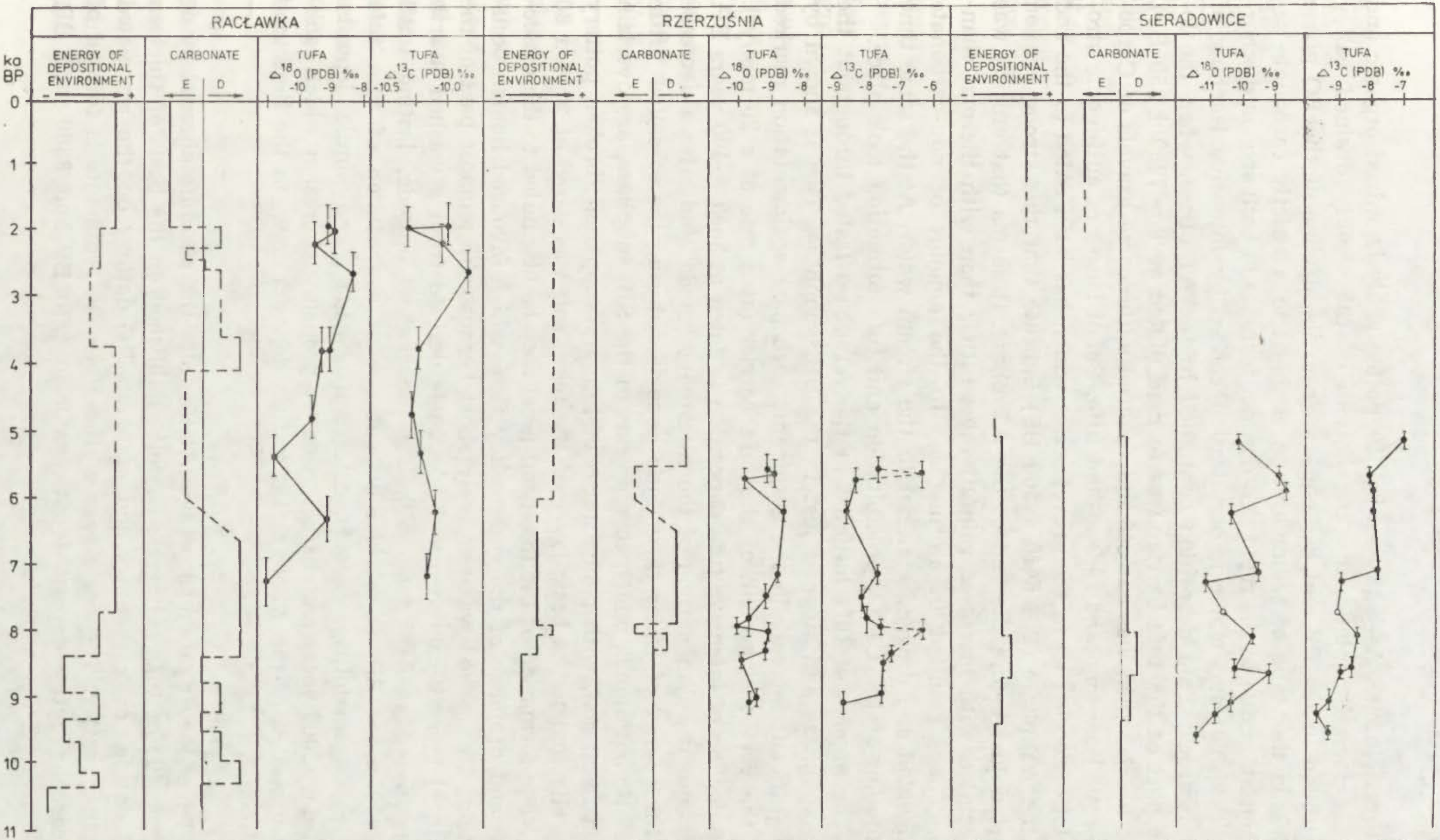

Fig. 69. Energy of the depositional environment, course of the carbonate deposition and the composition of stable isotopes in tufa at the Racławka, Rzerzuśnia, and Sieradowice sites

of the Holocene. As is proved by the pollen analysis, mixed organic and carbonate sedimentation on the bottom of the weakly drained valley continued in the PB and BO phases. From the decline of the BO phase onwards this type of sedimentation changed to a strictly carbonate sedimentation due to the rapid and distinct increase in both stream discharges (Fig. 69) and water mineralization caused by intensive leaching of the bedrock. Tufa deposition continued in the AT phase, when the lower part of the tufa barrier was formed (dated at T = 7280 ± 350 BP). The barrier then was cut off and covered with coarse gravels of Carboniferous limestone and redeposited tufa. Small lenses of authigenic stromatolites occurring in the gravel series which has been dated to the end of the AT phase (T = 5410 ± 360 BP) indicate that this strong erosion started just before the end of the AT phase. It seems that erosion was associated with increased rainfall rates rather than with thermal changes. These resulted in an increase in the amount of non-carbonate suspended and dragged material in the stream water. At the same time reduction of the $CaCO_3$ precipitation and tufa formation took place.

