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Transport of passive admixture in a multi-channel river system - the Upper Narew case study. Part 1. Hydrological survey

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Abstract

This paper presents information required for conducting tracer test to study transport of passive admixture in a multi-channel Upper Narew River system. A precondition for a proper understanding of the physical processes governing the transport of pollutants in a river is a detailed recognition of hydrological and morphometric state within the river channel. This paper examines these conditions within a part of the river connecting Suraż and Bokiny constituting the opening river reach within the Narew National Park. Brief descriptions are given of study area and channel network at the time of field experiment. Then overview of the flow field and hydrological, hydraulic and topographic characteristics are presented. This is the first study of that kind in this unique anastomosing river system allowing for the detailed understanding of the flow regime in this highly complicated hydrographic network.

Key words: Anastomosing river, channel pattern, river flow, mean velocity field.

1. Introduction

The present study has been motivated by the need for understanding of the dynamics of spread of pollutants in a unique river system situated within the Narew National Park (NNP). The transport of constituents, by dispersion, advection or other processes is dependent on the hydrologic and hydrodynamic characteristics of the river. Advective transport dominates river flow that results primarily from surface water runoff and groundwater inflow. Dispersion arises due to the non-uniformity of the flow velocity. The Narew River in the considered area has been recently identified as an anastomosing river, which is regarded as a separate group in addition to the braided, meandering and straight ones (Gradziński *et al.* 2000; Makaske 2001). The occurrence of braiding is, as a rule, associated with large values of the bed slope (Yalin, Silva 2001). In case of the Upper Narew we deal with the multi-channel system on a flood plain but in contrast to the typical braided rivers, they are represented by relatively small slopes. This is one of the reasons why it is suspected that the Upper Narew belongs to anastomosing type of fluvial systems despite numerous differences with other rivers of this type are observed (Gradziński *et al.* 2000). In general, one can say that anastomosing multichannel streams develop when vegetation has stabilized the stream banks and the channel. In case where the vegetation is abundant peat soils form and if this peat is coherent, channels resist erosion and develop stable channels. Even though such stream has multiple channels like a braided stream, it has some of the channel characteristics of a meandering stream. But the general pattern of the considered reach of the Upper Narew river is similar to a braided one in the sense that the stream branches in a couple of channels which subsequently rejoin and branch again forming a structure that looks like a braid. Understanding of this type of dynamical systems is at preliminary stage; bifurcation mechanisms are not clearly understood, channels present a morphology highly variable in space and time and for this reason they constitute a real problem for researchers (Rosatti 1999). The planform of alluvial rivers is controlled not only by the overall slope of the valley but also by overall hydraulic and sediment conditions, i.e. upstream sediment load and properties of the sediment, average and peak discharge during floods, property of river bank material. The Upper Narew is one of the least recognized rivers in Poland. Researchers studying hydrology and geomorphology of this river are not numerous. The reason of that fact is most likely difficult access to many sites due to their location in the wetland area, and high complexity of the river geometry. The river has, however, a very unique environmental value and as such constitutes a challenge for a scientific community worldwide. The channel pattern observed within the Narew National Park fosters smaller depths in comparison to just one-channel rivers. Such river takes up more space in the river valley due to its larger width, and flooding. Erosion of islands and floodplains occurs more frequently in such environment. The flora and fauna is very rich in such environment (e.g. Jaros, Biesiada 2001).

A precondition for a proper understanding of the physical processes that occur in a river (and among them the processes governing the transport of pollutants), is a detailed recognition of hydrological and morphometric state within the river channel. This paper, part 1 of a two-part series, examines these conditions within a part of the river connecting Suraż and Bokiny constituting the opening river reach within the Narew National Park. The extension of the dye tracer study to embrace the entire river reach located in the protected area is planned. The considered field studies took place in the end of May 2001, which determined relatively low vegetation and extremely low water levels. To have a more detailed picture of the hydraulic conditions in the given river section, field studies should be also performed at other water levels and discharges and in a different season. This is why the present study should be considered as of preliminary character.

In the present paper a detailed hydrologic survey in the considered river reach is described and it constitutes a complementary part to a dye tracer test performed there (Rowiński *et al.* 2003 this issue). From the viewpoint of the hydrologic recognition of the river flow, the dye present in the water allows the discrimination between active channels and steady or nearly steady water.

