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SPECIAL ISSUE No. 1

EVOLUTION OF THE VISTULA RIVER VALLEY DURING THE LAST 15000 YEARS

PART I

WROCŁAW · WARSZAWA · KRAKÓW · GDAŃSK · ŁÓDŹ
ZAKŁAD NARODOWY IM. OSSOLIŃSKICH
WYDAWNICTWO POLSKIEJ AKADEMII NAUK

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ГЕОГРАФИЧЕСКИЕ ТРУДЫ
СПЕЦИАЛЬНОЕ ИЗДАНИЕ № 1

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PART I

Editor:
LESZEK STARKEL

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PREFACE

Already since 1957 some volumes of Prace Geograficzne (Geographical Studies) edited by the Institute of Geography and Spatial Organization, Polish Academy of Sciences have been published in the other than Polish languages (see the enclosed list on the cover). As however those volumes together with those published in Polish were distributed mainly among Polish institutions or sold in the Polish bookstores, most of them never reached foreign readers, simply because the necessary information was not easily available.

To enable those foreign readers who would be interested in ordering only those volumes of the Institute's Geographical Studies that are published in the other than Polish languages (mainly in English) it has been decided that starting from 1982 all of them will be published as Special Issues of Geographical Studies. The present volume being a collective work on *The Vistula River Valley During the Last 15 000 Years* would thus be the volume No. 1 of this new series.

The Editors

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Geographical Studies
Evolution of the Vistula River Valley
PL ISSN 0373-6547

LESZEK STARKEL

INTRODUCTION
TO THE PROJECT ON THE EVOLUTION OF THE VISTULA RIVER VALLEY DURING THE LAST 15 000 YEARS
(REALIZED IN THE IGCP PROJECT No. 158 — A)

For a long time the largest river valley in Poland has been the subject of intensive geomorphological and geological research in the different valley reaches. In 1978 the interdisciplinary team affiliated to the National Committee for Quaternary Research was formed to study the paleogeographical evolution of the Vistula valley following the guide-lines of the newly established IGCP Project No. 158 "Paleohydrology of the temperate zone during the last 15 000 years". This volume presents the preliminary results of investigations in different reaches of the catchment area, even those which do not follow strictly the guide-book to the subproject A on the fluvial environment (preliminary edition 1978).

We hope these preliminary results will throw new lights on the role of different factors in the evolution of Central European valley floors during the Late Glacial and the Holocene. The final report covering other valley reaches and including a general picture and reconstruction of the palaeohydrologic and palaeoclimatic parameters will be ready after the next 4 years (Fig. 1). This volume includes 8 papers on the evolution of the Carpathian tributaries of the Vistula (the reaches of the Ropa, Wisłoka and San river valleys), of the Middle Vistula, Lower Vistula and deltaic plain.

CHARACTERISTICS OF THE VISTULA RIVER VALLEY

The Vistula drainage basin is one of the larger middle-European basins. Its catchment is 193 911 sq. km in size and the length is 1068 km (Fig. 1). The sources of the Vistula are in the flysch Carpathians from which it receives some mountainous tributaries. Headwater areas reach 1200—2500 m a.s.l. Farther downstream the Vistula flows along the Sub-Carpathian Basins, crosses the Upland belt, and then — in the Polish Lowland — it flows towards the Baltic coast through some narrowings

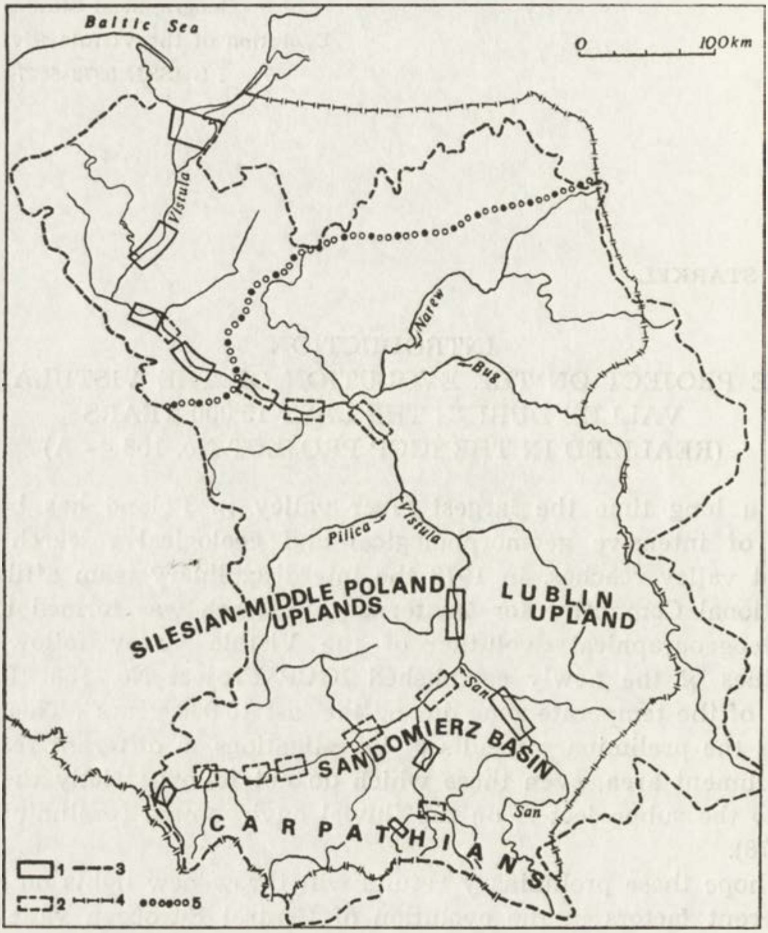


Fig. 1. The Vistula river valley reaches included in the Fluvial Subproject of IGCP Project No. 158

1 — reaches selected for elaboration in the first phase, 1978—1981; *2* — reaches proposed for elaboration in the second phase, 1981—1985; *3* — water divide of the Vistula drainage basin; *4* — Polish frontier; *5* — maximum extent of the Vistulian ice sheet

and basin-like depressions (Fig. 2). Due to its length the Vistula is at the present time a monozonal river (*cf.* Starkel 1979), but some hydrological features change gradually to the north. The annual precipitation increases in the upper course. The length of the winter season increases in the NE direction. Therefore, when in the upper course the summer floods are dominant, ice-jam spring floods are frequent in the lowland area. The régime of the main river is mainly under the influence of the headwaters. The differentiation in the S—N direction is well visible in the past. The late-glacial forest communities had moved from the south being accompanied by the retreat of permafrost. The lower course was covered by the last ice sheet. The subsequent ice retreat caused great

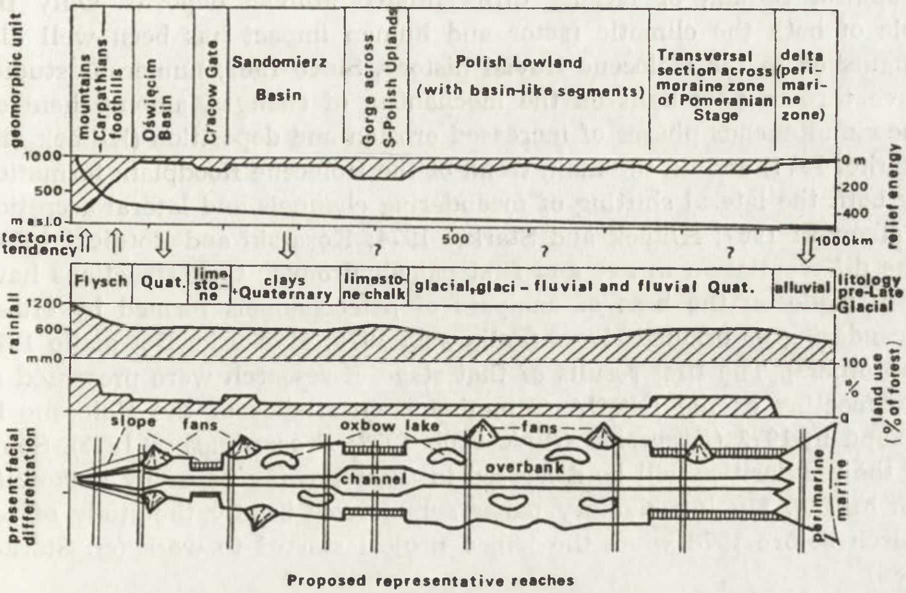


Fig. 2. Generalized transect diagramme of the Vistula river valley and its environment

changes in the river pattern and rapid incision (Galon 1968). During the Holocene the Vistula was influenced by the *Littorina* transgression of the Baltic Sea (Rosa 1963). Also the tectonic factor played some role. Differentiated tendencies can be observed in southern Poland: an uplift in the Carpathians and a subsidence in the sub-Carpathian basins (Fig. 2). In the 2nd half of the 19th century the channel correction was undertaken in the upper course in the sub-Carpathian basin (the former Austrian sector) and in the Lower Vistula Valley (the former Prussian sector).

HISTORICAL REVIEW

The beginnings of studies on the late-glacial and Holocene forms and deposits in the Vistula valley go back to the close of the 19th century (Łomnicki 1903; Friedberg 1903). The interwar period and post-war first 20 years were characterized by mapping of terraces and investigations of the horizons rich in organic material (see: review by Starkel 1980). The progress made during that period was summarized at the first national meeting on the Holocene palaeogeography in 1967 and the complex elaboration of the Vistula valley has been proposed (Starkel 1968). Up to that time the radiocarbon datings were very rare, the terrace formation was explained by the alternating phases of erosion and aggradation, and the sequence of changes was reconstructed on the base of the stratigraphical column of facially differentiated alluvial deposits. Only the role of both the climatic factor and human impact has been well distinguished in the Holocene fluvial history. Since 1967, numerous studies have thrown new light on the mechanism of changes, among them on the simultaneous phases of increased erosion and deposition (Klimek and Starkel 1974) and on the main trend of the Holocene floodplain formation by both the lateral shifting of meandering channels and lateral accretion (Falkowski 1967; Klimek and Starkel 1974; Kozarski and Rotnicki 1977). The differentiation in age and first paleohydrologic reconstructions have been made on the base of analyses of paleochannels formed by either meandering or braided rivers (Falkowski 1975; Mycielska-Dowgiałło 1977 and others). The first results of that stage of research were presented at the meeting of the INQUA Commission on studies of the Holocene in Poland in 1972 (*Excursion Guide-book* 1972; *Proceedings* ... 1975). Some of the regularities will be discussed in the following paper by Falkowski (*cf.* Fig. 3). My introductory paper summarizes briefly the study of research before 1978 when the joined project started to work (*cf.* Starkel 1980).

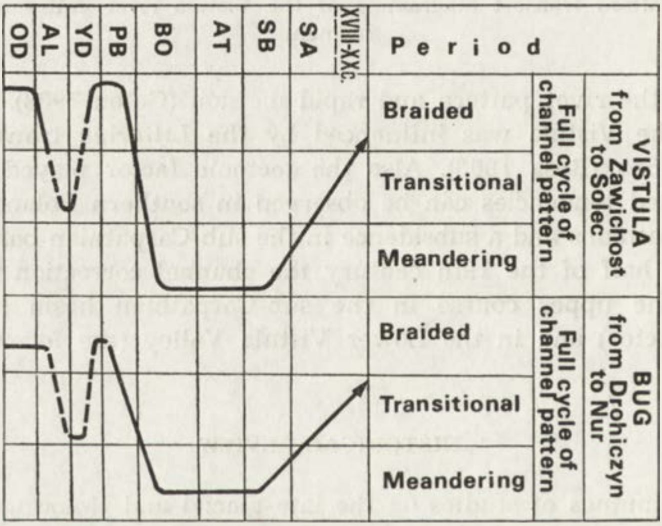


Fig. 3. Cycle of channel pattern changes in the Vistula river catchment, according to Falkowski (1975)

SA — Subatlantic period; SB — Subboreal period; AT — Atlantic period; BO — Boreal period; PB — Preboreal period; YD — Younger Dryas; A — Allerød; OD — Older Dryas

OUTLINE OF THE EVOLUTION OF THE VISTULA VALLEY DURING THE LAST 15 000 YEARS

The Vistula river valley is one of the Middle-East European valleys directed towards the north, with headwaters in the rising mountains. Its lower course was dammed by the ice-sheet which melted rapidly and caused intensive downcutting being later stopped by a sea transgression. The simplified longitudinal profiles show these different reaches (Fig. 2 and 4). Schematic cross-sections explain the complicated sequence of changes (Fig. 5). These show many features in common with other valleys like those of the Elbe, Odra, Niemen and Western Dvina.

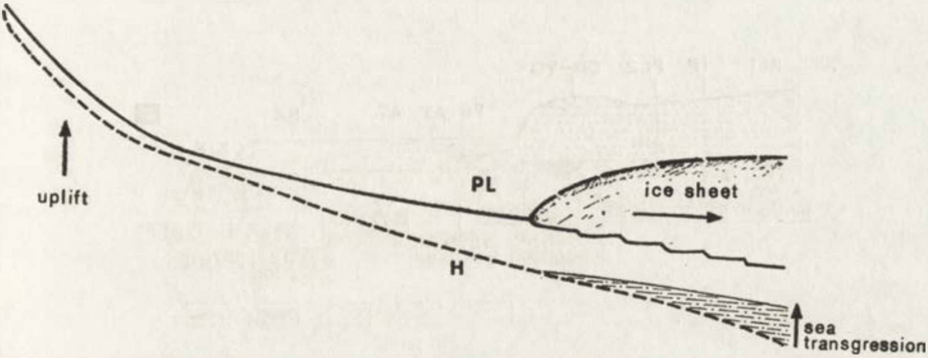
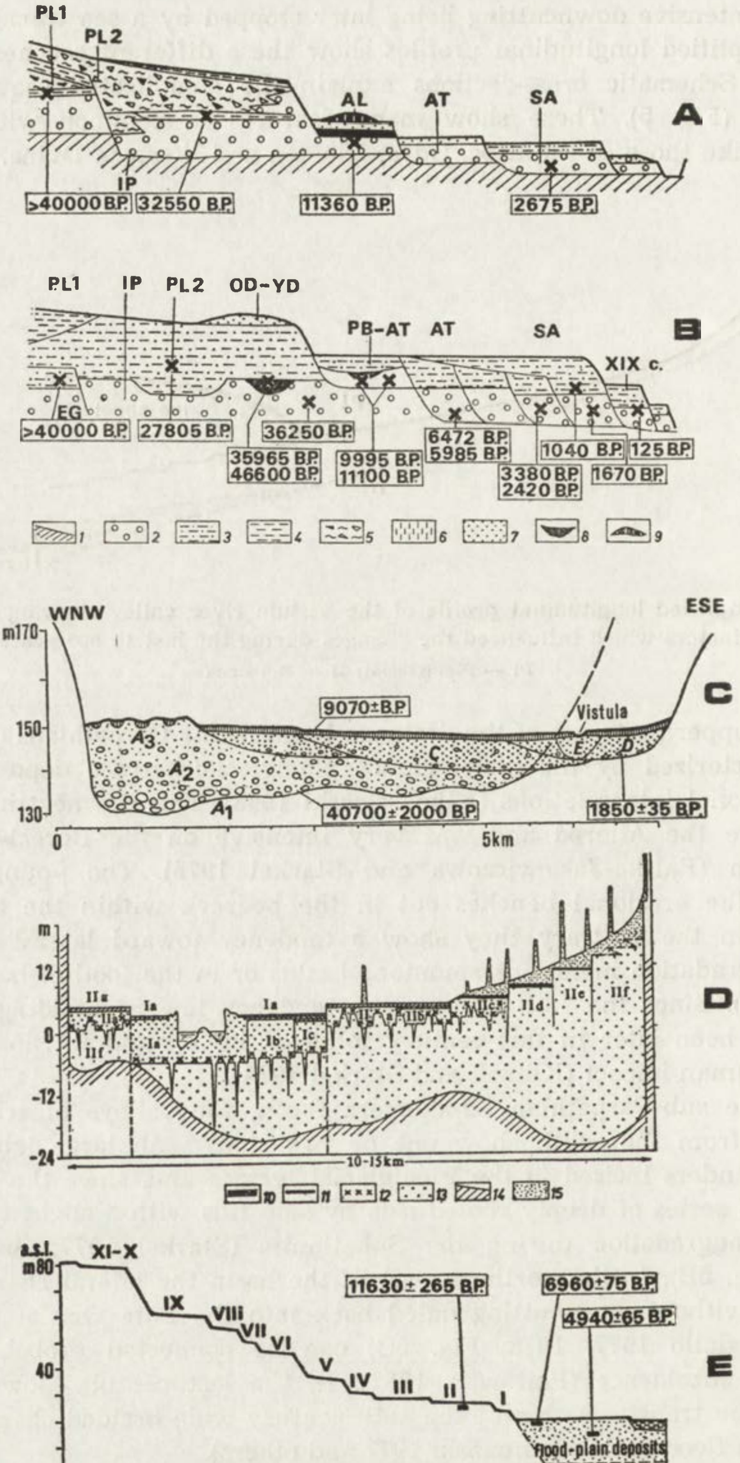


Fig. 4. Simplified longitudinal profile of the Vistula river valley showing the main factors which influenced the changes during the last 15 000 years
Pl — Pleniglacial; H — Holocene

The uppermost part of the drainage basin in the Carpathians (Fig. 5A) is characterized by the dissection of pleniglacial terrace deposits with soliflUctional intercalations (Klimaszewski 1948). This downcutting started before the Allerød and was very intensive on the Boreal-Atlantic transition (Ralska-Jasiewiczowa and Starkel 1975). The younger fills overlie the erosional benches cut in the bedrock within the zones of uplift. On the contrary they show a tendency toward lateral shift or even aggradation in the intramontane basins or in the foothill belt (Starkel 1977). Since the 18th century the tendency toward braiding started and has been later in this century followed by a rapid incision due to direct human impact (Klimek and Starkel 1974).

In the sub-Carpathian Sandomierz Basin, the valleys of tributaries flowing from the south show one or two steps with large late-glacial paleomeanders incised in the Pleniglacial terrace and, since the Atlantic period, a series of deeply rooted side by side fills with a slight tendency toward aggradation during the Subatlantic (Starkel 1977; Szumański 1972; Fig. 5B). In the northern part of the basin the lateral channel migration without downcutting dated back into the Late Glacial (Mycielska-Dowgiałło 1977, 1978; Fig. 5C) can be connected probably with a slight subsidence (Połtowicz 1962). In the last century downcutting caused the transformation of the 19th century wide braided channel into an active flood-plain (Szumański 1977 and others).

The gap through the Southern Polish Upland is characterised by the


PL1
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36250 B.P.
35965 B.P.
46600 B.P.
9995 B.P.
11100 B.P.
6472 B.P.
5985 B.P.
3380 B.P.
2420 B.P.
1040 B.P.
1670 B.P.
125 B.P.
1
2
3
4
5
6
7
8
9
WNW
ESE
m170
150
130
0
5km
9070±B.P.
Vistula
C
A3
A2
A1
C
E
D
40700±2000 B.P.
1850±35 B.P.
m
12
0
-12
-24
IIa
Ia
Ia
IIf
Ia
Ib
Ic
IIa
IIb
IIc
IId
IIe
IIf
D
10-15km
10
11
12
13
14
15
a.s.l.
m80
40
0
XI-X
IX
VIII
VII
VI
V
IV
III
II
I
11630±265 B.P.
6960±75 B.P.
4940±65 B.P.
E
Flood-plain deposits
Holocene
Pleistocene

occurrence of late-glacial erosional benches (Pożaryski 1955) and a wide Holocene flood-plain consisting of a few members of overbank deposits, with the Atlantic one at the base (Falkowski 1967). The top layers correspond in time with the braided channel of the Vistula which has shown this tendency toward aggradation since the 18th century.

Farther downstream (in the belt covered only by the penultimate ice sheet) a set of terraces bearing late-glacial dunes is typical (Biernacki 1975; Fig. 5D). On the lowermost terrace with archeological sites situated on the Allerød channel bars a dune, Younger Dryas in age, was found (Schild 1969).

Two levels of the Holocene flood-plain composed of different fills (Różycki 1972) show on the surface several generations of paleomeanders, differing from the braided patterns which were formed both in the early Late Glacial and in the last centuries (Falkowski 1975; Fig. 3).

The Lower Vistula valley in its present shape was formed during the deglaciation being associated with both lowering of the base level and a tendency toward the avulsion of Vistula waters to the next northern glacier margin valley train. This trend is reflected in a set of 11 terrace levels (Galon 1953, 1968). The age of bifurcation to the Bay of Gdańsk has been discussed for a long time. According to Roszko (1968), the 3rd terrace antedates the Younger Dryas. Later on it was found that even the 2nd terrace was formed prior to the Allerød, and only the lowermost alluvial plain is Holocene in age and shows a tendency toward aggradation due to the *Littorina* transgression (Drozdowski and Berglund 1976; Fig. 5E). It must be noted that for the Warta and Prosna river

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Fig. 5. Generalized section across the Late Glacial and Holocene alluvial fills in different parts of the Vistula catchment basin

A and B — sequence of terraces dating from the Last Glacial and the Holocene in the Carpathians (A) and in its Foreland (B), according to Starkel 1977; letter abbreviations refer to particular stratigraphic horizons and more significant ^{14}C datings

1 — rock-cut bench; *2* — alluvia belonging to the channel facies; *3* — alluvia forming the flood-plain; *4* — deluvial deposits; *5* — solifluction sheets; *6* — loess; *7* — dune sands; *8* — oxbow lake deposits and peat; *9* — raised bogs

C — Generalised section across the Vistula river valley near Tarnobrzeg (according to Mycielska-Dowgiałło 1977)

A_1 — A_3 — Pleniglacial sediments; *B* — Late Glacial sediments; *C* — *E* — Holocene fills of different ages

D — scheme showing the distribution of the Vistula terraces near Warsaw (according to Biernacki 1975)

Holocene terraces: Ia — recent flood terrace of the Vistula, Ib — Czersk terrace, Ic — Kiełpin terrace; Late Pleistocene terraces: IIa, IIb, IIc; Higher Pleniglacial terraces: IId, IIe, IIf; *10* — telematic mud of flood sedimentation; *11* — veneers of mud on the older terraces; *12* — gravel horizons; *13* — sand; *14* — substratum; *15* — aeolian sand

E — Generalized terrace sequence in the Lower Vistula river valley near Grudziądz (according to Drozdowski and Berglund 1976) valleys (next valleys to the west) Kozarski and Rotnicki (1977) constructed a model of valley floor evolution under the conditions of base level lowering and of changing hydrologic régime. The changes from the 19th century braided channel to the regulated channel have been studied in detail by Tomczak (1971).

The deltaic plain of the Vistula river entering into the Gdańsk Bay is built of Holocene sediments about 50 metres thick, the base of which corresponds to the very low level of the Yoldia Sea (Rosa 1963).

All of these briefly mentioned studies made before 1978 show a complicated pattern of valley floor evolution in the Vistula drainage basin. One of the main tasks of our collective work is: (1) to determine the role of direct climatic factors, of deglaciation, of tectonic movements and of human impact during the subsequent time units, and (2) to reach conclusions on either the synchronic or metachronic changes in the longitudinal profile.

ORGANIZATION OF COLLECTIVE WORK

The studies mentioned above should be a good starting point for the investigations undertaken in the project on the Vistula valley during the last 15 000 years.

Complementary information will be drawn from a series of geological, geomorphical, hydrological, soil and land-use maps on the scales of 1 : 1 000 000, 1 : 500 000 and even much larger. At many stations hydrologic and climatic records cover periods of 80—120 years. The state of more detailed knowledge before 1978 is presented in Figure 6.

Of these areas, including some other reaches located in key areas about 16 reaches have been until now selected. Some of them are discussed in this volume (Fig. 1). These are as follows (names of authors are in brackets):

1) the Vistula alluvial fan in the foreland of the Silesian Beskid (E. Niedziałkowska, collaborators: K. Szczepanek and E. Gillot);

2) the Vistula valley in the Oświęcim Basin including the Soła alluvial fan (K. Klimek);

3) the Vistula valley in the Cracow Gate (J. Rutkowski);

4) the Vistula valley downstream of Cracow (L. Starkel, collaborators: K. Wasylikowa and others);

5) the Vistula valley downstream of the Dunajec river mouth (J. Sokołowski);

6) the Ropa river valley at the margin of the Beskid Niski Mts (L. Dauksza, E. Gil and R. Soja);

7) the Wisłoka river valley at the mouth of the Jasiołka river and downstream (A. Wójcik and K. Klimek);

8) the Wisłoka alluvial fan in the Foreland of the Carpathians (L. Star-

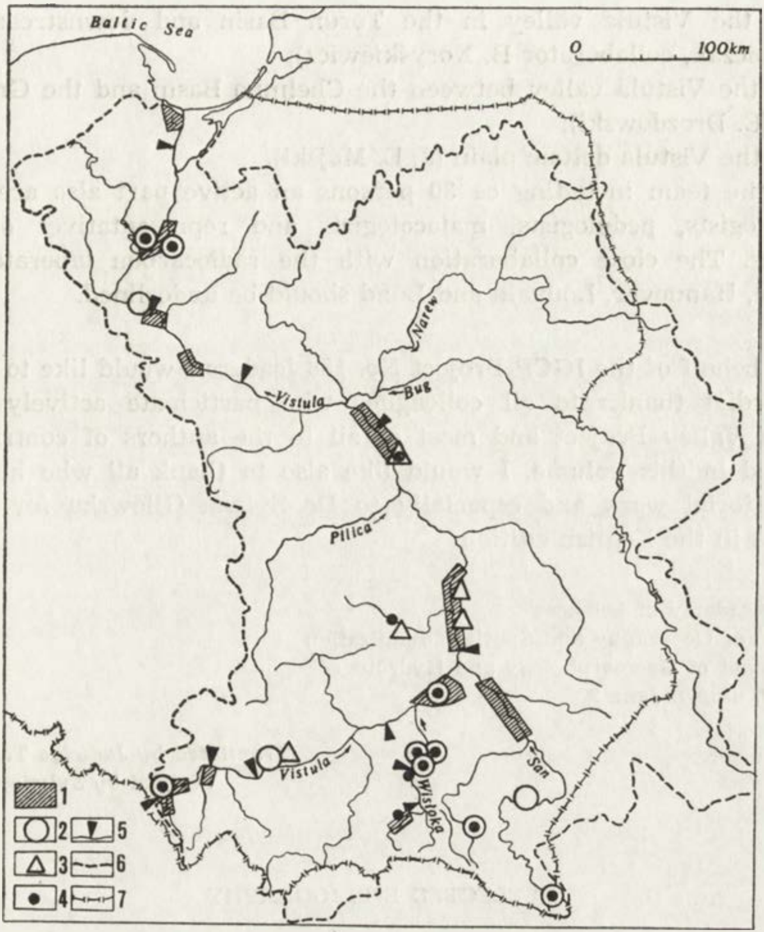

Fig. 6. State of information available for the Fluvial Subproject in the Vistula catchment basin

1 — valley reaches elaborated in detail; *2* — localities with stratigraphy based on paleobotanical data; *3* — localities with stratigraphy based on archaeology; *4* — localities dated by the radiocarbon method; *5* — gauging station; *6* — water divide of the Vistula drainage basin; *7* — Polish frontier

kel, collaborators: K. Mamakowa, E. Niedziałkowska, S. W. Alexandrowicz, A. Kowalkowski and M. Pazdur);

9) the Vistula valley downstream of the Wisłoka mouth (E. Mycielska-Dowgiałło, collaborator K. Szczepanek);

10) the lower reach of the San river valley (A. Szumański);

11) the Vistula gap in the Southern Uplands (E. Falkowski);

12) the Vistula valley downstream of Warsaw (E. Mycielska-Dowgiałło);

13) the Vistula valley between the Płock Basin and the Toruń Basin (E. Wiśniewski);

14) the Vistula valley in the Toruń Basin and downstream of it (A. Tomczak, collaborator B. Noryśkiewicz);

15) the Vistula valley between the Chełmno Basin and the Grudziądz Basin (E. Drozdowski);

16) the Vistula deltaic plain (J. E. Mojski).

In the team including ca 30 persons an active part also are taking palynologists, pedologists, malacologists and representatives of other sciences. The close collaboration with the radiocarbon laboratories in Gliwice, Hannover, Louvain and Lund should be underlined.

On behalf of the IGCP Project No. 158 leaders I would like to express my cordial thanks to all colleagues who participate actively in the Vistula Valley Project and most of all to the authors of contributions included in this volume. I would like also to thank all who helped in the editorial work and especially to Dr Sylwia Gilewska for the assistance in the English edition.

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THE HOLOCENE AND PRESENT-DAY EVOLUTION OF THE MOUNTAINOUS REACH OF THE ROPA RIVER VALLEY

HISTORY OF RESEARCH

The examined valley reach of the Ropa river — a tributary to the Wisłoka river — is in the marginal part of the Beskid Niski Mts, just upstream of the Sanok — Jasło Basin in the Carpathian Foothills.

According to Breitmeier (1938), the following river terraces are found on the entire Ropa river: 3—4 m (Holocene in age), 6—8 m, 18—24 m and higher levels (Pleistocene in age). Kotarba (1970), who studied the terraces in greater detail near Szymbark, noted that the 4 m and 6—8 m terraces have a common rock bench, whereas in the 18—24 m terrace he recognized a sub-gravel bench at 15 m. Świdziński (1973) found that upstream of Gorlice there are two bottom terrace stages and three higher terrace stages, all of the latter being capped with clay. The 4 m terrace plain is carved into a series of lower steps occurring at 1—3 m above mean water level. According to Dauksza (1975), these steps form part of the stream channel named the "passive channel", whereas the "active channel" is clearly subject to rapid change by processes of erosion and accumulation. The "passive channel" being ca 70 m wide is twice as wide as the "active channels". The lower terrace steps are liable to inundation at high stages. The dynamics of the Ropa river channel was characterized over the period 1780—1970 and related to the features on the valley floor by planetable mapping and analyses of cadastral maps.

Special attention was paid to the present-day changes affecting the Beskidian part of the valley (Dauksza 1975). This latter problem has been analysed for its relation to the geological structure of the valley floor by Dauksza and Gil (1972). Soja (1977) found that the rate of channel deepening at Szymbark was 30 cm during the years 1968—1974. Welc (1972) observed that the suspended load was 15 g/l at the maximum during the 1970 peak discharge. Finally, the hydrologic régime of the

Ropa was characterized by Soja (1981), who also related the discharge changes to changes in the land use pattern.

This paper is based on data which have been collected by the present authors and in particular on an unpublished work of Dauksza (1975).

CHARACTERISTICS OF THE PRESENT-DAY ENVIRONMENT

LOCATION OF THE STUDY AREA IN THE DRAINAGE BASIN

The valley reach examined, i.e. the "Szymbark" segment, extends over 38—44 km distance along the Ropa river which is draining the western part of the Beskid Niski Mts (up to 1000 m a.s.l.). The drainage area underlain by flysch sandstone and shales is 303 km² above the Szymbark water gauge. The "Szymbark" segments is a water gap aligned west to east and guided by a fault (Świdziński 1973). The Ropa river channel is at 320—297 m a.s.l. The surrounding peaks reach 740 m a.s.l. Along the 5.6 km reach examined the drainage area increases by 45 km², of which the largest partial watersheds are 11.8 km² and 13.6 km². The lower part of the segment enters the Carpathian Foothills (Fig. 1).

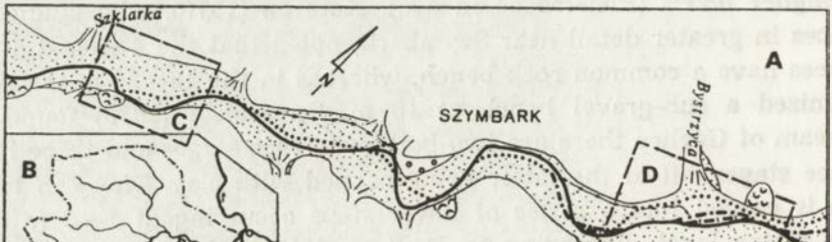


Fig. 1. Chosen reach of the Ropa river valley near Szymbark A — valley floor and channel changes

1 — middle terrace (Saalian); *2* — low terrace (Vistulian); *2* — alluvial plain (Holocene); *4* — alluvial fans; *5* — landslides; *6a* — present-day Ropa river channel; *6b* — channel about 1780; *6c* — channel about 1850; *6d* — channel in 1909; *7* — dug channel

B — location of the "Szymbark" reach in the Ropa catchment

C and D — sections presented in detail in figs. 2 and 6

THE FLOOD-PLAIN

A typical feature of the valley reach "Szymbark" is the nearly complete lack of a presently active flood-plain. The only inundated area are the lowest benches adjacent to the channel (Fig. 2). These are up to 80 m in width and affected by floods once in less than 50 years. During the 1973 high stage having a recurrence interval once in 75 years (1,33%) the inundated area was 0.1 km² throughout the valley reach examined.

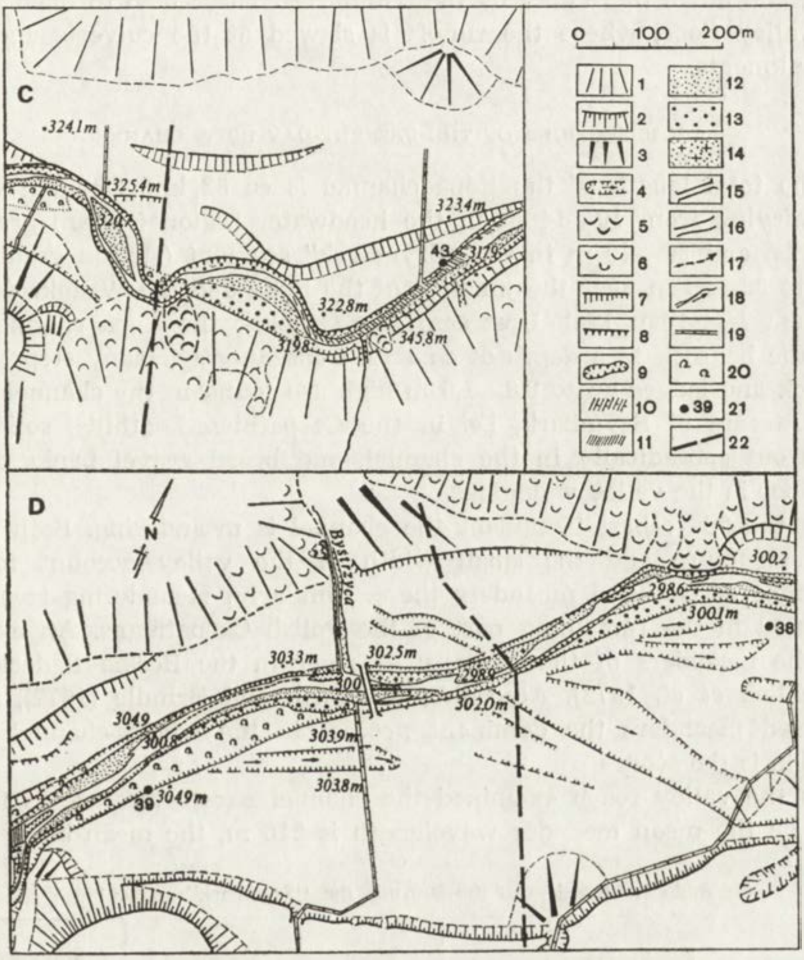


Fig. 2. Chosen sections C and D of the Ropa valley floor (by L. Dauksza)

1 — valley sides; *2* — terrace edges; *3* — alluvial fans; *4* — paleochannels; *5* — active landslides; *6* — inactive landslides; *7* — channel bank (stabilized); *8* — channel bank (active); *9* — potholes and troughs eroded in solid rock; *10* — ledges; *11* — rock floors; *12* — gravel bars; *13* — present-day flood loams deposited on the low terrace steps adjacent to the channel; *14* — gravel bars changed by gravel extraction; *15* — bridge; *16* — low water level in the Ropa channel; *17* — line of current; *18* — small tributaries; *19* — ditches; *20* — shrubs and *Alnetum* wood; *21* — kilometer along the river; *22* — lines of the geological cross-sections (fig. 7)

At the present time, bankfull discharge is equivalent to discharges having a recurrence interval once in 100 years. In the early 19th century the valley floor was largely flooded (personal communication). Today, even the highest discharge does not cause inundation of the valley floor due to the rapid channel deepening. The valley floor shows occasionally traces of both river cliffs and former channel paths. The levelling of the valley floor and the obliteration of the former channels is the effect from aggradation in the past centuries. At the present time, deposits are being laid down there only by the tributaries. These tend to flood locally the valley floor, where the runoff is slowed at the culverts and road embankments.

CROSS-SECTIONS OF THE PRESENT-DAY ROPA CHANNEL

The total length of the Ropa channel is ca 83 km. Channel widths are varying from 10—14 m in the headwater region (stream gradients of 20‰) and 30—40 m in the "Szymbark" segment (stream gradient of 4‰) to 50—80 m near the junction of the Ropa and the Wisłoka (stream gradient less than 1‰). Upstream of Szymbark the Ropa channel cuts into the bedrock to a depth of ca 1 m. Consequently, many steps, floors of rock and ledges up to 0.8—1.0 m high are found in the channel there. Downstream of Szymbark, i.e. in the Carpathian Foothills, solid rock crops out sporadically in the channel, and broad gravel banks occupy the floor in the valley widenings.

In the "Szymbark" segment the channel is meandering. Both geological structure and the small width of the valley account for the existence of confined meanders there. Similarly, meandering rivers are observed in the remaining part of the Polish Carpathians. An example are the meanders of the Dunajec — river in the Beskid Sądecki Mts (Froehlich *et al.* 1972). According to Lewin and Brindle (1977), in the confined meanders the dominant process in the whole channel cross-section is the scours.

In the valley reach examined the channel parameters are as follows (tab. 1): the mean meander wavelength is 216 m, the mean bend radius

Table 1. Meanders of the Ropa in the "Szymbark" segment

Parameters	Mean	Maximum	Minimum
Meander wavelength (m)	216	417	75
Bend radius (m)	512	2000	40
Channel width (m)	31	46	21
Channel cross-sectional area (m^2)	80	120	45
Average depth (m)	2.48	3.20	1.60
Maximum depth (m)	3.55	4.80	2.60
Stream gradient (‰)	4.0	8.5	2.40

is 521 m and the average channel width is up to 30 m. The most tightly looped meanders (bend radii 40—90 m) appear wherever on the undermined river banks landslips supply large quantities of waste and blocks (bank caving). Solid rock tends to form steps and floors in such meandering channels. Meanders having bend radii of 150—300 m are found wherever the channel is cut into the weak shale and sandstone series. Such meanders occur usually upstream of the more tightly looped meanders. The large meanders (bend radii above 300 m) were determined by the shallow river incision into solid rock being usually exposed only in the concave bank. In such channel reaches point bars are well developed.

The individual channel reaches having different radii of curvature also vary by cross-sectional shapes. Meanders having the smallest bend radii are most asymmetrical, the greatest depth being 1 m. Meanders having the largest bend radii are symmetrical and are chest-like in cross--section.

Because of the small increase in drainage area (only 45 km²), channel geometry does not change in the valley reach examined. Farther downvalley the Ropa channel becomes wider and shallower due to the lesser resistance of bedrock at the exit of the mountainous valley portion which shows distinct tendencies towards uplift (Starkel 1972). The relationships between the different basic channel parameters are as follows for the whole river, i.e. from the source to the mouth:

$$L/A = 0.17\ S + 2.50,$$
$$A = 0.38\ L - 69.24,$$
$$L = 2.30\ A - 248.3,$$
$$L = 19.17\ b + 182,$$

where L is the curve length [m], A — the meander amplitude, S — the channel gradient [‰] and b is the channel width [m]. The above ratios are significant statistically. It appears that both channel parameters and ratios tend to change gradually and not abruptly downstream. However, there ought to be a more rapid change in the channel parameters downstream of the "Szymbark" segment, where the river crosses the Carpathian Foothills. The valley width increases from 0.5 km to 2—3 km there. The gradual change is best illustrated by the relation between curve length and meander amplitude. In the headwaters the relationship L/A is 5.5, in the valley reach examined decreases to 4.0 and at the river mouth it is only ca 2.8. Except the short channel reach just immediately below the exit of the mountainous valley portion, where the ratio L/A is as much as 6.2, the above values diminish gradually down-valley. Thus the reach studied can be regarded as being typical of the entire mountainous section of the river.

CHARACTERISTICS OF THE HYDROLOGIC REGIME

According to Dynowska (1971), the hydrologic régime of the Ropa is marked by a ground-, rain-, and snow-fall recharge and by high-flow occurrence in three seasons: snowmelt high-flows occur in early spring, high flows being the result of prolonged rainfall occur in summer (VI—VII) and high-flows occasioned by rainfall and snowmelt tend to occur in early winter (December). Discharges are varying greatly because of the small retention in the drainage basin and its varied relief. In the upper Ropa catchment area (305 km²), the lowermost discharges drop frequently below 0.3 m³/s (specific runoff less than 1 l/(s · km²)). The highest discharges exceed 300 m³/s (specific runoff more than 1000 l/(s · km²)). As a rule the lowermost discharges are recorded in autumn (IX—X), and the highest discharges occur in July. The high flows as calculated on the base of Punzet's data (1978) have the recurrence intervals shown in table 2 at the Szymbark water gauge (303 km²).

Table 2. Expected high flows of the Ropa at Szymbark

Recurrence interval in per cent (P)	m³/s	l/s (km²)
100	20	66
90	30	99
50	88	290
10	225	742
5	282	930
2	357	1180
1	416	1370

In the 19 th century flows having a recurrence interval between $p_{2\%}$ and $p_{1\%}$ were recorded in 1934, 1970 and 1973. The period 1969—1974 was marked by an exceptionally high frequency of high flow occurrence. At that time 10 high flows were recorded that had a recurrence interval equal to or less than $p_{10\%}$.

In the Ropa drainage basin peak flows are recorded only in the summer season. They are caused by prolonged rainfalls which may attain 200—300 mm in one fall cycle.

The snowmelt high flows are described by maximum discharges of up to 100 m³/s which are equivalent to the frequently occurring flows ($p_{50\%}$). The annual march of discharges is shown in Figure 3. In the hydrologic winter halfyear runoff exceed by ca 20% that in the summer halfyear. In extremely wet years runoff values tend to be similar in both hydrologic halfyears.

Upstream of Szymbark the Ropa catchment basin is forested in 60%.

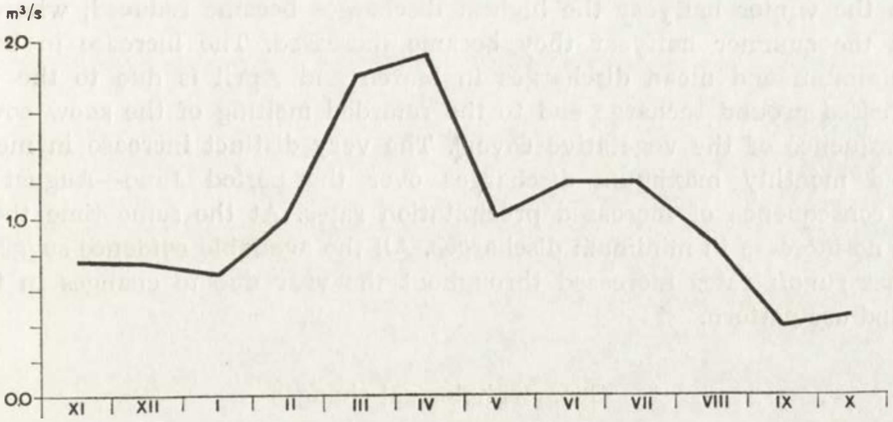


Fig. 3. Monthly discharge coefficient (by R. Soja)

Although ploughed areas occupy less than 10% of the headwater region, the Ropa carries abundant suspended load exceeding 10 g/l during the summer high flows. In the tributaries the corresponding values were 2—3 times as great as in the Ropa. The thaw season lasts about three weeks. The dominant thaws of radiation type are favourable for the rather slow runoff of the meltwaters. However, ice-floats are moving rapidly, and ice-jams which promote erosion of the river banks tend to form in the narrow channel reaches. The ice-cover may disappear and reappear twice in a winter.

HYDROLOGICAL AND GEOMORPHOLOGICAL CHANGES OVER THE PAST 100 YEARS

Hydrological changes

In the drainage basin of the Ropa the records of discharges are not long enough that one could obtain an answer to the question of hydrological changes during the last 80 years. An attempt to define the runoff changes over the period 1951—1970 was made in the mountainous portion of the Ropa drainage basin (482 km² at the Klęczany water gauge). It was accepted that changes in the land use pattern ought to be reflected in the runoff changes (Soja 1981). Such changes resulted from the deportation of natives in 1945. In the mountainous portion of the basin the population was 56 per km² in 1935 to drop to 12 persons per km² in 1956. The most distinct change in the natural environment was the abandonment of fields upon which forest and shrubs encroached. In 1951—1970 one observed an average rate of discharge increase of 0.006 m³/s per annum. Over the 20 year period there was a contemporaneous increase in minimum flows of the order of 30% of its mean value. The mean and annual peak flows also increased markedly. It has been recognized that in the winter halfyear the highest discharges became reduced, whereas in the summer halfyear they became increased. The increase in both minimum and mean discharges in March and April is due to the increased ground recharge and to the retarded melting of the snow cover (influence of the vegetative cover). The very distinct increase in mean and monthly maximum discharges over the period June—August is a consequence of increased precipitation rates. At the same time there is no increase in minimum discharges. All the available evidence suggests that runoff rates increased throughout the year due to changes in the land use pattern.

Geomorphological changes

The works of Augustowski (1968), Osuch (1968) and Lach (1975) show that a very rapid channel deepening takes place in the whole Ropa drainage basin during the last years. Dauksza (1975) and Soja (1977) have examined the Ropa channel in the "Szymbark" segment and explained both the rates and causes of down-cutting.

The varying rates of the Ropa channel deepening depend upon the nature of the substratum. Over the period 1900—1940, the individual channel reaches incised either into alluvia or into the very soft shales were cut deeper at the rate of up to 0.4 cm per annum. At the beginning of the 1940s the rate of channel deepening became accelerated attaining ca 4 cm per annum. Over the flood period 1969—1974, this value was nearly 8 cm per annum in the alluvial channel reaches. In post-1974 times the process of downcutting did significantly slow down. The march of channel deepening is schematically presented in Figure 2. The causes of accelerated channel deepening were complex. In the 1940s there began the extraction of gravel immediately from the channel bed of the Ropa. The working of coarse gravel and rock fragments here continues into the present days. In the 1950s the other factor promoting scour was the increase of local competence to carry debris because of the decreased supply of waste into the channel which in turn was brought about by changes in the land use pattern. The accelerated downcutting in the 1970s should be related to the high frequency of high flow occurrence.