The erosion of tufa initiated in the AT phase lasted throughout the SB_1 subphase and stopped just in the SB_2 subphase. This is shown by a significant increase in the authigenic carbonate sedimentation marked by the very fast growth of the tufa barrier (at a rate of *c* 20 mm/yr). The decline of intensive tufa deposition is dated at 3800 ± 400 years BP. Subsequent sedimentation of the calcareous "mada" indicates a decrease in the energy of water flow. Tufa deposited during the so-called "little climatic optimum", which corresponds to the SB_2 subphase, are overlain by a fossil soil, with many traces of human occupation (broken pottery and charcoals). The basic layer of the fossil soil was dated at 2710 ± 80 BP. The formation of the fossil soil level may be attributed to the dissection and drainage of the wide valley floor which favoured human occupation. This period was relatively short because the topmost part of the cultural layer became washed (charcoals derived from a washed hearth were dated at 2475 ± 60 BP). The next short episode, lasting until c 2000 years BP, is marked by subsequent aggradation of thin tufa layers (stromatolites, oncoids, calcareous "mada") and humic deposits. The last 2000 years are characterized by pronounced erosion which caused dissection of the whole series of tufa deposits down to the limestone bedrock.

The Rzerzuśnia site. At this site the absolute chronology of the profile of tufa sediments is well established on the basis of thirteen ^{14}C datings on carbonates and of seven ^{14}C datings on the associated organic matter. The basic part of the Holocene sediments is formed of calcareous gyttja deposited between 9040 ± 70 BP and 8360 ± 60 BP.

Around 8400 years BP a rapid increase in carbonate sedimentation is marked in the profile (Fig. 69). This episode lasted at least until 6500 years BP. Tufa deposition became interrupted between 8010 ± 140 years BP and 7910 ± 110 years BP due to high floods and deposition of a 0.5 m layer of redeposited tufa. The next phase which started around 6.5—6.0 ka years BP and lasted until 5560 ± 110 years BP is characterized by erosion and tufa redeposition. The layer of redeposited tufa is overlain by authigenic tufa which was laid down in turbulent water (oncoids and stromatolites). ^{14}C dates of these authigenic sediments show that they were deposited in the AT phase. Younger tufa are not present. The topmost part of the profile consists of a loessic deluvium which was deposited probably in the SA_1 phase.

The Trzebienice site. Though this profile has a significantly smaller thickness than the former one, it shows a similar sequence of depositional events. Its basic part consists of gyttja which rests immediately on the Jurassic—Cretaceous bedrock. This level has been dated at 8760 ± 100 years BP. It is overlain by tufa (calcareous "mada", stromatolites, and oncoids) which indicate the rapid drainage of the valley floor. The topmost tufaceous deposits are dated at 7380 ± 180 years BP. The lack of younger deposits is due to an erosional hiatus. A superimposed soil horizon developed around 2700 years BP. It shows the very same stratigraphical position as the fossil soil level in the Racławka Valley (2710 ± 80 BP). The topmost part is formed of a loessic deluvium.

The Sieradowice site. This site differs from those described above by having quite uniform conditions of carbonate sedimentation which took place in a shallow water body, either stagnant or with a very slow flow (Fig. 69). This is indicated by deposition of monotonous series of fine-grained calcareous sediments (mostly calcareous "mada") showing a variable proportion of organic matter (Jersak *et al* 1983). The basic part of the deposits consists of a calcareous gyttja overlain by a bog soil. The end of organic deposition is dated at around 9.7 ka years BP, though at this site the transition from organic to carbonate deposition is not observed. In the first phase of carbonate sedimentation (9600—8670 years BP) the rate of the latter was moderate (c 0.8 mm/yr). Subsequently it increased to 3.3 mm/yr (8670 ± 8080 years BP). In the final phase of carbonate deposition sedimentation rates were steadily decreasing (c 1 mm/yr within 8080—7100 years BP; c 0.6 mm/yr within 7100—5100 years BP). On the calcareous "mada" there developed a bog soil which has been dated at 4870 ± 70 years BP. It is covered with silty deluvia.

CONCLUSIONS

The increased intensity of calcareous precipitation at the beginning of the Boreal phase (*c* 9.5 ka years BP, see Figs. 69 and 70) is observed at all tufa sites examined. This high precipitation rate continued into the Atlantic phase at all sites studied, except Trzebienice, where calcareous sediments postdating 7.4 ka years BP do not occur. At Rzerzuśnia and Sieradowice sedimentation came to an end about 5.5 ka years BP, whereas in the Racławka Valley sedimentation continued throughout the Subboreal phase until around 2.0 ka years BP.

