Tracer test in the anastomosing- type river

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To better understand the flow processes, solute-transport processes and the interactions between the main channel and various lateral arms and bights, a fluorescent dye-tracer study was performed under steady-state flow conditions on a 16.8 km reach of an anastomosing type of a river. A part of the anastomosing section of the Upper Narew River was selected for the studies. This section extends in the wetland area lying within the Narew National Park area. A detailed survey of the hydrologic and hydraulic conditions and also of the bed morphology were performed in the considered river reach. Streamwise velocities were measured at the crucial cross-sections and volumetric flow rates were evaluated there. The response to the slug injection of a soluble tracer is assumed to imitate the characteristics of a soluble pollutant, so understanding of how tracers mix and disperse in a stream is essential to understanding the processes of pollution transport. The procedure applied during the considered experiment consisted in the instantaneous injection of a known quantity of the solution of Rhodamine WT into a stream and the observation of the variation in concentration of the tracer as it moved downstream. The measurements were also carried out in the main river arms. The conceptual model used for the analyses was the one-dimensional transient storage model allowing for the reconstruction of the abrupt leading edges and the long upper tails in the distributions of solute concentrations.

Introduction

Downstream contaminant transport is a problem of primary importance in aquatic sciences. The mechanisms of solute transport are widely investigated and in most cases the basic equations can be easily formulated. However, an incomplete understanding of turbulent flow, friction phenomena and exchange processes resulting in the detention of stream water leads to the necessity of restoring to a variety of empirical formulae which have yet to be fully substantiated by experiment. It is particularly the case when the plan-form geometry of the considered stream is complex. The present study has been motivated by the need for the understanding of the dynamics of the spread of pollutants in a unique river system situated within the Narew National Park. 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). 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. 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 and the researchers doing hydrological and geomorphologic studies there are few in number.

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Anthropogenic releases of toxic materials have a deteriorating impact on water quality and in this study an attempt has been made for determining both acceptable levels of effluent inputs above the Park waters and the concentration pattern of accidental inputs of toxic materials. These issues have not been addressed in respect to the considered river reach so far and moreover one can hardly find any information about the constituent transport in multichannel river reaches in worldwide literature. A widely accepted method to comprehend the fate of solutes in streams is to perform a tracer study in which a known mass of usually conservative solutes is released into the stream. The study consists in the examination of the concentration versus time curves of the artificially release dye at downstream stations and fitting appropriate models.

Study reach

A tracer experiment was carried out in a meridional part of the Upper Narew River. 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. Until 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. 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.

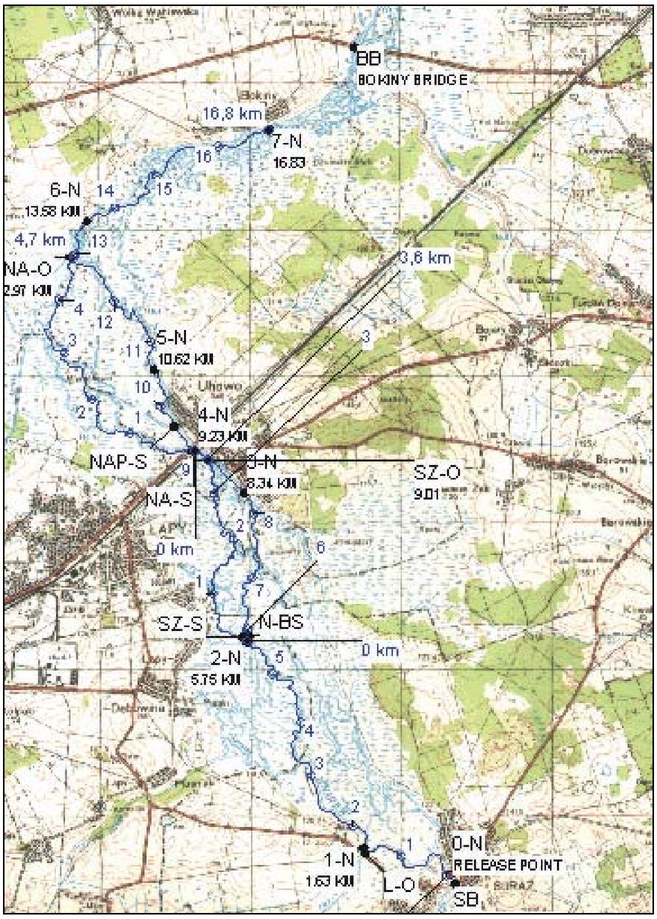

Fig. 1 Map of the experimental reach of the Upper Narew River

The present study has been concentrated on the initial reach of the river within NNP starting from the bridge in Suraż and with the last measuring site in Bokiny village and it extended along the main river stream over a distance of 16.8 km according to the GPS-reading (see Fig.1). As mentioned previously the Upper Narew River in the considered meridional part is of an anastomosing type. The Narew channel meanders and it influences the dynamics of water flow. The onset of turbulent 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.