To both the magnitude and type of high flow the accumulation of bed load in the Ropa channel is related. The patterns of changes in bed elevation at 38 km distance along the Ropa channel are shown in Figure 4. Scour predominates in the channel. Simultaneously fine materials are laid down on the adjacent narrow terrace benches. The rates of channel deepening are similar throughout the valley reach examined (Fig. 5). The entire 900 m channel reach of the Ropa was deepened some 25 cm in twelve years. The exception was a short (80 m) reach, in which

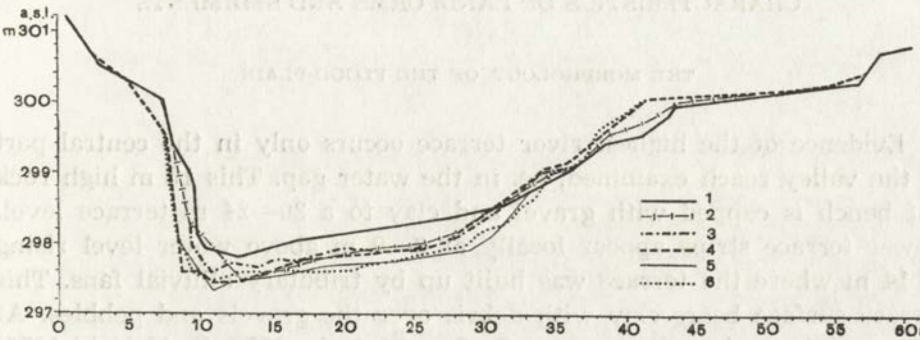


Fig. 4. Pattern of changes in bed elevation in a repeatedly measured section across the Ropa river on: *1* — 16 V 1969; *2* — 26 XI 1970; *3* — 19 XII 1972; *4* — 10 V 1974; *5* — 16 VII 1974; *6* — 16 VIII 1974 (by R. Soja)

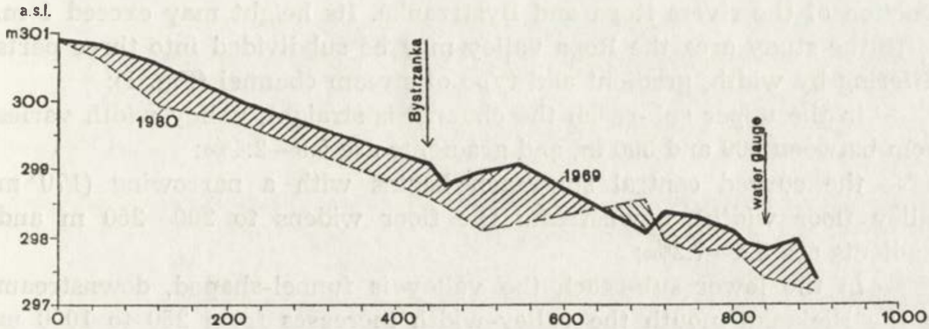


Fig. 5. Rates of channel deepening for the lower 900 m reach of the Ropa, 1969—1980 (by R. Soja)

after the building of embankments below the bridge, the river became aggraded.

The deepening of the river channel over 900 m distance has involved the removal of at least 5000—6000 m^3 of alluvia that were for the most part eroded from the solid rock. Data obtained from the measurements of two channel cross-profiles suggest that the total volume of channel-derived materials is 4-times greater than the above value. It follows that well over 100 000 m^3 of materials might have been removed in twelve years from the valley reach discussed.

As a direct effect from channel deepening landslides resulted on the undermined river banks. These slides supply great quantities of debris immediately into the Ropa river and also modify the meandering course of the main current (Dauksza and Kotarba 1973).

CHARACTERISTICS OF LANDFORMS AND SEDIMENTS

THE MORPHOLOGY OF THE FLOOD-PLAIN

Evidence of the highest river terrace occurs only in the central part of the valley reach examined, i.e. in the water gap. This 15 m high rock cut bench is capped with gravel and clay to a 20—24 m terrace level. Lower terrace strips appear locally at 8—9 m above water level rising to 14 m where the terrace was built up by tributary alluvial fans. This terrace surface bears clay with debris over the gravels and pebbles. At the gap exit the broad terrace at 6—8 m (Kotarba 1970; Świdziński 1973) is composed of gravels and pebbles, 4—6 m thick, below a 2 m veneer of loam. This sheet rests on a rock bench which appears locally in the stream channel.

The valley floor is occupied by the 4 m terrace. The rock bench in the channel is a continuous feature which extends upstream of the junction of the rivers Ropa and Bystrzanka. Its height may exceed 1 m.

In the study area the Ropa valley may be subdivided into three parts differing by width, gradient and type of stream channel (Fig. 1):

— in the upper sub-reach the channel is straight, valley width varies from between 200 and 300 m, and gradients are 5.9—2.4‰;

— the curved central sub-reach begins with a narrowing (170 m valley floor width), downstream the floor widens to 200—250 m and gradients are 3.6—7.2‰;

— in the lower sub-reach the valley is funnel-shaped, downstream of the Bielanka mouth the valley-width increases from 250 to 1000 m and gradients are 3.8—3.4‰.

In the upper and lower sub-reaches aggradation tends to prevail, whereas in the intervening central part erosion is predominant.

The 4 m terrace surface rises slightly towards the valley-sides, particularly where it was built up by the tributary alluvial fans. In places, it is divided into an upper (5—6 m above the present mean water level) and lower part, the two being separated by a bluff, 2—3 m high. In some places its flat surface is interrupted by elongated depressions 0.8—2.0 m deep (Fig. 2). These abandoned channels are common in the upper and central sub-reaches. In the latter the terrace as a whole slopes more steeply. This indicates the erosional character of the plain. The abandoned channels have asymmetrical cross-profiles, with a higher and marked edge close to the valley-side. The abandoned channels that were nearer the active channel became planed off by the subsequent floods (Fig. 6).

Both low terrace benches and abandoned channels mark the successive positions of the Ropa channel in the valley floor. It is impossible, however, to determine the channel parameters because the above features are poorly preserved. At the time of terrace plain formation a ten-

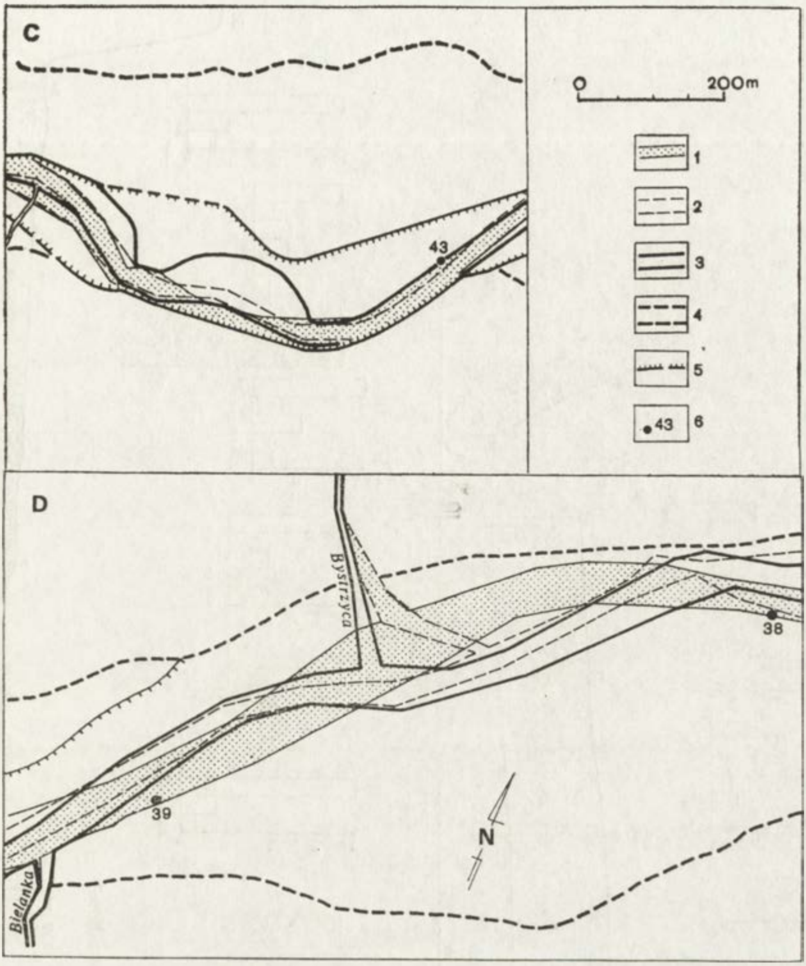


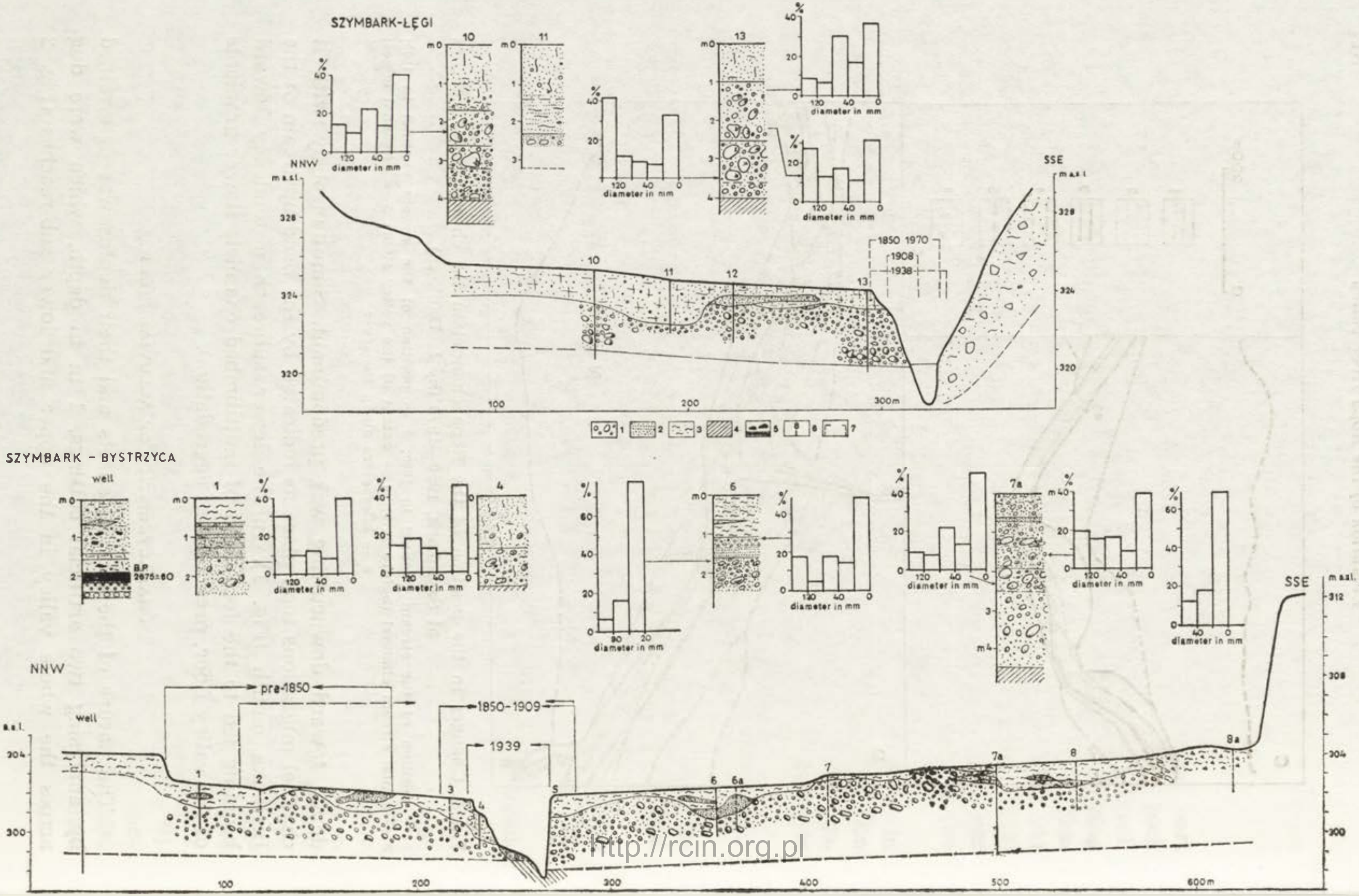
Fig. 6. Changes in the position of the Ropa channel in the chosen valley reaches at Szymbark, 1950—1970 (by L. Dauksza)

1 — position of the stream channel in 1850; *2* — position of the stream channel in 1909; *3* — actual stream channel (before 1970); *4* — extent of the valley floor; *5* — erosional edges; *6* — kilometers along the river

dency toward downcutting was predominant. Simultaneously with it channel migrations took place as indicated by the bend upstream of the Bielanka mouth (Fig. 1). In the lower subreach a tendency toward braiding led to the formation of multilimbed channels (lower gradients of the valley floor, predominant aggradation).

CHARACTERISTICS OF ALLUVIAL FILLS

The nature of the alluvial sheets and their depths was determined by analysing two artificial cuttings, 1 m in depth, which were dug across the whole valley in the upper and lower sub-reaches (Fig. 2


SZYMBARK-ŁĘGI
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SZYMBARK - BYSTRZYCA
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2
3
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304
300
308
312
400
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m4

and 7). Additional information was obtained from pits dug in the plane of each profile in which the solid rock was bottomed, and from the natural exposures in the channel bends. The method employed in obtaining the grain size has been to use sieves and areometers. Analyses of the coarse fraction were based on samples of 80—160 kg, and coarse particles were shaken through special sieves with hollows of the following diameters: 120, 80, 40 and 20 mm.

The 4 m terrace sheet shows a twofold division. The rock bench is covered by a 1.5—4.5 m layer of channel deposits including rounded boulders, pebbles and gravels with sand and clay. These are overlain by loamy and sand-and-silty sediments belonging to the overbank facies up to 1.5 m in thickness (Fig. 7). The layers of loam are discontinuous. The terrace sheet itself is frequently of uniform composition and consists of gravels and boulders. In places, the gravels are separated from the loam by lenticles of vari-grained sand showing a distinct bedding. This sand represents the earliest abandoned channel fills.

The grain size of gravel fraction (tab. 3) lies between 540 mm and less than 20 mm in diameter (30—50%) there. Sometimes more than 40% proved to be particles exceeding 120 mm in diameter. The above deposit is poorly sorted. In the upper sub-reach the sediment is better sorted than in the lower one (tab. 3). This may suggest a rapid accumulation of the stream load (compare Froehlich 1975) due to diminution of the stream gradients at the mountain margin. The other cause may be the

Table 3. The grain size of gravels forming the 4 m terrace sheet at Szymbark

Exposure no.	Depth (m)	Percentage of fraction (mm in diameter)					Sorting index *So* (according to Trask)
		more than 120	120—80	80—40	40—20	less than 20	
1	2.0	29.6	10.0	12.2	8.6	39.6	2.66
6	1.6—2.5	17.2	4.2	17.1	13.8	47.7	4.08
7	1.1—1.5	8.6	7.6	21.2	12.9	49.7	3.87
10	1.7—2.6	13.7	10.1	22.0	13.5	40.7	2.89
13	1.0—2.0	8.3	6.9	30.8	16.9	37.1	2.54
13	3.0—3.5	42.4	11.0	8.4	5.6	32.3	2.05

Fig. 7. Sections across the Ropa valley floor at Szymbark—Łęgi (C) and Szymbark—Bystrzyca (D), by E. Gil

1 — gravel and pebbles; *2* — sand; *3* — loam; *4* — solid rock (flysch); *5* — organic horizon dated by radiocarbon method; *6* — location of pits-chosen sequences of deposits are shown in detail in the upper part of the figure; *7* — position of the Ropa stream channel in the different time units. Additional information on the grain size of deposits revealed in the pits is shown on the corresponding diagrams large quantity of material laid down by two tributaries — the Bielanka and the Bystrzanka — that drain into the Ropa valley upstream of the cross-section.

In places, the gravel series includes a proportion of larger boulders, 200—500 mm in diameter (Fig. 7). The proportions of coarse fraction also increase slightly towards the base of the terrace. The above variations in the content of coarse particles in certain horizons indicate the existence of erosional pavements belonging to the lag sub-facies. It is likely that the greater resistance of the gravel pavement could account for the contrasts in terrace forms.

In the lower sub-reach (Fig. 7) a well dug in the plane of the profile within the upper terrace step showed pieces of wood and other plant remains (in the loamy sand) at the depth of 4 m. These were radiocarbon dated at 2675 ± 60 a B.P. (by M. Geyh in Hannover). The overlying gravel contains larger proportions of matrix than the underlying gravel. This suggests deposition by the tributary Bystrzanka. In the southern part of this section, at the foot of a small tributary alluvial fan the gravel interdigitates with loamy deposits containing poorly rounded gravel and sandstone debris.

The gravel series is overlain by loam belonging to the overbank facies. This loam contains increased proportions of sand and silt fractions and the content of clay fraction increases towards the valley-sides. In the basal loam there occur many sand intercalations and the deposit is clearly laminated. The flood deposited loam includes thin gravel layers. Occasionally gravels and pebbles up to 80 mm in diameter are found there. The whole deposit is poorly sorted (tab. 4). Today the terrace plain is being build up by alluvial fan deposits at the exits of tributary valleys and sunken roads and by slope-derived deposits (Dauksza 1975; Froehlich 1975).

Table 4. The grain size of 4 m terrace deposits belonging to the overbank facies on the Ropa-river at Szymbark

Exposure no.	Depth (m)	Skeletal particles (%)	Percentage of fraction (mm diameter)				Sorting index So (according to Trask)
			1.0–0.1	0.1–0.05	0.05–0.006	< 0.006	
1	0.3–0.4	1	47	21	17	15	1.36
8	0.4–0.5	traces	14	8	41	37	3.3
8	1.1	1	33	15	31	21	4.21
11	1.4–2.3	traces	45	13	21	21	4.95
12	0.0–0.5	1	26	15	34	25	4.28
13	0.0–1.0	1	45	12	21	22	3.07

The present-day accumulation of deposits belonging to the overbank facies is very intense on the low terrace benches adjacent to the channel. These are inundated at higher stages. The fine sand and silt becomes entrapped and fixed in the dense willow shrubs and others. During a single high flow 20—30 cm of sediment may be laid down there. However, before its fixation much of the sediment is washed down by rainwater into the stream channel from the sloping surfaces. The above series is up to 1.5 m thick (Fig. 7, pit 4) and it has some gravel up to 200 mm in diameter within it at 2 m above mean water level in the channel. This fact indicates the high competence to carry debris at high stages. The above fine sediments rest on gravels and pebbles, which laterally merge into gravel bars following the present channel.

THE RELATIVE AND ABSOLUTE CHRONOLOGY OF DEPOSITS

The valley reach examined has generally a well-defined terrace rising to 4 m above mean water level. This terrace shows a bench exposed in the river channel. On the higher terrace (at 6—9 m) slope-derived clay and debris is lying. Since such deposits are not present on the lower terrace, the 6—9 m terrace must have been formed during the Vistulian (compare Kotarba 1970). However, the rock benches are at the same level beneath both terrace plains. This indicates that in the study area the present valley floor has been formed by the partial removal of the Vistulian terrace sheet. Its remnants survived at the foot of valley-sides. Downstream of the valley reach examined, i.e. in the Carpathian Foothills, the 6—8 m terrace strips are well preserved.

The radiocarbon dating of 2675 ± 60 a B.P. of the pieces of wood (*Abies alba* and *Picea* or *Larix* — according to M. Reymanówna) indicates that at that time incision has already reached down to the rock bench on which the present-day terrace sheet is lying. The other contained plant materials (fruit and seeds of *Abies alba, Fagus silvatica, Alnus glutinosa, Carpinus betulus, Tilia platanophyllos, Rubus sp., Carex sp., Polygonum hydripiper* — after K. Szczepanek) indicate an age not older than the end of the Subboreal. It is likely that the stream channel must repeatedly have been cut down to that depth, and the river worked over the earlier fills in the entire valley floor. The boulder lenses contained in the gravel series can be explained as remnants of the erosional pavements that locally slowed erosion.

The above dated phase of downcutting coincides with the beginning of the Sub-atlantic period (SA_1). According to Starkel (1977), this was a phase of both increased humidity and stream activities. The phase of aggradation that began at the margin of the Carpathians — in the Wisłoka river valley (Starkel *et al.* 1981) — ca 900—1000 years ago is marked by a gradual change from meandering to braided pattern of the shallower river channel in the study area. Some channels cut into the top deposits of the gravel series and the capping loams can be related to fluvial processes that were associated with the development of both settlements and agriculture in the middle ages (*Nad rzeką Ropą* 1968).

The subsequent phase of aggradation (or the continuum of the latter phase) is noted on the cadastral maps dating from the 19th century (Dauksza and Gil 1972, 1975; Fig. 1) and in the cross-section (Fig. 7). To this phase the channelling of the gravel surface on the left bank and the deposition of fills belonging to the overbank facies is assigned. Today accumulation, i.e. the redeposition of coarse gravels, takes place only in the channel, whereas fine materials (clay and sand) are being deposited on the adjacent narrow terrace benches.

RECONSTRUCTION OF ENVIRONMENTAL CHANGES

In the valley morphology the transition between the Beskidy Mts and the Carpathian Foothills is marked by a widening of the valley floor, the appearance of higher terraces on the the Ropa (Breitmeier 1938: Kotarba 1970) and by decreased gradients. The Holocene morphogenesis is reflected in the dissection of the terrace plain dating from the Last Glacial, the partial removal of the valley fills and in the formation of the 4 m terrace. Hence, it may be suggested that it is a cut terrace. Because of the climatically controlled changes in processes of erosion and accumulation that have fashioned the present-day valley floor this model may prove to be more elaborate. Examinations revealed that both channel depths and positions in the valley floor have changed with time. The basal gravel series (Fig. 7) dated at 2675∓60 a B.P. shows that at that time the thalweg was nearly as deep as the present. It is likely that during the clearance of the channel the river cut repeatedly into the solid rock in Holocene times. The partially cleared channel was subsequently filled again. During the phases of increased aggradation the river swept across the flood-plain through the numerous shallow braids cut into the earlier fills. The process of lateral erosion was obviously facilitated by the shallow depth of loose alluvia lying on the more resistant bedrock. During the phases of increased fluvial erosion progressing upstream large quantities of load were supplied into the river. The materials were derived from both the eroded Vistulian terrace sheet and the side-valleys.

Sediments forming the present low terrace became completely mixed due to lateral erosion and channel migrations. Thus the low terrace is a cut-fill form.

Phases of both downcutting and lateral erosion and of aggradation are noted on the 19th century cadastral maps (Dauksza 1975). An additional proof of such an origin of the valley floor are the cross sections (Fig. 7). In the drainage basin the latter changes in the valley floor features were probably due to the advance of agriculture which accelerated supply of the slope-derived soil materials into the stream channel. The overload resulted in both valley aggradation and the adjustment towards a semibraided pattern. The above process is also noted in the other parts of the Carpathians (Klimek and Trafas 1972). The stream channel must have been shallower than at present, as is evidenced by the shallowly channelled gravel surface and by the shallow depths of the fills (Fig. 7). The partial correction of the lowermost channel reach completed in the early 20th century caused the fixing of the present Ropa channel. In the 1940s and 1950s the change from farmland to woodland and pastures in the upper portion of the drainage basin brought about a diminution in the supply of stream load and an increase in bed scour. Similar effects are due to the excessive gravel extraction from the channel bed for building purposes. As a consequence, the river cut through the whole alluvial sheet into solid rock.

Today the influence of channel-altering high flows is confined to the channel itself. Both scour and lateral erosion of meander bends and river banks occurs there. The undermining of the river banks is associated with land-slip formation (Dauksza and Kotarba 1973) from which debris is derived into the channel. On the low steps adjacent to the channel intensive accumulation of sand and silt takes place.

Both the landforms and sediments occurring in the valley floor allow the reconstruction of only some phases of evolution. The uniform composition of the whole gravel series suggests that the alluvia were repeatedly worked over by the river. The climatically controlled trends of the hydrological and geomorphological changes have obliterated the earlier phases of valley floor development. Hence, landforms and deposits related to larger time intervals are absent. The available data are too poor for channel parameter determination. The successive oscillations in the intensities of both erosion and accumulation being associated with tendencies towards meandering or braided channel formation were conditioned by the different magnitude of floods and their recurrence intervals. In historical times superposed on the climatically controlled tendency towards valley deepening are the man-induced changes.

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THE WISŁOKA RIVER VALLEY IN THE CARPATHIAN FORELAND DURING THE LATE GLACIAL AND THE HOLOCENE

HISTORY OF RESEARCH

In the drainage basin of the Wisłoka (tributary to the Upper Vistula) it is possible to give both exact dates of alluvia and their stratigraphy on the base of fine grain sizes and numerous organic remains contained in the alluvial fan deposits which occur in the immediate foreland of the Carpathians. As early as 1903 below the dune — covered Pleistocene terrace two lower Holocene terrace steps having "black oaks" were recognized by Friedberg. Konior (1936) raised objections to this division, and Klimaszewski (1948) pointed to the presence of Pleniglacial deposits at the base of the Holocene alluvial loams. The existence of several simultaneous Late Glacial—Holocene inset fills was shown by Starkel (1957, 1960) who also suggested a current tendency toward aggradation there. Late Glacial floras were reported by Środoń (1965). Before and after the Symposium of the INQUA Commission on the Holocene in Poland in 1972 (*Excursion Guide Book 1972*) detailed studies were made at four locations situated in the Wisłoka valley. These examinations, together with the geomorphological and geological survey of the surrounding area supplied data for both the construction of models of valley evolution and the collective preparation of a monograph on the Wisłoka valley near Dębica for the IGCP Project No. 158 A (Starkel 1981). The contributors were as follows: K. Klimek and L. Starkel (geomorphology), K. Klimek (hydrology and present-day channel changes), L. Starkel acting in co-operation with E. Niedziałkowska (lithology, granulometry and stratigraphy of sequences), K. Mamakowa (pollen analyses and plant macrofossils), S. W. Alexandrowicz (molluscs from the profile at Podgrodzie) and A. Kowalkowski (soils at Brzeźnica).

Out of the more than 50 radiocarbon determinations those on fossils at Brzeźnica and Podgrodzie were made by M. A. Geyh (Hannover), at Grabiny by M. Pazdur (Gliwice), and single analyses were made by G. Kohl (Berlin) and W. Mościcki (Gliwice).

CHARACTERISTICS OF THE PRESENT-DAY ENVIRONMENT

LOCATION OF THE STUDY AREA IN THE DRAINAGE BASIN

The Wisłoka river, 163.5 km long, is draining an area of 4096 km^2 situated in the lowermost part of the flysch Carpathian arc. Altitudes vary between 300 and 850 m. In the drainage basin, shale and poorly

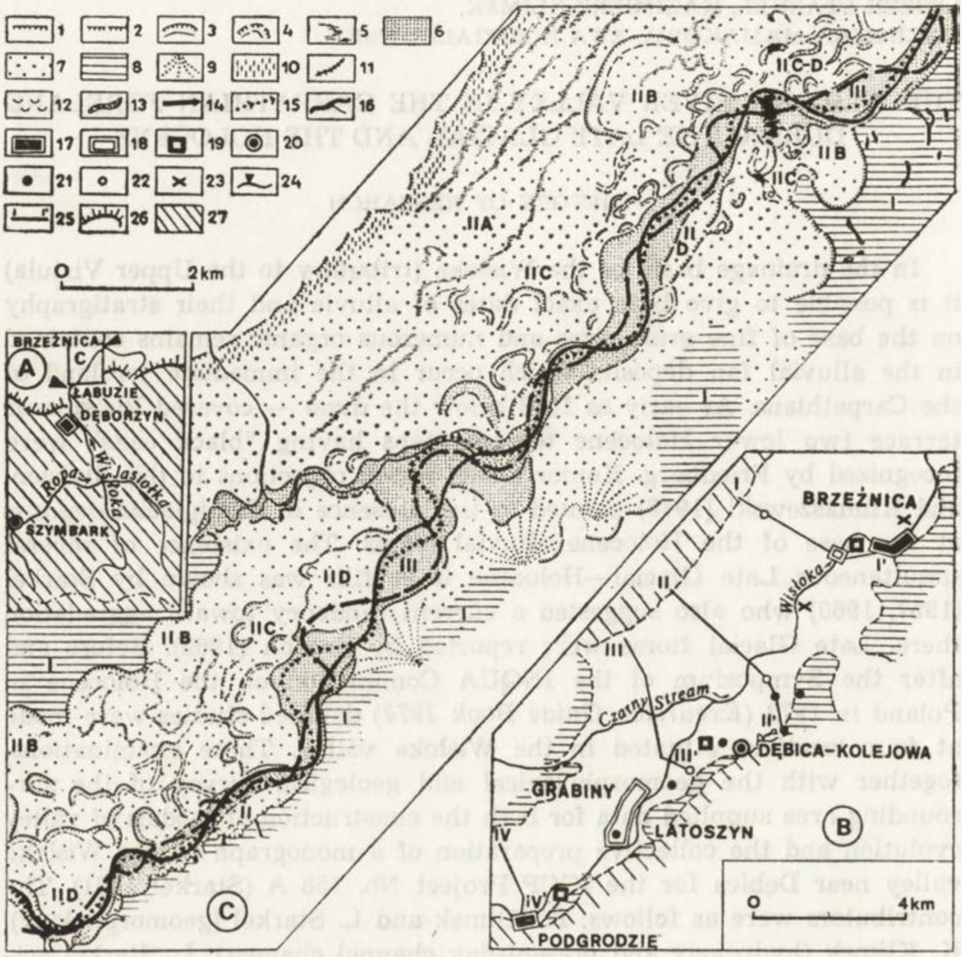

Fig. 1. Study area (A), localities (B) and geomorphological map (C) by K. Klimek and L. Starkel

1 — terrace and other edges well preserved; *2* — smoothed edges; *3* — abandoned channels well preserved; *4* — abandoned channels having smoothed banks; *5* — flat-floored paths of the paleochannels; *6* — flood-plain (level III); *7* — terrace level II; *8* — terrace level I; *9* — alluvial fans dating from the Atlantic period; *10* — deluvial-proluvial glacis; *11* — ravins; *12* — landslides *13* — dunes; *14—15* — course of Wisłoka rier channel: *14* — in 1780 from Mieg's map), *15* — in 1875 (from the 1:75 000 Austrian map), *16* — in 1954 (from the 1:25 000 map); *17* — localities of pollen diagrams and radiocarbon datings; *18* — localities of radiocarbon datings; *19* — other localities; *20* — borehole cores from which samples were obtained for pollen analyses and ^{14}C datings; *21* — pollen analyses; *22* — other borings; *23* — findings of mammoth bones; *24* — water-gauges; *25* — cross-section lines; *26* — escarpment of the Carpathians; *27* — mountains and plateaus consolidated sandstones predominate providing quantities of suspended load into the stream channel. The other source of fine material is loess overlying the older fluvial and glacial deposits at the mountain margin, where the area of special study is situated (Fig. 1). It includes the alluvial fan of the Wisłoka through its lowermost 94.5—115.5 km. In the sub-Carpathian Sandomierz Basin, both interfluves and terrace steps on the Wisłoka are cut into Miocene clay bearing fluvioglacial, fluvial and glacial deposits. In the drainage basin cultivated land dominates, and woodland covers up to 42 per cent of its mountainous portion. Agriculture existed here well back into Neolithic times.

THE FLOOD-PLAIN

The winding presently active flood-plain, 300—800 m wide, occupies some 10—20 per cent of the former flood-plain which stands 7—12 m above the mean water level in the channel and is 3—4.5 km wide. The now active 4—6 m flood-plain is characterized by varied relief including levées, evorsional troughs and cut-offs being either continuously planed off by alluviation or transformed by flood-water erosion. Channel correction through sedimentation is favourable for the addition of the abandoned channels to the flood-plain. During the last 200 years 2—3 metres of mud were laid down within the zone of lateral channel migrations (Klimek 1974a).

THE PRESENT-DAY CHANNELS

The active Wisłoka channel, 40—70 m wide, is incised to a depth of 4—6 m into the flood-plain. For this reason, there is no distinct difference between the moderate- and high-water channels. The longitudinal gradient of the water surface is 0.63‰ per 21.3 km between the Łabuzie and Brzeźnica water-stage recorders. The channel has a winding course, bend radius averages 625 m (from between 325 and 800 m). Straight reaches also occur. The above parameters are due to both discharges and channel correction. In the channel there are point bars, lateral bars and — less frequently — central bars. During the last 70 years bankfull discharges were recorded 29 times at Łabuzie.

THE HYDROLOGIC RÉGIME

In the catchment annual precipitation is 650—900 mm, of which 40% fall in the three summer months. The mean annual discharge at Brzeźnica is 26.2 m³/s and specific run-off is 10 1/(s/km²) (Punzet 1972). Snowmelt high-flows of long duration occur in spring and discharges then are up to 700 m³/s exceeding 2—3 times the mean annual peak discharge. During the continuous summer rains discharges may exceed

1000 m^3/s. The largest flow at Brzeźnica occurred in 1934, and it was 1820 m^3/s (Punzet 1972). Thus the peak flow experienced exceeded the value of peak discharge of ca 1650 m^3/s which can be expected once in a 100-year period. The differences between low- and high-flows reach 7 m, and values up to 6 m occur once in a 10-year period. The river is competent to carry a suspended load of 300—800 kg/s at discharge exceeding 500 m^3/s. This then is favourable for the upbuilding of the flood-plain.

CHANGES DURING THE LAST 200 YEARS

The reconstruction of changes is based on analyses of topographical maps dating from 1780, 1856, 1875 and 1956 and on field mapping. Two hundred years ago the channel had a more winding course than at present, the radii of smallest bends being 250—300 m. In the 19th century there occurred many central bars in the channel, 75—100 m wide. The thalweg lying 3 m higher than at present could easily migrate on the flood-plain which was only 2 m higher. The tendency toward braided channel formation can be explained by the increase in potato fields at the close of the 18th century. As the channel shifted laterally, suspended load became entrapped in the riverside willow shrubs. It is possible there to distinguish bars built during the successive high-flows (Klimek 1974 a). The river responded to the channel correction in the second half of the 19th century by channel deepening. This tendency was accelerated after 1954, the rate being 1 m per 10 years (Klimek 1974 b). This indicates that by 1910 discharges of the same order caused locally the inundation of the original flood-plain (which now takes off as a supra-flood terrace plain), whereas at present such discharges fit well in the channel and tend to flood only the 4—6 m flood-plain, i.e. the 19th century semi-braided channel. In places the presently active channel is cut into coarse gravel, and even in Miocene clay. This renders lateral shifting difficult. Increased erosion is caused by gravel extraction from the stream channel and by reduced material supply into the channel from the upper part of the drainage basin in which arable land decreased in size.

CHARACTERISTICS OF LANDFORMS AND DEPOSITS

MORPHOLOGY OF THE VALLEY FLOOR

In the valley segment examined the terrace sequence is asymmetrical on both banks of the river (Fig. 1 and 2). Upstream of Dębica the Wisłoka undermines the foot slope of the Carpathian Foothills escarpment, and the terrace sequence is well developed on the left bank there. In the down-valley direction, the middle terrace is on the right bank,

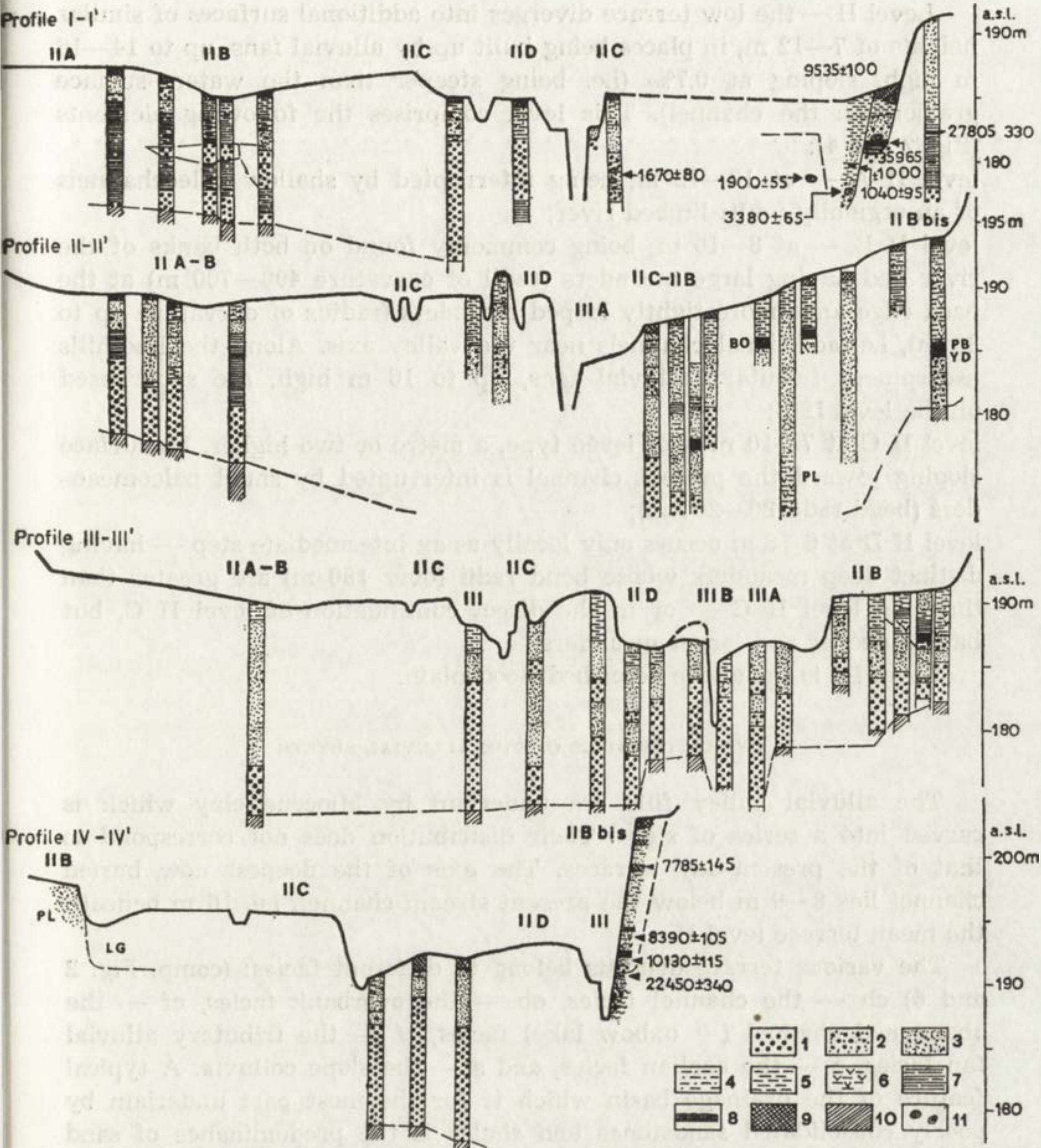

Fig. 2. Sections across the Wisłoka valley bottom (by L. Starkel). (For location of cross-sections see Fig. 1. Terrace level symbols explained in the text)
1 — gravel; *2* — gravel with sand; *3* — sand; *4* — sandy mud; *5* — silt; *6* — mud with organic matter; *7* — clay; *8* — peat; *9* — soil horizons; *10* — Miocene clay; *11* — logs

while lower terraces are on the left bank. Within the valley bottom, three main terrace levels of differing height and micro-features tend to occur:

Level I — the middle terrace at 12—15 m (199—191 m a.s.l.) is composed of sand blown locally into dunes.

Level II — the low terrace diverges into additional surfaces of similar heights of 7—12 m, in places being built up by alluvial fans, up to 14—16 m high, sloping at 0.7‰ (i.e. being steeper than the water—surface gradient in the channel). This level comprises the following elements (Fig. 2 and 4):

level II A — at 10—12 m, being interrupted by shallow paleochannels of an orginally multi-limbed river;

level II B — at 8—10 m, being commonly found on both banks of the river and having large meanders (radii of curvature 400—700 m) at the back edge and more tightly looped meanders (radius of curvature up to 30 m), i.e. additional channels near the valley axis. Along the Foothills escarpment tributary alluvial fans, up to 16 m high, are superposed on the level II B;

level II C at 7—10 m is of levée type, a metre or two higher. Its surface sloping toward the present channel is interrupted by small paleomeanders (bend radii 80—200 m);

level II D at 6—8 m occurs only locally as an intermediate step — having distinct deep meanders whose bend radii (over 180 m) are greater than those on level II C — or in the direct continuation of level II C, but having deeper and larger meanders.

Level III is the above described flood-plain.

CHARACTERISTICS OF THE ALLUVIAL SHEETS

The alluvial valley fills are underlain by Miocene clay which is carved into a series of steps. Their distribution does not correspond to that of the present-day terraces. The axis of the deepest now buried channel lies 8—9 m below the present stream channel, i.e. 16 m beneath the mean terrace level II.

The various terrace deposits belong to different facies: (comp. Fig. 2 and 6) ch — the channel facies, ob — the overbank facies, cf — the abandoned channel (= oxbow lake) facies, tf — the tributary alluvial fan facies, e — the aeolian facies, and s — the slope colluvia. A typical feature of the drainage basin which is for the most part underlain by poorly consolidated sandstones and shales is the predominance of sand and dust fractions. Both breaks in the depositional sequence and phases of erosion are recorded by the presence of either gravel pavements or fossil soils and by the lateral accretion of flood-plain deposits.. The highly complex nature of the level II B is indicated by the occurrence of two sedimentary cycles and by the frequent superposition of the tributary alluvial fan deposits (ch—cf—ch—ob/cf—tf). Sometimes the multiplication of the sedimentary cycles (ch—ob—ch—ob) has also been achieved within the levels II C and II D.

THE RELATIVE AND ABSOLUTE CHRONOLOGY OF THE VALLEY SPREADS

The chronology is based on special studies at several sites from which samples were obtained to make pollen analyses, radiocarbon datings and other supplementary analyses. Thus it became possible to give exact dates for the deposition of the valley spreads and to reconstruct their interrelationship (Fig. 1 and 2).

At the site at Brzeźnica (compare Mamakowa and Starkel 1974) the level I at 15 m consists mostly of rhythmically bedded silt and sand having remains of a shrub tundra flora (dominated by *Betula nana*) in the middle of the profile. These are dated at 28 000 a B. P. Lying on their top are dune sands.

The lower level II B comprises an erosional surface which cuts across gravel and Interpleniglacial oxbow-lake deposits dated at 35 000—48 000 years. The above surface was covered first with alluvia of the channel facies dated at 11 100 ± 125 a B. P. and then with point bar and oxbow-lake deposits. Samples taken from these deposits for pollen analyses give the sequence of changes from open pine communities with tree birches, *Larix* and *Pinus cembra* to the spread of *Corylus* and of such components of the deciduous mixed forests like *Quercus* and *Tilia*. Both the older gley horizons and the allogenic materials in the topmost deposit indicate that the infilling of the cut-off was associated with changes in the hydrologic régime (Kowalkowski and Starkel 1977). This Atlantic soil is found both *in situ* on the buried surface and in the fossil slump deposits (as redeposited features) on the terrace II A edge, but they lie buried by the level II C sheet. The latter one is composed of deposits belonging to both the channel facies and overbank facies, i.e. of a two-fold series of mud corresponding to two slump generations found on the buried terrace edge. The lower alluvia have been dated by logs. The dating on a *Carpinus* log indicates an age of 3380 ± 65 a B. P. Overlying deposits dated at 1040 a B. P. correlate to the distinct forest clearing in the valley floor as is shown by both the pollen diagram and the increased grain sizes of the topmost soil.

The veneer of mud indicates that progressive aggradation occurred in the valley floor during the middle ages.

At the lowermost level III, 5—6 m high, the river was flowing still in the 18th century. At the depth of 3 m the gravel and sand terrace deposits included a log (probably redeposited) dated at 1900 ± 55 a B.P.

The site at Podgrodzie, 15.80 m above present river, is in the apex of a tributary alluvial fan which is built out upon the level II B (Mamakowa and Starkel 1977; Niedziałkowska *et al.* 1977). At the depth of 12.10 m there occurs an erosional surface cutting across Pleniglacial fluvial sediments which interdigitate with solifluction deposits. Their datings suggest an age of ca 33 000 and 22 000 a B.P. The overlying gravel pavement is buried beneath about 1 m sand and silt. These oxbow lake deposits must be assigned to the very earliest part of the Holocene (Fig. 3).

The period between 9 955 ± 115 and 8 390 ± 105 a B.P. is represented by a 1.76 m series of oxbow lake deposits (gyttja, mud with woody peat, silt and sand) which gives the transition between the pine-birch forest communities and the deciduous forests in Atlantic times being associated with the overgrowing of the oxbow lake. This is shown by both the pollen data and the malacological spectrum (Alexandrowicz 1981). About 9 000 a B.P. began the supply of sand due to the revival of erosion in the drainage basin. However, flood frequencies increased generally about 8 400 a B.P. The accumulation of the 9 m sandy alluvial fan deposits with only silt and organic bands within them took place during slightly more than 1000 years.

On the opposite river-bank in the gravel pit a Grabiny—Latoszyn there is exposed the structure of the levels II D and III. Thus it is possible to reconstruct the history of stream channel changes from the Atlantic period onwards (Awsiuk *et al.* 1980). At the level II D the topmost part of the lowest gravel series contains oak trunks dated at ca 5 900 a B.P. This deposit has been worked over by the river as is indicated by loamy silt bands around the logs. The significant feature of pollen spectra from this silt are high percentages of *Abies* which might have spread simultaneously in the Dębica area and in the Beskid Niski Mts, i.e. about 3 300 years ago (Gil *et al.* 1974). At the northern end of the section logs and organic silt bands in this middle member gave dates of 2 260—2855 a B.P. The overlying upper 3—4.5 m sequence of channel and flood-plain deposits contains logs which become progressively younger going northward from between 960 and 475 a B.P. This suggests lateral channel migrations. In the direct continuation of this profile there occurs an abandoned loop with a greater bend radius ($r = 180$ m) than that of meanders on the terrace II C. The latter channel ceased to function already in the 18th century when the river descended to the level ± of the flood plain (*cf.* old maps). This channel deepening and the subsequent formation of the 4—5 m lower plain was stimulated by the increase in stream gradients due to a change from the meandering to the braided river.

SEQUENCE OF BOTH SEDIMENTARY SERIES AND LANDFORMS

The complex nature of landforms and deposits of differing age is shown on a schematic cross-section (Fig. 4). The changeability of stream activity and of the dominant facies is best illustrated by the relation of mean grain sizes of alluvia to their sorting index (Fig. 5).

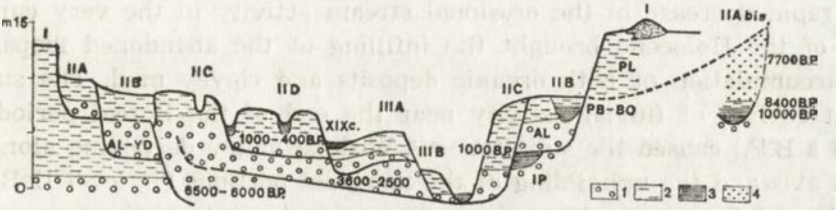

Fig. 4. Schematic section across the Wisłoka valley bottom (by L. Starkel)

1 — channel facies; *2* — overbank facies; *3* — oxbow-lake facies; *4* — aeolian sands

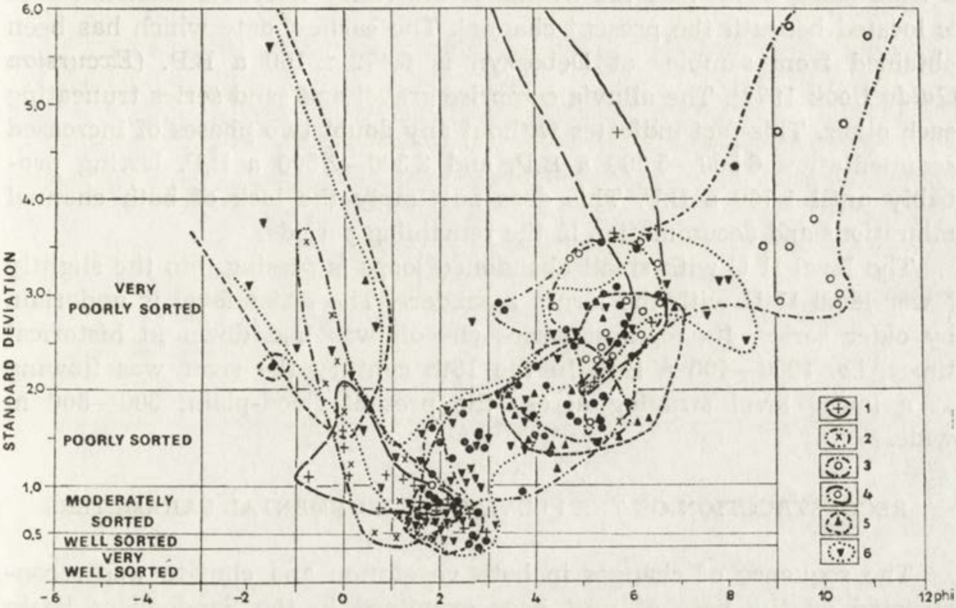

Fig. 5. Scatter plot of mean grain size (Mz) versus standard deviation (δ_I) by E. Niedziałkowska

Deposits of different ages:

1 — Pleniglacial; *2* — Late Glacial; *3* — Preboreal—Boreal; *4* — Atlantic; *5* — Subboreal—early Subatlantic; *6* — Late Subatlantic

The level I at 13—15 m is representing the younger Pleniglacial which is seen to overlie the remnants of Interpleniglacial and older deposits. Typical features are the sequence of ch-cf-cf-ob-e facies in the middle member and the rhythmically alternating thin sand and silt layers which were laid down during the snowmelt floods.