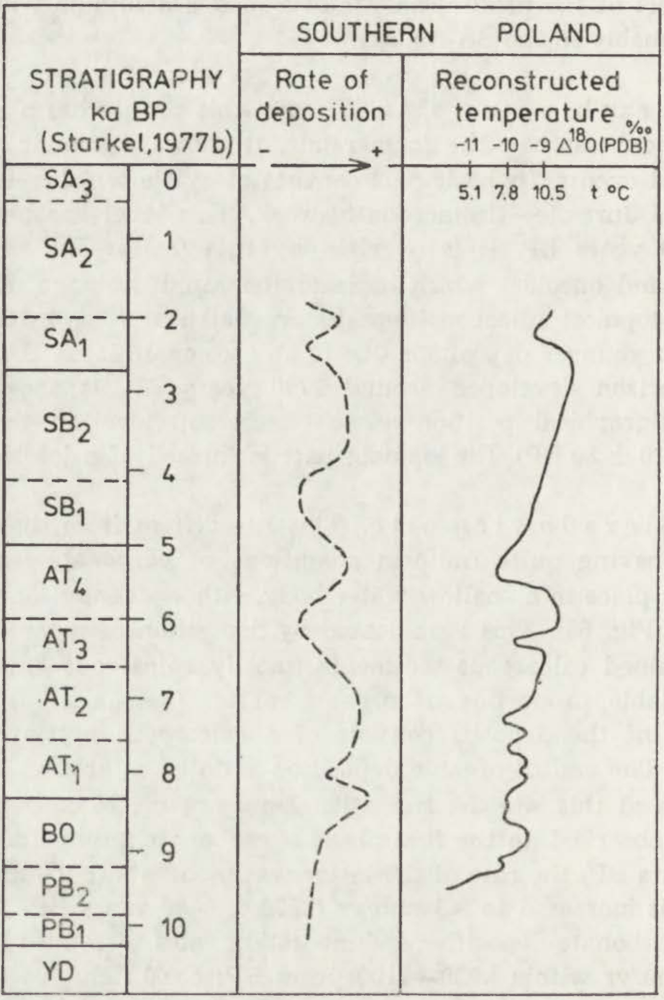

Fig. 70. Summarized course of the erosion and sedimentation at all tufa sites studied. The palaeotemperature curve which has been reconstructed from $\Delta^{18}O$ measurements indicates changes in the mean annual temperatures from around 9500 BP to as late as 2000 years BP

Erosional episodes being associated with increased fluvial activity, that has been observed at the sites investigated, correspond to cool periods. These are indicated by the isotopic concentration of both oxygen and carbon (small values of both $\delta\ ^{18}O$ and $\delta\ ^{13}C$).

Generalized results of sedimentological and isotopic ($\delta\ ^{18}O$) data are shown in Figure 70. The scale of mean annual temperatures was constructed assuming that secular changes in $\delta\ ^{18}O$ in the tufa are represented by seasonal changes in $\delta\ ^{18}O$ with variable temperature observed in the precipitation in the Cracow Upland (Pazdur 1987; Pazdur *et al*, in press). Figure 70 shows that warm and humid periods being favourable for tufa precipitation occurred between 8.6 and 5.0 ka BP, and between 4.5 and 2.4 ka BP. A similar short episode may be also noted around 2.0 ka BP. The rate of tufa sedimentation was especially high between c 8.4 and 8.0 ka BP. The correlation between erosional phases and temperature drops observed at the individual sites is not so clear in the generalized results. This difference may be explained by the fact that isotopic temperatures represent regional changes, while erosional episodes may have a local nature.

HYDROLOGICAL AND PALAEOGEOGRAPHICAL CHANGES WITHIN THE VISTULA CATCHMENT AGAINST THE BACKGROUND OF CENTRAL EUROPE

The presented results of investigation of both deposits and landforms, and of other elements of the environment show a similar rhythm of changes occurring as a response to changes in the thermal and humidity regimes of the catchment. Moreover, data for the whole of Central Europe and for regions farther east of the Vistula drainage basin show that fluvial and other changes were synchronous throughout this area.

ENVIRONMENTAL CHANGES IN THE VISTULA CATCHMENT

Fluctuations of both stream discharges and sediment transport in the Vistula drainage basin tended to decrease during the Late Glacial. This tendency is reflected in channel changes from a braided to a meandering river system and from a phase of large to small palaeomeanders. Superimposed on this tendency are rhythmical fluctuations of the flood frequency. These are documented by several inserted Holocene fills and channel avulsions which in turn became disturbed by man-induced aggradation (Fig. 59).

In the vegetational history there has been observed a similar change from tundra and forest-tundra assemblages to birch forests during the Bølling, and to pine-birch forests during the Allerød, with cool climate park assemblages which reverted to birch-pine forests in Preboreal times (Wasylikowa 1964; Ralska-Jasiewiczowa 1983a). The humidity of climate (8.5 ka years BP) shows itself in the change from pine forests with elm and hazel to dense mixed and deciduous forests. At the beginning of the Subboreal elm and line declined, whereas spruce expanded in the mountains. The subsequent temperature rise in the Subboreal brought about the expansion of hornbeam, beech, and locally of fir. The Subatlantic deterioration in climate caused the spruce to expand.