Hydrological Survey

Hydrological measurements were made in the end of May 2001. The conditions of river flow and ground supply were stable. Small precipitation didn't influence the increase of water level. The 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 $Q = 5.104\ m^3/s$ is not much higher than the medium low flow, which is $3.7\ m^3/s$.

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. Traditional methods that make use of current meters were utilized for the determination of point velocities. Point velocity distributions are usually in agreement with classical vertical velocity distributions with maximum values occurring in the range between the level 0.8H and the water surface. 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 greatest mean and maximum velocity were measured at the cross-section 5-N.

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 bench-marks levelled to a geodetic bench-mark in Suraż, in the Kronstadt reference system. The provisional bench-marks were installed in the measurement profiles except for the Bokiny profile, which is 10 cm below the bench-mark. 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.

The flow rate and its spatial variation in the period of measurements as well as other hydraulic and topographic characteristics are shown in table 1, where the hydraulic radius, local water surface slopes, Manning coefficient, Froude and Reynolds numbers are given in respect to all the measuring cross-sections. 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. 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).

Table 1. Hydrological characteristics of the Narew River, and its main branches

River	Cross-section	**Wetted area**	**Width**	**Average depth**	**Maximum depth**	**Average velocity**	**Maximum velocity**	**Flow rate**
		A [m^2]	**B [m]**	**T_m [m]**	**T_{max} [m]**	**V_m [m/s]**	**V_{max} [m/s]**	**Q [m^3/s]**
Narew	0-N	14,37	39,00	0,37	0,70	0,355	0,596	5,104
Liza	L-O	0,07	0,99	0,07	0,18	0,196	0,301	0,014
Narew	1-N	31,07	23,00	1,35	1,97	0,163	0,209	5,069
Narew	2-N	19,23	14,20	1,35	2,20	0,271	0,390	5,220
Szołajdzianka	SZ-S	1,22	5,50	0,22	0,42	0,171	0,317	0,207
Narew	N-BS	16,29	15,00	1,09	1,67	0,310	0,472	5,052
Narew	3-N	16,13	21,30	0,76	1,05	0,305	0,467	4,917
Narew	4-N	21,25	24,20	0,88	1,31	0,237	0,390	5,030
Napiórka	NA-S	4,42	5,50	0,80	1,39	0,124	0,193	0,547
Napióreczka	NAP-S	0,74	3,00	0,25	0,32	0,049	0,085	0,037
Narew	5-N	11,87	17,80	0,67	1,00	0,405	0,679	4,812
Narew	6-N	20,23	21,20	0,95	1,30	0,277	0,498	5,597
Narew	7-N	44,63	25,00	1,79	2,67	0,122	0,328	5,430

Dye tracer test

The course of the experiment was extorted by its needs, i.e. the evaluation of the threats by an accidental release of the pollutants at the downstream locations and by the economical and technical feasibility. Therefore the initial part of the stream where the solute mixes across the depth and the width of the river is ignored and the study is concerned with one-dimensional, longitudinal transport of the dye. Rutheford (1994) stresses that when studying longitudinal dispersion it is necessary to sample for long enough to measure the entire concentration versus time profile at each site and check for tracer loss and indeed it was extremely time consuming and made us to have people in the field for almost a week. The reason is the long tail associated with tracer becoming trapped in various river arms and bights and the classical dead zones. The method of instantaneous injection of the tracer was applied and it did not require the complex dosing facilities and allowed to obtain high initial concentrations of the tracer. The dye release consisted of 20 liters of 20% solution of Rhodamine WT, which was released at three points at the cross-section just downstream of the bridge at Suraż. The dye was injected at 5:50 a.m. on June 5, 2001. Concentrations were measured at six transects corresponding to flow distances of 3.62 km, 8.34 km, 9.01 km, 9.23 km, 13.58 km, and 16.83 km (Fig.1). First cross-section was established at a distance at which 1D conditions were supposed to be achieved. During the early stages of a test, dye is visible to the naked eye, which facilitates sample collections. The dye was detected by using the field fluorometer Turner Design with continuous flow cuvette system on the one hand and also water samples were collected at sampling points. Continuous measurements were performed at two transects denoted as profile 2-N and profile 5-N. The measuring crew was equipped in fluorometers, graphical register and the pumps enforcing steady flow through the flow cell of the fluorometer. Measuring data were stored on graphical registers in the form of concentration distributions and then digitized to obtain relevant concentration time series.