Into this level the erosional plain is incised at 8—9 m above present channel. This plain was built up by alluvia forming the level II A. These alluvia antedate the Allerød (= age of base of the level II B) and they were deposited by a braided river.

The level II B includes a distinct erosional surface at 3—5 m above present channel created during the Allerød and the Younger Dryas.

The rapid decrease in the erosional stream activity in the very earliest part of the Holocene brought the infilling of the abandoned loops, i.e. the accumulation of both organic deposits and clayey mud. The subsequent revival of fluvial activity near the end of the Boreal period (ca 8 400 a B.P.) caused the simultaneous Wisłoka valley deepening along its main axis and the upbuilding of the marginal portions (= level II B bis) by alluvial fans up to 10 m thick. The central points of the fans are at a higher level than the Pleniglacial terrace plain (level I).

The younger alluvia of the levels II C and II D are restricted to a tract being about half the widths of the valley floor. Its erosional base is located beneath the present channel. The earliest date which has been obtained from samples at Dęborzyn is 6 472 ± 100 a B.P. (*Excursion Guide Book* 1972). The alluvia comprise gravel and sand series truncating each other. This fact indicates without any doubt two phases of increased sedimentation 6 500—5 900 a B.P. and 3 300—2 500 a B.P. lasting probably until 1 700 a B.P. This does not imply the lack of both channel migrations and accumulation in the remaining periods.

The level II C with small abandoned loops is passing into the slightly lower level II D with the larger meanders. The latter level is underlain by older series. Its topmost series ch—ob was laid down in historical times, i.e. 1000—400 a B.P. In the 18th century the river was flowing at a lower level straying across the present flood-plain, 300—800 m wide.

RECONSTRUCTION OF THE FLUVIAL ENVIRONMENTAL PARAMETERS

The sequence of changes in both vegetation and climate was reconstructed on the base of peat bogs examined in the Sandomierz Basin and the Carpathian Foothills (comp. Mamakowa 1962). Changes also are recorded by analyses of both pollen and macro-fossils contained in the Wisłoka terrace deposits. In the Wisłoka valley the most significant changes in the composition of forests which occurred about 9 000 years ago were due to the spread of *Alnus, Quercus, Corylus* and *Tilia cordata.* The rapid expansion of the riverside alder forests (dominated probably by *Alnus incana*) might have been facilitated by the occurrence of the first larger flood that disturbed the equilibrium of the then existing communities. This flood is recorded by a thin layer of sand in the peaty member referable to the period of the first maximum of *Alnus* pollen in the sequence at Podgrodzie.

Reconstructions of changes in the hydrologic régime of the river can be based on analyses of parameters of the paleochannel geometry and on changes in both facies and grain sizes of the different deposits. The evidence so far available indicates that the above reconstructed elements were as follows:

The bend radii and channel widths were used in the discussion of the paleochannel geometry. The changes in the hydrologic régime of the river, i.e. the channel altering discharges were computed by the formulae (R — curvature radius, Qp — probable flood discharge):

$$L = 4.7\ R^{0.98} \quad \text{and} \quad Qp = \left(\frac{L}{29.6}\right)^2$$

(comp. Leopold, Wolman and Miller 1964). The small lithologic variability of the sandy deposits in the valley section examined is assumed to have not caused essential changes in the channel pattern. Behind the traces of braided channels at the level IIA, there are the first large meanders at the level IIB which were active during the Younger Dryas. The then channel altering discharges give a value of ca 1815 m³/s which is equivalent to the present discharge of recurrence interval 200 year (tab. 1).

Table 1. Radius (R), width (W) of different paleochannels in the Wisłoka valley near Dębica and estimated most probable flood discharge (Qp)*

Terrace level	Generation of paleochannels	Curvature radius R in metres (min--max)	Channel width in metres	Qp in m³/s
II A	Paleochannels of braided river pre-Alleröd		30–40 (each)	
II B	Large paleomeanders (Alleröd–Younger Dryas)	565 (400–700)	100–120	1815
II B$_1$	Very small paleochannels of anastomosing river	30	15–20	6
II C	Small paleomeanders (much older than 1000 years B.P.)	150 (100–200)	30	135
II D	Small, deep paleomeanders on the 8–10 m plain (10–17th c.)	80		39
II D	Mean paleomeanders at Grabiny--Latoszyn (11-17th c.)	180	60	193
III A	Mean paleomeanders on the 4–6 m plain (18th c.)	280 (240–360)		458
III A	Wisłoka channel on the map 1 : 75 000 in 1875	min. 530		1600

* The estimated probable channel forming discharges differ from data published in 1981 by K. Klimek and L. Starkel (Starkel et al. 1981) due to mistake in change from feet-to metric system.

Similar bends occur on the opposite river bank suggesting the existence of a multi-limbed river in the Late Glacial. There is some reason to suppose that the discharges Qp must have been much higher then. The younger more tightly looped meanders occurring on this plain ($Qp = 0.6$)

were lateral channels which functioned at the same time with the main channel. At the level II C the set of small and medium-sized paleomeanders suggests that both mean discharges and the mean dominant discharge Qp were very much lower than they are now reaching 100—200 m³/s in former times. This implies vegetation controls. But at the level II D both discharges and meanders began to increase in magnitude during the last one thousand years. The advent of more intensive agriculture in the 18th century was characterized by the formation of the younger paleochannels cutting into the level II D and descending to the level III. These are related to higher discharges $Qp = 458\,m^3/s$. The formation of the 19th century channel which corresponds to the presently active flood-plain, 300—500 m wide, was centered on the transition between the meandering and braided courses. Such conditions imply floods of recurrent interval 1—2 in one hundred years (by comparison with the present conditions). As analyses of old maps show, large floods brought about, really, continuous changes in bed contours. In the post--channel correction period, i.e. since the second half of the 19th century, channel deepening by some 3 m has resulted in its stability.

Changes in the hydrologic régime also are indicated by the dominant type of facies in a given time unit and by variations in grain size of deposits belonging to the different facies. Valuable results were obtained by analysing the ratio of mean grain diameter to sorting (Fig. 5). It appears, that the bar- and levée-forming sands are generally well sorted, whereas the gravel pavements on the bed, the silt-clayey oxbow-lake deposits and the tributary alluvial fan deposits are poorly sorted.

The Pleniglacial deposits represent different time units and they may differ only by the coarser and poorly sorted materials belonging to the various overbank- and oxbow-lake facies. The late glacial and early Preboreal deposits (11 100—10 000 a B.P.) are characterized by the occurrence of coarse pavements and better sorted ($\delta_I = 1.5$—2.5) bars. This fact, together with the presence of abundant redeposited pollen mostly Tertiary in age due to the cutting of benches into the Miocene clays (= lateral erosion) indicates high flood-flows.

The Preboreal and Boreal periods (10 000—8 400 a B.P.) are marked by the deposition either of well sorted sand or of silty-clayey muds. The latter is unusually fine and it was no more found, giving an indication of both reduced material supply into the channel and low discharges. The lateral channels become abandoned and the coarser materials were moved only along the valley axis.

The Atlantic period, especially its first part (8 400—7 500 a B.P.) is characterized by both larger grain sizes of deposits and increased rates of sedimentation. The tributary alluvial fan deposits provide evidence of the rhythm of large floods occurring at least every 20—30 years in the drainage basin which must still have been completely covered with forests. Precipitation was much higher than it is now, when discharges increased under conditions largely modified by man.

It is possible to infer the following phases of increased fluvial activity from pavements which are included in the younger alluvia: 6 500—5 900, 3 300—1 500 and from ca 1000 a B.P. onwards. The flood-plain deposits which have been formed in historical times, all are marked by coarser grain sizes and a poor sorting due to the accelerated soil erosion and increased flood frequency.

The simultaneous occurrence of channels marked by different parameters and of inserted fills suggests alternations of more stable conditions and of periods coincident with intense channel changes resulting in the abandonment of old channels and formation of new patterns (Fig. 2 and 6). The prime condition was the existence of phases reaching threshold values, i.e. the frequent occurrence of excessive floods (Selby 1974; Schumm 1977). The above described paleochannel systems prove the existence of phases of dynamic metastable equilibrium (Knox 1975). These are separated from both the older and younger channel systems and they indicate either the avulsion or the shifting of channels, i.e. a "phase

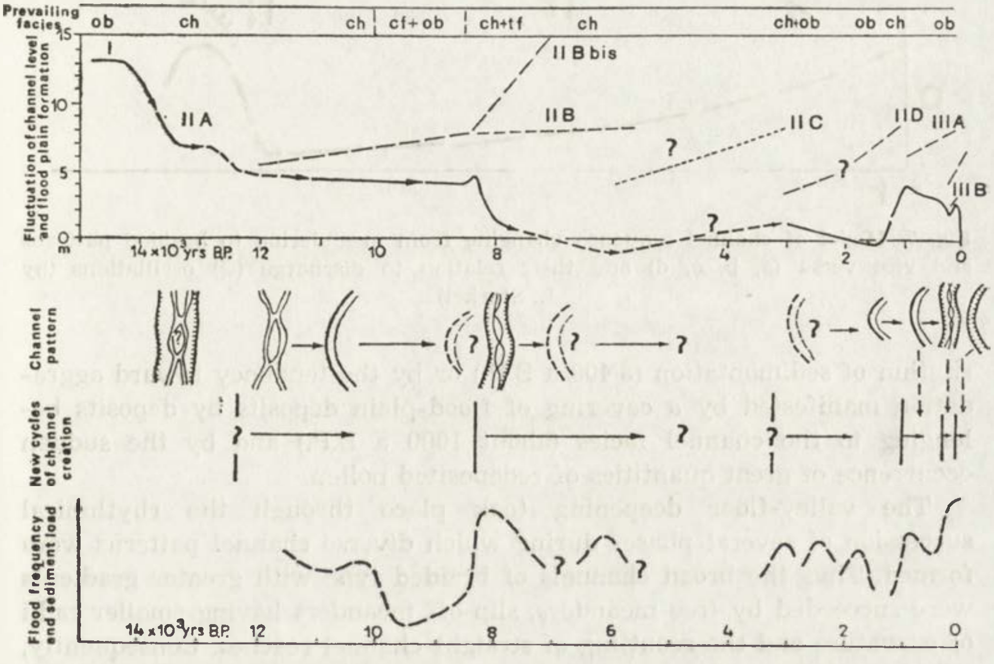

Fig. 6. Changes in bed- and flood-plain elevation accompanied by changes in alluvial facies, channels types and flood-flows in the Wisłoka valley in the Late Glacial and the Holocene (by L. Starkel)

ch — channel facies; ob — overbank facies; cf — abandoned channel facies; tf — tributary alluvial fan facies of erosion". During the successive floods the cutting of a new channel was accompanied by its deepening and formation of straight channel reaches (Fig. 7). Hence, some of the channels are hanging now. The evidence of such changes also is provided by the rapid change in the

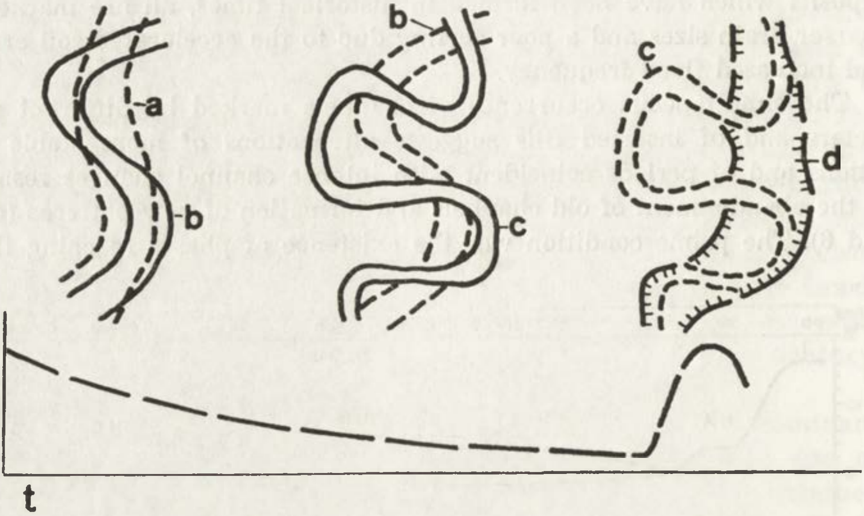

Fig. 7. Model of channel sequence changing from meandering to braided patterns and vice versa (a, b, c, d) and their relation to discharge (Q) oscillations (by L. Starkel)

rhythm of sedimentation (8 400 a B.P.) or by the tendency toward aggradation manifested by a covering of flood-plain deposits by deposits belonging to the channel facies (about 1000 a B.P.) and by the sudden occurrence of great quantities of redeposited pollen.

The valley-floor deepening took place through the rhythmical succession of several phases during which diverse channel patterns were formed. Thus the broad channels of braided type with greater gradients were succeeded by free meanders, slip-off meanders having smaller radii of curvature and the recutting of straight channel reaches. Consequently, the then existing flood-plain system became destroyed. In the valleys drained by the Carpathian rivers on which summer floods tend to occur the above equilibrium conditions became more easily destroyed in the wetter periods, e.g. about 8 400 a B.P., than in the valleys which are draining the lowland areas of Central and North Poland. During the Late Glacial and in the Early Holocene a general change from braided to meandering channel patterns took place there (Falkowski 1975; Kozarski and Rotnicki 1977). It seems likely that near the end of the Atlantic period the Wisłoka channel reached the profile of equilibrium. The younger alluvia do not descend to greater depths. During the last one thousand years the increased supply of materials derived from the mountains is associated with a tendency toward aggradation. The younger inset fills were built up to the level II B, and the majority of paleomeanders then came into being.

From about the 16th century onwards a tendency towards channel deepening was predominant. Incision rates increasing rapidlly led to the transformation of the 19th century broad flood-channel into the presently active flood-plain.

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ANDRZEJ SZUMAŃSKI

THE EVOLUTION OF THE LOWER SAN RIVER VALLEY DURING THE LATE GLACIAL AND THE HOLOCENE

HISTORY AND ORGANIZATION OF INVESTIGATIONS

Geological investigations in the Lower San valley started at the end of the 19th century (Rehman 1891; Łomnicki 1900; Friedberg 1903). The two latter authors distinguished in the valley bottom two low terraces named the *rendzina* terrace and the flood terrace, Late Pleistocene and Holocene in age (accentuating distinctly the further present-day upbuilding of the flood terrace spread). Later on, Klimaszewski (1937, 1948) and Starkel (1960) noted that at the outlet of the San valley from the mountains the *rendzina* terrace was composed of sediments belonging to the Vistulian Glaciation and the Holocene. They regarded the middle terrace (rising above the *rendzina* terrace) which in many places is preserved on the San valley sides as belonging to the Central-Polish Glaciation.

The most recent investigations, made among others in the Wisłoka valley, show that the middle terrace is composed of last Pleniglacial sediments (Laskowska-Wysoczańska 1971; Mamakowa and Starkel 1974).

During the examinations in the San valley, which were undertaken by the Institute of Hydrogeology and Engineering Geology, Warsaw University, near the end of the 1960s Falkowski's (1965) research method of alluvia was accepted. The analysis of landform sequences was based on a geological interpretation of air photos being supplemented by the mapping of both the river channel and some reaches of the valley floor. On the ground of archival maps the transformations of the San channel during the last 140 years have been documented. Pollen analyses and radiocarbon datings of biogenic fills of the San paleomeanders are continued.

CHARACTERISTICS OF THE PRESENT ENVIRONMENT

LOCATION OF THE STUDY AREA IN THE DRAINAGE BASIN

The investigations were carried out in a 40 km long section of the Lower San valley within the Sandomierz Basin, between Dębno at the Wisłok River mouth and Ulanów at the mouth of the Tanew River

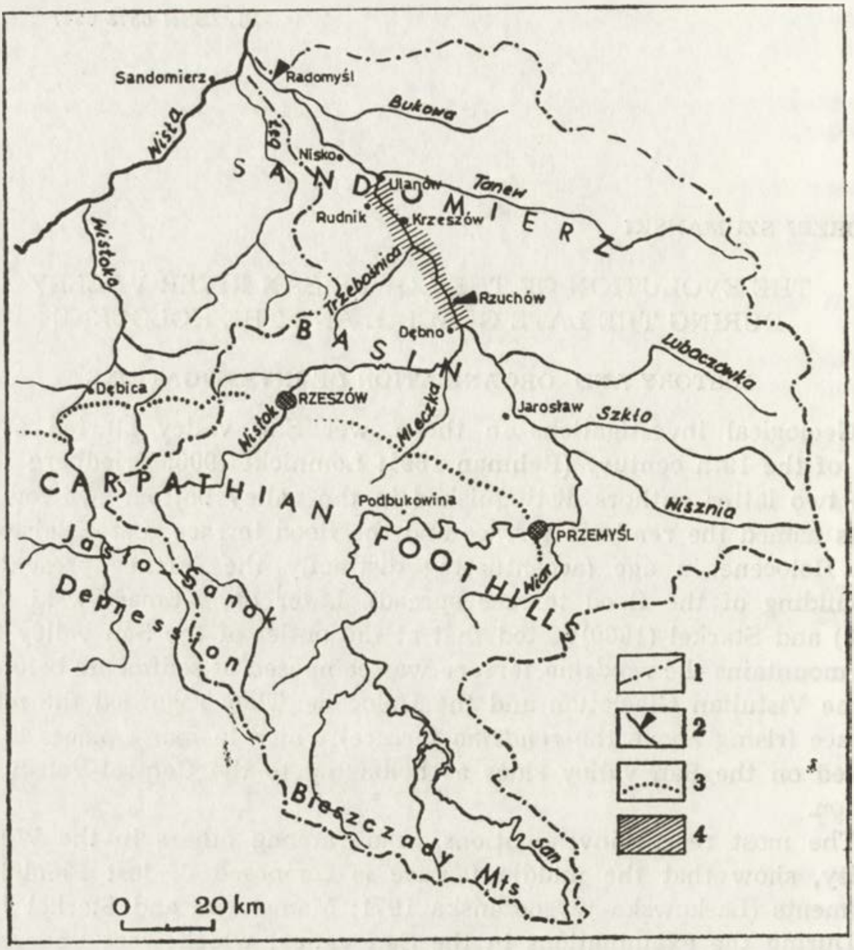


Fig. 1. Location of the San drainage basin

1 — limits of the San drainage basin; *2* — water gauges; *3* — the Carpathian Foothills escarpment; *4* — study area

(Fig 1). The San flows at altitudes from between 167.3 and 154.2 m a.s.l. The whole San drainage basin occupies an area of 16 780 km^2, of which 7000 km^2 are mountains and foothills of the flysch Carpathians (up to 1348 m a.s.l.). The remaining part is in the Sandomierz Basin. The mountaineous fragments of the San drainage basin are composed of sandstones, shales and marls overlain by a sand-clayey sheet of slope sediments varying in thickness. Along the northern margin of the Carpathian Foothills and in their foreland, between Rzeszów and Przemyśl, there occur thick series of loess. The Sandomierz Basin contains Quaternary glacial, fluvial and aeolian sediments (sand predominates) which are underlain by Miocene clays.

THE FLOOD-PLAIN

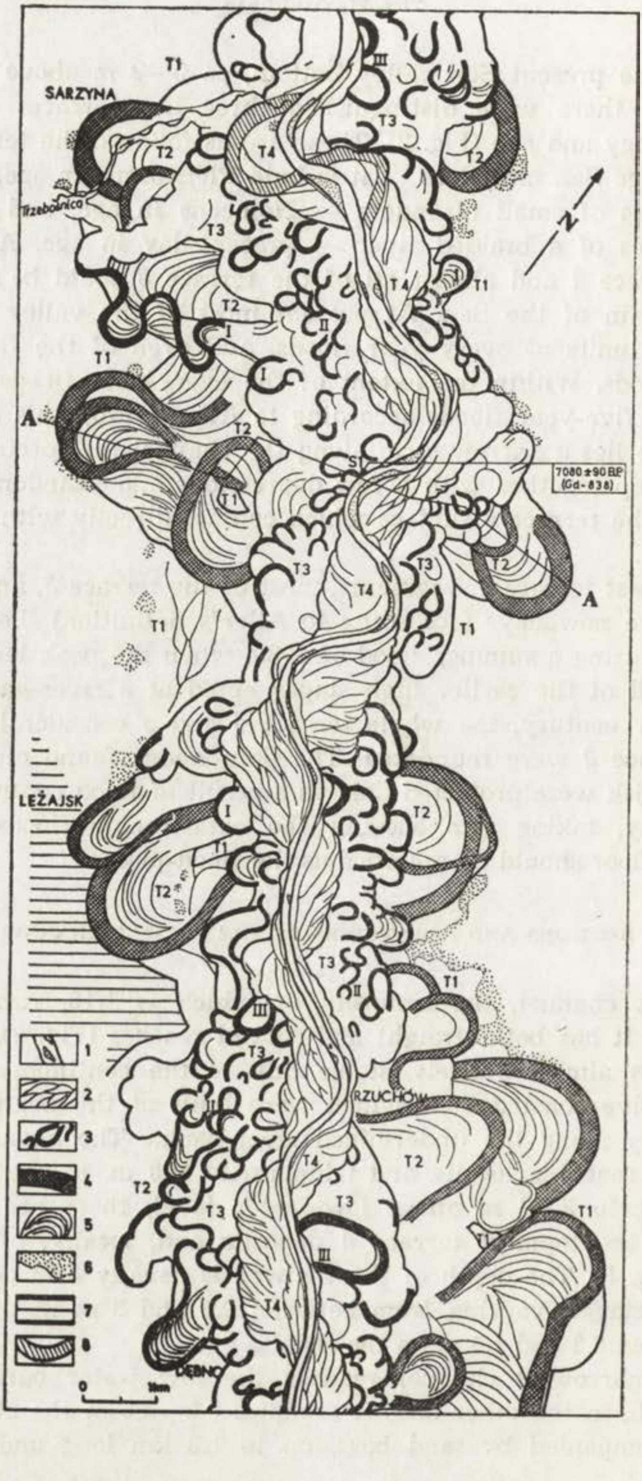
Within the present San valley bottom, ca 5—8 m above low stream water level, there were distinguished three low terraces of differing relief, lithology and age (Fig. 2). These are as follows: the terrace *2* with traces of large San meanders — it is Late Pleistocene in age; the terrace *3* with traces of small meanders — Holocene in age, and the terrace *4* with traces of a braided river — present-day in age. A short time ago the terrace *4* and almost all of the terrace *3* could be regarded as the flood-plain of the San. At present most of the valley bottom lies outside the limits of every year floods, and even of the five-year and ten-year floods. Within the extent of the every-year floods and of the one-year to five-year floods according to Allen (1970), this is the flood-plain, there lies a narrow strip along the channel that occupies a lower terrace *4* step together with a few depressions and abandoned loops interrupting the terrace *3* surface which contact directly with the present San channel.

The highest terrace *4* fragments, most of the terrace *3*, and the whole terrace *2* are nowadays (according to Allen's definition) the supra-flood plain. But during a summer flood of 1980, when the peak level exceeded by 0.5 m all of the earlier high stages noted at a river-gauge at Rzuchów in our century, the whole terrace *4* and a considerable fragment of the terrace *3* were inundated. The depressions found on the terrace *2* near Leżajsk were protected only as a result of flood control measures. Consequently, taking into account the catastrophic floods the whole San valley floor should be regarded as the flood-plain.

SECTIONS AND PARAMETERS OF THE PRESENT CHANNEL

The San channel, the sinuosity of which is 1.18, runs along the valley axis. It has both straight and curved reaches (Fig. 2). Its position is nowadays almost entirely stable due to the continuous restoration of anti-erosive constructions which were built at the beginning of the 20th century along the undermined river-banks. The channel width is 80—200 m, reaching locally and temporarily 300 m. In the San channel sides, rising to 3—7 m above low water level, there are usually exposures of the topmost terrace *4* deposits and, locally, of the terrace *3 sheet* (Fig. 3). The depth of the thalweg is usually 3 m or less during low water stages; varying from between 0.4 and 3 m in the deeps and from between 0.2 and 1.4 m on the shoals.

In the narrowest channel reaches the low water current fills its whole width, in the other ones it occupies 0.2—0.5 of the channel width and is accompanied by sand bars, up to 1.3 km long and over 2.5 m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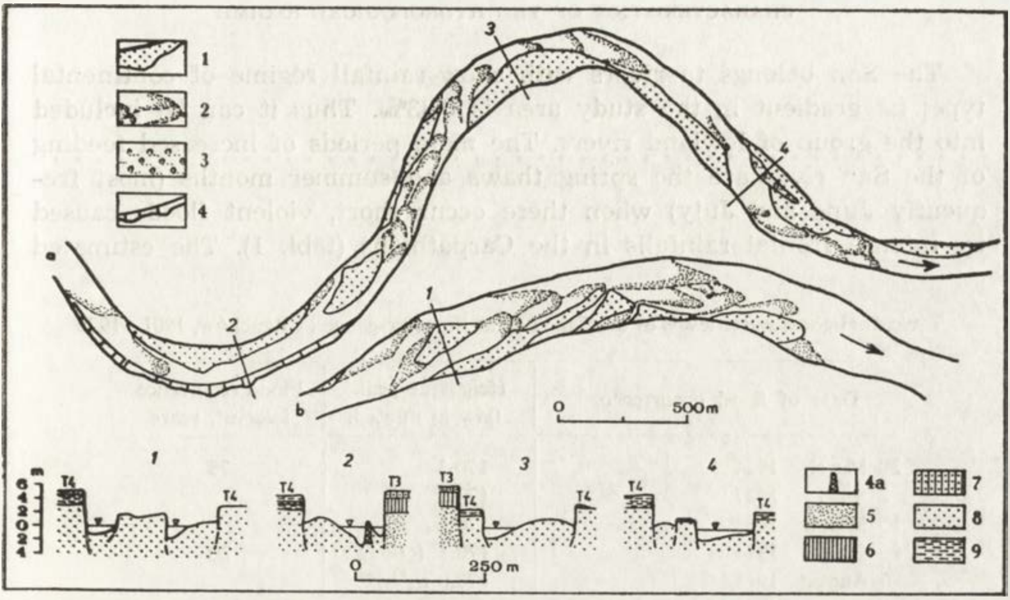


Fig. 3. Photo-geological sketch showing San channel reaches (a) near Leżajsk and (b) near Krzeszów in 1965

1 — sand bars rising above water surface; *2* — sand dunes wandering along the thalweg at low water in the channel; *3* — sand bars overgrown by osier; *4,4a* — anti-erosive dams on the river bed; *5* — fine sand; *6* — non-stratified loamy mud; *7* — "loess-like" mud; *8* — vari-grained sands; *9* — non-stratified loamy-silty mud; *T3* — Holocene terrace; *T4* — present-day terrace

high. In the sections, where the channel width is over 140 m, there are locally irregularly arranged central bars on the bed. The lateral and central bars tend to change their shapes and positions during every flood. At the same time, different features due to intensive bank erosion are noted. This suggests that the present San shows a natural tendency toward braiding. The river passing from the high- to low-water stages tends to dissect and to erode the large flood sand bars inserting sequences of sand dunes which are wandering along the low-water channel bed (Fig. 3).

Fig. 2. Photo-geological sketch showing the Lower San valley floor between Dębno and Sarzyna

1 — sand bars in the channel; *2* — traces of a braided pattern; *3* — traces of small meanders of the San; *4* — large paleomeanders of the San; *5* — outlines of point bars; *6* — dune fields; *7* — interfluve; *8* — meanders of the San, abandoned through dug cutoff in 1903; *S1* — location of the section San 1; A — A — section across the San valley (Fig. 9); *T1* — middle terrace (Vistulian); *T2* — low terrace with traces of large meanders (Late Glacial); *T3* — low terrace with traces of small meanders (Holocene); *T4* — low terrace with traces of a braided river (present-day); I, II, III — meander generations on the terrace 3

CHARACTERISTICS OF THE HYDROLOGICAL RÉGIME

The San belongs to rivers with snow-rainfall régime of continental type; its gradient in the study area is 0.33‰. Thus it can be included into the group of lowland rivers. The main periods of increased feeding of the San river are the spring thaws and summer months (most frequently June and July) when there occur short, violent floods caused by intense frontal rainfalls in the Carpathians (tabl. 1). The estimated discharge values at the river-gauge Radomyśl are ca 13 700 m³/s for a secular water and 1800 m³/s for a quadrennial water (PIHM 1967). For most of the year low water stages predominate in the San. Discharges then decrease to about 30 m³/s.

Table 1. Highest water levels of the San river at the river-gauge at Rzuchów, 1901–1975

Date of flood occurrence		Height at peak flow in m a.s.l.	Flood recurrence interval, years
28 March	1924	170.3	75
2 Sept.	1927	170.1	
15 March	1963	170.1	
16 June	1974	170.1 (Q–1420	20
5 August	1913	170.0 m³/s)*	
5 Sept.	1941	170.0	
4 May	1919	169.9	10
5 April	1964	169.9	
12 July	1906	169.8	
14 Sept.	1913	169.8	
18 July	1934	169.8	
16 July	1913	169.7	
9 June	1948	169.6	
8 June	1962	169.5	5
—		168.2**	0.8

* No data on discharges (Q) at the Rzuchów section were published until the 1970s.
** Approximate altitude at bankfull stage.

The low water levels oscillate from between 0.2 and 0.5 m above the lowest annual water level, many a time they are noted during several successive months (e.g. very low water levels lasting for two months and longer have been noted several dozen times in this century). Since 1968, the reservoir at Solina has caused further stability and further decrease in low water. In the summer half-year run-off varies from 22 to 62% of the annual total for dry years and from 47 to 60% for wet years (*Komitet Gospodarki Wodnej* ... 1958).

The irregularity coefficient of the San discharges near Rzuchów calculated from the formula $Q_{1\%\max}:Q_{1\%\min}$ is about 400; for comparison, for the West Carpathian Vistula tributaries this coefficient exceeds 1000 (PIHM 1967). Analysis of all of the bankfull stages and still higher flows of the San at Rzuchów in 1901—1975 (associated with channel-altering discharges being decisive for the shapes and dimensions of the channel — Falkowski 1965; Dury 1971) show that the general balance of the up-to-now occurring snowmelt and rainfall floods is compensated (45 : 44). But among the 14 floods with frequency of 20% or less (tab. 1), the rainfall floods predominated (11). The latter ones are clearly marked by greater dynamics — the violent and short-lasting rise (usually one or two days) and rapid fall after the peak flood stage. Therefore, one can conclude that the present dynamics of processes in the San channel is mostly influenced by the summer floods, but less by snowmelt floods with the same discharges.

Among the Carpathian rivers, the San is characterized by the greatest transport of suspended load (on average 700 000 tons per year at Radomyśl, compared with 2 million tons in the Vistula — downstream of the San mouth; Brański 1968).

HYDROLOGIC AND GEOMORPHIC CHANGES DURING THE LAST CENTURY

About one hundred years ago the Lower San was a braided river of a free flow. Its irregularly curved channel and in many reaches, also straight channel was 200—900 m wide, with sides about 1.5—4.7 m high. The water depths were similar to the present ones. On the channel bed there were vast lateral sand bars and many central bars, and even alluvial islands (Fig. 4). The river was marked by a great intensity of erosion-accumulation processes causing continuous changes in both the channel shape and its position (Fig. 5).

The mean rate of lateral shifting of the San channel in the second half of the 19th century was about 10—15 m per year. In places, the

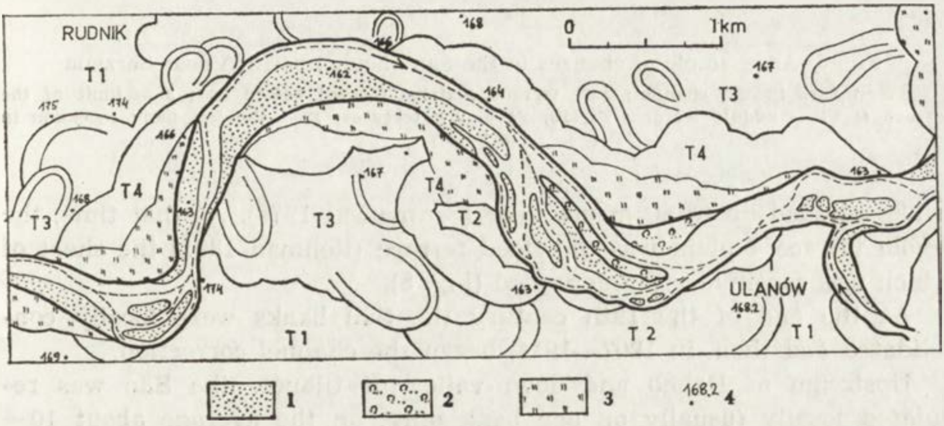


Fig. 4. Sketch showing the San valley reach near Ulanów, based on the 1875 map
1 — sand bars in the channel; *2* — bars overgrown by osier; *3* — meadows and pastures on the terrace *4*; *4* — heights in metres a.s.l.; *T1* — middle terrace; *T2, T3, T4* — low terraces

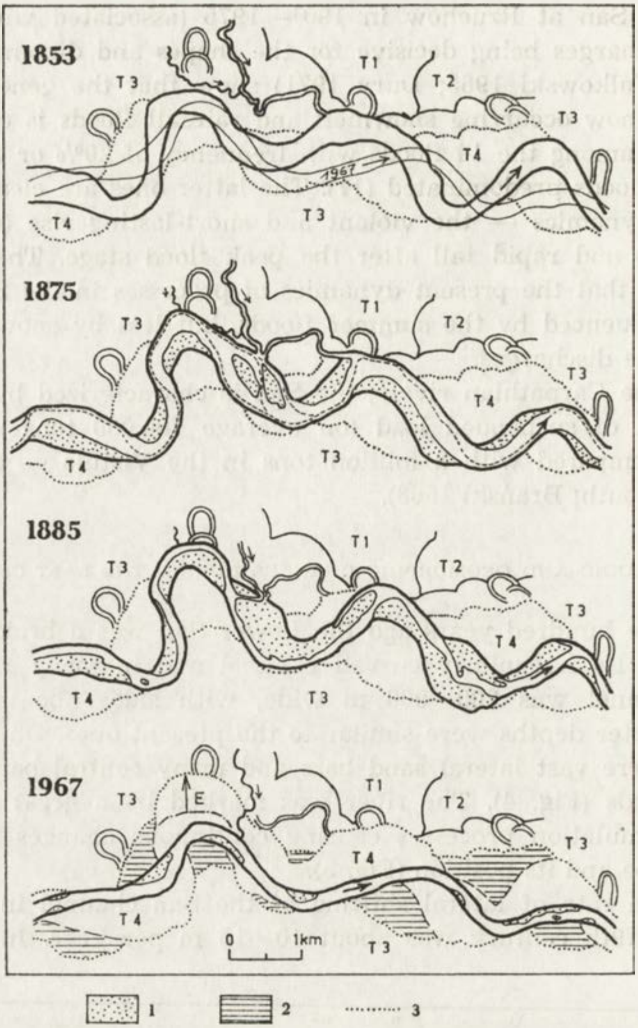


Fig. 5. An example of changes in the San channel position near Sarzyna

1 — sand bars in the channel; *2* — terrace *4* strips formed before 1853; *3* — limit of the terrace *4*; *T1* — middle terrace; *T2*, *T3*, *T4* — low terraces; *E* — the left bank recession in 1853—1903

banks receded up to 60 m per year (Szumański 1979). At that time, the whole terrace *4* plain was the flood terrace (Rehman 1891) the sheet of which was continuously redeposited (Fig. 5).

At the end of the 19th century the San banks were locally consolidated and then, in 1907—1914, began the channel correction.

Upstream of Dębno and down-valley of Ulanów the San was regulated locally (usually on one bank only, on the average about 10—60% of the total bank length became narrowed to about 80—110 m, the banks were consolidated with a rockfill).

In the section described between Dębno and Ulanów, where the San has natural banks today, the channel has been narrowed only by longitudinal and transverse dams to about 0.2—0.5 of its previous width (Fig. 6). Consequently, the narrowed river deepened its channel by 2—3 m. The subsequent deposition of sand and mud in the artificially dammed previous channel resulted in the formation of a lower terrace *4* step along the present river path. This step is the presently active flood-plain of the San.

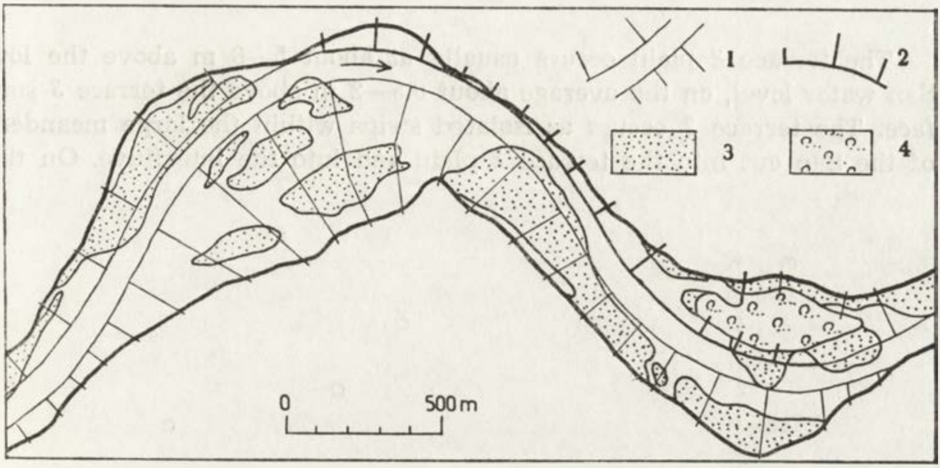


Fig. 6. An example of the projected San channel correction near Sarzyna (according to the 1905 plan)

1 — planned regulated path of the San (location of longitudinal and transverse dams); *2* — constructions done in 1905; *3* — sand bars in the channel; *4* — islands

LANDFORMS AND SEDIMENTS IN THE VALLEY BOTTOM

RELIEF OF THE VALLEY BOTTOM

The present Lower San valley floor is a flat, slightly terraced plain, 1-7.5 km wide, being interrupted by many dry or water-filled abandoned channels of differing size, and by terrace edges, up to 3—4 m high.

On the base of tonal differences noted on the air photos, three low terraces were distinguished in the San valley (Szumański 1972). In relation to the terrace *1* (known as the middle terrace) that occurs on the valley-sides, they were named the terraces *2*, *3* and *4*.

The terraces *2* and *3* vary by sizes of the ancient meanders. The area of the terrace *4* is marked by the occurrence of traces of braided river activities. The areas occupied by the terraces *2* and *3* as well as by some parts of the terrace *4* can be regarded as the supra-flood partition of the valley bottom.

Morphology of the terrace *2* (with traces of large paleomeanders)

The terrace *2* plain occurs usually at about 5—8 m above the low San water level, on the average about 0.5—2 m above the terrace *3* surface. The terrace *2* occurs as isolated strips within the large meanders of the San cut into the terrace *1* plain and into the interfluve. On the

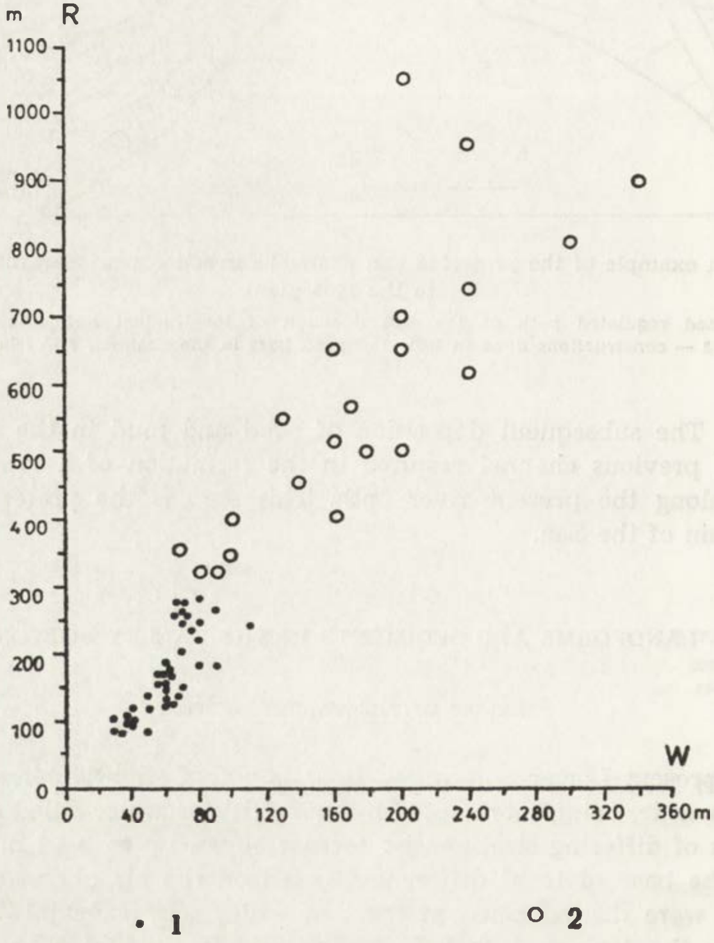


Fig. 7. Relation of the radius curvature of the paleomeanders of the San to channel width

R — radius of curvature of a meander; *W* — channel width (determined on the air photo); *1* — meanders on the terrace *3* (Holocene); *2* — meanders on the terrace *2* (Late Glacial) air photos these areas can be distinguished by the lightest tones and traces of regular outlines of point bars and by the dark contours of the wide meandering channel of the San (Fig. 2, 7). The largest of these meanders have curvature radii up to 1100 m and widths up to 350 m. The height differences between the flat meander bed and the convex banks on the inside of meander bends may be 1 m.

The highest areas on the outside of the bend rise some 1—3 m above the bed of the paleomeanders. Close to the terrace *3* there are mainly smaller meanders with curvature radii from between ca 320 m and ca 450 m as well as narrow channels with distinct, well preserved both edges. The majority of the vast ancient meander depressions interrupting the terrace *2* was until recently wet areas, fed with ground waters that came from the interfluve and the terrace *1*. Due to a lowering of the San channel bed and the digging of draining pitches, they are usually dry areas now being used as meadows, pastures and fields. Within the terrace *2* area there occur erosional outliers of the terrace *1*, several metres high, and small dunes.

Morphology of the terrace *3*
(with traces of small paleomeanders)

The terrace *3* surface at about 5—7 m, can be distinguished on the air photos as an area marked by the darkest tones in the San valley. Very sinuous abandoned loops and contours of buried meanders are abundant there, having narrow channels and relatively small radii of curvature (Fig. 2, 7). These meanders include three generations. The first one is represented by meanders situated in the marginal zone of the terrace *3*. These are cut directly into the terraces *2* or *1*. Their curvature radii are ca 200—300 m and they are about 70—100 m wide each. The meanders are filled with peat and have asymmetric banks (the convex banks are usually imperceptible in the field) and very distinct outlines of point bars (Fig. 2).

The second group — the largest one, includes the most crooked and, at the same time, the smallest meanders which are permanently or seasonally wet. These are frequently filled with peat or mud, and they are discernible only on the air photos. The curvature radii are about 80—180 m, whereas their widths are about 30—70 m. The majority of meanders belonging to this group shows features typical either of stable or of very slowly shifting channels. This is suggested by the presence of both paleochannel edges of similar heights and by the absence of traces of point bars.

The third generation includes a few well preserved, deep and usually water-filled single oxbow-lakes, about 80—120 m wide. Their radii of curvature are 200—300 m. These paleomeanders are concentrated at the contact with terrace *4*

In the marginal zones of the terrace *3* there also are outlines of much greater meanders. These are fragments of the lower terrace *2*, now buried beneath the mud veneer of the terrace *3*. The latter surface is usually the most fertile agricultural land in the valley bottom.

Morphology of the terrace *4*

The terrace *4* occupies a discontinuous zone, some 1.5 km wide, in the central part of the valley bottom. Its fragments occur alternately inside the bends of the San channel or on both banks of its straight reaches (Fig. 2). In this zone the surface is most irregular. Its typical photo-interpretation image shows a pattern of tangential straight streaks or lines with curved ends. These indicate the former outlines of sand bars and islands in the channel as well as river cliffs left by the channel moving down-valley. This image is similar to that of the flood-plains of the present braided rivers. In the upper parts of the individual terrace *4* fragments its contact with the terrace *3* is distinct on the air photos, but it is usually invisible in the field. In the middle and downstream sections this border is already a distinct edge reaching 3—4 m, on the present San channel. This edge is underlain by braids of the former multi-limbed San channel, now poorly preserved. Such depressions are mostly wet grounds.

From a morphometric point of view the terrace *4* surface is not a uniform feature. In the cross sections one can observe several steps sloping outwards and being separated by edges 1—3 m high.

The terrace *4* surface rises 4—6 m above low water level. In relation to the terrace *3* plain, the terrace *4* is usually 1—2 m lower. However, some of its small fragments built up by mud, crevasse splays, levèes and occasional small dunes are at the same height as the terrace *3* and even higher.

In the present topography of the terrace *4* is its lowest step. This is the most frequently flooded zone adjacent to the channel up to 200 m wide and about 3 m high. Within the terrace *4* are several fragments of broad meanders corresponding to the 19th century stream channel, which were cut off by man during the early correction of the San channel at the beginning of the 20th century (the best preserved meander cut off in 1903 occurs near Sarzyna — Fig. 2).

Among the secondary features found in the San valley floor are the shallow incisions of numerous tributary rivulets to the San (which are using the abandoned loops) as well as alluvial fans being superimposed locally on the large meander paths. No dunes were observed in the marginal zone of the San valley bottom.

DESCRIPTION OF THE ALLUVIAL SHEETS

The low terrace deposits on the San are inserted in the sand and gravel terrace *1* sheet. In places they rest on the Miocene Krakowiec clay (near Krzeszów and Ulanów) and on the interfluve-forming sediments (by Leżajsk). Sand is the main component of alluvia belonging to the channel facies in the valley section described. These result from the washing of the older deposits. The gravel fraction found in these sediments is a pavement lying at the depths to which a local bed erosion occurred. The Holocene and Pleistocene alluvia in the valley bottom are some 30 m thick (Buraczyński and Wojtanowicz 1966; Laskowska-Wysoczańska 1971).

Lithology of the terrace *2*

Its sheet is generally composed of sand. At higher altitudes there occur well sorted (locally wind-blown at top) light-yellow fine and medium-grained sands showing a diagonal bedding. In places these sands may be overlain by silty sands or, by silt, less than 1 m in thickness. The lower lying parts of the terrace are bearing locally 1—2 m thick silty coverings which can be identified with typical flood deposits (mud). The ancient San channel path contain mostly gyttja and peat, being locally underlain by a thin layer of clayey biogenic deposits. The total thickness of the above sediments is usually 1—4 m, locally up to 6 m. At the base of the channel sands, at a depth of ca 8—12 m there occurs gravel reworked from the terrace *1* deposits.