The Bronze Age was clearly dominated by man's activity which increased in late Roman times and in the Middle Ages. Many pollen diagrams which have been interpreted by means of numerical methods within the IGCP Subproject 158-B (Ralska-Jasiewiczowa 1987) allow us to recognize several sudden changes in the vegetation cover which may be correlated with climatic changes. Phases of either expansion or changes in vegetation 10.3—10.0, 9.1—8.7, and 3.7—3.4 ka years BP should be explained by a distinct temperature rise. Most of the vegetational changes may be correlated with wetter and/or cooler phases: 8.2—7.7, 5.1—4.9, 4.4—4.1 ka, and less clearly 7.3—6.9 and 2.3—2.0 ka years BP.

In the soil development there are discernible phases of both pronounced leaching and humus accumulation (Kowalkowski in press). In dune areas the latter are synchronous with wetter phases. Coastal dunes antedating the wetter Roman period (beginning *c* 400 years BC) show the same degree of podzolization (Prusinkiewicz, Noryśkiewicz 1966). On the contrary, during the Late Glacial humus accumulation took place in the warmer phases.

The picture of palaeolake fluctuations is very intricate because of diverse causes (cf. pp. 170 — 178). The recent list of more than ten Polish lakes and mires (Ralska-Jasiewiczowa 1987) revealed the occurrence of phases of rising lake levels. The first phase (9.7—9.2 ka years BP) probably corresponds to the melting out of buried ice masses. The later phases may be correlated with events that took place in the valleys 8.3—7.5, 5.0—4.2, 3.3—2.8, and 2.2—1.8 ka years BP. In some lakes the Boreal peats are overlain by lacustrine deposits (*eg* in Lake Gopło——8170 ± 250 years BP; Niewiarowski 1978). The inundation of the Hallstatt site at Biskupin, in the Noteć catchment, which occurred around 400 years BP provides the basis of the reconstruction of changes in the water balance. According to Skarżyńska (1965), in the preceding 300 years precipitation rates increased from 413 mm to 658 mm, and discharges increased from 60 mm to 204 mm. In the abandoned ice marginal channels ("pradoliny") there has been a continuous organic aggradation, but the groundwater tabel rise was most distinct 8.0—7.4 years BP and after 2.4 ka years BP (Balwierz, Żurek 1987).

Studies carried out in the Małopolska Upland revealed several fluctuations of calcareous tufa accumulation due to changes in both temperatures and the activity of flowing waters. Szulc (Pazdur *et al* 1988, in press) demonstrated that tufa growth was most intensive during the warm phases: 9—8, 7.5—6, 5.5, and 3.5—3 ka years BP. These phases correspond to phases of freshwater chalk accumulation in Pomerania (Gołębiewski 1981). Fluvial activity resulting in hiatuses of tufa deposition was greatest around 8, 6, 5—4, *c* 2.5 ka, and after 2 ka years BP. The succession of changes in both climatic and hydrological conditions can also be ascertained by changes in the malacofauna (cf. pp. 178—184). Alexandrowicz (1984) found that in the broad and flat-floored upland valleys a water fauna was dominant during the Younger Dryas and 8.5—7.7 ka years BP, whereas in the canyons the proportion of forest elements increased at the beginning of the Atlantic period and in the early Subboreal.