2. Description of study area

The Narew River as a whole is certainly a major Polish river, both in terms of its physical size, i.e. drainage area and length, and its socio-economic importance to the region. The river has always been used for recreational purposes, and the fish, wildlife and waterfowl of the area depend on the river and its tributaries for their survival. The multichannel Narew River section extends in the marshy area from Suraż to Rzędziany villages and this part of the river constitutes the basis for the Narew National Park (Fig.1). Above the Rzędziany section the river has a natural character, since no drainage works have ever been done there (Mioduszewski 2001). The only important unnatural factor influencing both the water quantity and quality in this area is the Siemianówka water reservoir built upstream, about 50 km from the Narew National Park. A large debate on the influence of this reservoir on the water system within NNP is carried on, nevertheless a number of researchers emphasis its interference in the hydrological regime of the river and the decline of its water transparency (e.g. Wiśniewolski 2001). Whatever is the case, the river system within NNP maintains its absolutely unique character with its frequently branching and rejoining streams. The Narew valley in this area is characterized by a relatively flat bottom bordered by gentle slopes of low hills built mostly of glacial clays (Gradziński *et al.* 2000). The present study has been focused on the initial reach of the river within NNP, starting from the bridge in Suraż and with the last measuring site at Bokiny village. The area extended along the main river stream over a distance of 16.8 km according to the GPS-reading (Fig. 2). In this sense the study can be complementary to the observations of Gradziński et al. (2000) who picked the middle stretch of the river localized near Kurowo, although the experimental range is different in each of those two surveys. The water level gauge station, operated by the Institute of Meteorology and Water Management, continuously controlling the changes in water levels and flow intensity, is situated near the bridge in Suraż. Hydrological measurements were made in the period 28-31 May 2001. The conditions of river flow and ground supply were stable. Small precipitation didn't influence the increase of water level. The

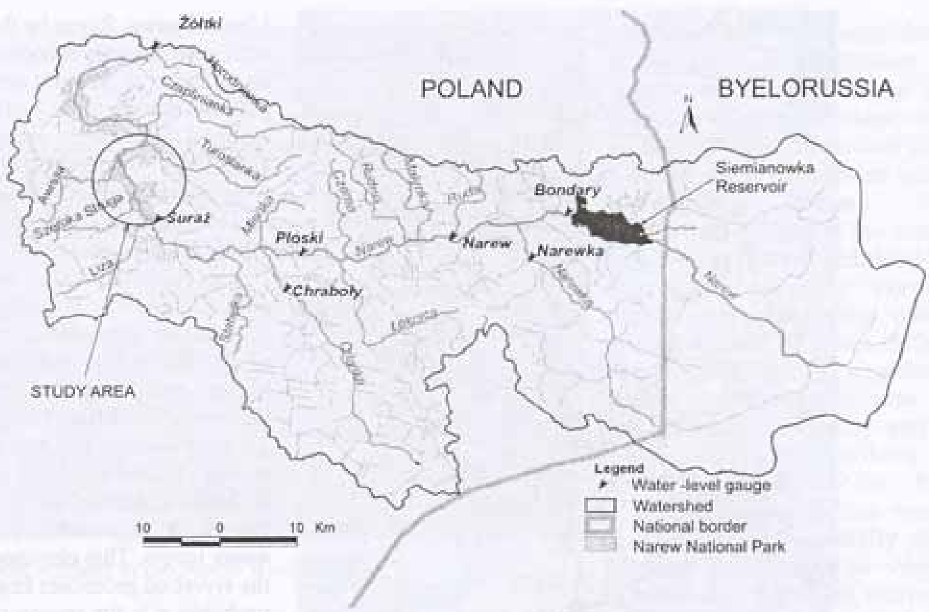

Fig.1. The Upper Narew River catchment (modified from Rowiński, Napiórkowski 2001).

water levels registered by the water gauge in Suraż varied in the range from 126 to127 cm. The medium flow here in 1949-1995 is 189 cm, the lowest of medium flows is 153 cm. Therefore the water flow during measurements was much lower than the lowest of medium flows, and only slightly higher than the medium of low flows, which is 116 cm in Suraż. Similarly, the flow in Suraż $Q=5.104\ m^3s^{-1}$ is not much higher than the medium low flow, which is $3.7\ m^3s^{-1}$.