Lithology of the terrace *3*

The channel facies of this terrace sheet is represented by well sorted white or gray fine- to medium-grained sands. These may show a diagonal bedding and frequently contain pieces of wood and logs, at a depths of 3—8 m. The above sands are underlain by a 0.5 m gravel pavement. The top of the channel sands occurs usually at a depth of 2—4 m, but in places it rises to about 1 m or it descends to ca 6 m, and even to 8 m in the paleochannels. The channel sands, together with the inserted oxbow-lake sediments are almost everywhere overlain by a continuous sheet of mud, 1—6 m thick, which is usually twofold (Phot. 1). The lower member is represented by a heavy clayey and clay-silty mud of varying thickness, with horizontal laminae, but most frequently it is structureless. The mud is of gley type, grey, grey-brown and brown with rusty spots and nodules of decomposed organic matter. In places these pass upwards into a degraded black paleosoil.

The upper member is composed of a silty yellow "loess-like" mud without any stratification. In the exposures it forms the vertically cracked slumps. The mud is locally underlain by sand.

Sediments belonging to the oxbow facies are significant component of the terrace *3* sheet. These are: the basal fine-grained and silty sands, non-stratified and grey-blue in colour, containing plant detritus, pieces of wood and molluscan shells. Overlying is a greyish-blue loam-clayey mud as well as gyttja and peat. The above deposits fill in all of the former oxbow-lakes noted at the terrace surface, but they also occur beneath a veneer of mud of various depths. The whole depth of the terrace *3* deposits in the San valley may be ca 15 m, as is indicated by a few boreholes there.

Lithology of the terrace *4*

The terrace *4* sheet in the San valley comprises several successive sandy fills being overlain by a discontinuous layer of loamy-silty mud with sandy intercalations belonging to the flood facies. The abandoned channel beds are covered with mud which contains an admixture of organic matter. Therefore two structural types of terrace *4* deposits can be distinguished:

type 1 (less frequent in the section) — there are only sands of the channel facies (Phot. 2). High sand bars formed recently in the channel during the floods possess an identical structure (Phot. 3);

type 2 — in the section the topmost deposit is composed of mud and mud-sandy series to a depth of 0.8—3 m (Phot. 4).

Sand belonging to the channel facies is vari-grained and unsorted within the diagonally bedded strata of varying thickness. The colour is greyish-yellow or light-brown. The sediment is slightly compacted. The overlying deposits belonging to the overbank facies include several layers of mud 10—100 cm thick, being interbedded with sand of the levèe and crevasse splays subfacies. The mud is commonly sand--silty, silty and loamy, horizontally laminated, brown and light-brown, without any organic matter within it, showing a tendency toward a vertical "cleavage". The intercalations consist most frequently of horizontally bedded silty and fine sand (less frequently of medium- and vari--grained sand) similar to the underlying sand of the channel facies. In many places such sands rest on the mud series forming the levées and crevasse splays fillings there. These owe a great deal to the especially high floods and ice-jams. They also occur on the terrace *3* surface at the contact with terrace *4* and along the present channel.

On the base of 19th century and recent measurements of the San channel parameters, of data cited by Leopold *et al.* (1964) of the depths to which sand is worked over on the channel bed during a flood, and of data obtained from a few boreholes, the total thickness of the terrace *4* deposits can be estimated at 10—12 m (Szumański 1977).

CHRONOLOGY OF THE SEDIMENTS

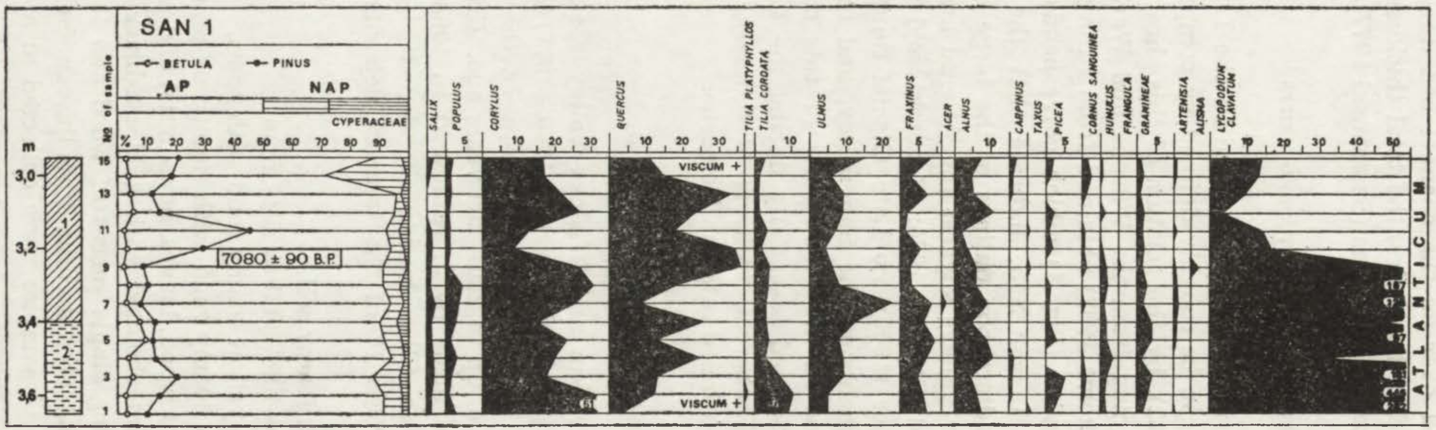
No datings of the terrace *2* deposits found in the Lower San valley are available. Their age can be roughly defined by comparison with data cited by Mamakowa (1962), by the relation of this sheet to the terraces *1* and *3* and by data coming from the Wisłoka and Warta river valleys. Palynologic data (Mamakowa 1962) obtained from filling of the San paleomeander at Podbukowina (Fig. 1) which corresponds to the earliest large meanders of the Lower San, indicate that the infilling there began in the Allerød. Radiocarbon datings of the large meanders in the Wisłoka and Warta river valleys suggest the Allerød and the Preboreal periods (Mamakowa and Starkel 1974; Kozarski and Rotnicki 1977). According to Wojtanowicz (1965), no Late Glacial dunes occur on the youngest terrace *2* fragments in the San valley, and only some traces of them have been found in the older parts of this sheet. It appears that the terrace *2* was formed essentially during the Late Glacial, between the Bølling and Preboreal. Infilling of the large paleomeanders by biogenic sediments continued into the Holocene.

Chronology of the terrace *3* sheet

Data referring to the San and Wisłoka valley reaches situated at the margin of the Carpathians (Starkel 1960, 1977) show that this sheet has been deposited in the Holocene, between the Boreal and not far-off historical times, i.e. up to 200—300 years ago. This also is suggested by a pollen analysis made by J. Niklewski in 1968 (Fig. 8) of the oxbow-lake deposits which fill a buried abandoned loop near Leżajsk (Fig. 2). The sequence “San 1” of the topmost deposits of the terrace *3* sheet was as follows:

to 0.3 m — black loamy soil,
0.3 — 1.0 m — “loess-like” yellow silty mud,
1.0 — 2.9 m — grey-yellow loamy mud with spots,
2.9 — 3.4 m — black loamy mud with numerous plant remains (pieces of wood, leaves, hazel nuts) and peat,
3.4 — 5.0 m — silt interbedded with a bluish-black silty sand containing single pieces of wood and logs up to 30 cm in diameter, and many molluscan shells.

For a pollen analysis 15 samples were collected at a depth of 3.65—2.95 m. According to Niklewski, the high percentages of trees growing in deciduous forests suggest an Atlantic age of the analyzed mud and



Anal. J. Niklewski, 1968

Fig. 8. Pollen diagram of the section San 1

1 — loamy mud; *2* — silt

Phot. 1. Exposure of flood deposits of the terrace *3*

1 — "loess-like" mud; *2* — loamy mud

Phot. 2. Exposure of sand forming the lower terrace *4* step

Phot. 3. Kame terrace on the western side of the Grudziądz Basin

Phot. 4. Exposure of the topmost part of the terrace *4* sheet

1 — flood deposits (stratified mud and silty sand); *2* — channel deposits (vari-grained sand) peat. His opinion was then confirmed by radiocarbon datings of plant remains taken at a depth of 3.20—3.00 m. Their age was 7080 ± 90 a B. P. (Gd-838). Therefore, the accumulation of the biogenic oxbow-lake sediments in this part of the terrace *3* started at least at the beginning of the Atlantic period, as is suggested among others by dates from the Wisłoka valley (Mamakowa and Starkel 1977).

The upper "loess-like" mud seems to be a much younger sediment. It was laid down probably in historical times as a consequence of the definite deforestation of the loess areas for agricultural purposes at the beginning of the 13th century. In the San valley the accumulation of the "loess-like" mud continued probably in the 17th century, as is proved by historical data (Strzelecka 1958) and archival maps (Piasecka 1976). It appears that both the Wisłok (the greatest tributary to the San) and the Lower San were still typical meandering rivers in the 17th century. Thus, the sand of the channel facies resulting from the lateral accretion of the flood-plain by the displacement of small meanders can be both Early Holocene and almost present-day deposits. Results of the photo-geological interpretation (Fig. 2) also suggest the possibility of occurrence of older terrace sheets beneath the veneer of mud, now forming the terrace *3* plain.

The terrace *3* surface also bears locally sand of levèes and crevasse splays and mud deposited during the formation of the terrace *4*. Hence it follows that even in the nearby sections dug into the terrace *3*, sediments of different ages (from the Late Glacial onwards) can be found.

The terrace *4* sheet is presently formed. Archival maps and plans show that at least 0.7 of its present surface came into being during the last 100 years, from 1853 onwards (Fig. 5).

The lower terrace *4* step, occurring along the channel came into being in the 20th century. This is the present-day reduced extension of the flood-plain, where most of the alluvia are laid down now.

THE EVOLUTION OF THE LOWER SAN VALLEY

The sequence of both sheets and landforms found in the San valley-floor is shown in Figure 9. Attempts to reconstruct the described changes in channel parameters and facies there were related to conditions under which the morphogenesis of the terrace *1* occurred. Its sheet was deposited by a braided river under periglacial conditions prevailing during the Vistulian in Poland. The traces of braiding are noted on the air photos (Szumański 1972, 1977).

The warming up of climate near the end of the Pleistocene must have changed the channel pattern from braided to a meandering one. According to Dury (1964) and Schumm (1965), such a trend of river development in the present temperate zone, with transitional phase du-

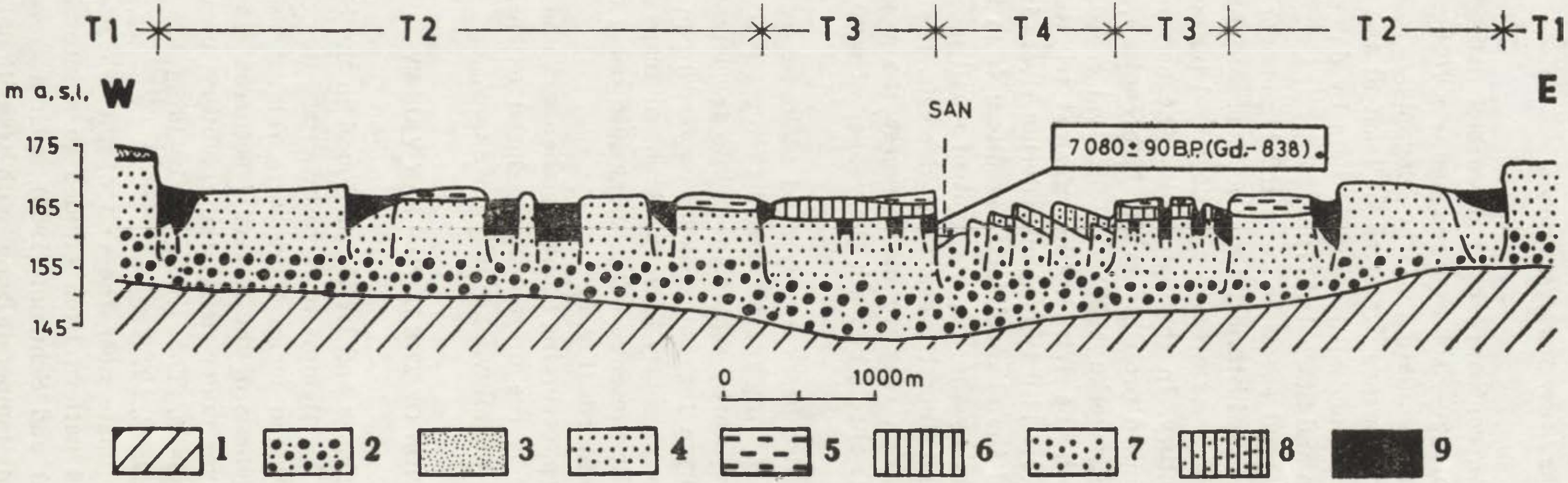


Fig. 9. Geological section A—A across the San valley

1 — Krakowiec clays (Miocene); *2* — gravel with sand; *3* — aeolian sand; *4* — fine- and medium-grained sand; *5* — silty mud; *6* — non-stratified loamy mud; *7* — vari-grained sand; *8* — non-stratified loamy-silty mud; *9* — peat and gyttja; *T1* — middle terrace (Vistulian); *T2* — low terrace with traces of large meanders (Late Glacial); *T3* — low terrace with traces of small meanders (Holocene); *T4* — low terrace with traces of a braided pattern (present-day) ring which large meanders in river channels developed near the end of the last glaciation, was a typical phenomenon.

Falkowski (1975) expressed the view that the diminution of snowmelt floods in spring and the prolonged river activities throughout the year have been favourable for the formation of meandering courses then. According to Wojtanowicz (1965), the major phase of dune formation on the terrace *1* in the Sandomierz Basin occurred before the Allerød. This suggests that the dissection of the main terrace level there must have begun before the time of increased wind activity. It is likely, that at that time the San was not meandering, but it was still a braided river, the traces of which are found on the lower terrace *1* steps near Rudnik and Nisko, without any dunes on their surfaces (Szumański 1972, 1977).

Conditions being favourable for the development of regular meanders in the San channel due to the spread of forests in the drainage basin, seem to have existed in the Bølling and in the Allerød (Środoń 1972). During the latter period large meanders were already cut off and new ones were formed. Their formation lasting until the beginning of the Preboreal period was favoured by a relatively cool and humid climate. The channel-altering bankfull discharges were then several dozen times as great as their Holocene equivalents. This factor, together with the liability of the sand and gravel terrace *1* sheet to erosion, facilitated the fast migration of freely developed large meanders. This was accompanied by the acumulation of sand and coarse suspended load on the former flood-plain (i.e. the present terrace-plain *2*). Furthermore the composition and quantities of sediment transported by the San have been influenced by aeolian processes fashioning the adjacent area.

The current warming being associated with the definite occupation of the whole drainage basin by vegetation favoured the further diminution of high discharges. Consequently at the beginning of the Holocene there was a trend toward dissection of the terrace *2* sheet by meanders of smaller and smaller bend radii. The transitional phase and, probably, also the Preboreal phase of meander shrinkage is represented by meanders of the I. generation which survived at the margin of terrace *3* (Fig. 2).

The early Atlantic wetter climate (Mamakowa and Starkel 1977), with the consequent lowest position of the flood-plain at ca 5 m below the present terrace *3* surface has caused the San to reach a sinuosity similar to that of the II. generation of small meanders interrupting the terrace *3* surface (Fig. 2). The latter are related to a minimization of channel-altering discharges and to the simultaneous high mean annual discharges. After the turning-point was reached in the cycle of valley-deepening the San channel began to rise. This event was preceded by the upbuilding of the flood-plain by mud during the period from the

Atlantic onwards. In the permanently wet San valley floor, dense alder forests and hazel shrubs were growing (Mamakowa 1962). Thus conditions were favourable for the long stability of the narrow and very sinuous San channel. At that time reduced slope processes and predominant chemical weathering in the drainage basin coincided with the slow accumulation of structureless loamy mud of the lower member on the flood-plain of the San.

At the end of the Subboreal period a short-lasting trend toward channel deepening was noted. This is marked by the occurrence of a discontinuous fossil soil horizon at the top of the lower mud member of the terrace *3* spread. The "loess-like" mud, which in many places rests on the channel sands, indicates the revival of channel processes. It is likely that deforestation of the area (initiated after Starkel 1960, about 3000 years B. P.) was associated with the temporarily increased irregularity in run-off occurrence and the supply of slope-derived materials into the channel, especially in the loess covered areas extending along the Carpathian margin.

However, on the air photographs no significant changes of the San channels are discernible. Until the 12th century, man acted with a varying intensity in the San drainage basin. Periods of deforestation alternated with phases of a total regeneration of the forests (Kunysz 1959). Under such conditions the accretion of "loess-like" mud might have occurred, but the meandering course of the San has not been changed. The hydrological effects of the rapid economic development in the 13th and 14th centuries have been partly reduced by the simultaneous stream management in Poland (Podwińska 1970). The great number of mills, sawmills, fish ponds existing on the rivers until the 18th century must have influenced and balanced the stream discharges, thus reducing the quantities of the transported load. For these reasons the San preserved its meandering pattern until the beginning of the 18th century. On the other hand, the above economic activity increased its dynamics. This is probably manifested by the larger meanders of the III. generation occurring in the marginal zone of the terrace *3* and by the increased height of the topmost part of the channel sand, noted locally within the terrace *3* sheet.

Near the end of the 18th century (or probably already in its middle part) the further development of agriculture, especially the introduction of root crops caused a sudden increase in the rates of slope wash in the drainage basin and marked irregularities in the San discharges (Gil and Słupik 1972; Szumański 1977).

The San channel became more straight and wider changing in its lower course into a braided river in the 19th century. A tendency toward aggradation predominated and the terrace *4* sheet came into being forming the flood-plain of the San at that time.

Because of increasing flood damage and losses of arable land, channel correction in the San valley was started near the end of the 19th and at the beginning of the 20th centuries. The river course was shortened and the channel narrowed. Its pattern became fixed. The antierosion constructions on the river-banks were continuously rebuilt. Under such conditions the San, retaining the features of a braided river, has deepened its channel by 2—3 m in the 20th century.

At the present time the accumulation of materials is restricted to a very narrow zone within its present flood-plain (i.e. the lower terrace *4* step). Thus the San plays the role of a transferring canal for the major part of the load carried during floods, especially of the suspended load. This reaches the Vistula increasing the dynamics of its present channel processes. Thus the channel correction conditions on this river are made more difficult.

At the same time, a deepening of the San channel and the stability of its position have improved the agricultural conditions on the terraces *3* and *4*. Extensive grassland and alder shrubs occupying the terrace *4* plain as well as paleochannel depressions became cultivated and flood-free land in the 20th century.

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THE PATTERN OF CHANGES IN THE MIDDLE VISTULA VALLEY FLOOR

INTRODUCTION

Field studies, the development of models which explain the geological structure of a valley reach and its representation on maps and profiles provide the basis for engineering-geological and hydrogeological work and for the evaluation of building mineral deposits. The knowledge of the history of changes in both the hydrological régime and the valley floor morphology makes it possible to predict the man-induced processes which may take place there.

When considering the life history of a stream, its young, mature and senile reaches are taken into account. To the stage of full maturity the meandering rivers tend to be ascribed, and the importance of the so-called base level overestimated. Similarly, every gravel horizon was believed to indicate a renewed phase of fluvial erosion. The ages of both fluvial landforms and alluvial series were defined on the base of their vertical position and of palynological and radiocarbon datings, but usually without a greater interest in the dynamics of channel processes as indicative of catchment response to all factors that were operating there. Hence, there is the possibility that the age of some fluvial sediments may be wrongly interpreted because the biogenic materials contained in the alluvia may be redeposited.

Examinations of the lowland rivers of Poland (e.g. the Middle Vistula and its tributaries the Pilica, Nida, Narew and Bug) which were made by the present author and his collaborators in 1960—1978 enabled them to establish the general laws of river valley evolution (Fig. 1). The methods used were as follows: cartographical analyses, field mapping, laboratory works, hydrological and sedimentological analyses as well as archaeological and palynological datings being supplemented by the geological interpretation of aerial photographs. Consequently, it is possible to use the following evidence:

— the geological structure of terrace sheets being genetically related to a distinctive régime of the river;

— the similar composition of samples of deposits obtained from chosen profiles reflects a distinctive lithogenic type of alluvium;

— the morphogenic variations in space of the different river reaches that were revealed by photogeological work can be applied to the description of their geological structure.

Furthermore, the data obtained make it possible to reconstruct:

(a) the velocities of channel-forming processes and their response to changes affecting the entire catchment, and

(b) the causes of present-day variations in the vertical and horizontal channel patterns and in the stream behaviour.

THE WAYS IN WHICH STREAM CHANNELS AND THE FLOOD-PLAIN MAY BE FORMED

In every geological region, the river valley is the youngest element of the relief that reacts rapidly to changes of all denudation parameters in the drainage basin. Thus, the river, its channel and alluvia are the most perfect indices of runoff and sediment load changes taking place in the catchment. Intense denudation here is associated with the increased supplies of both suspended sediment and bedload into the main stream. When this supply exceeds the transporting capacity of the river, this tends to be overloaded (= positive balance of alluvia — Wierzbicki 1965) causing channel- and flood-plain aggradation in the valley reach examined. While the processes of denudation are reduced on the adjacent plateaux, the transporting capacity will exceed the supply of suspended load. The transport of sand with occasional gravel is generally more rapid because of an underloading of the river. This deficit in alluvia is reflected in the lowering of both the channel bed and the flood--plain.

At the present time, the climatic control of fluvial processes is frequently replaced by the influence of man, i.e. the deforestation and agricultural activity (e.g. increased sediment yield brought about by the extension of row crops). In the Vistula and Odra drainage basins, although agriculture was extended during the 14th—18th centuries, no consequences of the increased denudation of the drainage basin have been observed in the valley floors. The high stream discharges and rates of sediment yield into the rivers were then significantly reduced by the construction of numerous ponds, millraces, steps and weirs on the rivers.

The history of land use patterns of Poland provides a useful indication of the manner in which to reduce the magnitude of stream discharge fluctuations in a drainage basin and to maintain a deep and most steady channel without bars and shallows.

Variations in water level are reflected in the course of erosion, sediment transport and accumulation, in the facies of alluvia and in the channel geometry and pattern. In the mature valley of the Middle Vistula, contrasts between the uniform stream discharges and the widely fluctuating discharges determine the occurrence of two contrasting types of channel patterns.

The relatively uniform flows are reflected in the constant meander bend radii which tend to increase downstream. Such a meandering channel is deep without shallows and islands. The concave bank is being undermined, whereas on the convex bank sandy point bars are formed (Falkowski 1967). The channel deposits are well sorted, the coarser ones occur at the base of the series. The loamy muds belonging to the overbank facies contain biogenic materials (Fig. 2). Since sand and gravel intercalations are lacking, the above deposits were not laid down by severe floods. Each of the members that may be distinguished in the vertical terrace profile corresponds to a strictly defined hydrological régime. Similarly, the shapes of meanders reflect both the dynamics of the fluvial régime and the type of sedimentation. Thus, it is possible to delimit areas of similar sedimentary sequences.

Furthermore, fine silt and peat belonging to the oxbow lake facies on a freely meandering river make it possible to reconstruct the paleochannel parameters, i.e. their depths and widths. The meandering rivers can be easily traced on both aerial photographs (Fig. 1 and 3), on 1:10 000—1:100 000 maps and in the field.

The other contrasting type is the braided pattern. The wide channel with a rather straight course has many riffles, pools and islands. During the low stages the main current travels in curved paths amid the shallows frequently changing its direction. In places, the braided channel is confined by natural levées.

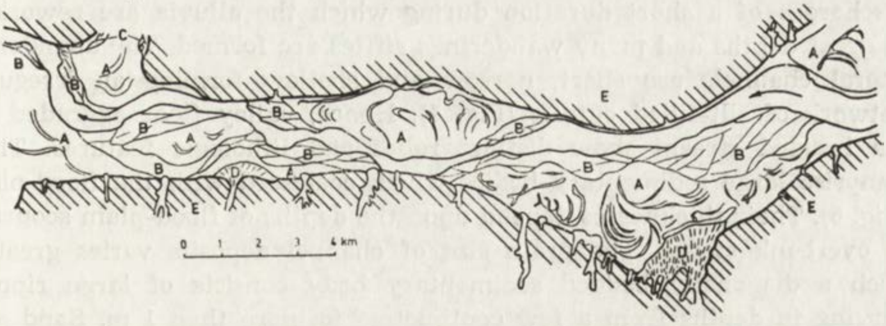

Fig. 1. Morphogenetical types of the alluvial plain of the Middle Vistula river in the gap across the South Polish Uplands

A — flood-plain strips formed by the meandering river; *B* — flood-plain strips formed by the braided river, with bar plains around distributary channels; *C* — Pleistocene terrace plains formed by a braided river; *D* — alluvial fans of different ages; *E* — plateaux consisting of Jurassic, Cretaceous and Quaternary deposits

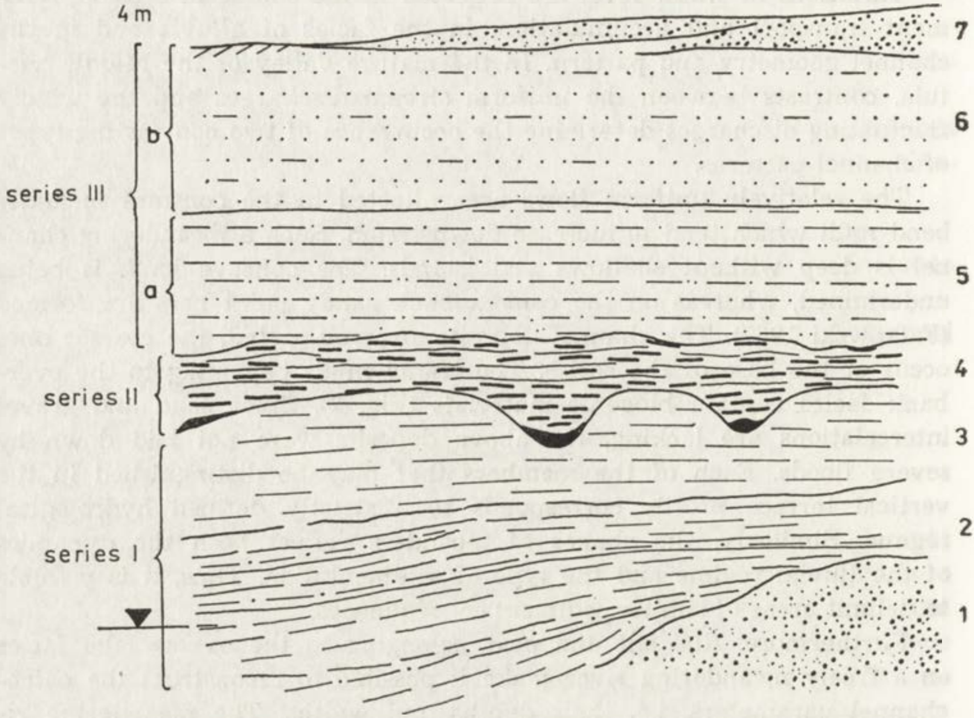

Fig. 2. The structure of flood-plain deposits at Świeciechów village

Soil and mud laid down by a meandering river (series I), fossil soil and mud corresponding to a stable phase (series II, IIIa), sandy mud accumulated by the present-day braided river (series III b). *1* — sand; *2* — silty loam interbedded with silt; *3* — silty loam; *4* — fossil soil with pottery and charcoal; *5* — unstratified sandy silt; *6* — unstratified silty sand; *7* — levée-forming sand

The channel morphology is a result of the rapid changes from minimum to highest discharges. The channel owes its braided form to high discharges of a short duration during which the alluvia are reworked to great depths and many wanderings riffles are formed. The abandoned lateral channels are short, narrow and shallow forming an irregular network of silt-filled cutoffs (Fig. 4). Hence, valley floor aggraded by the braided stream show distinct relief and lithologic features. They comprise large sedimentary bodies which coalesced with the flood-plain (Fig. 6). Their thicknesses depend upon the depths of flood-plain scouring at overbank stages. The grain size of channel deposits varies greatly. Such a diagonally bedded sedimentary body consists of large ripples varying in depths from a few centimetres to more than 1 m. Sand and gravel lenses tend to alternate throughout the profile. Fine sediments may form the top bed of a single flood-deposited series.

On the braided river, deposits belonging to the overbank facies contain much sand because of the rapid inundation of the flood-plain. These are sandy and sand-silty laminated muds with sandy intercalations. Clay-

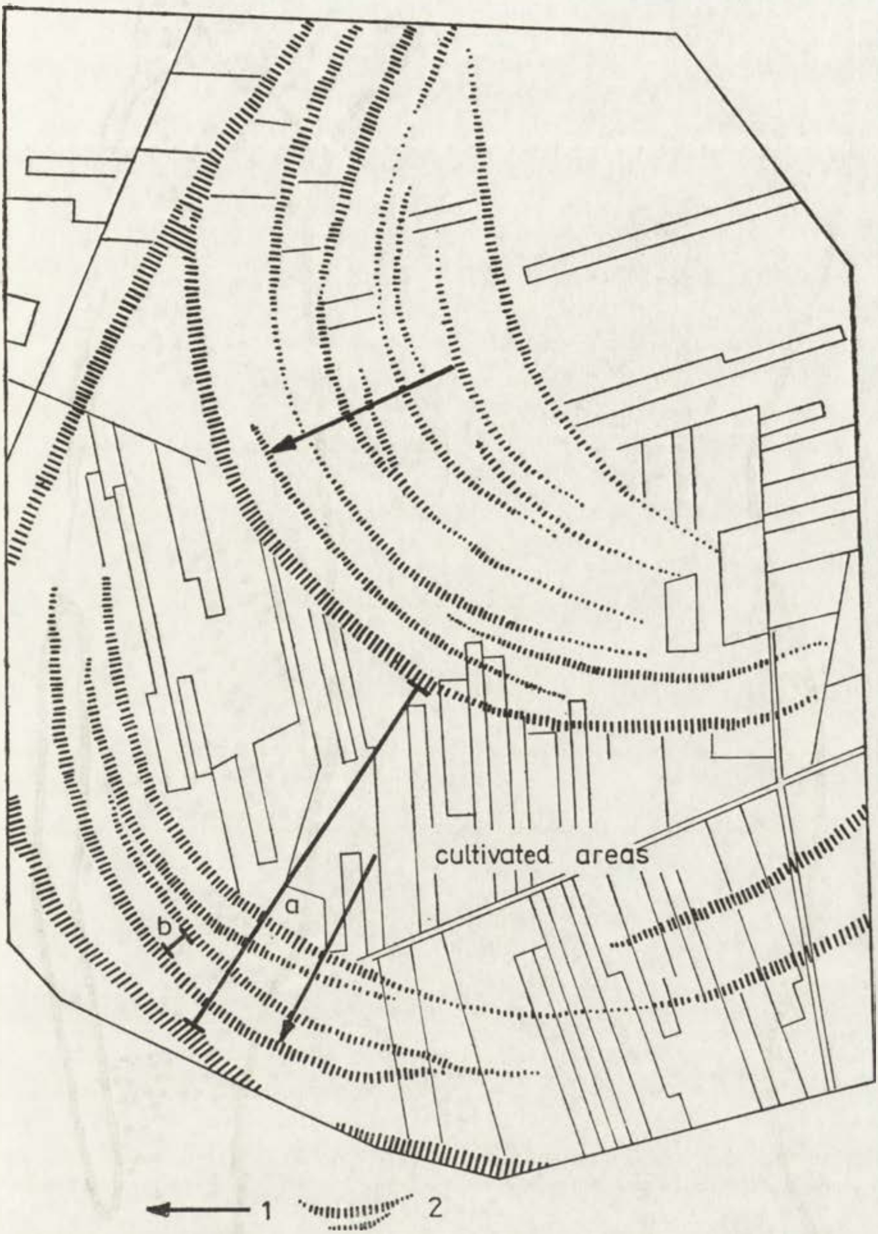

Fig. 3. Meander scrolls on the Vistula

1 — direction of progressive meander shift; *2* — completely or partially silted up channels; *a* — first order element of the flood-plain; *b* — second order element of the flood-plain

ey muds are accumulated only off the channel. In many places, the flood-plain forming mud that was laid down by the meandering river is overlain by mud which was brought by the younger braided river (Fig. 5, 7) during the period of human activity. On the braided river,

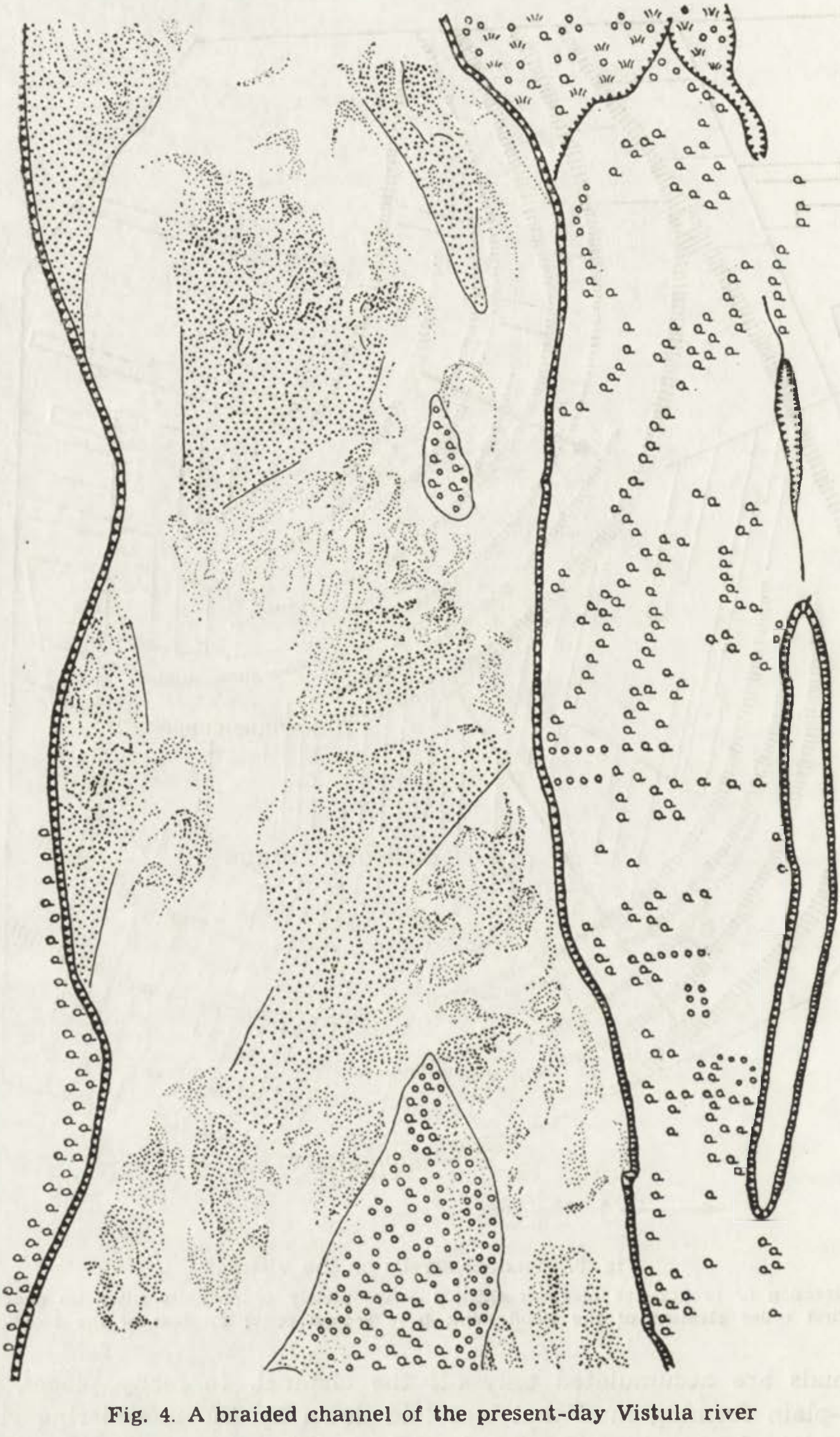

Fig. 4. A braided channel of the present-day Vistula river

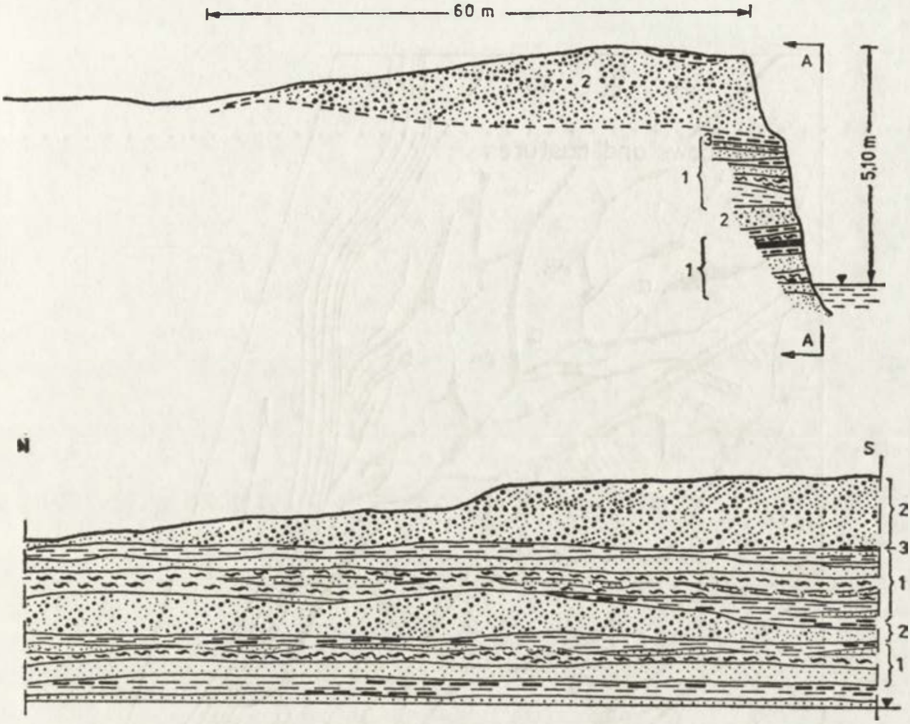

Fig. 5. Structure of a natural levée and of underlying flood-plain deposits

1 — alternations of medium- and fine-grained sand, silty sand and sandy silt, silt and sandy loam; 2 — medium- and coarse-grained sand with gravel; 3 — flood-plain surface

largely sand and peat belonging to the oxbow lake facies tend to occur in the shallow abandoned channels.

The braided river deposits and the recent aggradation by the braided stream reflect the régime controls of both channels patterns and sediments (Fig. 6). These are perfect criteria for a delimitation of areas varying by geological structure, for a reconstruction of the former channel patterns and for an understanding of the present tendencies of stream channel evolution (Falkowski 1971, 1972, 1975, 1980a, b).

The cyclic changes of climate were responsible both for the channel pattern changes and the formation of various alluvial fills of a clearly defined structure. The latter determines the different engineering, hydrogeological and other conditions.

The Figures 1, 2 and 3 as well as published data (Falkowski 1965, 1971, 1975; Falkowski and Szumański 1975; Kraużlis 1974, Allen 1970 and others) show that the deposition of alluvia took place according to certain principles. Therefore, the trend of changes can be reconstructed with ease.

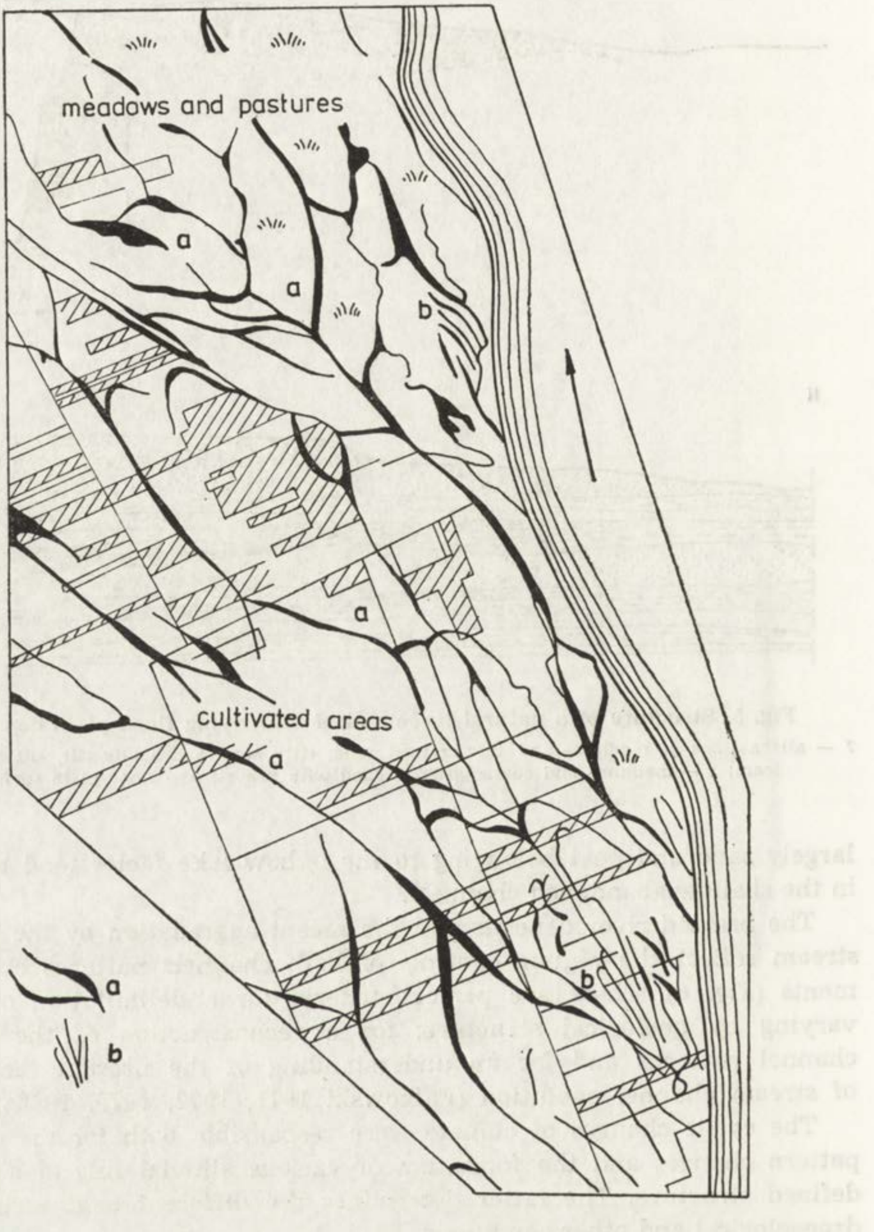

Fig. 6. Vistula valley floor showing traces of shoals that coalesced with the flood-plain

a — bar plains around larger distributary channels; *b* — junctions of smaller distributary channels, which influence the microrelief of bar plain

THE HISTORY OF CHANNEL EVOLUTION IN THE GAP OF THE MIDDLE VISTULA THROUGH THE SOUTH POLISH UPLAND

Under periglacial conditions prevailing near the end of the Vistulian the Vistula breaking the South Polish Uplands in a gap was a braided river with a violent hydrological régime. The river had as many limbs as today, and valley aggradation took place leading to the formation of the higher terrace plains. Their sheets consist of poorly sorted channel deposits and of sandy mud belonging to the overbank facies. The present paleochannels, which are shallow and narrow, are forming a braided pattern.

At the turn of the Pleistocene and the Holocene, during the Late Glacial, as the climate became warmer and moister, a dense forest cover was favourable for the uniform discharges and the reduced supplies of bedload into the river.

During the Allerød the underladen river began to meander, passing from a phase of large meanders (known from reaches farther upstream — *cf.* Mycielska-Dowgiałło 1972; Szumański 1972) through channel consolidation to a phase of tightly looped meanders being associated with a lowering of the flood-plain. This process of lowering lasted until the end of the Atlantic period. The thalweg was then ca 3 m below present-day mean water level in the channel. This very low position of the flood-plain is proved by mud which has been bottomed at 3 m depth below mean water level along the section Annopol—Józefów. The deepening of the Vistula channel was accompanied by a more distinct facial differentiation of sediments into the channel deposits and the flood-deposited loamy muds containing abundant organic matter.

The deep abandoned loops became filled with biogenic deposits which were subsequently covered by mud. These are fossil forms now.

During the wetter Atlantic period the inundations by the meandering river were heavier, and the suspended load of the river was greater. The flood-plain was rapidly built up by muds. The fine materials were derived by wash from the loess covered plateaux and from the silty waste covers in the Carpathians. It is likely that the channel was deep, and its banks were vegetated.

At the Boreal/Atlantic transition the presence of dense woodlands in the valley was responsible for the formation of both the curved course of the river and the marshes in the valley floor. Consequently, mud was laid down that contained abundant organic remains with logs (Laskowski and Kraużlis 1978). During the Atlantic and Subboreal periods the mud covered terrace plains became occupied by man who cleared the alder woods in the valley. In the mud the present author has found pottery remnants which belong to the Funnel Beaker- and

Globular Amphora Cultures dated at 3500—1700 a B. C. (Falkowski 1967, Fig. 8).

The slight climatic deterioration and desiccation as well as the influences of man caused a gradual opening of the forests. This was followed by a steady vertical position of the valley floor during the Trzciniec Culture from 2000—1300 a B. C. onwards through the Lusatian Culture (1100—400 a B.C.) until the 15th—16th centuries A.D.

The sediment input and output was balanced in the particular valley sections. The occurrence of a deep paleosoil in the mud series and indications of settlement there suggest a limited range of high discharges of the meandering Vistula River, i.e. the reduced channel process dynamics.

Since the 15th century the increase in ploughed land has upset the meandering pattern of the Vistula. The reaction to this has been the replacement of the meandering pattern by a braided one and the increased content of the sand fraction in the mud. Sandy intercalations indicate increased flooding. It is probable that the enlargement of the channel which became shallower was retarded by the formation of both fishponds and millraces on the streams (Podwińska 1970).