In addition, dates obtained from about ten Carpathian landslides

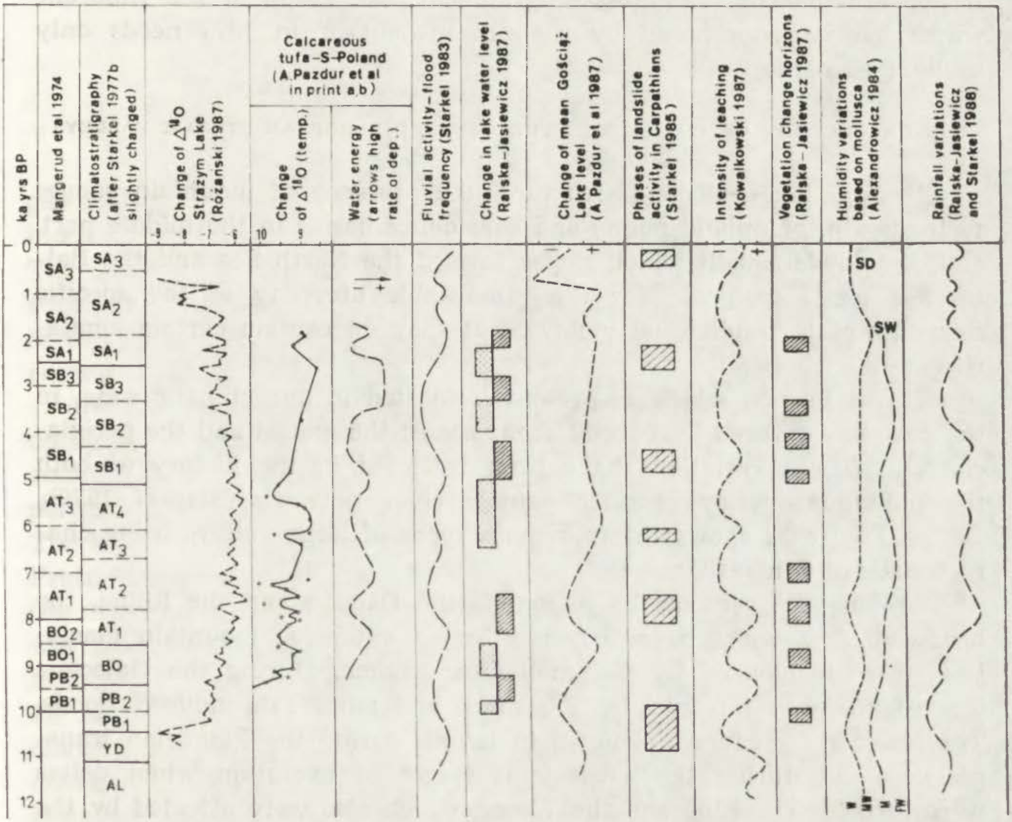

Fig. 71. Correlation of various events in the Vistula basin and their palaeohydrological and palaeoclimatic interpretation

Abbreviations in column on molluscs: SD—wide valley floors; SW—narrow canyons; habitats: W—water, MW—wet meadows, M—meadows, FW—forest and open woodlands

(Gil *et al* 1974; Starkel 1985) show that landslipping coincided with events that took place within the valley floors. Besides the Late Glacial phase of groundwater basin formation, dates from the base of depressions occurring on the landslides all fall into groups of similar ages: 8.4—7.7, c 6, 5—4.5 ka BP, and the last 300—400 years (cf. Alexandrowicz 1988a).

At several sites the ^{18}O and ^{13}C isotopic analysis has been made of both calcareous tufa and lake-deposited sediments. The tufas indicate a distinct temperature rise prior to 9.3 ka years BP and distinct culminations during the periods: 9.0—8.5, 7.5, 6.0—5.5 ka years BP, and in the late Subboreal (Pazdur *et al* 1988, in press). In Lake Strażym the rise in temperature could be dated to two periods—the onset of the Holocene and around 9.3 ka years BP. Culminations occurred around 8.4, 7.5, and 5.1 ka years BP (Różański 1987).

All data (Fig. 71) indicate that changes in both climatic and hydrological conditions were synchronous throughout the Vistula catchment. It appears that the climato-stratigraphical subdivision of the Holocene which has been proposed by the present author in 1977 needs only a slight correction.

THE CHRONOLOGY OF CHANGES IN THE CENTRAL EUROPEAN STREAM VALLEYS

The complex geological structure, the presence of mountain ranges to the south, of upland horsts and subsidence basins in the middle part, and of a lowland belt which slopes toward the North Sea and the Baltic Sea are responsible for the remarkable diversity of the specific segments of the individual valleys, but they do contain certain similarities.

Central Europe which at present is located in one climatic zone, in the past was covered by two different zones: the glacial and the periglacial one. These variations have been reflected in the history of both the individual valleys and the entire river network (Starkel 1979b, 1983a). Figure 72 shows the four main types of large valleys being characteristic of Central Europe.

The largest rivers of the region, *ie* the Danube and the Rhine, the headwaters of which were covered by an extensive mountain glaciation, were influenced by the meltwater regime. During the Holocene this regime was replaced by the more and more rain-induced floods. The lower river courses changed in length during the Flandrian transgression and during the subsequent stages of evolution when deltas were formed. The Elbe and the Weser, which also were affected by the Flandrian transgression, have their headwaters in the unglaciated low mountains and uplands (800—1500 m a.s.l.). Farther east the regime of the great rivers Odra and Vistula is influenced by high stream dischar-