The catchment area up to the water level gauge is 3376.5 km^2. Further, up to the bridge in Bokiny the catchment area increases by 543 km^2 and is 3919.5 km^2. As mentioned before, the Narew River flows along a flat valley, periodically flooded in a spread of 1-4 km. During high water levels multiple riverbeds can drain off water from the main riverbed and again fall into it. During the dry season the number of riverbeds is small; at the time of measurements only three branches - Szołajdzianka, and two unnamed rivers (for the purpose of this study named by the survey crew as Napiórka and Napióreczka Rivers) had significant flows that could be measured with the available equipment. The further study with the use of the tracer dye confirmed the activity of those river reaches (Rowiński *et al.* 2003 this issue).

3. Material and methods

The detailed survey and the recognition of the actual channel network was made from a boat with the use of a Global Positioning System (GPS) unit and the relevant profiles were localized on the existing map (see Fig.2). The GPS accuracy is related to GPS satellites positions in constellation. Highly favourable layout of satellites was observed during the time of measurements. This survey allowed us to validate the map and to reveal on it really active channels. Most of the channels that are shown on the map can be treated as abandoned ones under the low water conditions.

Water surface slope along the whole river reach, slopes between measuring cross-sections, local water surface slopes, riparian (overbank parts) of riverbed profiles and ordinates of the free surface were fixed by levelling in relation to provisional benchmarks levelled to a geodetic benchmark in Suraż, in the Kronstadt reference system. The provisional benchmarks were installed in the measurement profiles except for the Bokiny profile, which is 10 cm below the benchmark. Levelling of the section of the river was closed and checked. The deviation at the state benchmark in Bokiny was 50 mm, which is a very good result in technical levelling.

Traditional methods that make use of current meters were used for the determination of point velocities. The measurements were made at eight profiles in the main channel of the Narew River and three profiles in the considered river arms. ISO standards compiled into ISO Standards Handbook 16 (ISO 1983) were applied which assured a relatively small error made in the estimates of mean velocities not exceeding 7%. Detailed discussion of the hydrometric quality assurance systems may be found in (Hudson *et al.* 1999).

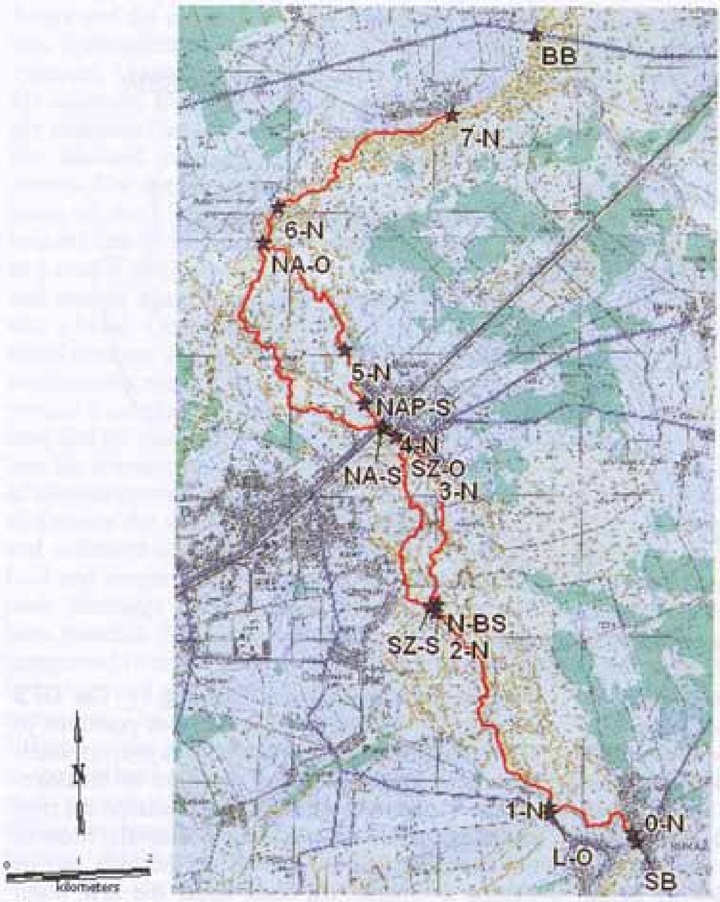

Fig.2. Map of the experimental reach of the Upper Narew River within the Narew National Park. Digits denote the number of cross-section, SB - Suraż Bridge, BB - Bokiny Bridge, N - Narew River, NA - Napiórka River, NAP - Napióreczka River, SZ - Szołajdzianka River.