During the period of the manorial system of working the land within the Vistula drainage basin during the 15th—17th centuries nearly all

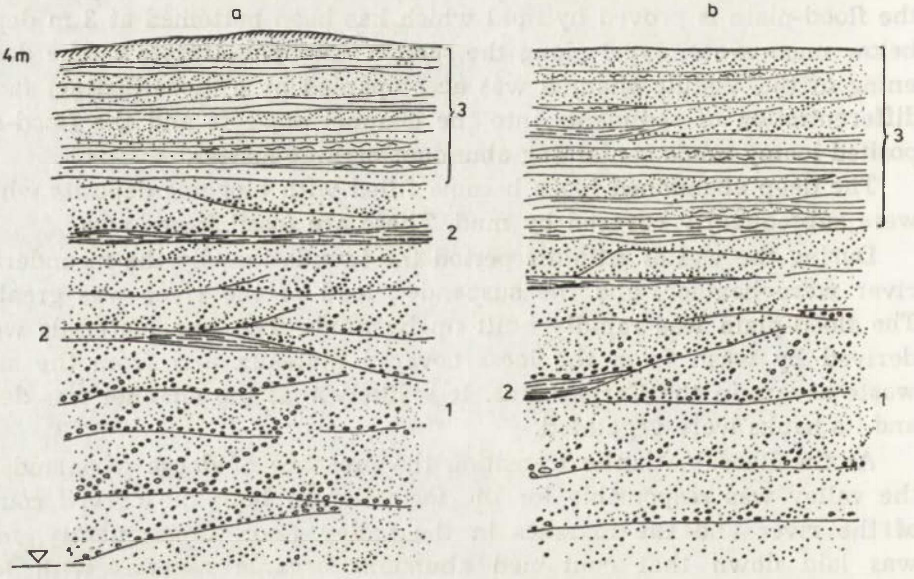

Fig. 7. Structure of flood-plain deposits laid down by the braided Middle Vistula river

Exposures at villages Rybitwy (a) and Wałowice (b): *1* — sand and gravel (channel facies); *2* — silty or loamy intercalations with organic remains; *3* — sandy mud, i.e. sand, silt and silty loam accumulated by the braided river

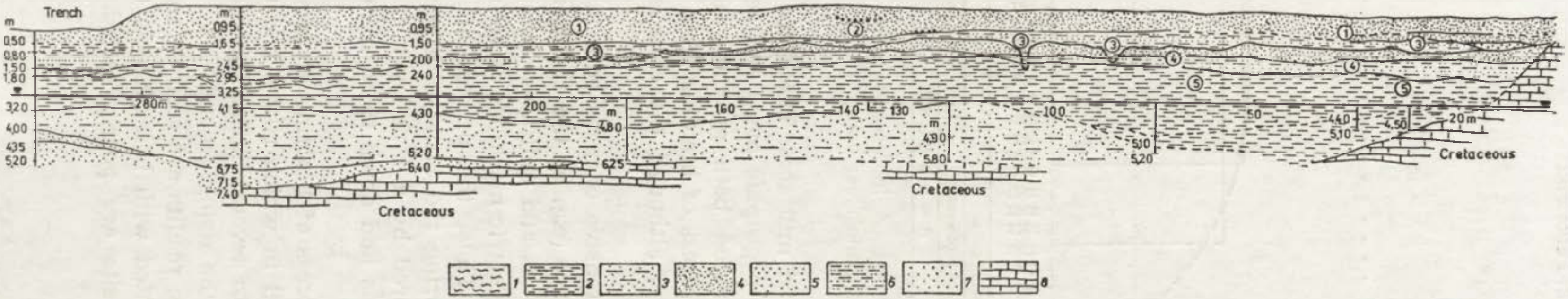

Fig. 8. Structure of flood-plain forming deposits revealed at village Basonia

1 — heavy silty loam; *2* — silty loam; *3* — silt; *4* — sandy silt; *5* — silty sand; *6* — silty or sandy fossil soil; *7* — medium-grained sand; *8* — Cretaceous marls. Encircled numbers refer to beds dated by the following cultural remains: 1 — First World War cartridge cases; *2* — 17th-19th century pottery; *3* — 12th-15th century pottery; *4* — pottery of the Lusitian and Trzciniec Cultures; *5* — pottery of the Globular Amphora and Funnel Beaker Cultures

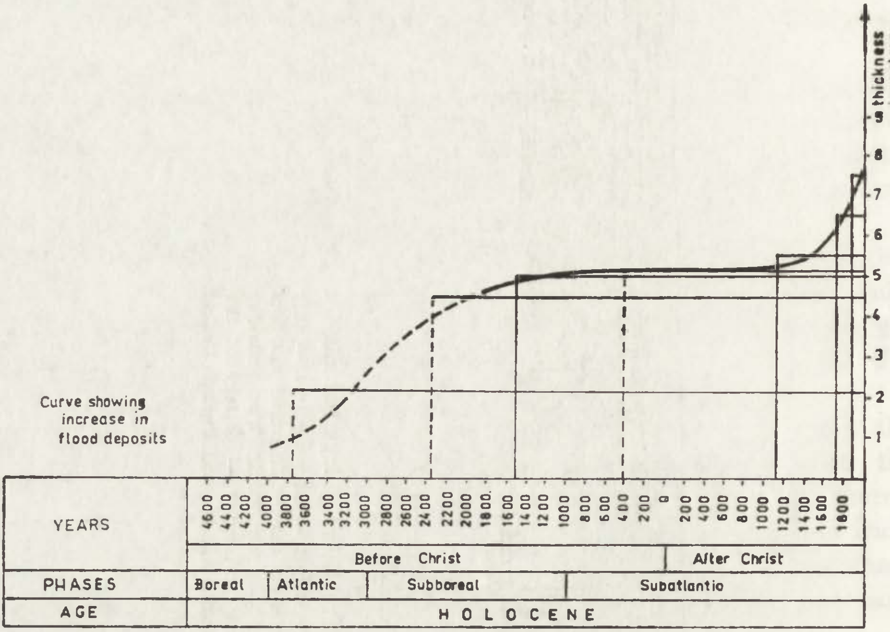

Fig. 9. Diagram illustrating the phases of increased valley aggradation in the Middle Vistula river valley

of the streams had fishponds and millraces. These are still traceable in the field and on the detailed topographic maps and aerial photographs. The ponds and millraces increased both ground- and surface water retention which retarded the process of braiding from the 15th century onwards until the 19th century, although the clearance of woodlands continued.

During the 19th century extensive changes both in social conditions and the economy have taken place (e.g. by the abolition of corvée large areas were divided), and the ponds and millraces disappeared gradually. When the steam- and later on electric machines came into use, the millraces ceased almost to exist. Thus, the process of braiding became accelerated. For comparison, during the 17th—19th centuries the flood-plain on the Vistula was covered by a 1 m layer of sandy mud, and as much as 1 m of sediment was laid down there from the First World War until 1963 (Figs 7 and 8).

At the present time, the process of braiding gives a broad and shallow form to the Vistula channel in which riffles and islands appeared. This causes the river to split into several limbs. The progressive channel aggradation is accompanied by the rising ground water level at the foot of the higher terrace edges. The results are seen in an abandonment of cultivated areas that are vegetated with bulrush now (Falkowski 1967). The present-day channel deposits are poorly sorted. In the vertical profile grain size varies greatly from sand to gravel being similar to that of the Late Pleistocene terrace sheet that has been accumulated by a braided river.

CONCLUSIONS

A brief analysis of changes in the Vistula channel process dynamics allow the following conclusions to be drawn:

(a) The present-day braided pattern of the Middle Vistula channel is the effect of human activity in the past, but especially over the last 200 years.

(b) Until the middle of the 19th century the Middle Vistula was still a meandering river, managed easily by man.

(c) During the Pleistocene and the Holocene the effects of changes of both climate and vegetative cover within the drainage basin have been reflected in the cyclic changes of the stream channel patterns (Fig. 1).

In the Central Polish Plateaux, the presence of extensive woodlands in the Middle Vistula drainage basin accounted for the meandering river pattern with fine and well sorted deposits. The lack of woodlands during phases of periglacial conditions or of a widespread forest clearance within the drainage basin caused the river to develop a braided pattern during which the poorly sorted and coarser series were accumulated. The effects of woodlands can be counterbalanced by the effects of water retention in the drainage basin because of man's influence.

It must be emphasized that the succession of stream channel pattern changes which is discernible in the height relations, lithology and morphology of the terrace plains can be used as a good index for climato-stratigraphic purposes in the Late Quaternary. It seems reasonable that the selection of profiles for palynological and radiocarbon datings should be preceded by an analysis of the fluvio-dynamic events.

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THE GEOMORPHOLOGICAL EVOLUTION OF THE VISTULA RIVER VALLEY BETWEEN WŁOCŁAWEK AND CIECHOCINEK DURING THE LAST 15 000 YEARS

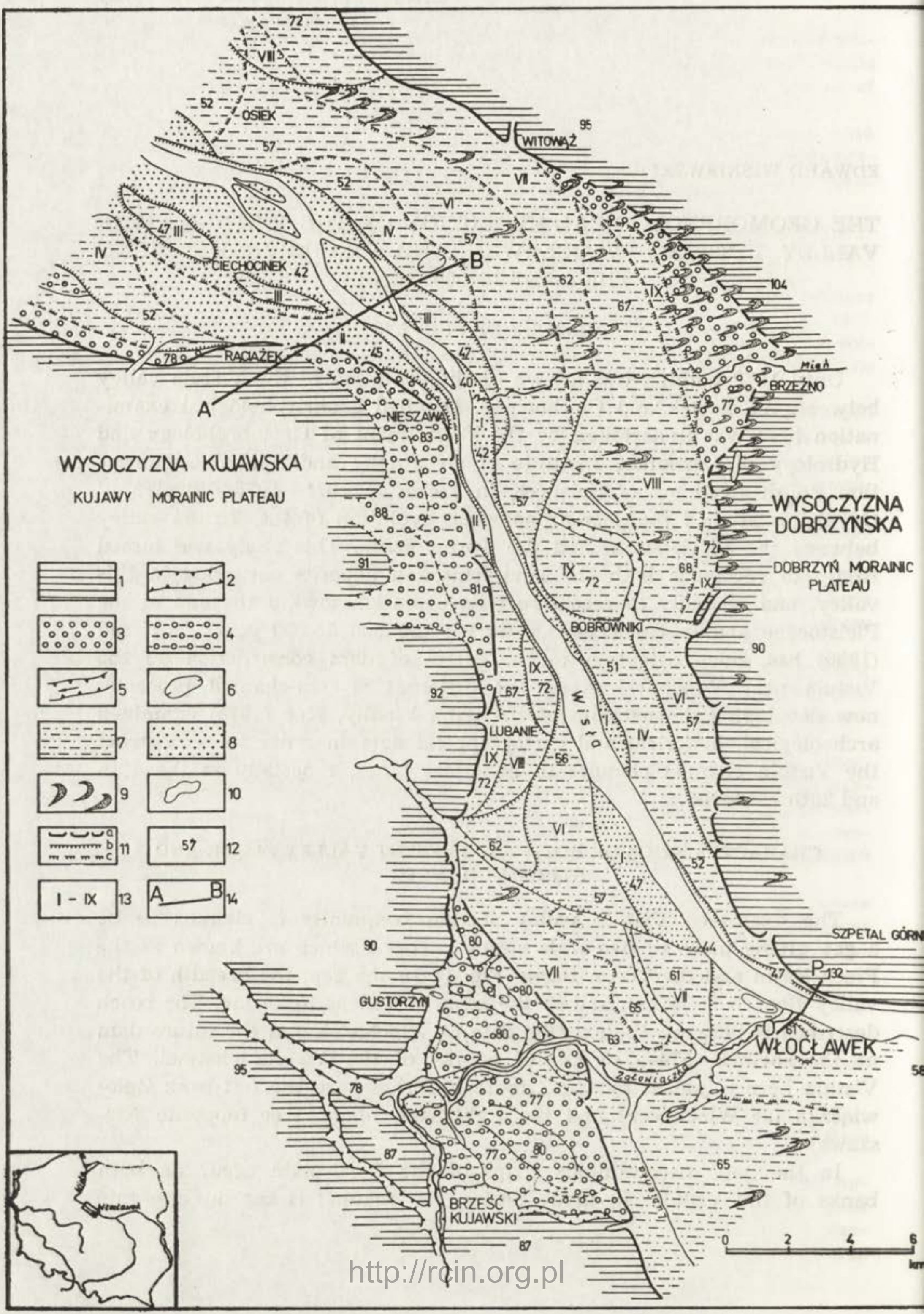
HISTORY OF SURVEYS

Until 1970 nothing was known of the evolution of the Vistula valley between Włocławek and Ciechocinek. Detailed geomorphological examination here was undertaken by the Department of Geomorphology and Hydrology of Lowlands, Institute of Geography and Spatial Organization Polish Academy of Sciences, in Toruń in 1971—1975. Wiśniewski (1976) has studied the geomorphological evolution of the Vistula valley between the Płock Basin and the Toruń Basin. This study was aimed firstly to recognize both the landforms and deposits occurring in this valley, and secondly to reconstruct its evolution toward the end of the Pleistocene and in Holocene, i.e. during the last 15 000 years. Babiński (1980) has given attention to the effect of dam construction on the Vistula near Włocławek upon the different stream-channel processes now developing downstream of the dam. Finally, Koc (1978) examined archeological, historical and cartographical data in order to reconstruct the Vistula channel changes in historical times, especially in the 19th and 20th centuries.

CHARACTERISTICS OF BOTH THE PRESENT VALLEY FLOOR AND STREAM-CHANNEL

The examined Vistula valley section frequently is claimed to be a gap giving place to two wide valley portions which are known as the Płock Basin and the Toruń Basin (Fig. 1). In the gap, the breadth of the valley floor is 7—8 km, and in the basin it widens to 20 km. The reach described is between the existing dam at Włocławek and the future dam at Ciechocinek, 674—713 km of course of the Vistula channel. The Vistula here is joined by two tributaries. These are the left-bank Zgłowiączka (at Włocławek) and the right-bank Mień river (opposite Nieszawa).

In the gap, discontinuous strips of the flood-plain occur on both banks of the Vistula. In many places, the channel is cut directly into


WYSOCZYZNA KUJAWSKA
KUJAWY MORAINIC PLATEAU
WYSOCZYZNA DOBRZYŃSKA
DOBRZYŃ MORAINIC PLATEAU
OSIEK
WITOWĄŻ
CIECHOCINEK
RACIĄŻEK
NIESZAWA
BRZEŹNO
Mień
BOBROWNIKI
LUBANIE
Wisła
GUSTORZYN
SZPETAL GÓRN
WŁOCŁAWEK
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the higher terraces. On the left bank strips of the 3 m flood-plain being up to 2—7 km long and 240—1500 m wide occur only locally. It is best developed some 5 km to the north-west of Włocławek and in the vicinity of Ciechocinek. On the right bank the flood-plain strips also are 7 km long and 250—700 m wide. Behind the flood-plain there are older terraces. These, however, will be dealt with in the latter part of this paper.

Upstream of Włocławek the Vistula is running east-westward along the foot of the morainic Dobrzyń Plateau. Downstream of Włocławek the river changes toward north to pass the gap across to the opposite morainic Kujawy Plateau slope near Nieszawa, where the Vistula makes its entry into the Toruń Basin.

At moderate stage the Vistula channel is 800 m wide by Włocławek. Farther downstream channel width is at its maximum 1100 m, being only 400 m near Nieszawa. At moderate stage the average depths at Włocławek are 1—3 m (Babiński 1980), the maximum being 6 m (Fig. 2).

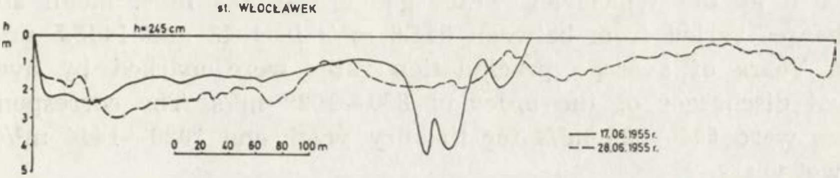

Fig. 2. Cross-sections of the Vistula river channel at the Włocławek water gauge on June 17, 1955 and June 28, 1955 (according to Babiński 1980)

The Vistula channel is marked by the occurrence of numerous islands known as *kępy* (= vegetation covered bars). These occur most frequently in the central part of the stream-channel, although lateral *kępy* also are found there, for instance, not far off Korabniki and Ciechocinek. According to Babiński (1980), who has studied the channel features in the 10 km Vistula reach downstream of the Włocławek dam, the other convex features in the channel are lateral bars and shallows. The latter ones include within the river bed: near-island bars, central bars, lateral bars and diagonal bars. The diagonal bars may be up to 2 km long, their local relief being 2—5 m. The Vistula responded to its channel correction by changing the former braided stream pattern to a slightly meandering one. The concave channel features include overdeepenings and pools. The latter ones are deeply entrenched in the bed and tend to

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Fig. 1. Geomorphological map of the Vistula valley between Płock Basin and the Toruń Basin

1 — morainic plateau; *2* — subglacial channels; *3* — outwash plain; *4* — meltwater-cut plains; *5* — glacial drainage channels; *6* — kettles; *7* — Late Glacial erosional terraces; *8* — accumulational terraces; *9* — dunes; *10* — lakes; *11*: *a* — plateau edges, *b*—*c* — terrace edges (*b* — distinct, *c* — obliterated); *12* — altitudes; *13* — terrace numbers; *14* — location of geological cross-sections migrate downstream, to be cut deeper at low flow and filled up at high flow.

The annual march of the Lower Vistula water level is marked by the regular occurrence of high flows of long duration in the snowmelt season (March—April) and of low flows in the autumn (September—November). High flows of short duration that may occur in some years are caused by abundant rainfall in the summer season (June—August), and they may exceed high flows occurring in the spring. According to Glazik (1978), in 1959—1968 the water level amplitudes were 598 cm at Włocławek, reaching 5.7 m in the summer and 4.4 m in the spring. At very high flows water may approach the ordinates 49—50 m a.s.l. corresponding to 700—800 cm at the Włocławek water gauge. When the water level reaches 600 cm, then both the flood-plain and the *kępy* are subjected to inundation. In 1959—1968 the mean annual water levels at Włocławek were 317—395 cm (with a multi-year average of 351 cm).

Over the 35-year period of 1919—1954 the mean stream discharge recorded at the Włocławek water gauge was 933 m^3/s. Mean annual discharges varied from between 544.6 m^3/s in 1943 and 1443.5 m^3/s in 1941. Years of average precipitation rates were marked by average annual discharges of the order of 830—1020 m^3/s. The corresponding values were 544—820 m^3/s for the dry years and 1020—1444 m^3/s for the wet years.

During the last 100 years the valley floor did not show any important changes in the gap. The late nineteenth century was characterized by the occurrence of three large floods and several years of generally high flow. At this time, all of the small *kępy* disappeared that were drawn in a military map dating from the turn of the 1820s and 1830s (compare Koc 1978). In contrast to the former irregular banks the present new flood-plain edges were smoothed due to lateral stream erosion. At the beginning of the twentieth century only one large flood occurred (in 1924), together with several very low flows. At that time, no significant bank changes took place between Włocławek and Ciechocinek and a few new small *kępy* appeared in the channel. The following years were these of the stable bank conditions. In some places, the *kępy* increased in number.

CHARACTERISTICS OF BOTH LANDFORMS AND DEPOSITS OCCURRING IN THE VALLEY FLOOR

On the river there are only strips of the flood-plain interrupted by narrow elongated depressions, i.e. the former lateral channels of the Vistula. These are filled either with peat or with water.

On the left valley-side, a large flood-plain strip is found to the north-west of Włocławek. It is 7 km long and 1.5 km wide. The longitudinal flood-plain gradient is lower than that of the water surface in the channel. The flood-plain as a whole slopes back toward the higher terrace edges, where there is a shallow, 200 m wide, abandoned loop in which peat, ca 4 m thick, has accumulated. The flood-plain is formed mostly of mud and fine sand belonging to the flood facies, 2—4 m in thickness, which rests on vari-grained sand with gravel intercalations. Below this series boulder clay was bottomed at a depth of 21 m.

On the left bank of the Vistula, the flood-plain is best developed in the vicinity of Ciechocinek. Above its surface (42 m a.s.l.) two elongated "islands" (3—3.5 km long) of the supra-flood terrace are rising there at ca 47 m a.s.l. These residuals are separated from the slightly lower supra-flood terrace plain at ca 45—46 m a.s.l. in the west by the former Vistula channel, 300—500 m wide. The numerous borings which have been put down in the so-called "Ciechocinek Plain" all showed the 4—5 m layer of mud, silt and fine sand belonging to the overbank facies. In some places, amongst others in the axis of the above mentioned abandoned channel organic deposits, 0.5—2 m thick, tend to occur below this sheet.

Interesting data on the geological composition of the flood-plain were obtained from a boring which has been made to the east of Ciechocinek, ca 120 m away from the Vistula channel. It appeared, that the 3.5 m layer of fine sand and sandy silt rests on a dark-grey clay to a depth of 4.22 m which in turn is lying on peat, 1.3 m thick. This is underlain by fine sand having gravel and organic remains within it to a depth of 6.2 m. The top layer of peat reaches ca 1 m below the present Vistula level. This suggests that at the time of peat accumulation in the abandoned loop the then functioning Vistula channel was at a lower level than at present.

According to B. Noryśkiewicz of the Institute of Geography, Nicholas Copernicus University in Toruń, four preliminary analyses of the peat in which *Pinus* predominates also revealed the presence of alder *(Alnus)*, oak *(Quercus)* and lime *(Tilia)* pollen, i.e. pollen of trees that appeared in post-Boreal times. This suggests the possibility that peat accumulation there began in Atlantic times, to be followed by the accumulation of the ca 4.5 m layer of sediments of the overbank facies during the Neoholocene. The deposition quantities of alluvia at the beginning of sub-Boreal times have also been observed by Falkowski (1967) in the middle section of the Vistula valley.

On the right bank of the Vistula the first flood-plain strip extends from Szpetal Dolny to 7 km downstream of Włocławek, and it is up to 250 m wide. To the east it closely undercut the 4—5 m higher terrace at 51—52 m a.s.l. The flood-plain here consists of mud and fine sand which frequently rests on peat. Sometimes its bottom layer corresponds in height to the present Vistula level.

The next right-bank strip of the flood-plain between Bógpomóż Stary and Bobrowniki shows a similar composition. In one place, however, a 1.3 m layer of rounded gravel was seen to lie below the veneer of mud and fine sand, 2.5 m in thickness. This gravel originated from the washing of the underlying boulder clay which was bottomed at 11.5 m. It lies on the Pliocene clay. In other places, peat up to 2 m thick is common at the base of the sandy flood-plain deposits. Sometimes the base of the peat is below the present Vistula level. This fact has confirmed the earlier conclusion that the former Vistula channel was lying at a lower level.

The whole depth of the Quaternary infillings which occupy the valley floor cut into Tertiary rocks varies from between 20 m and 28 m. The Quaternary infill is represented by invariably stratified sand of differing coarseness, gravel and rounded pebbles, having occasional layers of clay at 7—8 m depth. This sand and gravel series shows, it is possible to determine the position of the now buried thalweg of the Vistula as well as the rate of successive aggradation.

It has been shown that the flood-plain deposits contain organic remains. It might be argued that the best conditions for their accumulation prevailed in the cut-offs. The discordance of levels at which the organic deposits are seen to lie most frequently below the fine sand and mud is a proof of the existence of different fossil horizons yet their number is still unknown owing to the lack of a more complete geological record. Nevertheless it is possible to determine the thickness of fluvial sediment with accuracy, i.e. the depth to the deepest now buried thalweg of the Vistula. At Włocławek (compare profile O—P, Fig. 3) the fossil Vistula channel reaching to 12 m below the present-day river level is cut into Pliocene rocks. This value is thus the total thickness of alluvial fills which occupy the Vistula channel there. The result is similar to that obtained by Banach (1977) in the area 4 km to the east of Włocławek. The alluvia should decrease in thickness upstream of the above geological sections until a certain limit is reached. The reverse should be true for the reach downstream of Włocławek. It appears that to the east of Ciechocinek the base of alluvia with snail and molluscan shells lies at 17 m below the present-day Vistula channel (Fig. 4). There is thus the deepest now buried thalweg of the Vistula. The alluvia near Ciechocinek differ from those near Włocławek by a greater depth of 5 m.

It is noteworthy that borings which have been put down in the vicinity of Ciechocinek showed repeatedly a complex of dark-grey clay, peat and mud (described as "silty or sandy clay with intervening silts") within the sand and gravel series. The above deposits now lie 10 m below the present-day Vistula channel. It is likely, that they mark a buried terrace plain. Sediments belonging to mud, together with dated

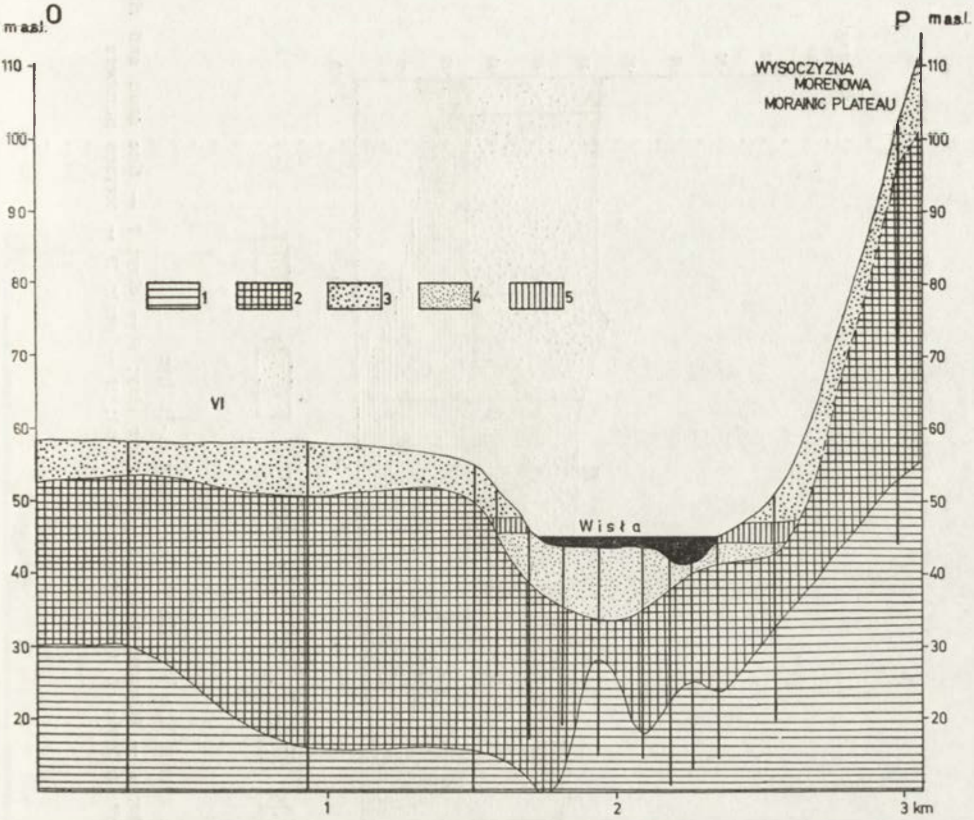

Fig. 3. Geological section across the Vistula valley along O-P line

1 — Miocene rocks; *2* — Pliocene rocks; *3* — sand and gravel deposits; *4* — sand and gravel deposits (alluvia of the Vistula); *5* — mud; VI — terrace number

peat also occur at higher levels there. These also may be buried Holocene features.

The age of the deepest valley incision is still open to doubt. In neither of the flood- and supra-flood terrace deposits was it possible to obtain absolute dates of the organic remains. The only dates which can be used are from the valley reach downstream of the sites considered here. According to Drozdowski (1974), the higher supra-flood terrace in the Grudziądz Basin (ca 100 km downstream) dates from the early Allerød. This terrace corresponds to the "islands" (at 47 m a.s.l.) on which Ciechocinek and Wołuszewo are built, rising 4—5 m out of the flood-plain in the Vistula valley section discussed. An indication of the Late Glacial age of this supra-flood terrace are Paleolithic implements which have been found on a dune on the Wołuszewo "island". The position of the Vistula channel toward the end of the Late Glacial can be indirectly

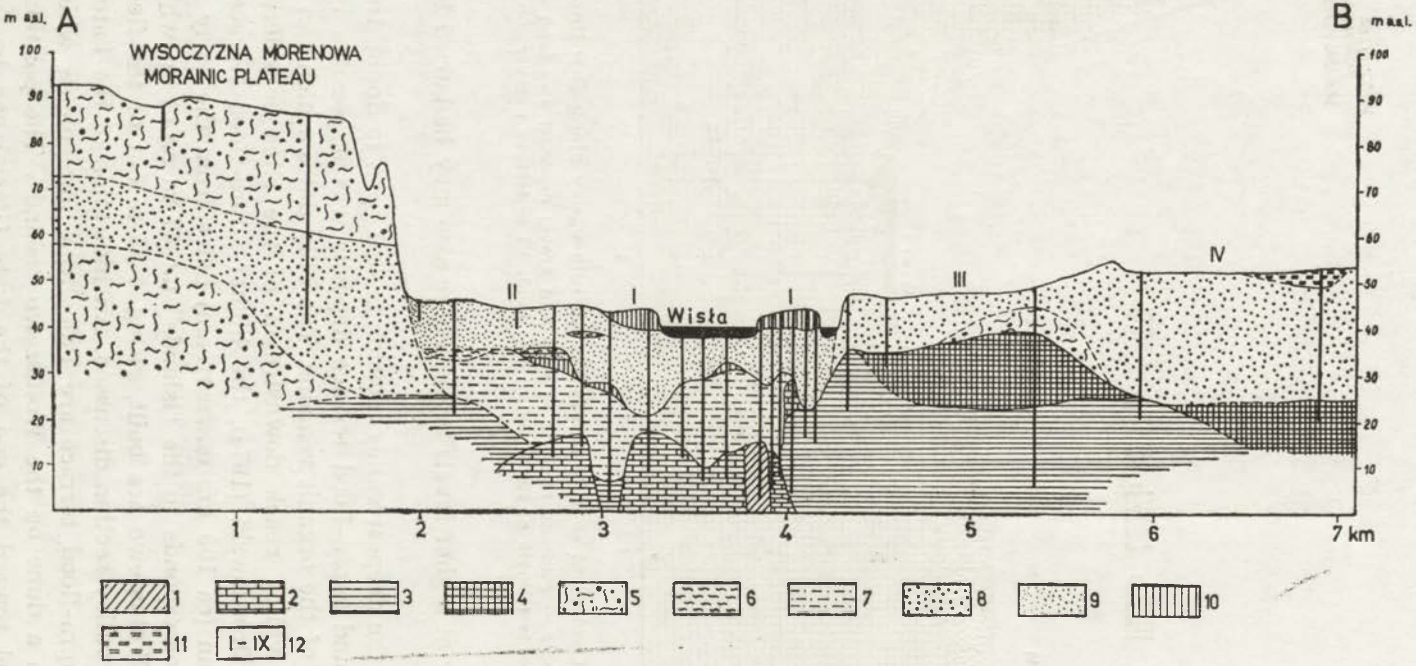

Fig. 4. Geological section across the Vistula valley along A-B line

1 — Jurassic rocks; *2* — Cretaceous rocks; *3* — Miocene rocks; *4* — Pliocene rocks; *5* — boulder clay; *6* — clay; *7* — fine sand and silt; *8* — sand and gravel deposits; *9* — sand and gravel deposits (alluvia of the Vistula); *10* — mud; *11* — peat; *12* — terrace numbers determined by the valuable results of detailed research made by Andrzejewski (1980) in the Zgłowiączka tributary valley to the Vistula. In this valley being cut into the higher terraces on the Vistula, 5—6 km above the junction of both rivers, there occur well developed paleo-channels (Fig. 5) which are for the most part filled with peat, 2—3.5 m thick.

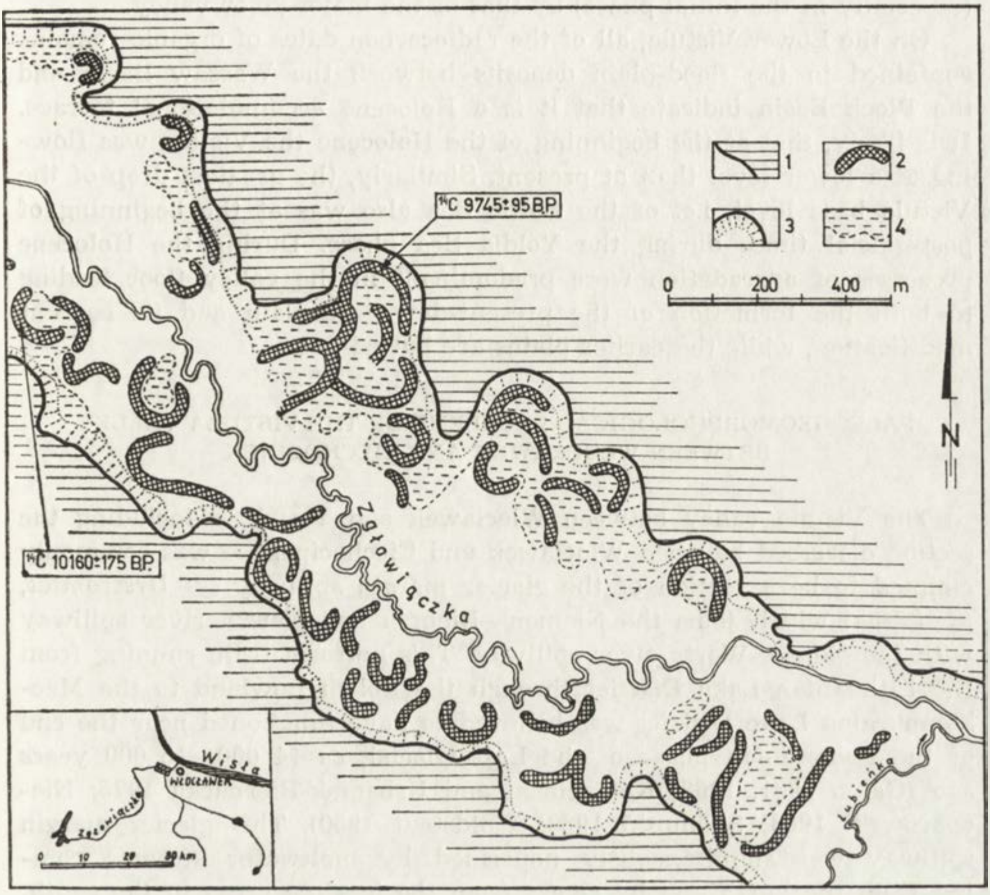

Fig. 5. Geomorphological sketch showing the lowermost portion of the Zgłowiączka valley floor (according to Andrzejewski 1980)

1 — terrace of the Vistula valley; *2* — abandoned loops; *3* — the Zgłowiączka valley slopes; *4* — supra-flood terrace strips

This rests frequently on a 5 cm gyttja band. In some of the abandoned channels the peat is covered by mud belonging to the flood facies.

The evidence used is based on radiocarbon determinations on the organic fills of two cut-offs situated on each bank of the Zgłowiączka river. In the right-bank cut-off dating of the gyttja which underlies the peat at a depth of 2.30—2.35 m indicates an age of 10 160 ± 175 a B. P. (Gd-1156). This suggests that accumulation of organic deposits in the abandoned channel began during the Younger Dryas. The lowermost organic fill of the left-bank cut-off, more than 2 m deep, is dated at 9745 ± 95 a B. P. (Gd-1153). Thus the work of Andrzejewski (1980) shows that the Zgłowiączka river was meandering on the present-day valley floor — close to the Vistula channel already in the Allerød. The evolution of the tributary Zgłowiączka valley was largely controlled (especially in the initial phase) by that of the major river valley.

On the Lower Vistula, all of the radiocarbon dates of organic remains contained in the flood-plain deposits between the Warsaw Basin and the Płock Basin indicate that it is a Holocene accumulational terrace. It is likely, that at the beginning of the Holocene the Vistula was flowing at a lower level than at present. Similarly, the greatest drop of the Vistula base level, i.e. of the Baltic Sea also was at the beginning of post-glacial times during the Yoldia Sea phase. During the Holocene processes of aggradation were predominant in the valley floor leading to both the formation of the present-day flood-plain and its current modification, while the earlier plains are buried now.

PALEOGEOMORPHOLOGICAL PROBLEMS OF THE VISTULA VALLEY BETWEEN WŁOCŁAWEK AND CIECHOCINEK

The Vistula valley between Włocławek and Toruń — including the section discussed between Włocławek and Ciechocinek — was commonly claimed to be a section of the glacier margin spillway (= *Urstromtal*, *pradolina*) which joins the Niemen—Biebrza and Narew river spillway with the Noteć—Warta river spillway. This uniform train running from the Lithuanian Lake District through the Polish Lowland to the Mecklenburgian Lake District was believed to have functioned near the end of the Pomeranian phase of the Last Glacial, ca 14 000—15 000 years ago (Galon 1961, 1968; Kotarbiński and Urbaniak-Biernacka 1975; Niewiarowski 1968; Skompski 1969; Woldstedt 1950). This glacier margin spillway was simultaneously nourished by meltwater streams coming from the north and by rivers from the ice-free areas in the south. The earlier views that the Vistula valley was drained northwards already at the uppermost terrace level found in the Noteć—Warta valley train were based on facts now observed, namely on the general northward slope of the area into which the Vistula valley is incised between Warsaw and Toruń, and to which the present course of the Vistula shows adjustment.

On the eastern side, there lies the morainic Dobrzyń Plateau rising 95—100 m a.s.l., while in the west the morainic Kujawy Plateau is at 90—95 m a.s.l.

Inspection of the relationship between the present valley and the relief of the sub-Quaternary surface indicates that the Vistula gap joining the Płock Basin with the Toruń Basin is clearly related to the course of a buried valley which had been carved into the Tertiary rocks. The existence of a valley prior to the Last Glacial, i.e. during the Eemian interglacial, is proved by the results of geological examinations of both the plateau slopes and valley terraces. In the Vistula valley, older fluvial sediments occur below a thin veneer of brown clay and boulder clay. This brown clay was doubtless deposited in a pro-glacial lake impounded between the inland ice expanding southwards and the river. The last ice sheet that covered the valley left boulder clay but did not fill the lake completely. Hence, after the withdrawal of the ice margin conditions here might have been favourable for the survival of detached masses of ice.

On the retreat of the inland ice, first meltwaters, but then extraglacial rivers followed the resulting shallow depression which marked the course of the Eemian valley between Włocławek and Ciechocinek. The successive stages of its dissection are evidenced by both levels (= valley benches) and terraces showing some variation in form (Fig. 1). The terrace numbers used in the present paper were first applied by Galon (1953) to the Brda sandur — and valley features, and then adopted by Mrózek (1958) to the Toruń Basin. The present numbers refer to terraces in the valley section discussed that can be correlated with similar features found in the Toruń Basin.

When followed in the field, however, the terraces can be correlated only from the IX terrace down. It is difficult to link up higher levels in the gap and uppermost terraces X, XI in the Toruń Basin. Two terms will be applied to features fashioned by flowing waters, namely level (= valley bench) and terrace. The first term includes surfaces due to meltwater activity, the second term refers to fluvial terraces formed by streams flowing from the south.

In the Vistula section examined the following levels and terraces are found: levels at (a) 88—89 m a.s.l., (b) 80—84 m a.s.l., (c) 80 m and 75—77 m a.s.l. at the junction of the Mień and Vistula valleys, (d) 78 m a.s.l.; terraces at (e) 72 m a.s.l. (IX), (f) 67—69 m a.s.l. (VIII), (g) 62—63 m a.s.l. (VII), (h) 57—59 m a.s.l. (VI), (i) 51—52 m a.s.l. (IV), (j) 45—47 m a.s.l. (III), (k) 43—45 m a.s.l. (II), (l) flood-plain at 42 m a.s.l. in the vicinity of Ciechocinek.

The two uppermost levels at 88—89 m and 80—84 m are cut in the ground moraine of the Kujawy Plateau, and they border the Vistula Valley there. Smoothed slopes which separate from each other the plateau surface and both levels are being often difficult to determine in the field. These levels consist mostly of boulder clay with an occasional veneer of fine sand, 1—3 m in thickness. In many places, a gravel and boulder pavement can be found on top of the exposed boulder clay. Since these cut levels slope clearly southwards, they might have been

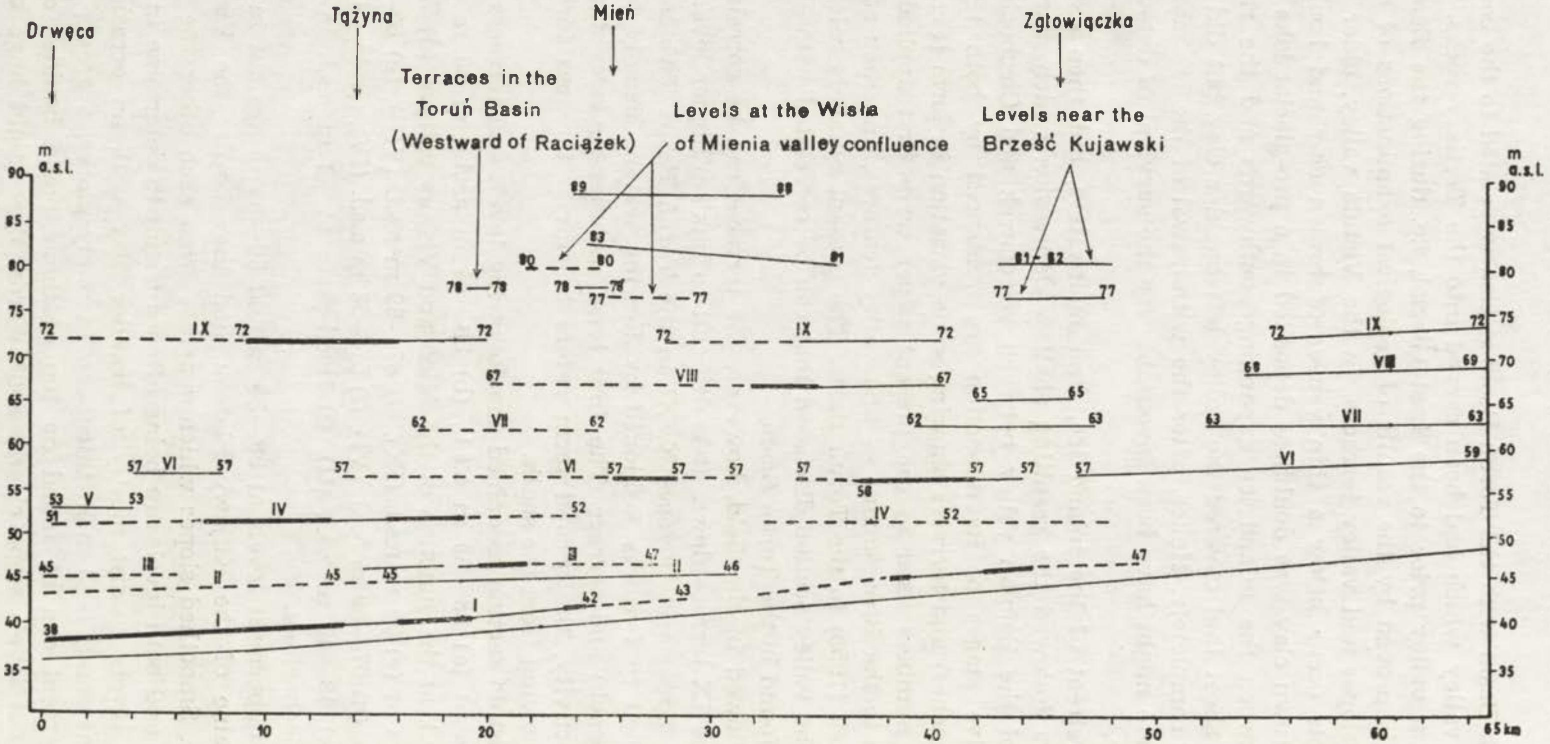

Fig. 6. Longitudinal profile of terraces in the Vistula valley between the Płock Basin and the Toruń Basin

Continuous line — left-bank terraces; broken line — right-bank terraces; thick line — terraces on both sides of the Vistula fashioned by meltwaters during the deglaciation of the area discussed (Fig. 6).

Both geomorphological and geological studies made in the vicinity of Brześć Kujawski revealed that the meltwater-cut levels at 80-82 m and 75—77 m correspond to the above features in the marginal part of the Kujawy Plateau. At these stages of the valley evolution the glacial meltwaters had flowed to the south, entered the Bachorza valley and flowed down this valley to the west (Wiśniewski 1974). It is probable, that simultaneously the Bachorza valley has functioned as the escape route for the meltwaters from the Płock Basin (in the south-east) occupied by the melting dead ice blocks.

Since in the vicinity of Brześć Kujawski the glacial meltwaters still entered the Bachorza valley at the 75—77 m stage, it is inferred that the non-glacial drainage could not have been in a northward direction at the uppermost levels which were believed to correspond to the two uppermost terraces in the Toruń Basin and in the Noteć—Warta glacier margin spillway. In the Toruń Basin, however, these terraces are at higher altitudes, namely at 80—81 m (XI) and 78 m (X). Furthermore, these tracts proved to be spillways opening southwards into the Noteć—Warta spillway near the end of the Pomeranian phase.

The work of the present author shows that during this phase no stream water flowing from the south along the Vistula valley could have entered the Noteć—Warta spillway. Thus the earlier view on the functioning of a uniform glacier margin spillway which carried confluent waters along the Niemen—Biebrza and Narew spillway and thence through the Vistula valley westward into the Noteć—Warta spillway near the end of the Pomeranian phase had not been proved.

It is suggested that, as the drainage westwards via the Bachorza valley was retarded through the uplift of the valley floor above the rising Kujawy-Pomeranian elevation, the Płock Basin and the Toruń Basin became connected probably at the 72 m stage (terrace IX). According to Galon (1961, 1968) in the Toruń Basin the IX terrace may be related to the bifurcation period, when some of the waters continued to flow westward through the Noteć—Warta spillway and some of the drainage was diverted northward to the Gdańsk pro-glacial lake which had begun to form at this time.

The IX terrace between Włocławek and Ciechocinek survived in the form of benches and residual "islands". This is a typical erosional feature, and so are the successively lower terraces including the higher supra-flood terrace strips (III).

The river maintained its level at the IX terrace stage for a short time. At the VIII terrace stage the Vistula was a multi-limbed river. Evidence are two well defined tracts. At present the Vistula breaks the IX terrace residuals in a tiny gap by Bobrowniki. This might have been the third limb.

The successive stages of downcutting are recorded by a descending terrace sequence. The present distribution of the individual terraces makes it possible to reconstruct the channel migrations with fair accuracy. It is noteworthy, that by Bobrowniki the Vistula channel position had not significantly changed since the VIII terrace stage, whereas between Włocławek and Bobrowniki channel migrations were of common occurrence. At present, on the left valley-side to the north of Włocławek the highest feature is the VII terrace, while on the right side it is the lower VI terrace which does not occur on the opposite river-bank.

It is difficult to reconstruct the former course of the Vistula channel at a level corresponding to the V terrace in the Toruń Basin, since terrace remnants are lacking in the valley section examined. At the IV terrace stage, the channel between Włocławek and Bobrowniki shifted to the east. A shallow peat-filled cut-off occurring near Bobrowniki indicates that the winding Vistula has first undermined the VI terrace and then the IX terrace.

Between Włocławek and Bobrowniki the channel shifted repeatedly from one side of the valley to the other, whereas between Bobrowniki and Osiek the Vistula channel showed a current tendency to slip off at the VII—IV terrace stages when the downcutting Vistula flowed along the Dobrzyń Plateau. Consequently, a sloping terrace was formed there, having a width of more than 4000 m. This terrace reaches from the former VII terrace down to the flood-plain. However, on the geomorphological map (Fig. 1) a set of terraces (VII, VI and IV) is to be found within this sloping surface, but the delimination of these hypothetic terraces is based solely on the height criterion.

The above tendency demonstrates that after the Vistula had opened the gap which joins the Płock Basin with the Toruń Basin a tendency towards entrenchement was predominant there. This process proceeded at a fast rate. In the Toruń Basin the Vistula bifurcation occurred 13 000—14 000 years ago, i.e. at the IX terrace stage. The now buried thalweg has reached its greatest depth near the end of the Late Glacial. Thus it appears that in the Vistula gap the whole sequence of terraces was formed over the period of 3—4 thousand years. In Holocene times only the formation of the accumulational flood-plain and lower supra-flood terrace (II) took place in the vicinity of Ciechocinek.

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Geographical Studies
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THE EVOLUTION OF THE VISTULA RIVER VALLEY BETWEEN TORUŃ AND SOLEC KUJAWSKI DURING THE LATE GLACIAL AND THE HOLOCENE

HISTORY AND ORGANIZATION OF RESEARCH

It is 48 years since R. Galon published his fundamental work on the morphology and evolution of the Lower Vistula valley (1934) and there appeared many important contributions to the geology and geomorphology of the area examined. These also included the 1:50 000 geomorphological maps and the 1:200 000 geological maps prepared at the Toruń centre.