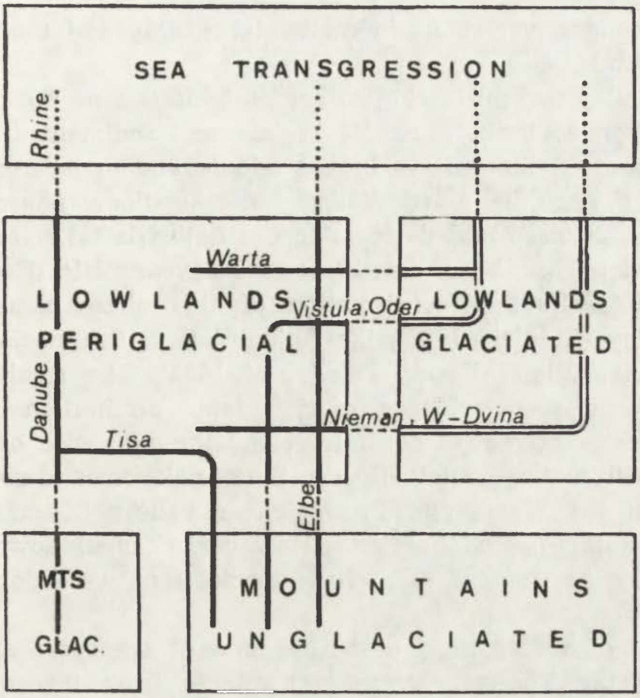

Fig. 72. Reaches of valley types being characteristic of Central Europe

ges rising in the mountains. The lower reaches of these rivers were blocked by the Scandinavian inland ice, and water escaped westward. The remaining rivers whose lower reaches were blocked by the ice sheet, *ie* the Western Dvina, Nieman, and Warta have their headwaters in the lowland areas. The structure of their alluvia does not reflect the second-order fluctuations of precipitation.

In the Pomeranian phase of ice retreat in the ice foreland there operated a huge river which carried glacial meltwater from the surroundings of Vilnius to Jutland. At the same time, it carried water of the periglacial rivers Nieman, Bug, Vistula, Warta, Odra, and Elbe (Fig. 60). The longest segment was the Vistula. Hence, the river may be called the Proto-Vistula which drained to an oceanic bay in the northern part of the North Sea. As the inland ice retreated and the Baltic depression was laid bare, this fluvial system became disrupted. The Nieman, Vistula, and Odra diverted to the Baltic Sea. Between 14 ka and 10 ka years BP rapid downcutting took place in the lower river reaches (cf. Voznyachuk, Valczik 1977; Starkel ed. 1982; Brose, Präger 1983). In the abandoned wide reaches of the ice marginal channels which carry underfit streams, *ie* the Noteć and Narew, together with the Biebrza, slow organic aggradation takes place today (Galon 1961; Balwierz, Żurek 1987). The intricate history of the system of different "pradoliny" and the cross-connections between them (Woldstedt 1958; Galon 1968) reflects baselevel changes, variations in meltwater supply and the influence of glacial rebound.

In the valley system of the former periglacial zone the climatic evolution of changes in both runoff regime and sediment transport was similar to that of the valleys in the middle and upper reaches of the Vistula. In the middle Warta Valley the transitional phase of changes from the periglacial braided rivers to the Late Glacial rivers possessing large meanders has been dated at 13 ka years BP (Kozarski 1983; Antczak 1986). Further confirmation of this phase comes from the Prosna Valley (Rotnicki 1983), the Rhine Valley (Brunnacker 1978) and the Hungarian Plain (Borsy, Felegyhazi 1983). The smaller Holocene palaeomeanders give evidence of the later diminution of sediment supply, the final retreat of permafrost and the expansion of forest communities within the valley floors. Such palaeomeanders have been identified in the Warta and Prosna River valleys (Kozarski, Rotnicki 1977) and in the Alpine Foreland. However, channel downcutting and stepwise dissection of the great fluvioglacial fans were dominant there (Troll 1957).

Evidence of reactivation of both sediment transport and aggradation during the Younger Dryas is available from the upper Vistula drainage basin, from the Nieman Valley (Voznyachuk, Valchik 1977), from the upper Main Valley (Schirmer 1983), from the Aar Valley (Heine 1982), and from northern Belgium (Munault, Paulissen 1973).

In the valleys which are drained by rivers fed by the catchments entirely located in the lowland both continuity of alluvia reworking and lateral channel migrations during the Holocene are frequently accepted (Kozarski 1983; Rotnicki 1983). However, recent measurements of palaeomeander parameters of the Prosna and discharges inferred from them indicate temporal variability (Rotnicki, in press). In the small valleys found in the surroundings of Łódź a distinct reactivation of creeks occurred around 8.5 and 5.0 ka years BP (Turkowska 1988). In the Neris (= Viliya) Valley, a tributary of the Nieman, channels were abandoned around 8.0, 6.1—3.9, and 2.9 ka years BP (Gaigalas, Dvareckas 1987).