4. Channel network at the time of field survey

The Upper Narew River in the considered meridional part is of an anastomosing type. The Narew channel meanders (Fig. 3) and it influences the dynamics of water flow. The onset of flow deflects some of the water towards the channels sides. As it reaches the side of the channel it is reflected back toward the opposite side of the channel. As the water changes side, it obviously also flows downstream, resulting in a zigzag flow line pattern. Meanders are an essential large-scale feature of river topography. The ratio of the length of the main riverbed to the length of the valley (the sinuosity index) is 1.4 which depending on different sources classifies the Narew River in this section as a meandering or sinuous river (Herschy, Fairbridge 1998; Yalin 1992). It is worth to note that the sinuosity index obtained by Gradziński *et al.* (2000) in respect to the further section of the Narew River was less than 1.3. Anyway, the statement that the planform of the Upper Narew River in the considered area presents mixed characteristics between straight and sinuous patterns seems to be justified. It is claimed that straight channels most commonly occur in combination with anastomosis (Makaske 2001) and in case of the Upper Narew the obtained picture is not so clear. Numerous sandbanks and shoal patches can be seen on concavities. In spite of apparent homogeneity of the studied section, the hydrological and hydraulic characteristics reveal significant variability of the flow conditions. Referring now to Fig. 2, starting from the bridge in Suraż the riverbed is relatively wide with large declivity and small water levels. This elevated slope of the riverbed promotes braiding and probably it is the reason of the creation of an island that is seen below the profile denoted as "0-N" in the middle of the stream. This island is covered by a variety of plants. At about 600 m below that profile there is a distinct sandy river bar and multiple shallow areas and shoals. The Narew River changes its character and the riverbed becomes much deeper, the bed slope is much smaller and the water levels are higher starting from the mouth of the tributary - the Liza River. The riverbed on the both sides is covered by a 10 cm layer of mud. This can be observed up to the profile "2-N" - Łapy Szołajdy where the river bifurcates. Below the profile "2-N", the left branch - Szołajdzianka river - carries about 4% of the Narew River flow at the time of measurements. Starting from that bifurcation up to the bridges in Uhowo the flow velocities increase and the water levels decrease. Below the profile "3-N" a vast vegetated island divides the river current directing the flow towards both riversides. The Szołajdzianka River reunites again with the main riverbed before the railway bridge in Uhowo (profile "4-N"). Under the bridges the river becomes shallower, and another branch, called Napiórka outflows on the left side (see Fig.4). A little bit further, below the road bridge, the second much smaller Napióreczka branch outflows. Both branches outflow about 12% of water flow. The branches reunite creating a large broad where the velocity of water significantly decreases but it does not disappear. The reunited branches come back to the Narew River upstream in the vicinity of the profile "6-N". Below the bifurcation of the

Fig.3. Typical bending in the Narew River.

Napióreczka branch, both shoal patches and the vegetation emerging above the water surface can be still observed. Then the riverbed becomes regularly shaped with cross-sections similar to the one denoted as profile "5-N", which is situated about 500 m downstream from the island. Between profiles "5-N" and "6-N" the main channel is on the right side of the valley, on the left side vast broads and waterlogged areas occur. Below profile "6-N", the main river channel moves to the left high valley side, broads and waterlogged areas are on the right side. It is not an easy task to understand what processes drive the exchange of water between broads and the main riverbed between profiles "5-N" and "7-N". It can occur through depressions and multiple branches; broads are fed by the main river almost in every conditions. Profile "7-N" is located below complicated forms of the riverbed. The sand bar and shoal patches can increase the intensity of the flow turbulence and consequently out-of-parallelity of the streamlines. Profile "7-N" is located in a definitely deeper area; a thick layer of mud is observed on the bottom there. The water surface slope increases again and hence the riverbed is rather irregular with multiple branches.