Consequently, we have a fairly good knowledge of the morphology of the Vistula valley. Both the extent and geological structure of the 11 terrace levels recognized by Galon (1961) have been defined there. The established pattern of the Lower Vistula valley evolution also included the Toruń Basin, the entire Noteć—Warta glacier margin spillway (Galon 1961, 1968) and the valleys drained by the Brda (Galon 1953) and the Drwęca (Niewiarowski 1968). The above scheme was based mainly on the morphological correlation of the different terrace levels and on their dependence upon the process of deglaciation. The limiting dates for the Lower Vistula evolution are given by the Allerød peat which is covering the bottom of the Noteć—Warta glacier margin spillway (Galon 1961), and by the pre-Younger Dryas age of the lower terrace (IV) in the Grudziądz Basin (Roszko 1968).

The other lower terraces, i.e. the flood-plain and the supra-flood terrace have not been studied in detail. Their age was referred generally to the Holocene (Niewiarowski and Tomczak 1969).

In the Lower Vistula valley the first ^{14}C datings of the lowest terrace levels were obtained from samples in the Grudziądz Basin (Drozdowski and Berglund 1976). These datings suggested an Allerød age of the supra-flood terrace (II) and confirmed the earlier conclusions (Drozdowski 1974) based on palynological analysis.

Some information on the lowest terraces in the Vistula valley upstream from Toruń can be found in a publication by Wiśniewski (1976).

In the Drwęca valley, on the terrace II Niewiarowski has found gyttja which was accumulated in an abandoned channel during the Younger Dryas. This indicates the Allerød age of the above terrace. In the Toruń Basin this date has been confirmed by a pollen analysis of the profile at Czarne Błota (Niewiarowski and Noryśkiewicz, in print).

The Vistula valley reach between Toruń and Solec Kujawski is 24.5 km long including the whole floor of the Toruń Basin. The selection of the study area also was determined by the distribution of both archeological sites and archival borings, and the prospect of obtaining samples from new borings.

The work is based on the present author's field and laboratory research, and on unpublished data (compare "References"). Moreover, sedimentological and pollen analyses have been made especially for this purpose by Preisner (sedimentology) and by Noryśkiewicz (palynology) of the Institute of Geography, Nicholas Copernicus University in Toruń. The other sources used were master's theses (Tarkowski 1980; Balcerak, unfinished) and absolute age determinations made by Pazdur in Gliwice.

The existing geological and cartographical documentation for the Toruń Basin made it possible to trace the hydrographical changes and to analyse both the land forms and sediments. Data from archaeological sites, pollen analyses and the first in the Toruń Basin radiocarbon datings made within the IGCP Project No. 158 A, enabled to determine the chronology of events and to reconstruct the evolution of the above valley reach towards the end of the Pleistocene and during the Holocene.

THE PRESENT-DAY ENVIRONMENT

LOCATION OF THE STUDY AREA IN THE DRAINAGE BASIN

The study area is in the eastern part of the Toruń Basin, 734—768.5 km distance along the Vistula channel (Fig. 1 A), i.e. a distance of 24.5 km, where the Vistula is joined by only one left bank tributary, the Zielona river.

There are two gauging stations in the valley reach studied: one in Toruń (installed in 1817) and one in Solec (installed in 1905), where daily observations of the water level are made. Furthermore, in Toruń measurements of suspended load and discharges were made during the past few decades.

By Toruń the Vistula is draining a total area of 180 585 km² and before reaching Solec Kujawski the drainage area increases to 181 059 km². The Vistula drainage basin shows a marked asymmetry being particularly pronounced between Włocławek and Fordon, where the reach in question is situated (Fig. 1 A). The catchment differs widely in relief and lithology. On the adjacent morainic plateau there occur diverse young glacial land forms dating from the Poznań phase of the Vistulian. The Toruń—Eberswalde glacier margin spillway cutting into the morainic plateau widens to 20 km in the Toruń Basin. In this basin numerous extensive dune fields occur on the broad sandy terraces (Mrózek 1958). To the south-east of Toruń the Vistula valley narrows to only 6 km.

THE FLOOD-PLAIN

On either side of the river there stretches the flood-plain, 2—4 km wide (together with the stream channel). In Toruń its width does not exceed 1 km, and it occupies 30—50% of the Toruń Basin bottom. At present, only its channel confined by dikes is inundated at high water stages. Thus the presently inundated area termed here the flood-plain is immediately adjacent to the channel which varies from between 100 and 1400 m in width, reaching up to 2400 m.

This flood-plain is 3—4 m above the mean water level in the river, and its altitude diminishes along the river from 37 m to 33 m a.s.l. The flood-plain is rather uneven, and denivelations are up to 5 m there. In the near-channel zone there occur oxbow lakes which vary greatly in size. They have formed by sealing off of both lateral channels and marginal parts of the channel. In the former case, the cut-offs are 50—100 m wide and up to 2 m deep.

The flood-plain constitutes the presently active zone. The processes of erosion lead to bank caving and locally to the surficial washing of the plain. However, accumulation predominates. Detailed measurements show (Tomczak 1971) that the structure of flood-deposited alluvia is highly differentiated. These vary greatly in space, thickness (0—15 cm) and in the lithology, i.e. from fine sand to clayey silt. It was found that these variations depend on three factors including the type of vegetative cover, the distance from the main current and both the configuration and height of the surface in relation to the given high stage.

SECTIONS ACROSS THE PRESENT-DAY CHANNEL

In the reach examined the Vistula channel is regulated. This fact determines both its present-day cross-section and parameters. The channel has widths of 400 to 475 m, narrowing to 375 m by the old centre of Toruń.

Between Toruń and Solec the gradient of the Vistula is 0.175‰ at mean water level equal to the mean gradient calculated for the entire lower course between Włocławek and Tczew.

The present-day channel depths are generally 2—4 m (in relation to the multi-year mean water level) varying from ca 0.50 m to 9 m in the greatest deeps, which tend to be located asymmetrically in the channel cross-section and occur always near its banks. The streamline shows then a natural sinuosity which, however, is not equivalent to the river's tendency toward meandering, since the channel has an uneven bed.

The course of the streamline is somewhat different in the straight reaches (e.g. near Solec) and in the curved reaches with distinct bends due to channel improvement (e.g. downstream of Toruń). Near Solec the streamline crosses over from one side of the channel to the other (wave length ca 2 km), whereas downstream from Toruń it does not coincide with the convex banks. In the curved reach a characteristic feature of the present channel bed are two deeps in its cross section, while the largest shallows occur in its central part.

Today the intense displacement of pools and riffles is being observed in the Vistula channel. Since 1969, the transportation of sediment load has been disturbed and increased due to the construction of a dam in Włocławek. Resulting erosion below the dam has greatly increased the sediment supply, and the hydroelectric power station is responsible for frequent changes in discharges.

Thus conditions are suitable for the easy migrations of both the streamline and the shallows. The repeated detailed measurements made in 1971—1973 (Hydroprojekt 1974) revealed that shallows migrated with a velocity of 0—1.9 m per 24 h through the section Toruń—Solec. The mean daily velocity of current migration was 1.0—3.10 m near Toruń, and 0.97—1.70 m near Solec.

The above parameters have been established for the moderate water channel. The increase in height of water surface by ca 3 m causes channel overflow.

The valley cross-sectional area at mean water level (MW) is 1050 m^2 in Toruń, and 1348 m^2 in Solec; at the mean high water level (MHW) it is 3490 m^2 in Toruń and 4228 m^2 in Solec. It appears that during the mean high discharges (MHW) the valley cross-sectional area is increased by 3.32 for Toruń and by 3.13 for Solec.

CHARACTERISTICS OF THE HYDROLOGICAL RÉGIME

The Vistula carries waters from areas of different hydrological régimes. Since all of the major tributaries join the Vistula upstream from Toruń discharges are much the same along the whole lower course of the river (tab. 1).

Table 1. Discharges of the Lower Vistula in m^3, 1921—1967 (according to Tuszko 1977)

High water once in 100 years	Mean high water	Annual mean water	Mean low water	Low water once in 100 years
9200	4040	904	322	209

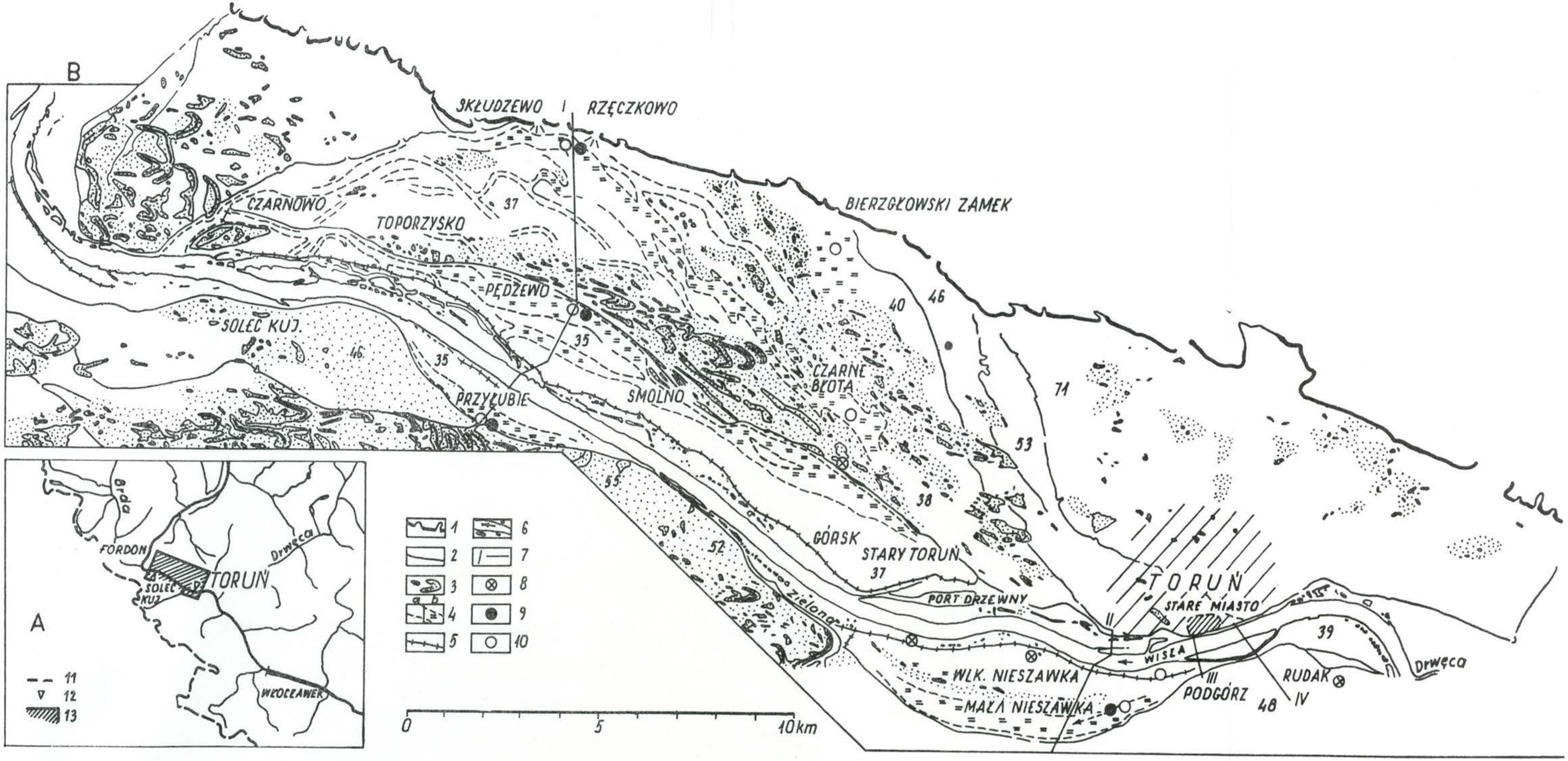


Fig. 1. B. Geomorphological sketch showing the Vistula valley reach between Toruń and Solec Kujawski (according to Z. Churski, M. Pasierbski, A. Tomczak) with localities and geological cross-sections, together with landforms detected on aerial photographs)

1 — edges of morainic plateaus and deluvial fans; *2* — terrace edges; *3* — aeolian forms; *4*: *a* — paleochannels, *b* — peatfilled paleochannels; *5* — dikes; *6* — the river and young oxbow lakes; *7* — geological cross-sections; *8* — archaeological sites; *9* — localities with radiocarbon datings; *10* — localities with pollen analyses

A. Location of the valley reach in the drainage basin

11 — boundary of the drainage basin; *12* — gauging stations; *13* — boundaries of the study area

The ratio of mean discharges is 1:12.5; the ratio of extreme discharges of a probable recurrence-interval once in 100 years is 1:44.

The river is characterized by great variations in annual and multi-year discharges. In the valley reach studied, the highest discharges are recorded at the end of February and at the beginning of March (water level at the gauge in Toruń is 7—9 m). The lower rainfall floods occur at the turn of July and August (6—7 m). High water levels are also noted in the second half of June (5—6 m). In former times disastrous floods also occurred when ice-dams clogged the river channel.

Data on water levels that have been recorded in the 19th and 20th centuries show that stages exceeding 7 m at the gauge in Toruń tend to occur every 3—5 years (mean multi-year value). During the last 100 years flood flows were 1.0—1.5 m higher due to an artificial narrowing of the channel.

HYDROLOGICAL AND GEOMORPHOLOGICAL CHANGES OVER THE PAST 100 YEARS

In the environs of Toruń the man-induced hydrological and geomorphological changes included mainly the construction of dikes, channel correction and the digging of a network of amelioration ditches on both the flood-plain and the supra-flood terrace.

In the surroundings of Toruń such activities were not confined to the last century, since as early as the 16th century a dike was built to prevent inundation of the area situated to the west of Toruń on the right bank of the Vistula. In the second half of the 18th century this dike followed the river channel on the right side for 22 km reaching the upper terrace edge.

In the 19th century the Vistula valley was subjected to improvement from Silno (16 km upstream of Toruń) down valley to its mouth. In the middle of the 19th century the channel regulation was begun by the construction of jetties. These works continuing with varying intensity into the beginning of the 20th century resulted in the liquidation of some islands and shallows and, consequently, in the narrowing, planing off and deepening of the channel.

The building of dikes parallel with the channel on its left side began only in the second half of the 19th century. In 1879 a dike was built near Mała Nieszawka to reach eastwards as far as Toruń at the beginning of the 20th century. To the west this dike extends down to the junction of the rivers Vistula and Zielona, where further westwards the channel had a perfect natural protection against floods. At that time the so-called Timber Port was built on the right bank of the Vistula by using cut-offs and islands near Stary Toruń.

In addition to channel correction amelioration was started already in the 18th century, and the network of ditches carrying excess ground waters to the Vistula has become more dense. Their high location is conditioned by the geological structure of the substratum, by the ground water outflows at the morainic plateau edges, and by its impeded run-off at high water stages in the river. In spite of the now dense network of amelioration ditches, the ground water level is at shallow depths, and in the peat-filled depressions the water tends to reach the surface.

Other hydrological changes were due to the construction of a dam in Włocławek (ca 55 km upstream of Toruń) in 1969. Discharges are artificially controlled by the work of the hydroelectric power station there, and variations in discharges show a diurnal rhythm.

In Toruń the right bank is covered with concrete for a distance of ca 2 km. The channel is spanned by two bridges (railway bridge since 1873 and road bridge since 1933).

LAND FORMS AND SEDIMENTS

MORPHOLOGY OF BOTH THE FLOOD-PLAIN AND THE SUPRA-FLOOD TERRACE

In the study area there occur the two lowermost terraces: the supra-flood terrace and the flood terrace being very well developed at the cost of the higher terrace levels (Fig. 1 B).

The supra-flood terrace

The supra-flood terrace (40 m a.s.l.) occurs only on the right bank of the Vistula, where it forms a 6 km wide strip at 6—8 m above mean water level in the channel between Przysiek (40 m a.s.l.) and Czarnowo (37 m a.s.l.). In the central part of the area, the terrace is bordered by the steep morainic plateau slope (ca 80 m a.s.l.) in the north. In the eastern and western parts of the valley reach discussed the supra-flood terrace plain is separated by a bluff from the higher terrace levels at 43—45 m and 53—55 m a.s.l.

The surface of the supra-flood terrace includes three characteristic relief elements, namely fragments of the flat terrace plain, elongated depressions and aeolian forms. The terrace plain proper occurs in the form of lenticular elevations having a relatively flat surface with denivelations up to 1 m. This surface has preserved its most original features near Toporzysko; in other places it has been modified by aeolian forms.

The most characteristic relief element are elongated depressions without any marked edges, lying generally ca 1—2 m below the mean terrace level. They are difficult to read on a hypsometrical map, but they are clearly visible in the field and on aerial photographs (Fig. 1). They are marked by flat floors and very shallow ground water levels.

Consequently, their paths and extents are underlined by a dense network of amelioration ditches. The depressions contain frequently peat greatly varying in thickness, indicating the varying depth of the above forms.

The depressions are semicircular in shape, and they are more or less parallel to the plateau edge. They are most distinct in the central part of the terrace; westwards they become narrower and shallower, and in its eastern part they are obscured by aeolian forms. Both the outlines of these elongated depressions and their distribution indicate that these are traces of former channels varying in width from 70 to 400 m. An exception is the depression near Czarne Błota village, where it is ca 1 km wide. This may be due to runoff impeded by dunes.

The aeolian ridges are more or less parallel to the above described depressions. This suggests that they originated by transformation of the former levées. Dunes occur most frequently in the eastern part of the terrace diminishing gradually towards the west, where the terrace also decreases in width. They are commonly only small elongated elevations or areas of windblown sands. Most of the dunes do not exceed 5 m in height, higher ones are found only in the marginal zone of the terrace adjacent to the edge. The dunes here are well developed ridges and parabolic forms, 8—12 m high. Their shapes indicate that their formation was due to the action of westerly winds.

The flood-plain

The flood-plain which constitutes the present-day valley floor is developed at 3.0—4.0 m above the mean water level in the channel, and its altitude decreases downstream from 37 to 33 m a.s.l. Its different development along either side of the river indicates that during the initial phase of flood-plain formation the channel tended to shift toward the left bank.

On the right bank the terrace is continuous and it grows wider westwards attaining a maximum width of 2.5 km. On the left bank of the Vistula the flood-terrace forms two characteristic semicircular widenings (near Nieszawka the width is 2.5 km and near Przyłubie it is 1.2 km). Along the remaining channel reaches the terrace is reduced to a strip 200—500 m wide or it is absent. The channel is bordered by the higher terrace edges (45 m a.s.l.) The extensive flood-plain whose denivelations do not exceed 3 m is interrupted by elongated depressions filled locally with peat, by oxbow lakes resulting from channel regulation and being in various phases of overgrowing, and by the levées and anthropogenic forms. Near Nieszawka there occur small dune hillocks.

The characteristic paths of depressions interrupting the flat flood--plain are abandoned channels. They have no clear edges and are distinguishable thanks to their different lithology and high ground water level. On aerial photographs they are indicated by the darker phototone and different kinds of land use. They tend to lie close to the bluff of the higher terraces bordering the valley floor. These abandoned channels took generally one path there and exceptionally two parallel paths over a short reach on the right side. In some places, the depressions become shallower (Fig. 1B). In many places they contain peat varying in thickness from between 0.3—4.0 m. This may indicate that the channel depth was originally greatly varied suggesting the presence of deeps in the channel. The depression widths vary from between 40 m and 200 m attaining 400 m.

On the flood-plain adjacent to the present-day Vistula channel there occur many young oxbow lakes. These loops are usually filled with water, 1—3 m deep, and they were artificially cut off by channel regulation. They have connection with the presently active channel, although all of them occur between the river and the dike. Along the channel there is a natural levée which rises 1.0—1.5 m above the mean terrace level. There also is an artificial levée, or dike built of earth which was improved in 1870—1880, being as high as 5—6 m. It prevents inundations of the flood-plain even by the greatest floods.

On the flood-plain near Nieszawka there occur locally dunes, i.e. small elongated hillocks, 1—3 m high. The aeolian forms here are confined to a narrow belt of slightly higher ground, 100—200 m wide and 6 km long, between two former channel paths. This suggests that the dunes result from the aeolian remodelling of former point bars.

The following conclusions can be drawn from the above morphological data:

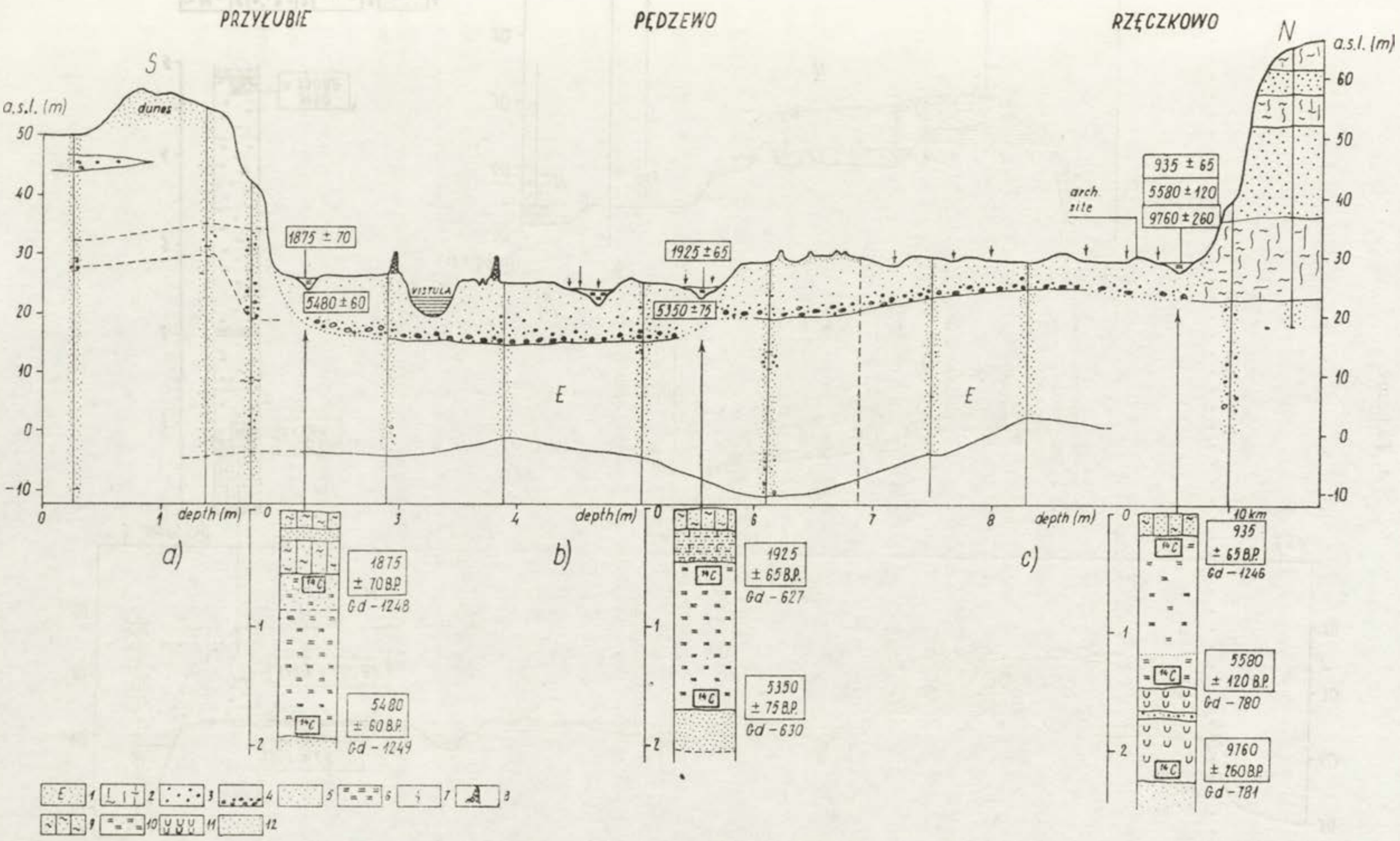
Both the wide extent of the supra-flood terrace, and the occurrence of secondary fluvial forms on its surface indicate that terrace formation took place under conditions when compared with the formation of the higher terrace levels in the Toruń Basin.

It is noteworthy that the supra-flood terrace attaining a width of 6 km in the middle part of the valley reach discussed does not occur on its margins. The flood-terrace also is poorly developed here. Hence, the part played by the melting of dead ice blocks in the spatial development of the supra-flood terrace cannot be excluded.

The shapes of both the paleochannels and the intervening dune-covered smooth elevations indicate clearly that the river tended to divide into multiple limbs which shifted successively toward the south-west.

Fig. 2. Geological section I — with profiles of biogenic sediments (a) Przyłubie, (b) Pędzewo, (c) Rzęczkowo and radiocarbon dates

1 — Eemian sand; *2* — boulder clay; *3* — fluvioglacial sand; *4* — pebbles and cobbles (pavement on the channel bed); *5* — alluvial sand; *6* — peat; *7* — drainage ditches; *8* — dikes. Explanation of profiles: *9* — fine silt, *10* — peat, *11* — gyttja, *12* — sand. Vertical lines — borings


PRZYŁUBIE
PĘDZEWO
RZĘCZKOWO
S
N
a.s.l. (m)
a.s.l. (m)
dunes
VISTULA
E
E
1875 ± 70
5480 ± 60
1925 ± 65
5350 ± 75
935 ± 65
5580 ± 120
9760 ± 260
arch site
50
40
30
20
10
0
-10
60
0
1
3
4
6
7
8
10 km
depth (m)
depth (m)
depth (m)
a)
b)
c)
1875 ± 70 B.P.
Gd - 1248
5480 ± 60 B.P.
Gd - 1249
1925 ± 65 B.P.
Gd - 627
5350 ± 75 B.P.
Gd - 630
935 ± 65 B.P.
Gd - 1246
5580 ± 120 B.P.
Gd - 780
9760 ± 260 B.P.
Gd - 781
14C
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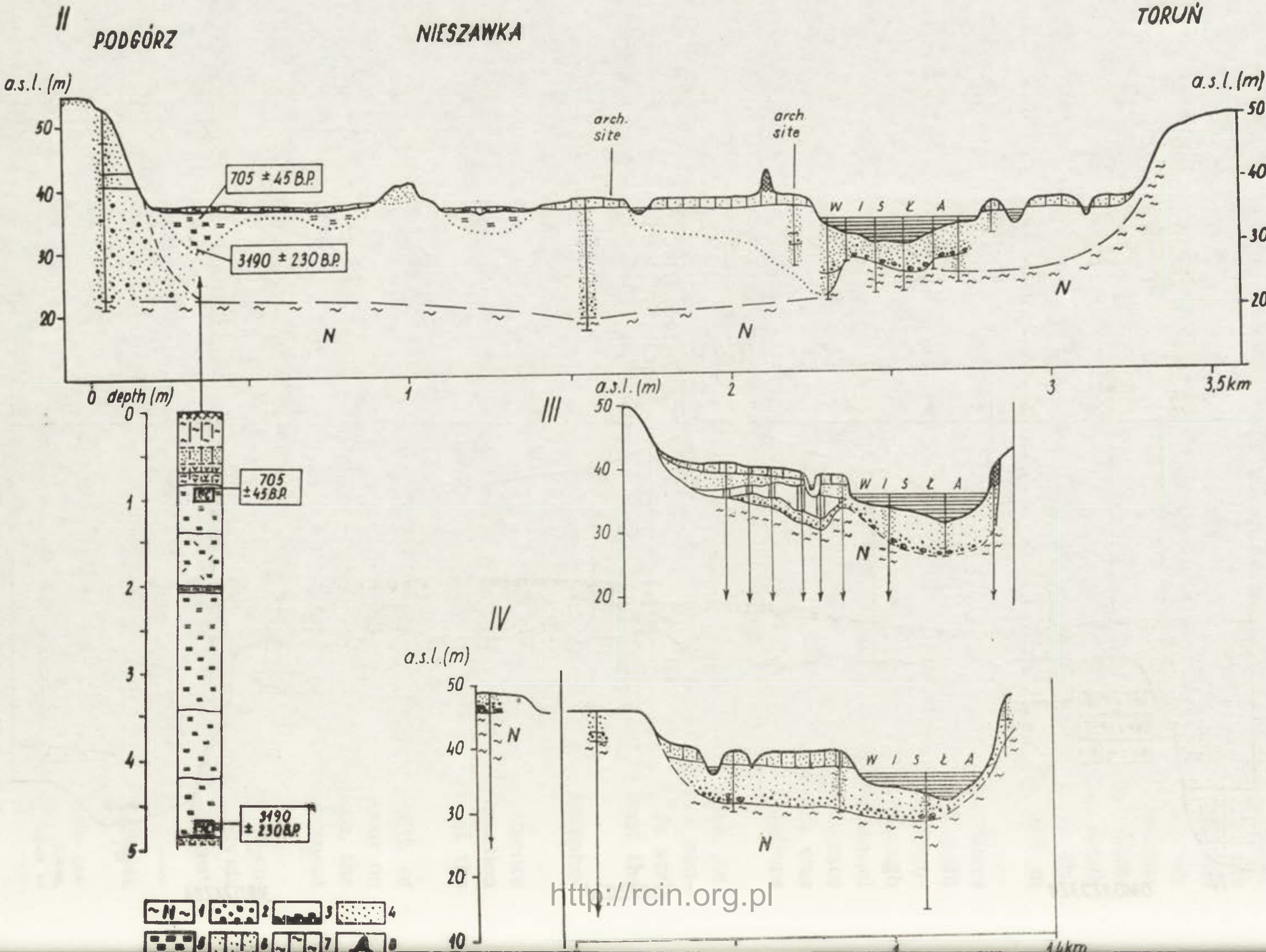
II
PODGÓRZ
NIESZAWKA
TORUŃ
a.s.l. (m)
a.s.l. (m)
50
40
30
20
arch. site
arch. site
705 ± 45 B.P.
3190 ± 230 B.P.
WISŁA
N
N
N
0
1
2
3
3,5 km
depth (m)
0
1
2
3
4
5
705 ± 45 B.P.
3190 ± 230 B.P.
III
a.s.l. (m)
50
40
30
20
WISŁA
N
IV
a.s.l. (m)
50
40
30
20
10
N
WISŁA
N
~N~
1
2
3
4
5
6
7
8

No complete image of the channel pattern at this terrace level has been preserved, since part of its surface became destroyed by the river cutting down to the lower level. It is likely that the dunes developed at the time of the supra-flood plain formation by the braided Vistula.

The morphology of the flood-plain points to an increasing concentration of the channel which, however, maintains its braided pattern. This braiding which continues into present times is to be linked with the great variability of discharges (Falkowski 1980a, b). This also accounts for the lack of any traces of meanders which tend to form at relatively regular annual discharges.

CHARACTERISTICS OF THE ALLUVIAL FILLS

Both the composition and thickness of the alluvial sediments forming the supra-flood terrace and the flood-plain are illustrated by the cross profiles in Figure 2 and 3.

The recognition of an alluvial series was based on the occurrence of a pavement at its base. This pavement rests usually on the Neogene clays. In the central part of the valley reach discussed this pavement is underlain by older fluvial sediments dating from the Eemian Interglacial (Makowska 1979). Beneath the present-day Vistula valley there occurs a deep (10 m to 5 m a.s.l.) fossil valley, 5—6 km wide, trending generally in a N—S direction.

The base of the alluvial series lies at 27.5—34 m a.s.l. below the supra-flood terrace. In general it slopes from north to south. The buried surface is a distinct erosional feature which cuts into deposits that also are forming the adjacent morainic plateau.

The thickness of the alluvial supra-flood terrace deposits varies from between 3 and 11 m, the extreme values being 1.6 m and 15.6 m. Where there occur relatively thin layers, the deposit is medium- and fine-grained sand. Where the thicknesses are 8 m or more, sand and gravel with an admixture of pebbles is predominant. This indicates the existence of erosional channels beneath the present terrace surface. The composition of the alluvia suggests the gradual shifting of the main stream current toward the south, where it subsequently cuts down to the flood terrace level. The alluvial supra-flood terrace sheet shows a fairly uniform composition throughout the vertical profile. The prevailing deposit is sand, 0.25—0.8 mm in diameter. The particular layers differ only by the content of gravel and pebbles.

Fig. 3. Geological sections II (with profile of biogenic sediments Podgórz and radiocarbon dates), III and IV

1 — Neogene clay; 2 — sand with gravel; 3 — pebbles and cobbles (pavement of the channel bed); 4 — sand; 5 — peat; 6 — sand and silt; 7 — clayey silt; 8 — dikes and anthropogenic layer

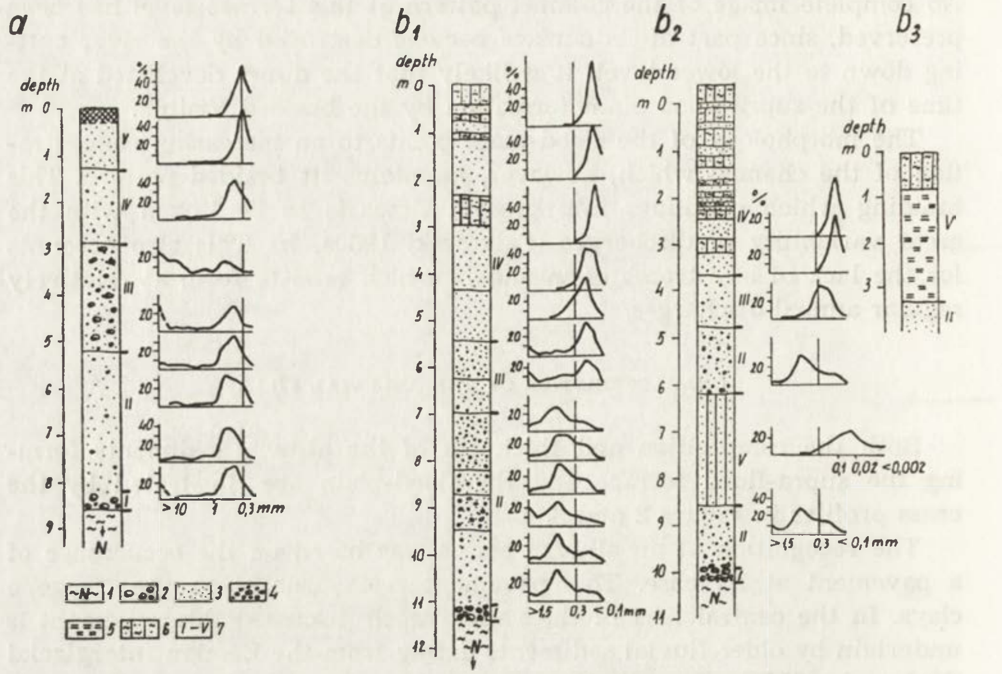

Fig. 4. Alluvial sheet forming the supra-flood terrace (a) and the flood-plain (b_1—b_3), with curves showing the granulometric composition

1 — Neogene clays; 2 — pebbles and cobbles (pavement of the channel bed); 3 — sand; 4 — gravel with pebbles; 5 — peat, 6 — clayey silt; 7 — members distinguished

In the typical vertical profile five members (Fig. 4a) can be distinguished. These belong to the channel, overbank and oxbow lake facies.

The channel facies:

I. The pavement on the channel bed is up to 0.5 m thick. It consists of pebbles with coarse- and medium-grained sand. The pebbles measured up to 8 cm in diameter, and probably larger boulders also occurred there. The pavement is made up chiefly of crystalline rocks with occasional limestones. The pebbles vary by rounding. This can be explained by the continuous supply of fresh materials derived from the nearby eroded morainic plateau. Moreover, frost weathering cannot be excluded.

II. Medium-grained sand with a few pebbles, 3—5 m in thickness. The dominant fraction includes grains 0.25—0.8 mm in diameter (62—65% rounding) with a considerable admixture of the 0.1—0.25 mm fraction (11—21%). The grains are fairly well rounded. Quartz grains having frequently a mat surface dominate. There also occurs an admixture of gravels and pebbles. These include for the most part poorly rounded limestone fragments as well as flint and crystalline rocks.

III. Medium- and coarse-grained sand with gravel and numerous pebbles, 2—3 m in thickness. The fractions (Fig. 4a) vary greatly, and the poorly rounded pebbles attain the highest values throughout the profile. Diameters are up to 9.5 cm (limestones, flints, crystalline rocks). Grains belonging to the sand fraction have frequently mat surfaces and they are well rounded.

IV. Medium- and fine-grained sand (dominance of shiny quartz grains) with occasional gravel up to 4 mm in diameter. The thickness of this layer is 1.5—2.0 m.

The overbank facies:

V. Fine- and very fine sand belonging to the overbank facies, 1—3 m thick, is forming the uppermost member. It covers almost the entire terrace surface. In places, mainly near the plateau slope the sand, 3—3.5 m thick, overlies only a 0.5 m thick layer of various-grained sand with a few gravel deposited on the Neogene clays.

The oxbow lake facies:

Va. Deposits belonging to the oxbow lake facies fill in the above described paleochannels. Most frequently they are peats lying immediately on fine sand. In a few places peat is underlain by gyttja, 0.7—2.5 m in thickness. It should be noted that the biogenic fills are found in the deepest parts of the former channels. The peat is overlain by a thin (20—30 cm) veneer of silty-clayey deposits.

The above-mentioned alluvial supra-flood terrace deposits are in places built up by aeolian sands, by deluvial sediments (also as deluvial fans) at the foot of the plateau scarp and by peat connected with the outflow of groundwaters.

The varying thickness of the alluvial sheet is due either to the partial reduction or lack of its middle members. The alluvial flood-plain deposits attain a thickness from between 5—6 m and 14—15 m (maximum 20 m). The ordinates of the lowest portions of the erosional surface are 28—29 m a.s.l. in the east and 13—14 m a.s.l. in the west. It is difficult to reconstruct in detail the relief of this surface. It seems, however, that its height differentiation is the joint result of two processes: of scour leading to the formation of the lowermost part of the surface and of the subsequent lateral erosion, widening the then existing valley floor.

Although variations in thickness are considerable, the composition of this alluvial sheet is similar throughout the flood-plain. Everywhere the sand fraction predominates, and the sediments become finer towards the top. The paleochannels are filled with biogenic sediments. In several places drillings revealed a layer of dust (Fig. $4b_2$) and pieces of wood (non identified).

The typical sedimentary sequence that is forming the flood-plain comprises five members (Fig. 4b):

I. The channel pavement (lag facies) occurs commonly at its base.

It consists of both 10 cm pebbles and blocks up to several metres in diameter, found in the valley floor narrowing near Toruń. This member does not exceed 1 m in thickness.

II. Coarse sand with gravel, 1.5—6.0 thick, may contain remains of the molluscs *Viviparus fasciatus* and *Pisidium* also living at present.

III. Fine sand with a few coarse-grained fraction. This is a transitional horizon, 1.0—1.5 m thick, between the channel and flood deposits.

IV. Fine and very fine sand belonging to the overbank facies alternates with silt-clayey deposits. The individual layers are marked by a generally fine rhythm of sedimentation in the area beyond the dikes. Within the dikes the layers are much thicker due to the post-regulation constriction of the flood area now containing the greatest floods.

V. The deeper portions of the paleochannels are filled with peat, which lies on a mineral substratum (fine sands) and is covered by silty-clayey flood deposits (ca 0.8 m in thickness).

In order to improve the quality of such areas as meadows, these have an artificial 0.5 m veneer of loam on the peat. A bed of silty deposits lying among coarse channel sands at a depth of 5—7 m (Fig. $4b_2$) should also be referred to the oxbow lake facies. These deposits contain some well preserved pollen of present-day plants including cereals.

BASES OF RELATIVE AND ABSOLUTE CHRONOLOGY

The chronology of the sediments was based on the pollen diagrams and spectra (by Noryśkiewicz) and on ^{14}C datings (by Pazdur) of five profiles from the paleochannel fills.

On the supra-flood terrace the following profiles have been analyzed: "Czarne Błota" (Fig. 5) — pollen diagram (Niewiarowski, Noryśkiewicz, in print), and "Rzęczkowo" — three ^{14}C datings and pollen spectra of the limiting horizons (Fig. 2c).

On the flood-plain the following profiles have been studied: "Przyłubie" (Fig. 2a), "Pędzewo" (Fig. 2b) and "Podgórz" (Fig. 3 II) — radiocarbon datings and pollen spectra at the base.

Radiocarbon determinations were made on the lowermost and uppermost parts of biogenic deposits:

profile "Rzęczkowo":	top peat	— 935 ± 65 a B.P. (Gd-1246),
	basal peat	— 5580 ± 120 a B.P. (Gd- 780),
	basal gyttja	— 9760 ± 260 a B.P. (Gd- 781),
profile "Przyłubie":	top peat	— 1875 ± 70 a B.P. (Gd-1248),
	basal peat	— 5480 ± 60 a B.P. (Gd-1249),
profile "Pędzewo":	top peat	— 1925 ± 65 a B.P. (Gd- 627),
	basal peat	— 5350 ± 75 a B.P. (Gd- 630),
profile "Podgórz":	top peat	— 705 ± 45 a B.P. (Gd-1250),
	basal peat	— 3190 ± 230 a B.P. (Gd- 784).

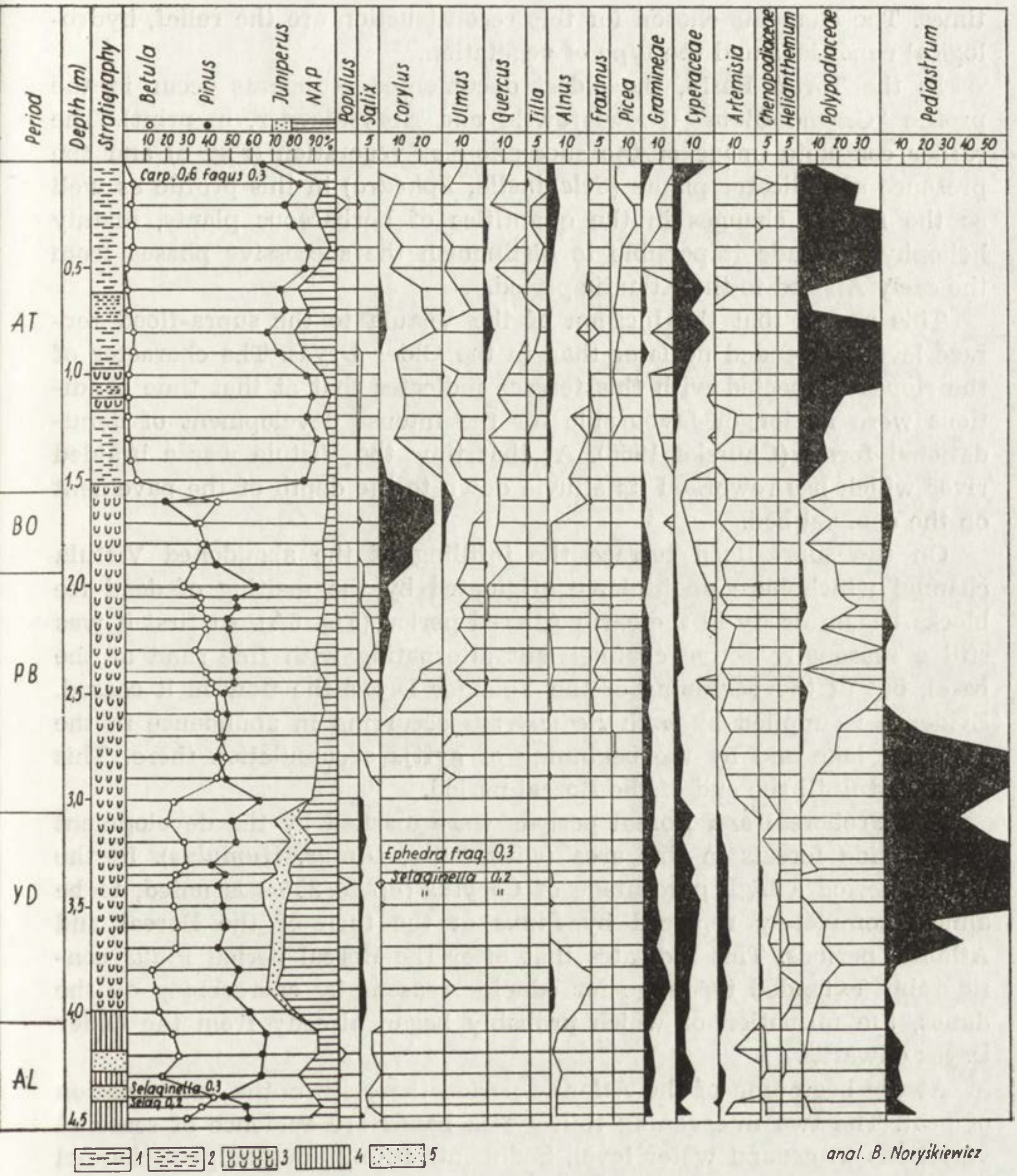

Fig. 5. Pollen diagram of biogenic sediments from the supra-flood terrace plain (according to B. Noryśkiewicz)

1—2 — peat; 3 — gyttja; 4 — silt; 5 — sand; AL — Allerød; YD — Younger Dryas; PB — Preboreal period; BO — Boreal period; AT — Atlantic period

ENVIRONMENTAL CHANGES AND VALLEY EVOLUTION

The attempt to reconstruct both changes in the environment and evolution of the examined reach of the Vistula valley refers to a period of ca 12 000 years, i.e. from the Older Dryas onwards to the present times. The elements chosen for this reconstruction are the relief, hydrological conditions and the type of vegetation.

In the Toruń Basin, the oldest documented sediments occur in the profile "Czarne Błota" (Niewiarowski and Noryśkiewicz, in print). The rather complete image of the succession of vegetation (Fig. 5) and the presence of indicator plants (*Selaginella, Ephedra*) in this profile as well as the radical changes in the quantities of herbaceous plants, mainly heliophytes, made it possible to distinguish the successive phases from the early Allerød to the Atlantic period.

This means that the incision of the Vistula to the supra-flood terrace level has ended no later than in the Older Dryas. The character of the slopes connected with this terrace indicates that at that time conditions were no longer favourable for the intense development of denudational forms (Churska 1966). At that time the Vistula was a braided river which has reworked its alluvia down to the depth of the pavement on the channel bed.

On the supra-flood terrace the infilling of the abandoned Vistula channel which here might have originated by the melting of dead ice blocks began alredy in the early Allerød period (Fig. 6A). At first it was still a seasonally active channel (silt alternating with fine sand at the base), but at the beginning of the Younger Dryas the flow in it ceased. Evidence is implied by both *Pediastrum* occurring in abundance in the resulting lake and by the beginning of gyttja accumulation there. This continued until the end of the Boreal period.

The Preboreal and Boreal periods were marked by the development of riverside forests in this area (with *Salix, Ulmus, Humulus*). In the Boreal period a high percentage of *Corylus* (up to 25%) is noted, to be almost completely replaced by *Pinus* at the turn of the Boreal and Atlantic periods. This indicates that after the Boreal period *Pinus* considerably extended its range for edaphic reasons by encroaching on the dunes, the formation of which probably began already from the Older Dryas onwards.