In the valleys drained by mountain and upland rivers, on which there occur frequent floods induced by long-lasting rains, several Holocene inserted fills, traces of channel avulsions, and isolated terrace benches are found usually. Phases of increased activity of the Central European rivers are shown in Figure 60. Such phases were early recognized in the Carpathian Foreland (Starkel 1960) and in the Weser Valley (Lüttig 1960). Terrace systems occur in most valleys of the Alpine Foreland (cf. Schreiber 1985). In the Austrian reach of the Danube Valley phases of increased erosion were dated at 8.1—7.6, 5.1—4.5, and 3.0—2.7 ka years BP (Fink 1977). Several terrace steps and inserted alluvial fills were recognized in the upper Main Valley (Schirmer 1983). Systems of inserted terraces have been described by Paulissen (1973) from the Maas Valley and by Brunnacker (1978) from the lower Rhine Valley. It should be noted that in the Rhine Valley dates of 6.45—6.1, 5.3—4.6, and 4.1—3.4 ka years BP denote phases of distinct aggradation being rather independent of sea level fluctuations (van der Woude 1981). Of great value in correlating the events which took place in the catchments of the Rhine and the upper Danube are dendrochronological studies. According to Becker (1982), phases of increasing accumulation of the black oaks (being synchronous with phases of deposition of new alluvial series) were dated as: 8.7—8.0, 5.0—4.3, 3.9—3.1, 3.0—2.7, 2.4—1.9, and 1.7—1.3 ka years BP. It is probable that the youngest phases are related to phases of increased human interference. In the Hungarian Plain, where aggradation is dominant (Mike 1975; Vaskovsky 1977; Borsy, Felegyhazi 1983) numerous channel avulsions and inserted fills have been extensively explored and more accurately dated by Borsy in recent times. Attempts to reconstruct discharges by palaeochannel parameter analysis, nearly devoid of datings (Gabris 1985), need verification. In the Elbe catchment inserted Holocene fills were recognized by Händel (1969). An alluvial sheet with stumps dated at 5.2—4.6 ka years BP has been found in the Bóbr Valley in Poland (Florek 1982).

The fairly well synchronism of events became disturbed during the last 3000 years. This may be attributed to the increasing human impact on vegetation. Undisputable evidence for deposition of "mada" and deluvia is already available from the advanced Neolithic (the Leine Valley—4.5 ka years BP; Meyer *et al* 1983) and from the late Bronze Age. This deposition was due to the expansion of arable grounds (Brunnacker 1971; Ložek 1982; Bouzek 1982). Aggradation which coincides with the Roman period within the Vistula drainage basin was fairly common in the rest of Europe: in the valleys of the German Mittelgebirge (Richter 1965; Händel 1969; Schirmer 1974, 1983), and in the Danube catchment (Somogyi 1975; Havliček 1983). The thick medieval "mada" sheets vary from valley to valley because of the different periods of both colonization and considerable forest clearance there (Jäger 1962; Schirmer 1974; Havliček 1983). "Mada" deposition in near Moravia was synchronous with that in the upper Vistula Valley and its tributary valleys (from the 11th century onwards).

On the whole it must be said that the rhythm of climatic changes is similar in the Vistula Valley, in its tributary valleys, and in the remaining river valleys of Central Europe. At the same time, the history of the lower reach of the Vistula reflects the common evolution of the river network in the European Lowland during the deglaciation period when rivers were diverted to the developing Baltic depression.

THE SYNCHRONISM OF ENVIRONMENTAL CHANGES IN CENTRAL EUROPE DURING THE LATE GLACIAL AND HOLOCENE

The comparison of changes in the vegetation cover, fluvial systems, palaeolakes, soil development, sedimentation in the karstic areas, glacier fluctuations and oscillations of the tree line in the Alps (Fig. 73) indicates common climatic and hydrological causes of changes which took place during the Late Glacial and Holocene. We are increasingly able to correlate these results with the reconstructions of temperature changes by the ^{18}O analysis and by other methods (Fig. 73). The history of those changes reflects both long-term tendencies of the glacial—interglacial cycle on which the threefold division of the Holocene is based (Firbas 1949—1952; Neustadt 1965, 1982) and the second order rhythmical oscillations of 1500—2000 years duration each. The latter included a longer stable phase being separated by a shorter phase of between 200 and 500 years duration. This was characterized by high amplitudes of climatic variations which were mostly cooler and wetter (Starkel 1983a). It should be noted that similar phases of "discontinuity" were recognized in the evolution of both ecosystems and fluvial valleys in North America (Wendland, Bryson 1974; Knox 1975). Some of them appear to have a global range being synchronous with the climatic phases in Europe.

Some of these phases have a clearly specified general direction, *eg* the very sudden temperature rise at the beginning of the Holocene which accelerated the long-term trend to warming toward the climatic optimum. The phase of cooler and wetter climate, being probably twofold, which has been dated at 5.0—4.5 ka years BP initiated the steady tendency toward the post-optimum temperature decrease. Other climatic variations were only episodes which disrupted the general tendency to changes. The most important changes in the evolution of the landscapes of Central Europe were pronounced around 8.5—7.7 ka years BP when the wetness suddenly increased, the *Quercetum mixtum* forests stabilized (Beug 1982; Starkel 1984a), and the system of westerlies was finally established over the northern hemisphere.