An important factor influencing the flow and also the mixing of matter carried by the river is the riparian vegetation extended over the width of 0.5-1.0 m, and in some cases like at the profiles "3-N", "5-N", "7-N" over as much as 1.0 to 2.0 m of a wetted area. The smallest influence of vegetation on the river flow was observed in profile "0-N". The influence of vegetation on the water flow has strong physical justification and is mainly manifested in the overall decrease of velocity values and the uniform pattern of vertical distributions of mean streamwise velocities (Rowiński, Kubrak 2002). Vegetation influences the resistance of the watercourse considerably, creates additional drag exerted by plants, causes a violent transverse mixing caused by great differences in velocities in both vegetated and non-vegetated regions, also affects the turbulence intensity and diffusion (Nepf 1999; Nikora 2000; Rowiński *et al.* 1998). Another important role of riparian vegetation is that it can substantially alter the channel geometry. The vegetation reduces the number of active channels as smaller channels become choked and are unable to reestablish themselves (Gran, Paola 2001). Mainly high and rigid water plants (such as reeds) were observed along the entire river reach and they were not subject to any elastic strains due to water flow. They were, however accumulating a lot of floating matter. The mean velocities in the vegetated cross-section were 0.5 to 0.6 less than in the vegetation-free flow. In case of the Napióreczka stream an inactive area of the width of 1.3 on the right side of the channel was observed. On the river bottom vegetation occurred only occasionally. In most cases the bed was rather flat, although in some case moving sand waves were observed on the river bottom. It is not a meaningless fact and there is strong evidence that the moving sand waves influence the flow field and particularly its turbulent compo-

Fig.4. Napiórka - shallow branch of the Narew River.

nent, i.e. turbulence intensity and turbulent energy dissipation (Nikora *et al.* 1997). Such investigations were not carried out in the considered river reach as yet but it can be a challenge for the future research. Only in a few sites a high increase of bed roughness due to the occurrence of special obstacles had an effect on the water flow. In profile "4-N", for example, devastated rock filling on the bottom was observed.

Variation and irregularity of the channel cross-sections influence the flow resistance and consequently the water flow, which obviously determines the transport and deposition of sediments. It was observed that aggradate mud filled a layer of 0.1-0.2 m in thickness in deeper areas; in profile "7-N", for example that thickness reached as much as 0.5 m.

5. Overview of the flow field

Recognition of the streamwise velocity field was the main challenge for the hydrological survey. The knowledge of actual velocity distributions allowed also for the determination of the discharges at the selected cross-sections.

Point velocity distributions at the selected verticals of each cross-section under consideration are shown in Fig. 5. Usually they are in agreement with classical vertical velocity distributions with maximum values occurring in the range between the level 0.8H and the water surface. Only in a few cases the vertical velocity distribution was disturbed (e.g. vertical I at the cross-section "1"). Note that the maximum streamwise velocities did not occur at utmost verticals located close to the riverbanks. The reason is that the measuring cross-sections were selected at possibly straight river reaches in which the parallelity of water streams occurred. In general in the areas where meandering was observed, the maximum velocities usually occurred close to the convex riversides. Greater values of point velocities were observed below the Szołajdzianka branch down to the profile "6-N". The highest mean and maximum velocity were measured at the cross-section "5-N".

6. Hydrological, hydraulic and topographic characteristics.

The flow rate and its spatial variation in the period of measurements are shown in Table I. At the beginning of the studied reach the rate of flow was $Q=5.104\ m^3s^{-1}$ while in the subsequent cross-section "1-N" situated 1630 m below, the measured flow was $Q=5.069\ m^3s^{-1}$. In between these profiles there is the Liza tributary with the discharge of $Q=0.014\ m^3s^{-1}$. In the profile "2-N"- 5750 m below the beginning of the section the flow slightly increased and it was $Q=5.220\ m^3s^{-1}$ which could possibly be a result of a ground supply. Below the profile "2-N", the Szołajdzianka branch drains the flow $Q=0.207\ m^3s^{-1}$ from the main riverbed. In the profile "3-N" the rate of flow was $Q=4.917\ m^3s^{-1}$, which was 2.7 % of the flow at the profile "2-N" below the Szołajdzianka branch. Such decrease is within the measuring error. In the profile "4-N" - 9230 m below, the discharge was evaluated at the level of $Q = 5.030\ m^3s^{-1}$. The influence of the Szołajdzianka branch discharging up-stream to the "4-N" profile is evident there. Below the profile "4-N" two branches Napiórka and Napióreczka outflow together $Q=0.584\ m^3s^{-1}$. It is revealed in the subsequent profile "5-N" - 10620 m below the first cross-section, where $Q=4.812\ m^3s^{-1}$. In the profile "6-N"- at 13580 m, the common Napiórka branch is united with the main stream and the flow is $Q=5.597\ m^3s^{-1}$. Groundwater or hyporheic zone supply is most likely the reason of that increase in the value of discharge. At the last profile "7-N", in Bokiny (16830 m), the flow decreases till the value of $Q=5.430\ m^3s^{-1}$. Any explanation of this decrease is of rather speculative character. Some possibility can be the feed of the vast wet areas on the right riverside by the main riverbed and the more intensive evaporation of water than within the actual river channel.