At the beginning of the Atlantic period there starts the accumulation of peat. The two intervening thin gyttja bands are evidence of seasonal variations in ground water level. Sediments filling another paleochannel on the supra-flood terrace at Rzęczkowo are somewhat younger. In that channel the accumulation of gyttja started 9780 ± 260 a B.P. or at an earlier date. Pollen analysis points to the Younger Dryas. Near the end of the Atlantic period gyttja accumulation ceases. This indicates a lowering of the water level in the lake, and peat began to form there. Its basal part has been dated at 5580 ± 120 a B.P. Archaeological research (Matuszewska-Kola 1974) revealed the presence of many traces of Neolithic man on the supra-flood terrace in the Vistula valley to the west of Toruń. Most probably farming encroached on the less humid valley

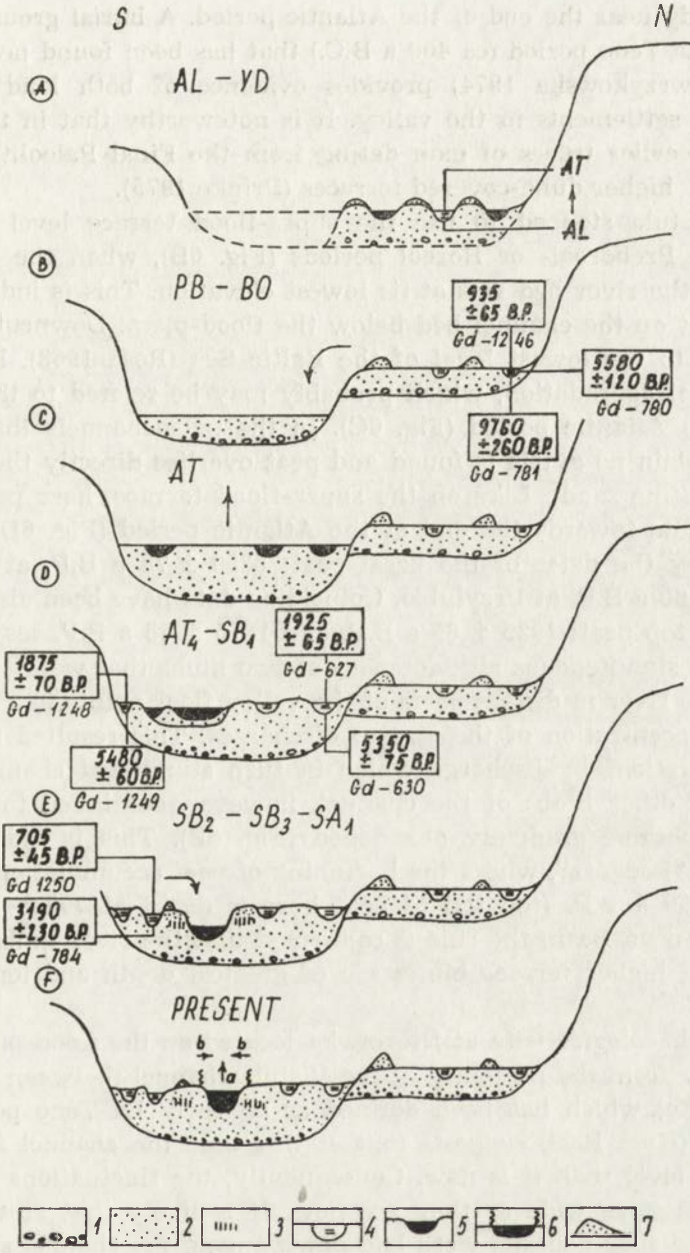

Fig. 6. Evolution of the Vistula valley reach between Toruń and Solec Kujawski

1 — pebbles and cobbles (pavement on the channel bed); 2 — sand; 3 — silt; 4 — peat-filled paleochannels; 5 — active channels; 6 — dike; 7 — dunes. F: *a* — phase of channel aggradation, *b* — phase of post-regulation channel narrowing and deepening. AL — Allerød; YD — Younger Dryas; PB — Preboreal period; AT — Atlantic period; SB — Subboreal period; SA — Subatlantic period

floor already near the end of the Atlantic period. A burial ground dating from the La Tène period (ca 400 a B.C.) that has been found near Rzęczkowo (Wawrzykowska 1974) provides evidence of both land use and permanent settlements in the valley. It is noteworthy that in the Toruń Basin the earlier traces of man dating from the Final Paleolithic occur only on the higher dune-covered terraces (Prinke 1975).

The Vistula stopped to use the supra-flood terrace level probably before the Preboreal- or Boreal periods (Fig. 6B), when the river cut down and the river bed was at its lowest elevation. This is indicated by a pavement on the channel bed below the flood-plain. Downcutting corresponded to the lowest level of the Baltic Sea (Rosa 1968). Following was channel aggradation, which probably may be related to the earlier part of the Atlantic period (Fig. 6C). In the paleochannels that dissect the flood-plain no gyttja is found and peat overlies directly the mineral sediments (fine sand). Like on the supra-flood terrace, here peat began to accumulate towards the end of the Atlantic period (Fig. 6D). This is indicated by the dates of the basal peat: 5350 ± 75 a B.P. at Pędzewo and 5480 ± 60 a B.P. at Przyłubie. Coinciding data have been also obtained for the top peat: 1925 ± 65 a B.P. and 1875 ± 75 a B.P. respectively. The almost simultaneous abandonment of two limbs that were previously used by the river in distant parts of the valley floor points to a tendency towards concentration of the stream discharges. This resulted from less wide fluctuations in discharge which in turn stimulated channel deepening. The other limbs of the channel, however, continued to function and they became gradually abandoned (Fig. 6E). This is indicated by the profile "Podgórz", where the beginning of peat accumulation is dated at 3190 ± 230 a B.P. (the top of peat here is dated at 705 ± 45 a B.P.)

In the Toruń Basin the rule is confirmed that the river limbs that lie close to the higher terrace bluffs are of greatest depth and longest duration.

The archaeological site at Nieszawka located on the flood-plain some 200 m away from the presently active Vistula channel (between the river and the dike) which has been defined as an early La Tène permanent settlement (Kola 1969) suggests that at this time the channel floor was at a lower level than it is now. Consequently, the fluctuations in water level were not as wide as they are now. It is likely that at that time (Fig. 6E) the silty deposits were laid down among the channel sediments at a depth of 5—7 m below flood-plain surface and aeolian processes took place leading to the formation of small dunes on the flood-terrace near Nieszawka.

The above phase of downcutting was followed by channel aggradation. Until the Early Middle Ages there was no thread of disastrous floods, since many remains of large constructions dating from that period have survived on the flood-plain in the Toruń Basin. Historical data report on permanent fords, e.g. near Stary Toruń (Jasiński 1980). These may indicate a stability of the Vistula channel far greater than that of the present time.

It is difficult to say precisely when the Vistula began to built up the channel bed. This was the result of increased material supplies to the river brought on by the development of new settlements and of intense forest clearance. In the drainage basin of the Middle and Lower Vistula the above process occurred in the 13th—16th centuries. Because of aggradation the river channel was built up to a higher level (Fig. 6F, *a*) and many shallows and islands appeared there. Such a picture of the Vistula channel is presented on the oldest 1:50 000 map of the study area made by Schrötter in 1796. Consequently, the flood crests increased (in the paleochannels silty-clayey deposits were laid down on the peats during floods), and the configuration of the channel bed favoured the formation of ice-jams.

Further changes were due to regulation which was completed here in the second half of the 19th century. Both the construction of dikes and improvement of the channel has resulted in its narrowing and deepening. This greatly reduced the area experiencing inundation (Fig. 6F, *b*). An obvious consequence are both higher water stages during floods (it was necessary to built up the dikes at the end of the 19th century), and increased aggradation of the flood-plain. This plain, therefore can be built up only to the maximum flood water level.

These considerations lead to the inference that a river must not always and everywhere respond to climatic changes by changes from braided to meandering course (compare Starkel 1977; Kozarski and Rotnicki 1978). Despite the changes in environmental conditions which took place near the end of the Pleistocene and in Holocene times, no typical meanders did develop in the valley reach examined. This is likely to be the result of both wide fluctuations in discharge and the lack of adjustment to accomodate the load currently contributed by the drainage basin, i.e. the local competence to carry debris.

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Geographical Studies
Evolution of the Vistula River Valley
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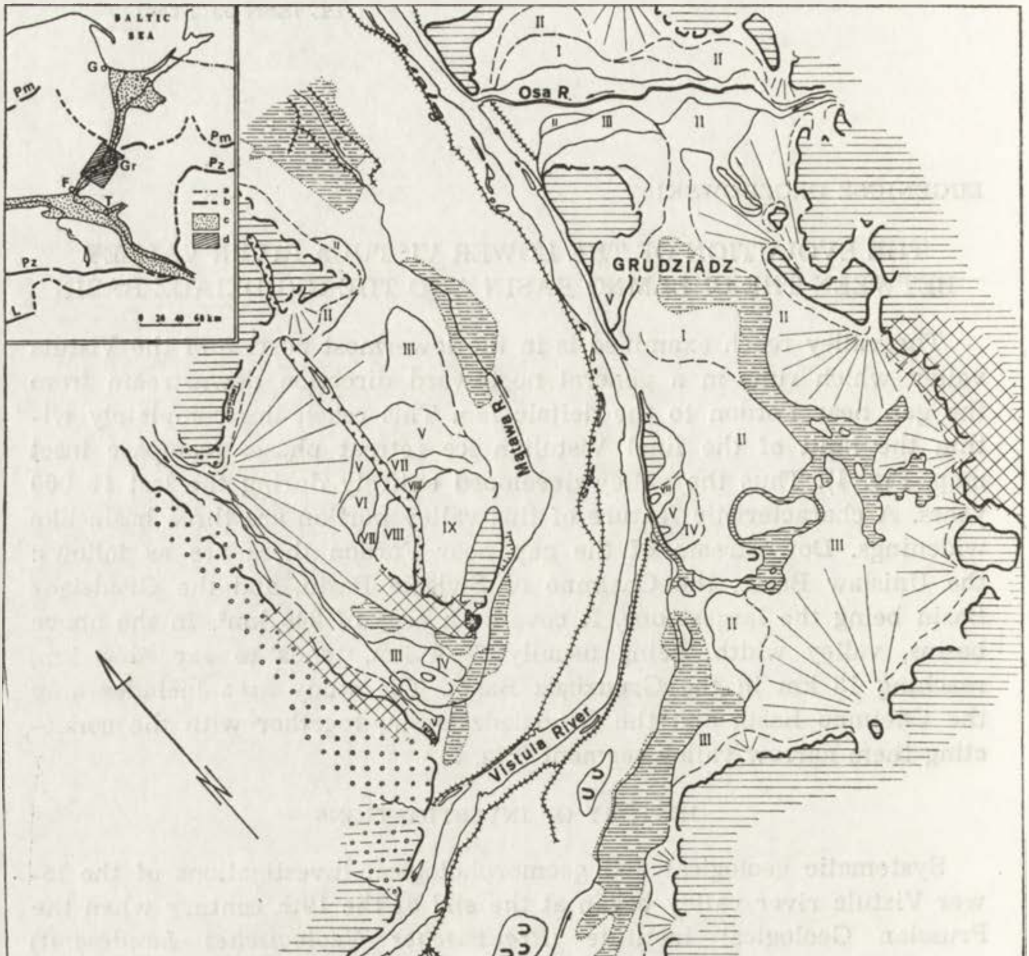
THE EVOLUTION OF THE LOWER VISTULA RIVER VALLEY BETWEEN THE CHEŁMNO BASIN AND THE GRUDZIĄDZ BASIN

The valley reach examined is in the lowermost portion of the Vistula valley which runs in a general northward direction downstream from the gap near Fordon to the deltaic fan. This reach lies completely within the limit of the final Vistulian ice retreat phases (compare inset map, Fig. 1). Thus the valley developed entirely during the last 15 000 years. A characteristic feature of this valley portion are three basin-like widenings. Downstream of the gap near Fordon these are as follows: the Unisław Basin, the Chełmno or Świecie Basin, and the Grudziądz Basin being the largest one. It covers an area of 240 km². In the above basins, valley width, being usually 3—4 km, tends to exceed 8 km, reaching 18 km in the Grudziądz Basin. The study area includes only the Chełmno Basin and the Grudziądz Basin, together with the connecting them narrow valley segment (Fig. 1).

HISTORY OF INVESTIGATIONS

Systematic geological and geomorphological investigations of the lower Vistula river valley began at the end of the 19th century when the Prussian Geological Institute (*Preussisches Geologisches Landesamt*) started the regular geological mapping on the scale of 1:25 000. The published maps gave an impulse to further geological studies evoking an increasing interest in the problem of evolution of the lower Vistula valley. Among the early investigations are those by Jentzsch (1911) and Sonntag (1914) who distinguished besides the flood-plain, three river terraces (40—41 m, 18—25 m, 10—15 m) which were referred to the "post-glacial" time.

The classification of the river terraces which is still in use was elaborated by Galon (1934, 1961, 1968). He distinguished a 9-step set of river terraces (indicated by Roman ciphers) as a uniform system occurring both in the lower Vistula valley and in the Noteć—Warta *pradolina* (glacier margin valley train) as well as in other minor tributary valleys linked with them. The occurrence of this terrace system has been confirmed by recent geomorphological studies (Drozdowski 1974; Roszko 1968;


BALTIC SEA
Gd
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Gr
F
T
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L
a
b
c
d
0 20 40 60 km
Osa R.
GRUDZIĄDZ
Mątawa R.
Vistula River
Wda R.
ŚWIECIE
CHEŁMNO
I
II
III
IV
V
VI
VII
VIII
IX
1
2
3
4
5
6
7
8
9
10
11
12
0 1 2 3 4 5 km

Niewiarowski 1970), although with some corrections concerning the age of the lower terraces. Modern investigations including biostratigraphical studies of terrace depressions, together with the first radiocarbon datings indicate that all terraces are Late Vistulian in age (Drozdowski and Berglund 1976).

Particular scientific interest evokes the largest basin-like widening at Grudziądz with its three *kępa*-islands being remnants of the morainic plateau. Jentzsch (1911) relates the origin of this valley widening to a large proglacial lake at the mouth of the Mątawa outwash valley, whereas Zaborski (1927) and Galon (1934) have regarded the meandering of the Vistula as a process responsible for its formation. However, recent field examination has revealed that besides landforms and deposits of a fluvial origin, there also are hitherto unrecognized features associated with the melting of dead ice blocks (Drozdowski 1974, 1976). They indicate that both fluvial and glacial processes participated in the evolution of the Grudziądz Basin.

The alluvial fill forming the flood plain bas been considered *en masse* as a result of Holocene river aggradation without much further discussion of the processes involved in its formation. Therefore, recent studies of the valley fill have mainly concerned the chronology in order to establish some time limits for the reconstruction of the history of the valley infilling (Drozdowski and Berglund 1976).

This article summarizes all known evidence concerning the evolution of the lower Vistula River valley by laying emphasis on the presentation of new data on the depositional history of the flood-plain (Fig. 2).

CHARACTERISTICS OF BOTH STREAMFLOW AND CHANNEL FORM

The water levels and discharges of the Vistula recorded at the Grudziądz stream-gauge are characterized by great amplitudes. The highest water stages leading to the inundation of the flood-plain, are associated with the melting of the snow cover mostly in March or April. The absolute maximum recorded at Grudziądz on March 26, 1877, was 1063 cm. Over the period 1921—1935, the mean high water level was 677 cm with the corresponding discharge (Q) of 3875 m^3/s, at bankfull stage — 544 cm discharges were 2400 m^3/s, the mean low water level was 220

Fig. 1. Morphogenetic map of the Lower Vistula river valley between the Chełmno Basin and the Grudziądz Basin

1 — morainic plateau; *2* — outwash terraces; *3* — erosional plains; *4* — subglacial channels; *5* — kame terraces; *6* — dead-ice moraine on valley sides; *7* — alluvial fans; *8* — flood basins and kettle-holes filled with peat; *9* — landslide terraces; *10* — morainic plateau edge with adjacent aggradation zone; *11* — dunes and dune fields; *12* — number indices of river terraces, according to Galon's classification (1968). Inset map: *c* — valley bottom; *d* — study area; L — Leszno recessional phase of the Vistulian ice sheet; Pz — Poznań phase; Pm — Pomeranian phase; F — Fordon; G — Gdańsk; Gr — Grudziądz; P — Poznań; T — Toruń

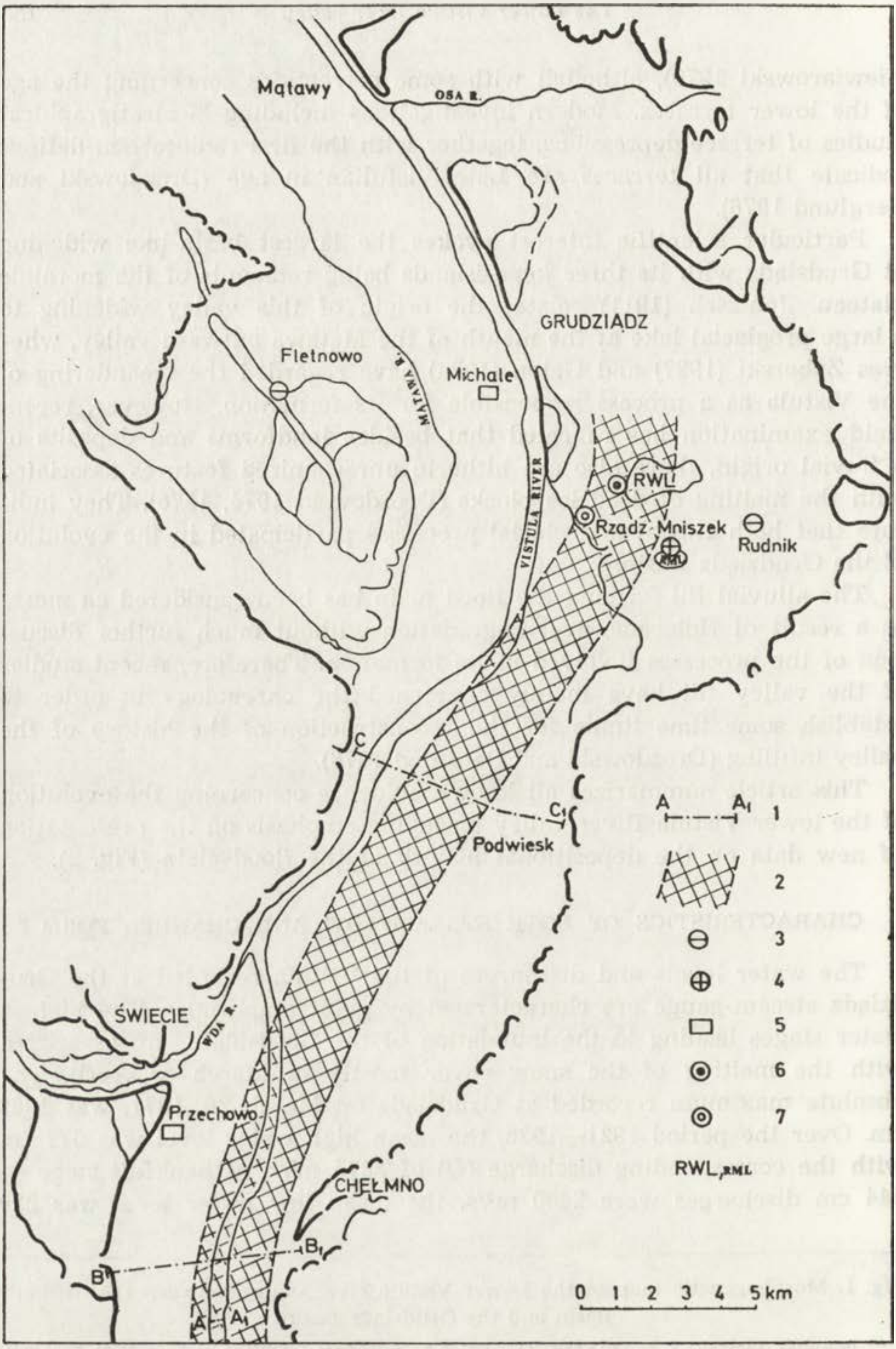

Fig. 2. Location sketch

_1_ — lines of geological and morphological cross-sections; _2_ — buried valley dating from the Eemian Interglacial; _3_ — sites of pollen analytically determined Allerød deposits; _4_ — sites of pollen analytically and ^{14}C determined Allerød deposits; _5_ — sites of radiocarbon dated flood-plain deposits (Holocene); _6_ — floristic site of the Eemian Interglacial investigated paleobotanically; _7_ — site of organic deposits preliminarily determined as being derived from the Eemian Interglacial; RWL — Rudnickie Wielkie Lake; RML — Rudnickie Małe Lake

cm with the corresponding discharge of 414 m^3/s (Siebauer 1947), the lowest water stage recorded by PIHM on December 9, 1959, was 115 cm. These data show that the amplitude between the mean high and low water stages at Grudziądz amounts to 697 cm with the corresponding amplitude of discharges (Q) — 3461 m^3/s, whereas the absolute amplitude between the maximum flood level and the lowest water level amounts to 948 cm. At mean annual water level the river gradient in the sector discussed is 0.18‰.

In the last centuries the river channel experienced considerable changes. As a result of severe forest clearance which began in the Vistula basin about 300 years ago, numerous bars and islands (colonized by plants) appeared in the Vistula channel as evidence of aggradation. These are separated from each other by multi-limbed channels (*cf.* Koc 1972). Comparison of different topographic maps showing the Vistula channel in the Grudziądz Basin (Fig. 3) revealed that on the map dating from the end of the 18th century (Schroetter 1803), downstream from Sartowice Dolne, there existed group of islands and the main channel passed them from the north. The next map dating from 1898 (i.e. a few decades after the beginning of the river regulation) shows only two major islands, namely the so-called Kępa Szynyska and Kępa Bratwińska resulting both from the coalescence of islands and river incision. Finally, on the 1964 map these two islands became attached to the flood-plain due to the abandonment of the dividing minor channel.

The river regulation which began systematically in the middle of the 19th century is leading to the renewed meandering of the river within its low water channel. At present, pools and bars tend to form in the channel developing into typical pool-and-riffle sequences of a meandering stream. Very often in the place where a pool now occurs a bar can be formed in the next year. A typical cross-section of the river channel and its changes shows Figure 4 (for location see Fig. 2). This is based on the measurements performed every year along the same cross-section line by "Hydroprojekt". Striking is the abrupt change in 1973 when the asymmetrical channel shape with a deep pool on the right and a broad shallow on the left underwent complete modification causing probably shifting of the low-water depths for navigation from the right side of the channel to its left side. Thus, it seems to be reasonable to infer that the effect of river regulation is manifested not only by the vertical incision of the river channel but simultaneously by an increased sediment transport in a mode typical of meandering streams.

Parameters of the present-day river channel calculated by Babiński (1981) from bathymetric plans at the mean water levels between Włocławek and Chełmno are as follows: width — 240—1100 m; mean depth — 2 m; maximum depth of pools — up to 8 m; length of pools — 1—2 km; width of pools — 0.1—3.0 km; mean height of bars ± 1 m below the mean water level.

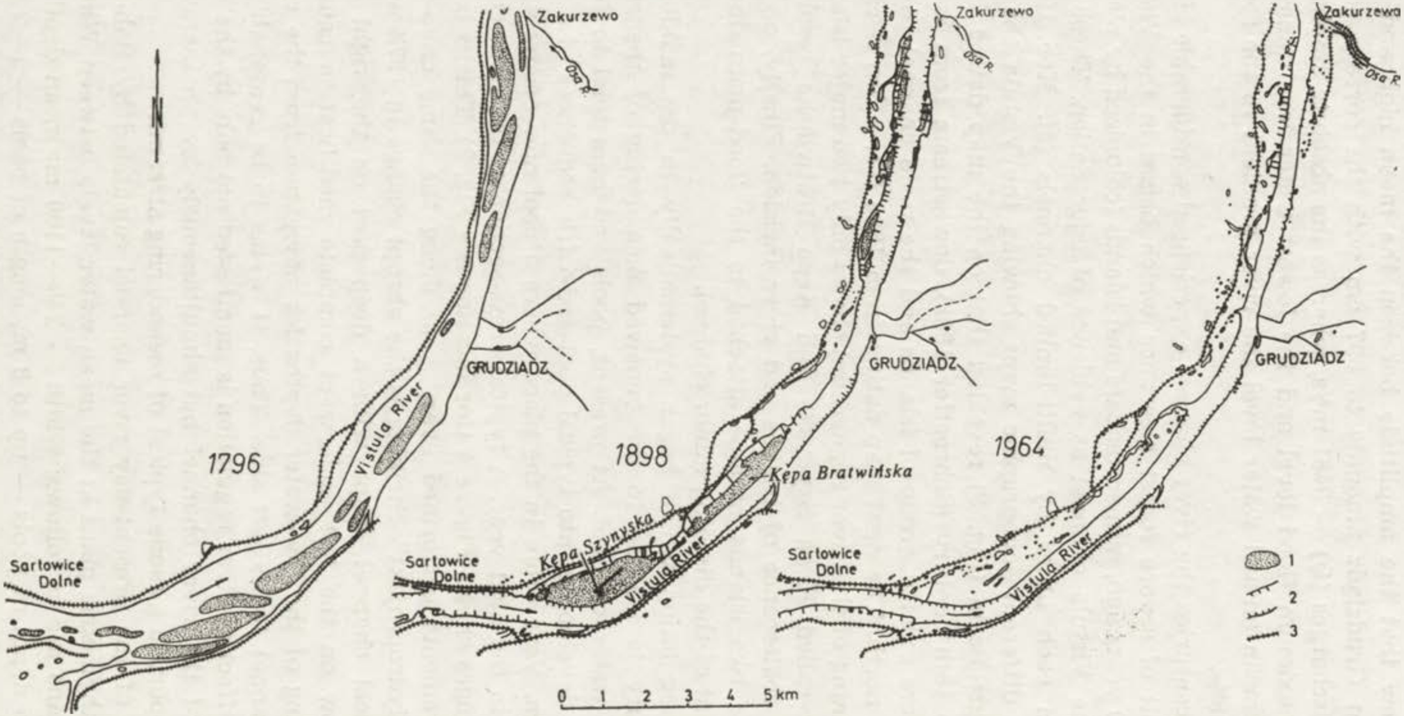

Fig. 3. Changes of the Vistula river channel in the Grudziądz Basin from the end of the 18th century to the present time (compiled by Kopczyński, 1981)

1 — channel bars; 2 — channel banks with groynes; 3 — embankments; 1796 — topographical map, according to Schroetter (1803); 1898, 1964 — topographical maps prepared by German and Polish government map surveys

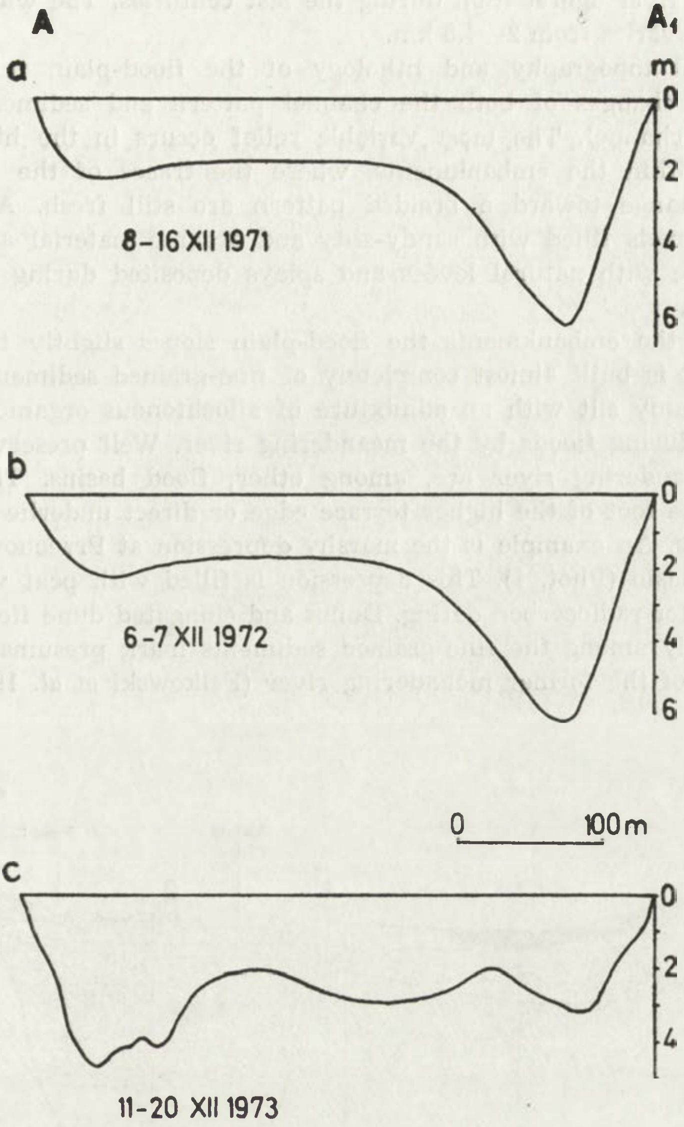

Fig. 4. Morphological section across the low-water channel (for location see Fig. 2)

THE FLOOD-PLAIN

The flood-plain is the main continuous element of the valley bottom formed entirely during the Holocene phases of valley evolution. Its relatively flat surface slopes downstream approximately 0.18 m per km within the discussed valley segment from 24.0 m a.s.l. at Chełmno to 16.5 m a.s.l. at Mątawy. Close to the river channel its surface rises 1—2 m above the adjacent portion of the flood-plain due to the described previously river aggradation during the last centuries. The width of the flood-plain varies from 2—4.5 km.

Surficial topography and lithology of the flood-plain reflects the history of changes of both the channel pattern and sediment moved along the channel. The most variable relief occurs in the high water channel within the embankments, where the traces of the last river channel change toward a braided pattern are still fresh. Abandoned minor channels filled with sandy-silty and organic material are closely spaced here with natural levées and splays deposited during the overbank flows.

Behind the embankments the flood-plain slopes slightly toward its margins. It is built almost completely of fine-grained sediments, i.e. of silt and loamy silt with an admixture of allochtonous organic material deposited during floods by the meandering river. Well preserved traces of the meandering river are, among other, flood basins. These may occur at the foot of the higher terrace edge or direct underlie the steep valley-sides. An example is the marshy depression at Przechowo in the Chełmno Basin (Phot. 1). This depression is filled with peat which has been used for radiocarbon dating. Dunes and elongated dune fields which occur locally among the fine-grained sediments mark presumably natural levées of the former meandering river (Falkowski *et al.* 1979).

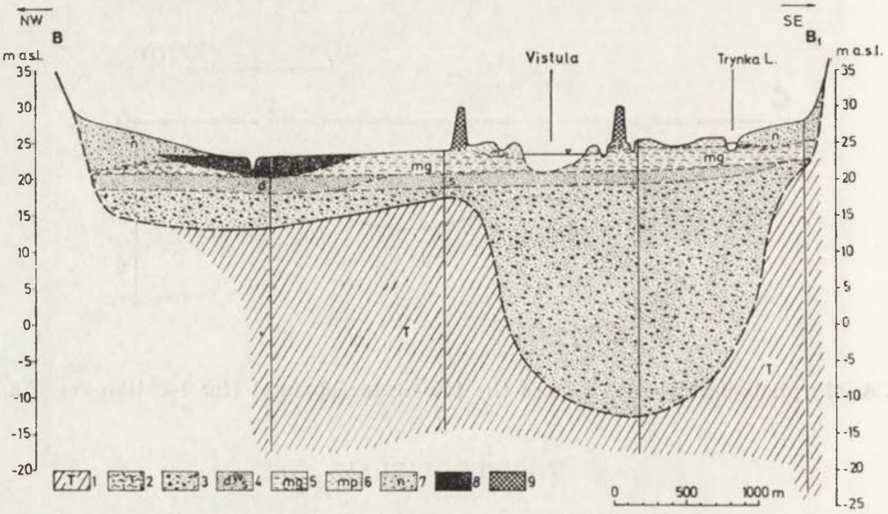

Fig. 5. Geological section B—B$_1$ across the Vistula flood-plain south of Chełmno (for location see Fig. 2)

1 — Tertiary deposits; *2* — till; *3* — coarse sand and gravel; *4* — sand: *d* — fine-grained, *s* — medium-grained, *w* — dune; *5* — loamy silt with admixture of allochtonous organic material (overbank facies of the meandering river); *6* — sand with silt (deposits resulting from channel and overbank deposition by the braided river); *7* — alluvial fan deposits; *8* — peat; *9* — embankments

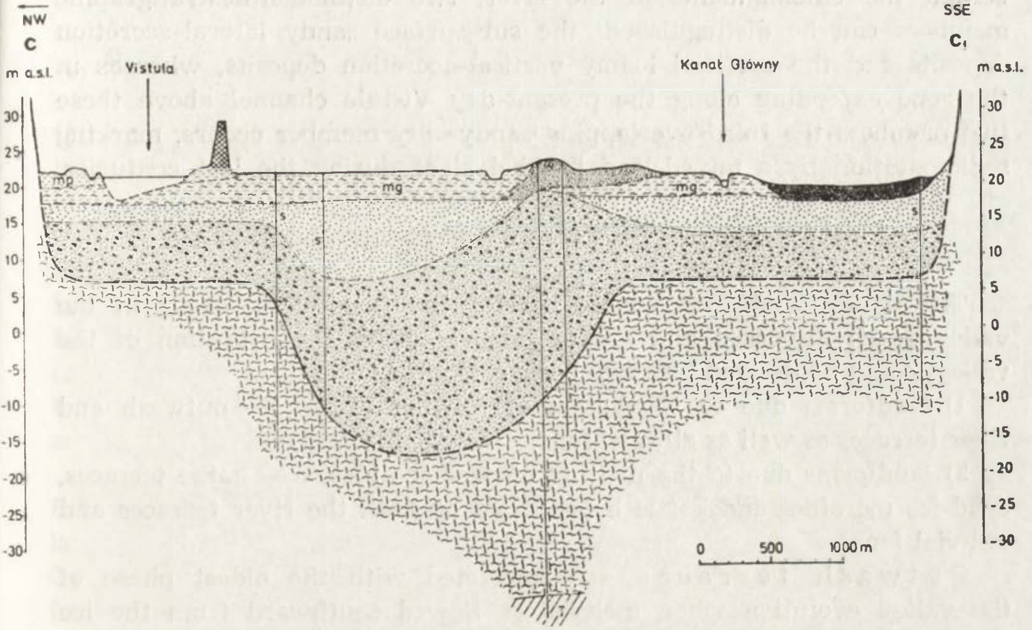

Fig. 6. Geological section C—C_1 across the Vistula flood-plain near Podwiesk (for location see Fig. 2). Key as for Fig. 5

Little is known about the valley morphology buried below the alluvial fill. The cross-sections (Figs. 5 and 6) are based on a limited number of borings, therefore they can provide only a very generalized configuration. It is, however, noteworthy that beneath the alluvial fill of the present-day valley there occurs in both presented cross-sections an additional channel up to 38 m deep. This is filled with coarse sand and gravel which most probably represents a valley fill of the ancient Vistula dating from the Eemian Interglacial. This interpretation is supported by the buried valley fill farther north toward the Grudziądz Basin (Fig. 2), where it contains oxbow lake deposits rich in Eemian plant remains (Drozdowski and Tobolski 1972).

The total thickness of the alluvia filling the present Vistula valley is of the order of 16 m, maximum 19.5 m. It can be divided into two lithostratigraphical units. The lower alluvium is represented in the two cross-sections by coarse sand and gravel, 10—12 m thick. This relatively great thickness, the coarsenes of material and also its continuous occurrence suggest rapid and continuous deposition probably in a type of bed-load or mixed-load channel of a straight or braided river, as classified by Schumm (1977).

The lithostratigraphy of the upper alluvium is differentiated in accordance with the relief zonation described previously. Within the zones, where the features of the meandering stream are preserved, that is behind the embankments of the river, two distinct lithostratigraphic members can be distinguished: the sub-surface sandy lateral-accretion deposits and the surficial loamy vertical-accretion deposits, whereas in the zone extending along the present-day Vistula channel above these two members the third overlapping sandy-silty member occurs, marking sedimentation by a mixed-load braided river during the last centuries.

MORPHOLOGY OF THE VALLEY ABOVE THE FLOOD-PLAIN

The valley landforms which, besides the flood-plain, occur in the valley reach discussed and are of importance in the evolution of the valley, could be divided into two basic categories:

1) landforms due to the action of flowing waters — outwash and river terraces as well as alluvial fans;

2) landforms due to the melting of dead-ice blocks — kame terraces, dead-ice moraines and kettle holes found on both the river terraces and alluvial fans.

Outwash terraces are connected with the oldest phase of the valley evolution when meltwaters flowed southward from the ice sheet at the Pomeranian end moraine belt. In the Vistula valley distinct outwash terraces are not preserved. They occur in the tributary valleys Wda and Mątawa at 70—85 m a.s.l. They are separated by a steep slope, 10—15 m high, from the highest river terrace indicating abrupt river incision during the subsequent phase of valley evolution.

River terraces here occur in a set of nine steps (Table 1). According to Galon's classification (1968), these correspond to the terrace levels IX—I. The terraces are comparatively well preserved in the valley widenings, especially in the Grudziądz Basin (see Fig. 1). The upper terraces (IX—VII) are preserved only in the Grudziądz Basin, whereas the middle ones (VI—IV) are preserved in the basins of Gru-

Table 1. River terraces in the Chełmno Basin and in the Grudziądz Basin

Number of terrace	Relative elevation above the flood-plain in m	
	Chełmno Basin	Grudziądz Basin
IX	—	42—43
VIII	—	35—37
VII	—	32—33
VI	26—27	28—30
V	16—17	16—18
IV	10—12	12—13
III	5—6	8—9
II	4—5	6—7
I	2—3	3—4

dziądz and Chełmno. The remaining terraces can be traced here and there throughout the discussed valley reach. All of the above listed terraces are of erosional or cut type, with alluvial veneers the thickness of which increases generally from the older to the younger levels. On the erosional surfaces of the older terraces IX—IV the alluvial coverings are only 1—2 m thick, while on the terraces III and II this veneer is locally as much as 6—7 m thick (Phot. 2).

Alluvial fans were formed at various terrace levels at the mouth of small valleys incised into the adjacent morainic plateau. The largest alluvial fans occur in the Grudziądz Basin at the mouth of the Mątawa River valley and at the outlets of many small valleys in the eastern part of this valley widening. It is evident from the spatial distribution of the above landforms that in the large valley widenings, such as the Grudziądz Basin, conditions were favourable for their formation.

Kame terraces are found on the western side of the Grudziądz Basin (Phot. 3) and on the eastern slope of Kępa Forteczna, i.e. the largest "island" — a residual of the morainic plateau occurring in the Grudziądz Basin (Fig. 1). The kame surfaces lie at various altitudes, from 75 m down to 27 m a.s.l. The kame terrace deposits are mainly glaciofluvial sand and gravel, locally also sandy till of flow till type. Close to the edge frequently collapse structures occur. These resulted from the melting out of dead-ice blocks which supported from one side the accumulated glaciofluvial material.

Dead-ice moraines are the other conspicuous landforms associated with the melting of dead-ice blocks. The best developed landforms of this type occur along the eastern slope of the Grudziądz Basin (Fig. 1, Phot. 4). They were described in detail in an earlier publication by the present author (Drozdowski 1976) as dead-ice slope topography. These features include hills and depressions distributed chaotically on the valley-side due to the melting-out of small and large dead-ice blocks situated behind the stream channel within the valley.

Kettle-holes on the river terraces are represented, among others, by the depressions of Rudnickie Wielkie Lake and Rudnickie Małe Lake on the terrace II which is elevated 6—7 m above the flood-plain. Their original glacial bottoms lie 10—5 m a.s.l., that is approximately 75—80 m below the surface of the adjacent morainic plateau.

THE AGE OF RIVER TERRACES AND FLOOD-PLAIN DEPOSITS

Previous estimates of the age of terrace and flood-plain formation were approximate and relative because of the lack of more precise dating techniques. The age of the terraces was usually estimated in relation to the roughly dated main paleogeographical events associated with recession of the ice and changes in level of the developing Baltic

Sea (Sonntag 1914; Galon 1934). In his later studies Galon (1961, 1968) relates the age of river terraces from IX to IV inclusive to the Late Vistulian. Of the same opinion has been Roszko (1968), basing on the pollen analysis of organic deposits filling the channel depression of Fletnowskie Lake (Fig. 2) in the western part of the Grudziądz Basin (also see: Kępczyński and Noryśkiewicz 1968). However, new geochronological information published by Tobolski (1972) for terrace III at Rudnik village and by Drozdowski (1974) for terrace II at Rudnickie Małe Lake allows the age of these terraces to be related at least to the Allerød Chronozone. This is supported by radiocarbon dating of the peaty bottom layer from the depression of Rudnickie Małe Lake, occurring on the terrace II (Drozdowski and Berglund 1976). The result was: 11630 ± 265 years B.P. (Lu-984), i.e. an age corresponding to the earlier part of the Allerød Chronozone.

For estimating the first preliminary chronology of the valley filling and its relationship to terraces two samples were taken for radiocarbon dating. The first was derived from the flood basin already mentioned in the Chełmno Basin (Fig. 2). The sample was collected from the basal peat layer (3.40—3.48 m below surface). The date 6960 ± 75 years B.P. (Lu-983) corresponds to the middle part of the Atlantic Chronozone.

The second sample was collected from a bore-hole located near the present-day river channel at Michale village (Fig. 2). The bore-hole fortunately penetrated abandoned channel deposits with alternating minerogenic and organic layers and reached at 19.5 m the buried valley floor (Fig. 7). A sample of mud at 7.00—7.05 m was radiocarbon dated and the result was 4940 ± 65 years B.P. (Lu-1044). This corresponds to the transition between the Atlantic and Subboreal Chronozones (Drozdowski and Berglund 1976).

The above dates imply that the flood-plain near its topographic surface consists of several sedimentation units of different age ranging at least from the Atlantic Chronozone to the present. This diversity is the result of a meandering of the river through several thousand years. A similar river behaviour during the same time has been identified by Falkowski (1967) in his study on the Holocene evolution of the middle Vistula valley between Zawichost and Solec.

The data presented necessitate a modification of the previous chronological concepts concerning the history of the lower Vistula valley, especially of the lower portion of the terrace sequence, from terrace IV downwards. On the basis of the presented data the age of these terraces must be considered older than the Younger Dryas. The terraces III and II were formed probably before the Allerød. Such a chronology provides an arctic-subarctic climate when the valley developed until at least the formation of terrace II. This is in fact supported by the results of geomorphological and lithostratigraphical studies (Drozdowski 1974, 1976)

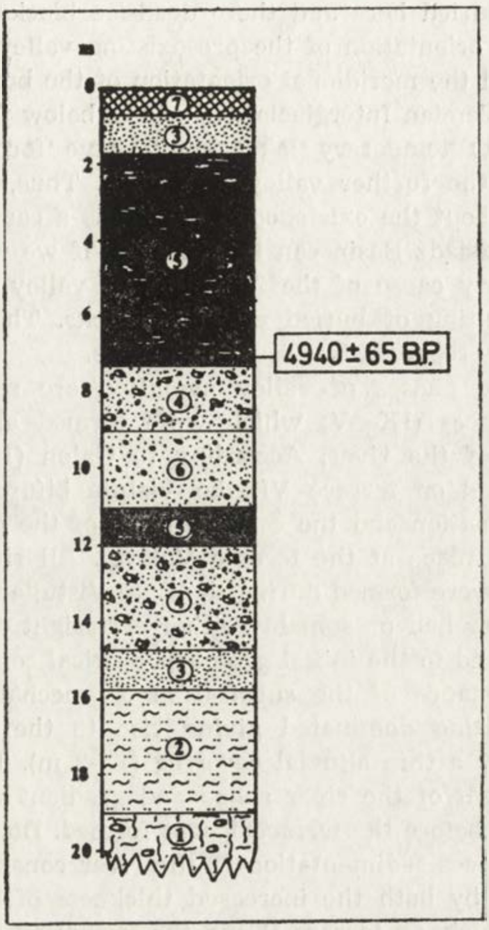

Fig. 7. Sequence of flood-plain deposits at Michale

1 — till dating from the Central-Polish Glaciation (Saale); 2 — silt; 3 — fine sand; 4 — coarse sand and gravel; 3 — oxbow lake deposits (silt and clay mixed with organic substance); 6 — sand with gravel; 7 — humus; 4940 ± 65 B.P. — radiocarbon date

which indicate the existence of dead-ice blocks on terraces III and II. Successive amelioration of the climate and further downcutting of the stream brought about a gradual melting of the buried ice blocks and formation of kettle-holes.

RECONSTRUCTION OF THE VALLEY EVOLUTION

The initial phase of the evolution of the lower Vistula river valley is associated with the erosion and sedimentation by meltwater streams flowing to the south during the Pomeranian phase (approximately 15 000 years ago). These streams flowing on the surface freshly released from the ice and on buried here and there dead-ice blocks were adjusted to both the general orientation of the pre-existing valley depression of the lower Vistula and the meridional orientation of the buried Vistula valley dating from the Eemian Interglacial (70—80 m below the surface). Above the buried blocks temporary lakes could have formed, marking the first outlines of the further valley widenings. Thus, the hypothesis of Jentzsch (1911) about the existence of a lake as a cause of the development of the Grudziądz Basin can be accepted, if we will treat this lake not as the primary cause of the formation of valley widenings, but as the effect of melting of buried dead-ice blocks. This initial phase of valley evolution is recorded by outwash terraces.

The successive phases of valley evolution are represented by the upper river terraces (IX—V) which were formed already during the northward flow of the river. According to Galon (1961, 1968), at the upper terraces and on terrace VI, the Vistula bifurcation occurred at Fordon. Its termination and the establishment of the present-day course of the river took place at the terrace V level. All river terraces, from IX to I inclusive were formed during the Late Vistulian time. In the Late Vistulian, the river had presumably either a straight or a braided channel pattern adjusted to the initial geomorphological conditions and variations in the resistance of the substratum on mechanical and thermal erosion. Downcutting dominated giving rise to the formation of cut terraces with only a thin alluvial covering (1—2 m). The possibility for the free adjustment of the river shape and gradient was limited, especially at the time before the terrace V was formed. During the formation of the lower terraces sedimentation in the river considerably increased. This is indicated by both the increased thickness of the alluvial coverings up to 6 m thick, on terrace II and the formation of numerous large alluvial fans. These processes and their geomorphological effects reflect most probably the accelerated melting of the dead-ice blocks being accompanied by excessive sediment yield into the river which tended to meander at that time. This, however, does not mean that the meandering stream alone may be responsible for the formation of the valley widening at Grudziądz. Its morphology was determined by the buried glacial relief rather, than by free adjustment of the river to discharge and type of sediment load. Thus, the present-day incised curves of the Grudziądz Basin developed on the foundation of concave glacial landforms fillled with dead ice (as a result of large-scale aerial stagnation of the ice sheet in the Middle Vistulian) which melted during the development of the lower Vistula valley.

Striking is the relatively rapid downcutting of the river in the Late Vistulian time. The annual average rate of incision from the initial phase of valley incision by proglacial waters (about 15 000 years B.P. —

Phot. 1. Flood basin at Przechowo. Note the ponds which have formed as a result of peat exploitation. View looking from the river terrace V

Phot. 2. Fine-grained alluvial sands on the river terrace II at Grudziądz-Mniszek

Phot. 3. Kame terrace on the western side of the Grudziądz Basin

Photo. 4. Dead-ice moraines on the eastern side of the Grudziądz Basin

Pomeranian phase) to the beginning of the melting of buried dead-ice blocks on terrace II (minimum date 11 630 years B.P.) was approximately 18 mm. Such a large value resulted not only from high discharges and a rapid lowering of the Baltic Ice Lake level but also from the melting of dead-ice blocks and certainly also from a glacioisostatic rebound of the area after the waning of the ice sheet.