Researches on fluvial systems against the background of both climatic changes and ecosystems also offer examples of evident lag in the response of the geosystems to changes in climate. The lag in the deglaciation response to climatic amelioration retarded the northward spread of trees in Europe. The invasion of Central Europe by some species such as *Abies* also was very retarded (Kral 1972; Ralska-Jasiewiczowa 1983a). In the mountains, where both temperature and precipitation variations throughout the Holocene were more distinct, this was reflected in clear oscillations of the vertical ecological belts. Variations in the fluvial regime (*ie* the variable frequency of flood

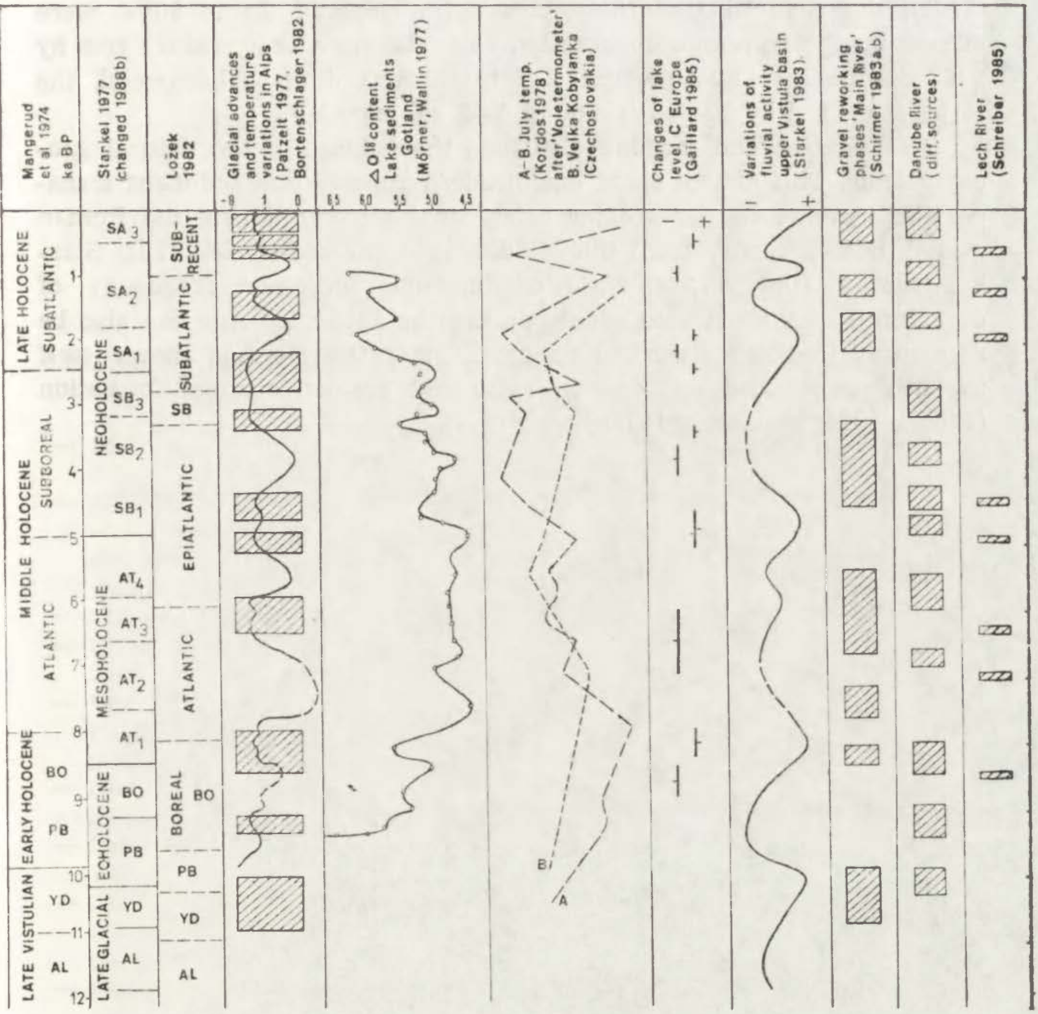

Fig. 73. Correlation of various palaeogeographical elements in Central Europe, showing synchronous course of hydrological changes

occurrence) are reflected in changes in both channel patterns and the character of sedimentation (Starkel 1984b). Those changes proceeded downvalley (Vistula, Rhine), whereas the lowland river systems slowly responded to changes. The effects of climatic cooling which expressed itself in both reduced evaporation rates and groundwater table rises are more distinct than the floods. The Atlantic period, formerly acknowledged to be the time of great wetness, appeared to be an intricate period. Between 7 and 5 ka years BP, the rates of peat growth (Ralska-Jasiewiczowa, Starkel 1988) and lake level rise (Gaillard 1985) decreased. Rivers were also active. According to Lockwood (1979) and Frenzel

(1983), the reduced stream discharges (in England up to 50%) were caused by the increased evaporation rates due to a temperature rise by 2°C, despite increased precipitation rates. According to Lockwood, the latter increased by 10—15% around 6—5 ka years BP.

Deforestation and farming disturbed the balance of the natural geoecosystems. This caused flood magnitude/frequency and sediment transport to increase in the greater catchments already during the Roman period, but especially from the Middle Ages onward (Ložek 1982; Starkel 1987a). However, climatic cooling and increased frequency of occurrence of the extreme events during the Little Ice Age can also be recognized in those disturbed systems. The Little Ice Age shows itself in both pronounced soil erosion rates and braided channel formation (Pfister 1974; Falkowski 1975; Lamb 1977).

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