Other hydraulic and topographic characteristics are shown in Table I, where the wetted area, the width of the channel, its average and maximum depths, maximum velocity, flow rate, local water surface slopes and Manning coefficient are given in respect to all the measuring cross-sections. The greatest free surface slope occurs between the profiles "4-N" and "5-N", and is equal to 0.22‰, the smallest one was observed between profiles "6-N" and "7-N" and it was as low as 0.10‰. The local surface slope is considerably greatest below the profile "0-N". The roughness coefficient n varies in a relatively large range $0.032<n<0.194$. The smallest resistance to motion was observed in the profile "0-N", the largest one in profile "7-N", i.e. in Bokiny village. Such large value of coefficient $n=0.194$ at the last measuring cross-section - Bokiny most likely results from a complicated and strongly differentiated character of the riverbed along the relatively short section. Particularly large were changes of the channel depth in the longitudinal direction. Changes of the roughness coefficients due to channel shape have been recently studied by Strupczewski and Szymkiewicz (1996a; 1996b). Observation at the Bokiny cross-section is not unique and such great values of the roughness Manning coefficient may occur in lowland rivers (e.g. Szkutnicki 1996).

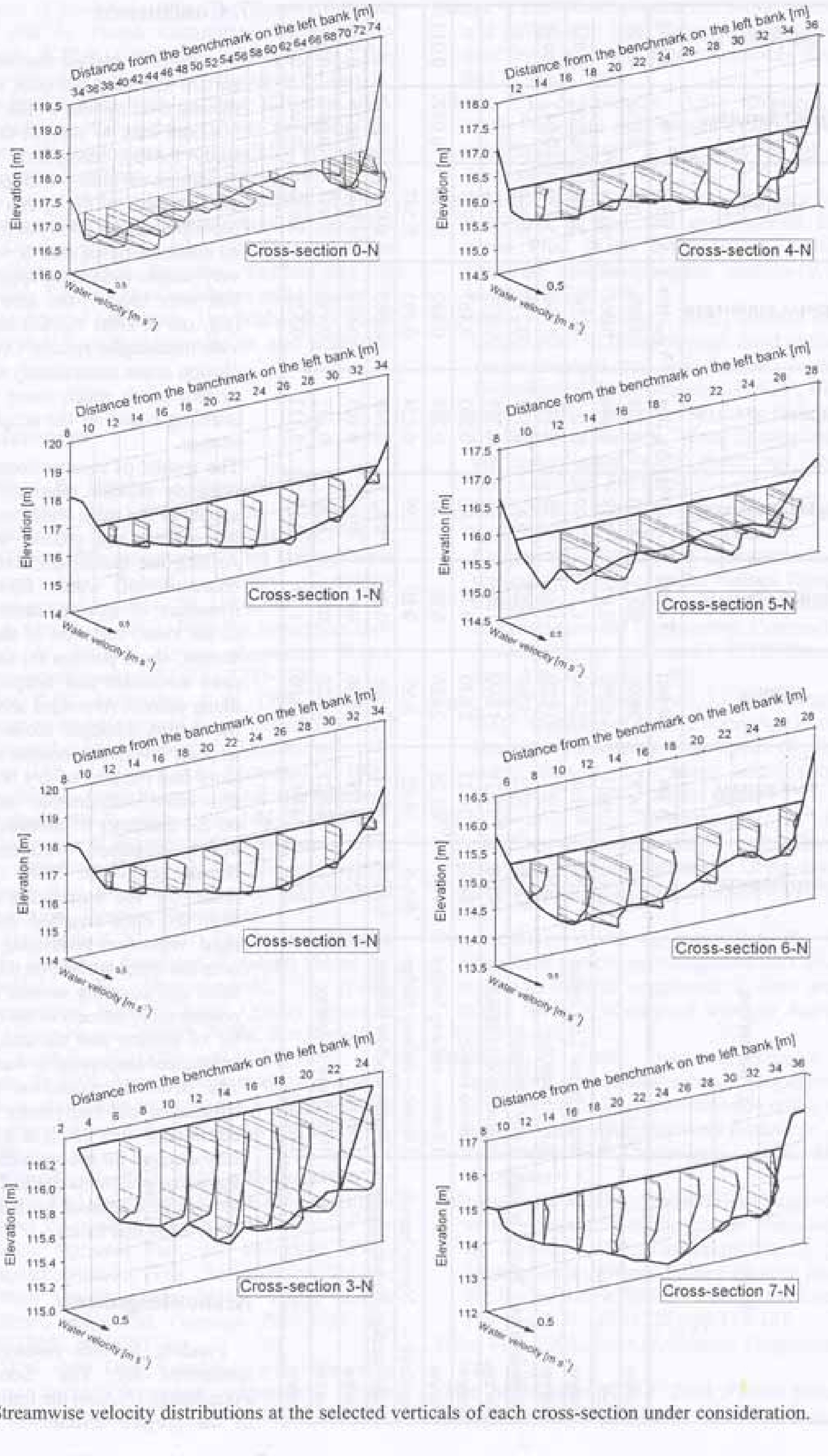

Fig.5. Streamwise velocity distributions at the selected verticals of each cross-section under consideration.

Table I. Hydrological characteristics of Narew River, main branches and flow.

River	Cross-section	Cross-section	Wetted area	Width	Average depth	Maximum depth	Average velocity	Maximum velocity	Flow rate	Manning coeff.	Local slope
			A [m^2]	B [m]	T_m [m]	T_{max} [m]	V_m [ms^{-1}]	V_{max} [ms^{-1}]	Q [m^{3}s^{-1}]	n	J [%]
Narew	Suraż	0-N	14.37	39.00	0.37	0.70	0.355	0.596	5.104	0.032	0.026
Liza	outlet	L-O	0.07	0.99	0.07	0.18	0.196	0.301	0.014		
Narew	Suraż below Liza outlet	1-N	31.07	23.00	1.35	1.97	0.163	0.209	5.069	0.105	0.028
Narew	Łapy Szołajdy	2-N	19.23	14.20	1.35	2.20	0.271	0.390	5.220	0.042	0.018
Szołajdzianka – Narew branch	Łapy Szołajdy	SZ-S	1.22	5.50	0.22	0.42	0.171	0.317	0.207		
Narew	below Szołajdzianka	N-BS	16.29	15.00	1.09	1.67	0.310	0.472	5.052		