Little is known about the subsequent phases of valley entrenchment and the age of the erosional valley floor now buried beneath the flood-plain deposits. It seems reasonable to relate the lowest erosional surface of the valley to the lowest level of the Baltic Ice Lake and of the *Yoldia* Sea (Younger Dryas and Preboreal Chronozones, 11 000—9 000 years B.P.), which is generally accepted as being approximately 60 metres below the present sea level (Rosa 1968; Gudelis 1969; Kolp 1974).

The depositional history of the flood-plain is more complex and for its detailed reconstruction further studies on the lithostratigraphy and chronology are required. Basing on the data so far available, it can be tentatively divided into three main periods and a fourth one which is lasting at present. The first period began with the rapid deposition in the valley as a process accompanying the rise of sea level from approximately 60 m below sea level to about present-day sea level. This period lasted from the beginning of the Holocene to the middle part of the Atlantic Chronozone. Coarse sand and gravel forming the lower alluvium suggest that at that time the Vistula was a braided stream rich in channel bars. Then followed a period of flood-plain stability coincident with the amelioration of the climate and with minor fluctuations of the Baltic Sea level. Both the upward grade of the upper alluvium from sand to silt and the radiocarbon dates indicate that in this period the river meandered. A meandering pattern the river also maintained during the last 5000 years. This is recorded from elsewhere in the Northern Hemisphere (Kozarski and Rotnicki 1978; Brakenridge 1980) as a period of recurring episodes of erosion and deposition. At that time the Vistula reworked the flood-plain deposits by the lateral shifting of the channel.

During the fourth period including the last some hundred years, when the supply of sediment was greatly increased due to forest clearance in the drainage basin, the channel pattern began to change toward a braided one. This process was stopped by the stream correction. Consequently, the Vistula is entering to the meandering habit again at present times.

In summary, it can be concluded that in the depositional history of the Lower Vistula flood-plain a great role was played by downstream control, especially in the first phase of the valley infilling when a rapid rise of the base level occurred. It is probable that during the successive phases of flood-plain evolution upstream climatic control predominated.

Since the period of severe forest clearance, anthropogenic control, i.e. the man induced changes in both the drainage basin and the stream channel has become the most important factor.

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GEOLOGICAL SECTION ACROSS THE HOLOCENE SEDIMENTS IN THE NORTHERN AND EASTERN PARTS OF THE VISTULA DELTAIC PLAIN

HISTORY AND ORGANIZATION OF INVESTIGATIONS

In the coastal part of the *Żuławy Wiślane*, i.e. the Vistula Deltaic Plain, geomorphological and geological investigations were started over a hundred years ago (*cf.* References). Studies began with the prime purpose of finding amber deposits and of obtaining supplies of water. At the turn of the 19th and 20th centuries a detailed geological survey of the north-western part of the Vistula Deltaic Plain was undertaken and 1 : 25 000 geological maps were published. Many papers that appeared at that time and later on dealt with various problems of both the Quaternary and its immediate substratum, with the age and origin of the Vistula delta and with hydrological and hydrogeological conditions. Research has been intensified after 1945. The sheet "Gdańsk" of the handdrawn 1 : 100 000 geological map was prepared for the 1 : 300 000 Geological Map of Poland to be followed by the 1 : 25 000 soil map of the Vistula Deltaic Plain (Witek 1959).

This paper is based partially on the geological examinations made by the present author in order to prepare several sheets of the Detailed Geological Map of Poland on the scale of 1 : 50 000 including the Vistula Deltaic Plain. The above studies were preceded by the edition of both sheet "Gdańsk" of the 1 : 200 000 Geological Map of Poland (Mojski and Sylwestrzak 1978) and sheet "Elbląg" prepared by Makowska (1979a). The whole archival borehole data and other archival geological materials have been completed and analyzed. Samples for radiocarbon datings of some biogenic sediments have been obtained from both borings being in progress and somewhat earlier ones put down in the coastal part of the Vistula Deltaic Plain. For the eastern fragment of this section the archival and field data were collected especially for the purpose of this paper. The Lake Drużno district was analyzed by using the unpublished materials of Dr. J. Zachowicz, Sea Branch of the Institute of Meteorology and Water Management in Gdynia. The author is indebted to Mrs Zachowicz for making these data available.

DESCRIPTION OF THE PRESENT ENVIRONMENT

LOCATION OF THE AREA IN THE DRAINAGE BASIN

The Vistula valley section discussed comprises the lowermost part of the Vistula Deltaic Plain between Gdańsk and Elbląg, where the Vistula flows into the Gdańsk Bay and the Vistula Lagoon. The geological section across this area is 75 km long and several kilometres wide, extending 1—5 km to the south of the coastline. In its eastern and western parts the section reveals the structure of the bordering morainic plateaus which have been analyzed in detail in the Kaszuby Plateau (southwest of Gdańsk). The section shows not only the Holocene sediments but also, locally, the underlying Pleistocene deposits. Thus, it was possible to recognize the influence of the geological structure of the substratum on both the lithofacial development of the Holocene deposits and their spatial arrangement in the Vistula Deltaic Plain.

THE FLOOD-PLAIN

In the study area the whole Vistula Deltaic Plain is the flood-plain in a genetic sense and considering the present-day hydrological processes. It is only the existing hydrotechnical system which prevents partially inundation of the flood-plain now. In some places the section cuts across the post-lacustrine plain around Lake Drużno.

The deltaic plain is at 1.7 m below sea level to about 2 m above sea level. Its origin is mainly due to the formation of channel bars, accumulation from flood stages of the river, formation of biogenic coverings and subsidence of the surface as a consequence of both compression of the organic deposits and pumping of the underground waters. This subsidence resulted in the formation of a depression. In some places, the topography of the flood-plain near Gdańsk is greatly modified by anthropogenic veneers, up to 8 m thick, and by dikes up to 5 m high, which were built parallel with the river channels.

SECTIONS ACROSS THE PRESENT STREAM CHANNEL AND ITS PARAMETERS

The present-day Vistula channel in the sectional zone has been active since 31st March, 1895, when the dug channel Przekop Wisły was completed by Świbno. This shortened the river length by 9 km (Fig. 1). The cut was 7 km long and its present depth varies from between 3 and 6 m depending on the changes in the longitudinal profile of its bottom (Fig. 2). From the dug channel over 7 million m^3 of earth were removed (Winkel 1939). The cut is 450 m wide. The shape of its bottom is shown in Figure 3. Since 1895, a fan has been growing far out into the

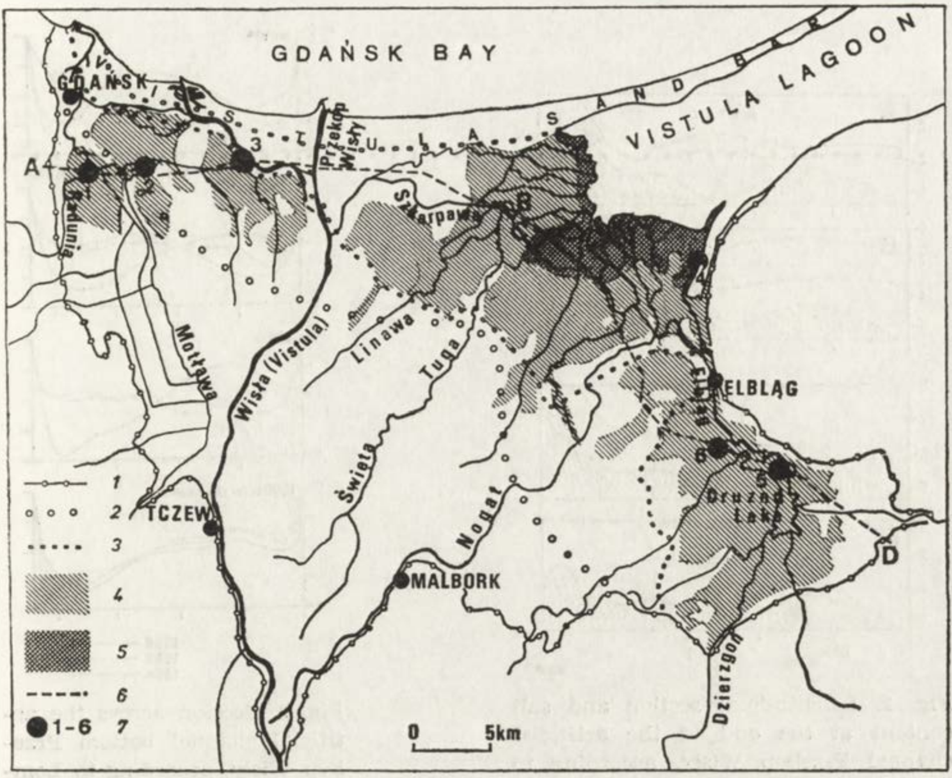

Fig. 1. Map showing the Vistula Deltaic Plain (= *Żuławy Wiślane)*

1 — boundary of the Vistula Deltaic Plain; *2* — shoreline about 4000—5000 a B.P., according to Majewski (1969); *3* — body of water in the Vistula Deltaic Plain about 890 A.D., according to Wulfstan, interpreted by Uhle (1942); *4* — body of water in the Vistula Deltaic Plain in the 13th century, according to Bertram and others (1924), simplified; *5* — body of water in the Vistula Deltaic Plain until 1900 A.D., according to Majewski (1969); *6* — geological cross-section A—B, C—D shown in Fig. 5; *7* — significant boreholes: *1* — "Orunia", *2* — "Bystra", *3* — "Wiślinka", *4* — borehole IV, according to Gross (1942), *5* — Lake Drużno, according to Zachowicz, unpublished, *6* — "Tropy", Eemian interglacial, according to Makowska (1979b)

Gdańsk Bay. This fan is formed of about 40% of the load carried by the river into the sea. The remaining 60% are transported farther northwards coming to rest on the bottom of the Gdańsk Bay to form a new 0.2 mm layer every year. The average composition of materials being transported farther northwards is as follows: below 2 microns — 11.4%, 2—50 microns — 48.1%, 50 μ—2 mm — 39.26%, and over 2 mm — 1.24% (measurements made over the period 1895—1953; Łomniewski 1960). On the bottom of the Gdańsk Bay 555 000 m^3 of sediment is annually deposited forming the underwater fan. This indicates the rate of sediment supply by the Vistula into the Gdańsk Bay. Both the shape and size of this growing fan being several dozen years old is shown in Figure 4.

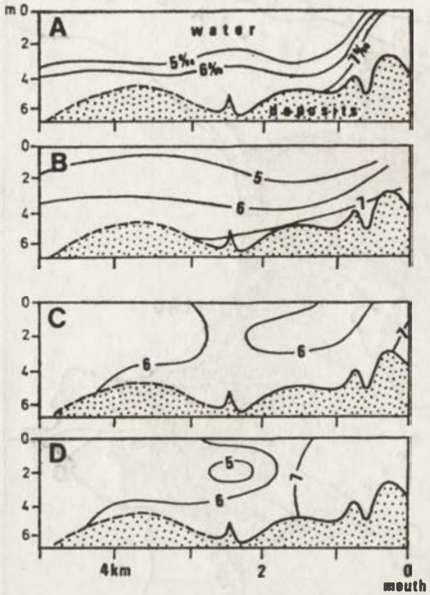

Fig. 2. Longitudinal section and salt content at the end of the artificial channel Przekop Wisły, according to Kaptur (in Cyberski and Mikulski 1976)

A — 7 X 1962, wind from SE, 5 m/s; *B* — 18 XII 1962, wind from S, 1 m/s; *C* — 23 IX 1962, wind from WNW, 4 m/s; *D* — 20 X 1962, wind from N, 9 m/s. Salt content in promille

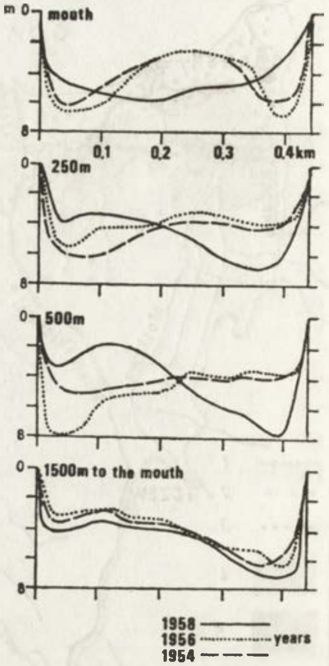

Fig. 3. Section across the artificial channel bottom Przekop Wisły, according to Łomniewski (1960)

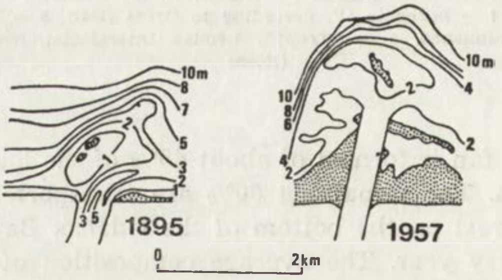

Fig. 4. Development of the fan at the end of the dug channel Przekop Wisły in 1895 and in 1957, according to Łomniewski (1960)

Beyond the dug channel Przekop Wisły the section cuts accross the Motława river and the former distributaries: the Martwa Wisła, the Szkarpawa and the Nogat, and many other delta distributaries and artificial channels.

CHARACTERISTICS OF THE HYDROLOGICAL RÉGIME

Today the Przekop Wisły collects the whole quantity of stream water. This varies from between 1018 m³/s (mean for 1921—1960) and 954 m³/s (mean for 1951—1960). The mean monthly values are presented in Table 1. The mean low flows are about 380 m³/s, whereas the mean high flows reach 4200 m³/s being eleven times as large as the former. The lowest discharges of about 250 m³/s occur usually in autumn, and the highest discharges are up to 10 000 m³/s occurring mainly during snowmelt periods. Thus the latter are about 40 times as large as the lowest value. The water current velocity is generally about 0.5 m/s, whereas the maximum velocity during floods is 3.8 m/s.

Table 1. Mean monthly discharges at the Vistula mouth in m³/s (according to Cyberski and Mikulski 1976)

Months	1921–1960	1951–1960
XI	920	777
XII	888	844
I	922	814
II	1041	1040
III	1600	1430
IV	1864	1830
V	1150	1140
VI	820	771
VII	790	801
VIII	775	812
IX	720	581
X	736	631
year	1018	954

Fluctuations in discharges are associated with fluctuations in the water level up to 10 m. This is because dikes contain the overbank flow. The above fluctuations reflect the quantity of water transported into the sea. The water level fluctuations in both the Przekop Wisły and the other distributaries in the sectional area also are controlled by wind velocity and directions. Winds from the northern sectors can cause a 1.5 m rise of the water level in the cut. A ca 2.4 m lowering of the water level can be brought about by winds blowing from the south-western sectors. At tidal high water the rise is 1—2 cm. Hence it does not influence the water level in the Przekop Wisły.

The Vistula water contains 48 mg/l of Cl (Stangenberg 1958). The great quantity of fresh water transported by the Vistula does not favour the penetration of salt water into the river. The reverse is true of the other distributaries, e.g. the Martwa Wisła water contains 4—5 g/l Cl in winter, whereas in spring the Cl content is below 1 g/l. Salinity changes in the Przekop Wisły are illustrated in Figure 2. The origin of salinity of both the stream waters and surficial beds in the north-eastern part of the Vistula Deltaic Plain has not as yet been satisfactorily explained. It may be the effect either of storm water intrusions from the Vistula Lagoon or of saline underground water migrations taking place at low surface water levels. Both opinions are still discussed (Schroedter 1933; Ostendorff 1944; Pazdro 1958; Pietrucień 1969 and others).

Lake Drużno is a curious body of water in the Vistula Deltaic Plain. According to Mikulski (1955), it can be defined as an overflow pond-and-lake. However, its area depends much on the water level. At low level (10 cm below sea level) the surface is about 12.6 km^2, at mean level (at sea level) it is 14.5 km^2, whereas at high level (10 cm above sea level) it is 17.9 km^2 being as much as 29. 8 km^2 at a very high level. The mean depth of the lake is 1.2 m reaching a maximum of 3 m. Fluctuations of the water level are about 1 m. The high levels are controlled by storms in the Vistula Lagoon. As a result, the Cl content increases to 500 mg/l. The supply of stream water into Lake Drużno can also cause a rise in the water level. Upon the open water there encroaches a congeneric vegetation (Cyberski and Mikulski 1976).

HYDROLOGICAL AND GEOMORPHOLOGICAL CHANGES OVER THE PAST CENTURY

In the coastal part of the Vistula Deltaic Plain hydrological changes have been recorded since a long time. From the Middle Ages onwards the extreme phenomena, inundations and man's activities have been noted there. They also resulted in changes of both the land surface and the underwater surface. The following information on the hydrological changes that took place over the past century was derived from a paper by Majewski (1969).

In 1888 there occurred the greatest in the 19th century inundation of the Vistula Deltaic Plain. In face of this disastrous flood, under close control which began in 1889, an artificial channel was cut by Świbno. This floodway was designed to increase the river gradient by shortening the channel length and to pass excessive discharges from the river channel to the sea. The dug channel was finished in 1895. Since that time the Vistula has used a new channel named the Przekop Wisły. The distributaries Martwa Wisła and Wisła Elbląska were cut off and in 1914 the Vistula-Lagoon Canal was closed. Next year the correction of the Nogat channel was completed. In 1917 the Nogat started to be navigable. In 1945 the Vistula Deltaic Plain was flooded during the military operations, but already in 1947 the Nogat and the Vistula Canal were navigable. Over the period 1895—1965 the end of the Przekop Wisły was extended by the construction of the eastern and western jetties, 2.2 km and 2.3 km in length. Thus the hydrological conditions in the cut have been generally changed. Finally, the years 1924, 1928, 1947, 1951/52, 1955, 1956, and 1980 were marked by the occurrence of extreme phenomena including large-sized rise of the river stages, ice blocking of the Vistula mouth, great storm blocking the waters etc.

The digging of the Przekop Wisły was followed by the rapid formation of an underwater fan projecting into the sea. During the first 16 hours 2 millions m^3 of sediments were laid down there (Łomniewski 1960).

The other morphogenetic processes include man's activities, i.e. the construction of dikes, embankments, ditches as well as relief changes due to both exploitation of amber deposits and other earthmoving projects. On the spit the aeolian landforms are being destroyed in the recreational zones. The natural morphogenic processes include the intense overgrowing of the shores of Lake Drużno and aggradation adjacent to the river channel between the dikes on both sides of the Vistula. The latter process occurs during high water levels.

CHARACTERISTICS OF LANDFORMS AND SEDIMENTS

MORPHOLOGY

In the study area the surface of the Vistula Deltaic Plain is almost completely flat, the height differences being less than 5 m. The flat delta surface extends from between −0.8 m and ca +2 m a.s.l. The depressions occur by Bystra and close to the Radunia river in the west and around Lake Drużno. Between Stegienka and Rybina there occurs slightly higher ground at ca 2 m a.s.l. On the western border at the foot of the Kaszuby Plateau Early Holocene alluvial fans are found. The alluvial fan plains rise up to about 4 m a.s.l. there. The formation of the depressions resulted from compaction of peat under the weight of the overlying mineral deposits and from draining a ground water way as an effect of pumping.

Road embankments and dikes are a striking anthropogenic element of the topography. The latter are up to 5 m high and run along all of the distributaries.

The Kaszuby Plateau bordering the Vistula Deltaic Plain, in the west rises up to 60 m a.s.l. The Pasłęk Plateau which surrounds the Vistula delta from the east reaches similar altitudes. The middle part of the geological section A—B is situated at a distance of several kilometres from the coastal dunes which are well displayed on the sandy Vistula baymouth bar. The dunes reach heights of 36 m a.s.l. there.

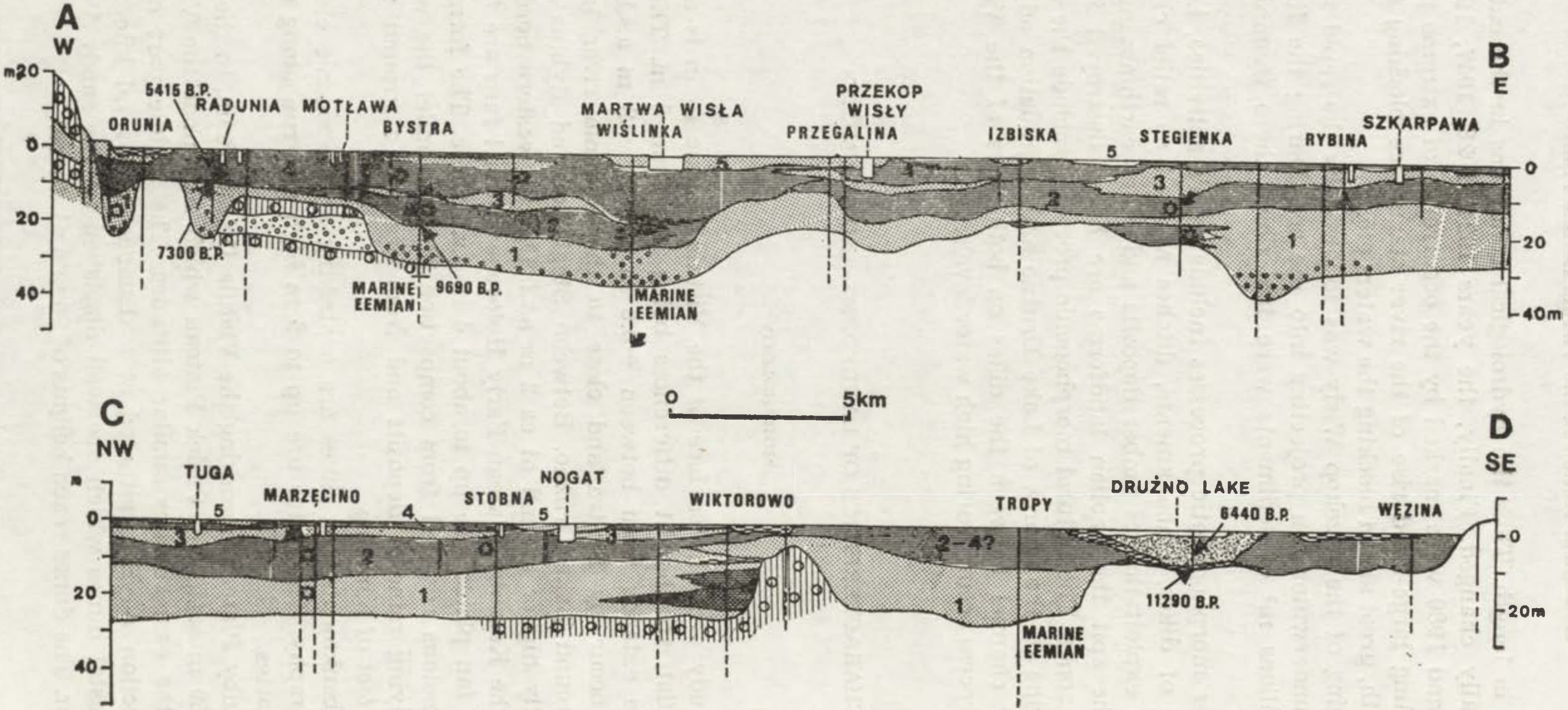

Fig. 5: Geological cross-section A—D

1 — 5 numbers refer to horizons described in the text. For other explanations see Figure 6

THE CHRONOLOGY OF ALLUVIAL SHEETS AND THEIR SEQUENCE

The structure of Holocene sediments shown on the geological section A—D (Fig. 5) has been compiled from analyses of borehole data obtained for the whole section, and of covered geological maps. The geological section also includes two borehole profiles of which radiocarbon datings have been made. These are presented in Figure 7. For the interpretation of both sediments and events, the boring at Wiślinka and the sequence of bottom fillings of Drużno Lake are significant. The latter data are contained in both the unpublished and partially published results of work of Zachowicz.

The Holocene sequence comprises five lithostratigraphic units named horizons. Each of the units consists of sediments varying by origin, facies and developmental conditions. This applies especially to the horizons *1*—*4*. Their dynamic interpretation is limited to the reconstruction of the general trends in types and evolution of erosive-accumulative processes, although the local processes have varied greatly there. The geological section presents the first preliminary approach to the sedimentary sequence. It illustrates generally the evolution of both processes and controlling factors. Therefore, the sediments described in the successive horizons can slightly vary by their ages in some places.

The substratum of alluvial covers

In the study area Holocene sediments rest on the Pleistocene substratum consisting of deposits of varying age and origin. Along the geological section A—D this substratum is composed of boulder clay dating from the Central Polish and North Polish Glaciations. of marine sediments belonging to the Eemian Interglacial and of fluvioglacial sand and gravel. In the western part of the geological section, in the profile "Bystra" the till is of North Polish Glaciation (= Vistulian) in age because the underlying sands contain a marine fauna dating from the Eemian Interglacial (analyses are continued by Dr A. Makowska of the Geological Institute, Warsaw). The geological section revealed that in the west the till is covered by sands with gravel and by another layer of till. It appears that in the westernmost part of the section the substratum is composed of two layers of till dating from the North Polish Glaciation. Two tills, and locally even three glacial horizons of the Vistulian also occur on the neighbouring morainic plateau (Mojski 1979a, 1979b, 1980b).

Marine sands assigned to the Eemian Interglacial were found to underlie immediately the Holocene series in two boreholes, namely at Wiślinka (Janiszewska-Pactwa and Leszman 1976) and at Tropy (Makowska 1979b). The lack of Vistulian sediments in these places indicates that intense erosion has affected some parts of the coastal lowland towards the end of this glaciation and at the beginning of the Holocene.

Characteristics of the alluvial sheets

The well-known facts suggest that the alluvial coverings in the Vistula delta began to form already during the Late Glacial. Insufficient geological work has been done in the Vistula Deltaic Plain to permit a use of indisputable criteria for defining the boundary between the Pleistocene and Holocene alluvial sediments. For this reason, different criteria were applied that support one another. The non-calcareous sand were considered to be Holocene in age particularly if they contained biogenic sediments, pieces of wood etc. In general deposits can be related to the Holocene by means of their flora and fauna content as well as frequent occurrence of lacustrine, muddy, non-calcareous or slightly calcareous sediments. There are only a few localities of determined freshwater fauna. The presence of fauna, if undetermined, is insufficient by itself to provide a basis for defining the age, since the fauna can be Eemian in age and occur *in situ*.

Too little radiocarbon datings are available. As a matter of fact the only date of samples obtained from a borehole at Bystra in the western part of the geological section makes it possible to define precisely the boundary between the Pleistocene and Holocene sequences. The age is 9690 ± 150 a B.P. (Gd-539). It corresponds to the upper Preboreal period. Similarly, in the eastern part of the geological section both a pollen diagram of the bottom sediments in Lake Drużno (unpublished work of Zachowicz) and an examination of the diatom content there (Przybyłowska-Lange 1976, 1978) enabled to determine precisely the lower boundary of the Holocene deposits.

The above data, together with analyses of both the positions of the sediments in the geological section A—D and its vicinity, and their depositional enviroment against the background of palaeogeographical conditions prevailing during the Late Glacial and the Holocene suggest that in the Vistula Deltaic Plain the Pleistocene/Holocene boundary is coincident with the sediments that belong to horizon 1 with the alluvial cover sequence. These are sands with a varying admixture of gravel in the lower part. Both their median and calcium carbonate content decreases topwards. In places, the gravels are not apparent there being replaced by silt or clay. In some localities, e.g. at Stegienka, pieces of wood and fauna are found then. Unfortunately, the fauna has not as yet been identified. In the borehole "Bystra" seven specimens of *Bithynia tentaculata* L. (analysis by A. Makowska) were recorded at a depth of 21.6—23.6 m. At Izbiska the sands of horizon *1* are underlain by peat that may represent the Late Glacial.

The thickness of sediments belonging to the first horizon is great when compared to other Holocene deposits. It varies from several metres to 22 m. The basal surface lies at 37—7 m below sea level, whereas the top surface is at 26—3 m below sea level. But usually it was bottomed at a depth of several metres. The above marked height differences of the basal surface and the underlying Pleistocene sediments of different origins and ages indicate its erosional genesis.

The lithological features of the above described horizon prove that the deposits were laid down under changing sedimentary conditions. Their lower part was deposited by waters of great transport capacity, whereas their upper part came into being in a more quiet environment. The erosional surface into which the sediments are inserted also indicates the great intensity of flow. It may be suggested that at first these were meltwaters flowing from the waning ice sheet and from single detached masses of ice near the end of the areal deglaciation. Such type of deglaciation was favoured by local topographic conditions, i.e. the lower position of the ice in the study area than in the neighbourhood. In the Vistula Deltaic Plain dead ice bloks might have been melting until the end of the Boreal period, i.e. longer than in the surroundings. The fluvioglacial origin of the lower part of horizon *1* is also proved by its calcium carbonate content.

The above data suggest that the lower part of horizon *1* may still belong to the Pleistocene. There also may be thus evidence of the formation of outwash deposits due to the waning of dead ice blocks at the beginning of the Holocene.

The upper part of horizon *1* is Early Holocene in age. It consists of fine sand in which the content of calcium carbonate is small or not apparent. Such sediments were deposited during the increasing stabilization of the hydrological régime and the decreasing part played by the channel facies. This is suggested by the top surface being more smoothed than the basal surface.

The above scanty data lead to the conclusion that the Pleistocene/Holocene boundary is coincident with horizon *1*, or rather with its upper part. The only locality where this boundary is precisely defined is the sequence of bottom sediments in Lake Drużno (portion of the section C—D, Fig. 1). Pollen analyses made by Zachowicz (according to Przybyłowska-Lange 1976) revealed that the boundary between the Younger Dryas and the Preboreal period occurs at the depth of 8.56 m, i.e. between the underlying sandy peat and the overlying slightly decomposed peat.

Horizon *2* is the accumulational continuation of horizon *1*. It consists of silt, sandy silt, clayey silt, mud, lacustrine clay interbedded with peat, especially in the lower part, and of lake marl with vivianite. Flora and fauna fossils are abundant there. The former include plant detritus, mosses, pieces of wood etc. The fauna remains include a freshwater fauna which has been identified in some places. At the section "Bystra" (Fig. 6) A. Makowska revealed the presence of *Valvata piscinalis* (Müll.)

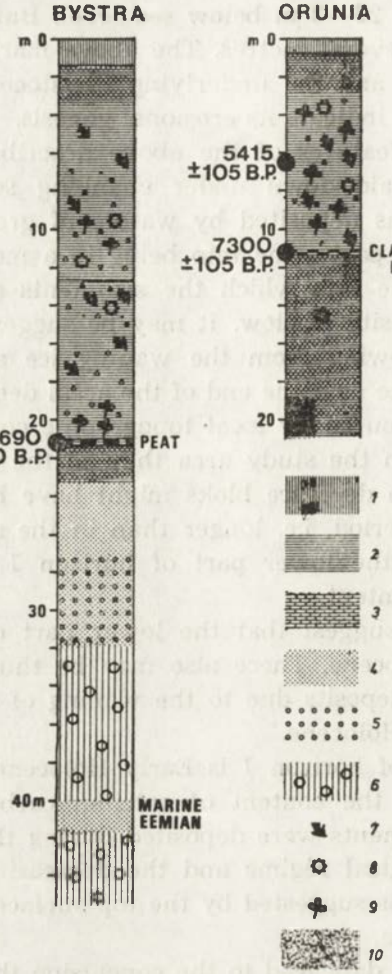

Fig. 6. Borehole profiles at Bystrzyca and Orunia

1 — alluvial soil; *2* — muds; *3* — clays interbedded with sand and peat; *4* — sands; *5* — gravels; *6* — boulder clay; *7* — macroscopic plant remains; *8* — molluscan shells; *9* — plant detritus; *10* — gyttja

at a depth of 15—18 m and *Pisidium moitessierianum* Palad. at depth of 18—21 m. These are oxbow lake sediments (mainly of mud type) on an aggrading river with a broad valley floor. At Bystra the peat recorded immediately beneath a layer of mud at a depth of 21.4 m has been dated at 9690 ± 150 a B.P. (Gd-539) at $T^{1}/_{2} = 5568$ years (the same value is valid for the other dates).

In the Marzęcin—Stobna area the age of horizon *2* can be determined indirectly. This portion of the geological section C—D is situated only several kilometres from the locality at which Gross (1942) has identified the Vth period of the Holocene evolution of vegetation on the base of pollen analysis of carbonate and clayey gyttja from a depth of 16—18 m in borehole IV (Fig. 1). The above period is believed to coincide with the *Ancylus* phase dated at 9000—8400 a B.P. (Fig. 8). The geological sequence in the borehole IV is similar to the sequence of deposits along the geological section C—D: muds, alluvia and gyttja predominate to a depth of 18 m. These are overlain by sand with gravel. The *Ancylus* phase coincides thus with the lowermost part of the above sediments, i.e. with the gyttja.

In the eastern part of the geological section, particularly to the east of Wiktorowo, horizon *2* is considerably reduced. In the bottom sediments of Lake Drużno it is represented by thin peats varying by decomposition.

Horizon *2* is usully 8—12 m thick. The top surface of its sediments occurs at a depth of several metres. The horizon seems to lie much deeper in the western part of the study area (*cf.* geological section), particularly between Wiślinka and Bystra, but it rises eastwards. Such a situation may suggest that at that time the river channel (or channels) were situated in the western part of the Vistula Deltaic Plain. The continued valley aggradation caused the channel to shift eastwards. Such processes occurred prior to the *Littorina* marine transgression, if the date 7300 ± 105 a B.P. is given to the beginning of accumulation of the younger mud cover (*cf.* geological section A—B at Orunia).

Horizon *3* is composed mainly of fine- and medium-grained sand. Fine gravel tends to occur locally but silt is more common. This horizon is discontinuous, and it occurs at two different heights. In the western part of the geological section between Wiślinka and Bystra the above sediments occur beneath 10 m below sea level. Between Przegalina and Wiktorowo they are at a depth of several metres. It is possible that there are two beds of slightly different ages. The type of materials indicates predominance of channel accumulation over accumulation from flood stages. The sediments are usually several metres thick.

Horizon *4* is composed of alluvia, mud and silt varying quantities of organic remains intervening with fine sand and peats. Peat bands occur in various places and at different depths. Plant macrofossils, pieces of wood and shells of freshwater fauna are common. At Orunia (Fig. 6) radiocarbon determinations on the humus band at the depth of 6.2—6.4 m and on the clayey peat at the depth of 11.2—11.4 m indicate an age of 5415 ± 105 a B. P. (Gd-540) and 7300 ± 105 a B. P. (Gd-549). At present it would appear that both dates define the age of the lower part of horizon *4* at least in the western part of the study area and as far as Przegalina in the east. Further eastwards, the sediments belonging to horizon *4* can be related only to its upper part in the western portion of the geological section. Thus they may be there younger than 5400 years. In the Marzęcin—Stobna area (*cf.* geological section C—D) the accumulation of sediments began from historical times onwards leading to the rapid growth of the fan of the Nogat, the Święta (Tuga) and the Linawa — the former distributaries that emptied out into the Vistula Lagoon (Fig. 1). In the western portion of the geological section, the top sediments are quite young. Evidence are the remains of three boats which have been found in the ancient channel of the Radunia river at the depth of 1.6—2.0 m. These boats have been dated at ca 1100 years (Lienau 1934; Ostendorff 1942).

Sediments belonging to horizon *4* are best developed in the western part of the study area where they are usually several metres thick and fill a buried river valley. Towards the east their thickness decreases to ca 10 m being several metres to the east of Izbiska. Their top surface is usually at shallow depths and in many places it forms the present-day surface.

The most recent horizon 5 is composed of vari-grained sand and silt being locally sandy. These deposits belong mostly to the channel facies. Their majority was laid down along the Vistula channel and the delta distributaries in historical times. The deposits are several metres thick. Shallow peats occurring by Orunia, Wiktorowo and Węzina as well as the top calcareous gyttja from Lake Drużno also represent historical times (according to Zachowicz). Because of artificial dikes, the sediments belonging to the horizon 5 were deposited in the inter-dike areas at flood stages. Today deposition takes place only in the inter-dike area on either side of the Vistula channel.

On the geological section A—D the soils are not shown because of scale. These very fertile and young soils are named the Żuławy. They are of alluvial type including peaty-brown mud and humus mud, i.e. the black muddy earths and the hydrogenic soils of peaty and marshy types (according to Witek 1976). The evolution of the soil cover was controlled greatly by hydrological factors and by vegetation and ground waters. Since the 13th century, man has become an important factor. The result are peat- and gley-processes.

Chronology of sediments

The chronology of the Holocene cover forming the Vistula Deltaic Plain is based on radiocarbon datings, on pollen analyses made of the bottom sediments in both Lake Drużno and the southern part of the Vistula Lagoon, and on examinations of fauna remains. The most significant results are presented in Figure 7 and related to the stratigraphic subdivision of the Holocene by Starkel (1977), the chronology of developmental phases of the Baltic Sea by Pieczka (1980) and to the evolution of the marine transgression in the Gdańsk Bay (Rosa 1963). It appears that the successive lithostratigraphic horizons of the Holocene sediments forming the Vistula Deltaic Plain can be related to both the stratigraphy of the Holocene and the evolution of the Baltic Sea. Firstly,

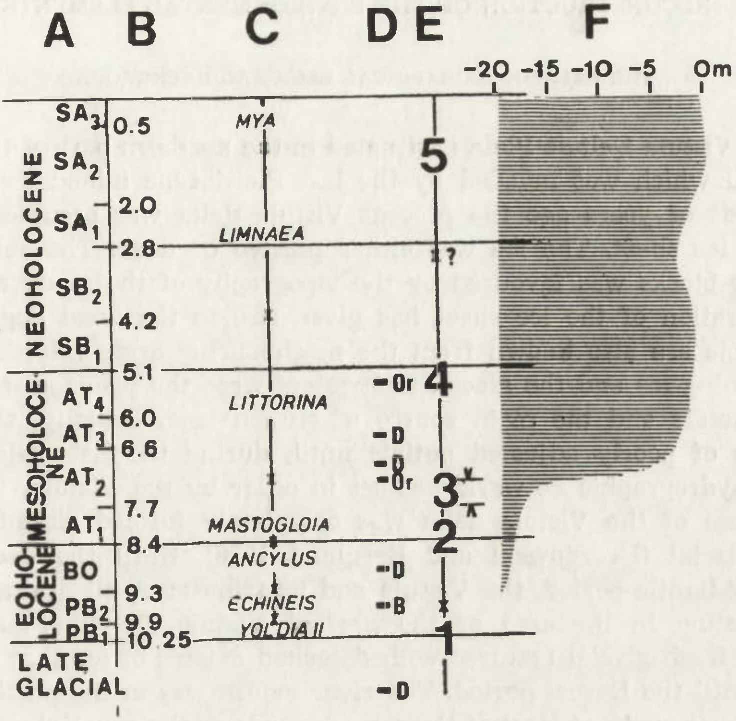

Fig. 7. Correlation of processes of accumulation in the northern part of the Vistula Deltaic Plain with the evolution of the Baltic Sea

A — stratigraphic subdivision of the Holocene, according to Starkel (1977); *B* — limiting dates for the Holocene stratigraphic units; *C* — phases of evolution of the Baltic Sea, according to Pieczka (1980); *D* — chosen radiocarbon dates in the northern and eastern parts of the Vistula Deltaic Plain; *E* — ages of successive lithostratigraphic horizons of Holocene sediments in the northern part of the Vistula Deltaic Plain; *F* — evolution of the marine transgression on the southern shores of both the Gdańsk Bay and the Vistula Lagoon, according to Rosa (1963)

the horizons *1*—*3* are considered to be pre-*Littorina* in age, i.e. older than 7000—7200 years. The accumulation of sediments belonging to horizon *1* ended during the Lower Preboreal period (*Yoldia* II). The fine sediments belonging to horizon *2* have been deposited until the end of the Lower Atlantic period (AT_1), i.e. ca 7700 years ago. In the western part of the study area horizon *3* was formed over the short period of a few hundred years, at the beginning of AT_2 — the second phase of the Atlantic period. Horizons may be slightly younger in the eastern part of the area. Horizon *4* has been formed since the younger part of AT_2 until the end (?) of the Subboreal period. It coincides then with the whole Atlantic period and with the beginning of the *Limnaea* phase. Since datings are lacking, the upper limiting date for horizon *4* cannot be determined precisely. Finally, the formation of sediments belonging to horizon *5* coincides with the Subatlantic period, i.e. with the Upper *Limnaea* and *Mya* phases of the Baltic Sea.

RECONSTRUCTION OF THE ENVIRONMENTAL ELEMENTS

THE PALAEOGEOGRAPHICAL REGIONAL BACKGROUND

The Vistula Deltaic Plain is situated in the northern part of the Polish Lowland which was invaded by the last Pleistocene inland ice. Several thousands of years ago the present Vistula delta was occupied by the waning ice sheet. The ice was either passive or dead. The survival of dead-ice blocks was favoured by the topography of the study area. The disintegration of the ice sheet has given rise to the areal deglaciation. Its effects are also known from the neighbouring areas (Mojski 1980b). The waning ice and the glacial meltwaters were the principal relief-forming factors and the main source of stream load. Initially, there was a series of poorly adjusted outlets until, during the Late Glacial, the whole hydrographic network was set in order by the Vistula. Its valley up-stream of the Vistula delta was completely formed already in the Late Glacial (Drozdowski and Berglund 1976). Until the end of the Lower Atlantic period, the Vistula and its tributaries all drained a valley existing in the area of the present Vistula Deltaic Plain which showed fresh glacial features with detached masses of ice that survived there until the Boreal period. The river mouth was in the north, maybe in the north-west, at least at the same latitude as the spit Hel.

The deposition of horizon 2 was primarily controlled by decreasing height differences brought about by the melting of dead-ice blocks and by a decrease in stream gradients — the Vistula channel inclusive. As the transgression continued (this, however, did not reach the Gdańsk Deep (= *Głębia Gdańska*), the gradient of the Vistula channel became markedly lower and this permitted the increased accumulation of flood deposits on the valley floor. These processes primarily affected the western part of the present Vistula Deltaic Plain as far as Wiślinka in the east. It is likely that sediments being regarded as the submarine Vistula delta now found in the Gdańsk Bay to the north of Gdańsk (Bukowicki 1980; Ejtminowicz, Zaborowska and Zachowicz 1980) have been deposited at this stage of river evolution. The above area forms part of a shallow plain shown on a map by Jurowska and Kroczka (1978). According to Rosa (1968) and Pikies (1976), this plain lies at depth of 40 m below sea and it is bounded by an edge (cliff?) in the east, i.e. from the side of the Gdańsk Deep.

As the accumulation continued, the sheet belonging to horizon 2 also began to form in the eastern part of the Vistula Deltaic Plain. Its formation was due to the activities of both the Vistula and numerous small rivers rich in water flowing from the south and east.

While the rate of positive base level changes has attained a state of balance, the secondary climatic fluctuations became significant at the beginning of the Atlantic period. The drier phase AT_2 (Starkel 1977) is represented in its lower part by channel deposits being displaced from one place to the other in the eastern part of the Vistula Deltaic Plain. At that time the present Lake Drużno was still a peat-bog (Przybyłowska--Lange 1978). But during the late phase AT_2, the *Littorina* sea transgressed the whole Gdańsk Deep, together with the shallow plain on its landward side to an elevation of less than 10 m below present sea level. Following were rapid changes in depositional conditions which favoured the last formation of both the younger muddy-organic covering and the proper Vistula delta in the Vistula Deltaic Plain. Such a rapid rise of the sea level lasted up to one thousand years (*cf.* curve by Rosa, 1963, in Fig. 7). At the beginning of phase AT_3, i.e. about 6600 a B.P. the sea level was several metres below the present one. This caused the first invasion of euhalobic diatoms into Lake Drużno (Przybyłowska-Lange 1976, 1978). Following were two short intrusions of brackish water into this basin. According to Przybyłowska-Lange, the last marine overlap occurred during the Lower Subboreal, i.e. 4500—5000 years ago. This was the maximum limit of the *Littorina* marine transgression. The above three phases of rising sea level were interrupted by short episodes of very small regressions.

The above known course of the *Littorina* transgression in both the Gdańsk Bay and the Vistula Lagoon has not as yet been recognized in the lithologic differentiation of sediments forming horizon *4*. It is likely that changes in the position of the sea level and shoreline were too small and too short to influence both the type and rate of accumulation on the land. There can be no doubt that its traces are present on the shore, i.e. slightly to the north of the geological section examined.

According to Rosa (1963), there was a small marine regression about 3000 years ago. Probably at that time or rather slightly earlier, sand predominated locally over mud. Finally, about 1500 years ago on the *Limnaea—Mya* transition there increased the accumulation of mud due to a small marine transgression. Since that time, the delta has been growing mainly in the eastern part of the Vistula Deltaic Plain. Some stages of its growth are presented in Figure 1 based on historical data. The extent of the Vistula Lagoon 4000—5000 a B.P. which has been reconstructed by Majewski (1969) on the basis of Neolithic site distribution, according to Bertram, La Baume, Kloeppel (1924), Łęga (1953) and Uhle (1942) is but little precise. The shorelines about 890 A.D. are also very hypothetical. At this time, i.e. in the first centuries A.D. Lake Drużno became separated from the Vistula Lagoon.

In the 13th century one-third of the present Vistula Deltaic Plain was still under water, especially to the south-east of Szkarpawa and around Lake Drużno. Nearly all of the Vistula waters flowed into the Vistula Lagoon via the distributaries Nogat and Szkarpawa (Cyberski and Mikulski 1976), whereas the distributary Leniwka became less important. In the 13th century there was another ephemeral mouth of the Vistula delta distributary Przemysława of a short duration. Its end was situated to the north of Mikoszewo, i.e. slightly to the east of the dug channel Przekop Wisły (Mielczarski and Odyniec 1976). The connection of Lake Drużno with the Vistula Lagoon must have still existed, since a Viking boat dating from the 8th century was found there (Pelczar and Szeliga 1976).

REMARKS ON THE RECONSTRUCTION OF ELEMENTS OF THE HYDROLOGICAL RÉGIME

In accordance with the requirements of the IGCP Project 158—A, chapter *Description of the present environment* includes some Vistula channel parameters at the river mouth, together with some data on the accumulation taking place on the underwater shallow plain in the Gdańsk Bay. These values, however, do not refer to the natural hydrological processes, especially to the depositional ones. In the Vistula Deltaic Plain the river is controlled, at least partially by man's activities (chapter *Description...*). This is so important that it makes impossible the correct estimation of both hydrological conditions and geological processes due to river activities. For many centuries man has interfered with the natural hydrological régime of the whole Vistula delta. This has indirectly influenced the conditions prevailing in the Vistula channel. The examined valley reach may be thus a fine example of man's control of the natural environment in the whole Vistula valley (Mojski 1980a).

At present, the lack of a natural environment makes difficult the reconstruction of the hydrological régime of the Vistula in the past. Some remarks on this subject are included in chapter *The chronology of alluvial sheets and their sequence.* This dealt mainly with the approximate position of the Vistula channel in the Vistula Deltaic Plain during the Holocene and with the qualitative evaluation of the amounts of stream water. The above remarks are simply as follows:

1. During the Early Holocene the channel (channels?) of the Vistula was localized in the western part of the present Vistula Deltaic Plain. Another channel of this river (or of another?) existed between Rybina and Wiktorowo, but rather at a later date. There is evidence of the occurrence of a change from channel to predominant overbank facies first in the western part of the area, where the flood deposits are at their lowest elevation. Later on this facies appeared in the eastern part of the Vistula Deltaic Plain.

2. At the time of the *Littorina* transgression being associated with fluvial accumulation, the Vistula channels also were situated in the western part of the present Vistula delta. Over the last 2000 years the

hydrographical network became divided into delta distributaries, or rather the main Vistula channel was displaced further to the east.

3. From the Middle Ages onwards man's activities have brought about greater and greater changes in the hydrographical conditions. As a consequence, since 1895 the Vistula has flown into the Gdańsk Bay in an artificial channel. The former channels were cut off. Thus accumulation comes to an end at their mouths.

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