Narew	Uhowo beach	3-N	16.13	21.30	0.76	1.05	0.305	0.467	4.917		
Narew	Uhowo – railway bridge	4-N	21.25	24.20	0.88	1.31	0.237	0.390	5.030	0.042	0.013
Napiórka – Narew branch	Uhowo – railway bridge	NA-S	4.42	5.50	0.80	1.39	0.124	0.193	0.547		
Napióreczka –Narew branch	Uhowo – below bridges	NAP-S	0.74	3.00	0.25	0.32	0.049	0.085	0.037		
Narew	Uhowo	5-N	11.87	17.80	0.67	1.00	0.405	0.679	4.812	0.025	0.019
Narew	Blockhead's Cottage	6-N	20.23	21.20	0.95	1.30	0.277	0.498	5.597	0.057	0.030
Narew	Bokiny	7-N	44.63	25.00	1.79	2.67	0.122	0.328	5.430	0.194	0.030

7. Conclusions

- The authors picked the simplest part of the very complex anastomosing river system within Narew National Park to support the pilot study for the recognition of the dynamics of both water quantity and quality in the given reach. Nevertheless the highly complicated situation raises doubts whether very simple modelling approaches that were used in the area so far (e.g. out-of-kilter model) can provide meaningful results. One conclusion arises immediately that the system needs much more understanding based on the actual field studies.
- The results of measurements surprisingly indicate relatively small supply of the main watercourse by the surface and ground inflows. Among the factors decisive for a character of water flow and dynamics of mixing, meandering of the river, variation of the midstream, shoal patches on the concave riversides and deeper areas along convex riversides should be mentioned. Multiple erode niches in peaty riversides, coastal depressions and remains of dry branches also have considerable influence on the character of motion. Three active branches, wetlands and broads below the "5-N" profile drain off the suspended matter from the main riverbed. Also the rigid vegetation protruding much over the water surface on the riversides and covering several islands considerably influences the character of motion and the mixing of substances suspended in water.
- The detailed recognition of the hydraulics and bathymetry of the considered river reach is a necessary element for the analysis of the spread of pollutants there. The latter will be discussed in (Rowiński *et al.* 2003 this issue).

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