Samples were collected to the glass bottles with Teflon-lined caps to prevent adsorption and were protected from sunlight. The dye concentration curves were registered until the complete decay of fluorescence, i.e. until the background concentrations were achieved.

Experimental results

The response of the stream to a slug injection of the tracer is presented in the form of the variation of concentration with time at the cross-sections downstream of the injection. Those breakthrough curves are shown in Fig.2.

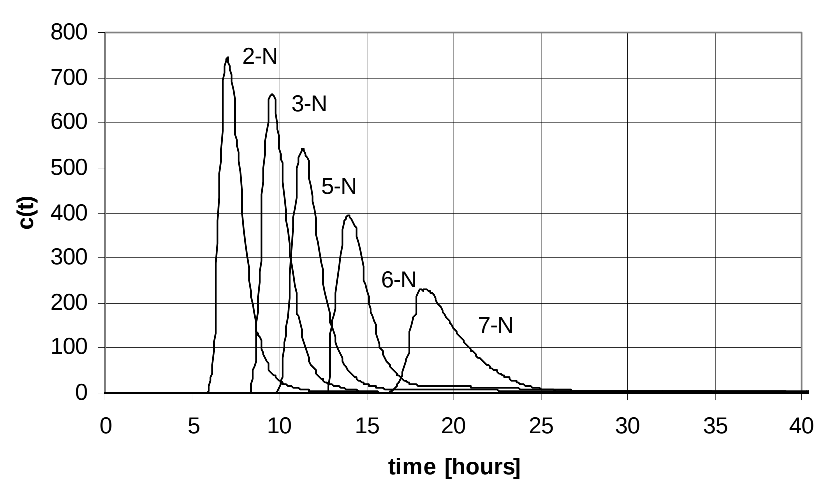

Fig.2 Variation of concentration with time at the cross-sections downstream of the injection

Their shapes are characteristic with their strong asymmetry, i.e. long tails stretching upstream. Those tails are caused by the temporary storage of the dye in various stagnant areas occurring in the irregularities of the river channel and in the numerous river arms and bights. The only exception is the breakthrough curve obtained at the estuary of Szołajdzianka River where the bimodal temporal variation of concentration was recorded (Fig. 3).

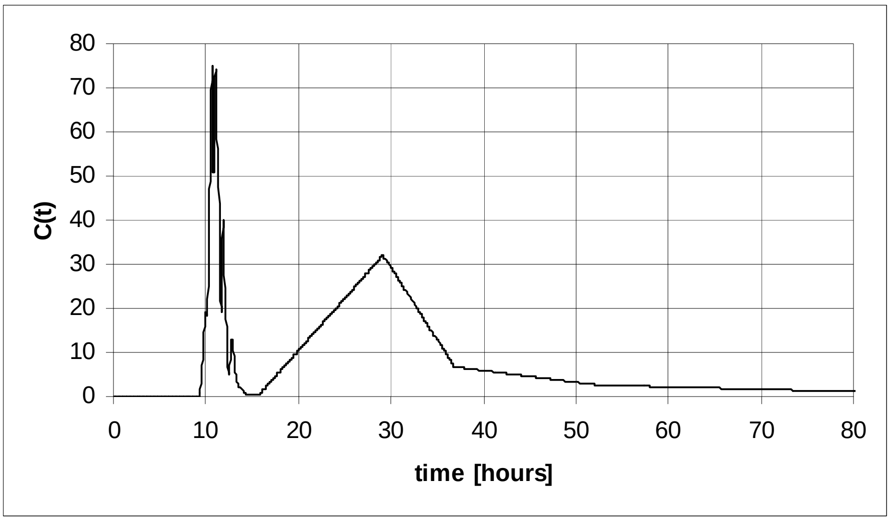

Fig.3 Breakthrough curve at the outlet of Szołajdzianka River

The origin of this curve is not totally clear but one can suspect that the additional peak was obtained due to the delay in the release of the dye from some area where the flow was hindered but it was hydraulically coupled with the Szołajdzianka River and where the dye got bogged down for some period of time. One may suspect that it is the area where the pollution would tend to accumulate for longer periods of time and it can be a warning for the National Park but more evidence is needed to derive any further conclusions.Table 2 presents the first three statistical moments in respect to the normalized temporal distributions of the admixture concentration. Large values of skewness reflect the situation with the existing long tails in the concentration distributions indicating non-applicability of traditional Fick approaches for pollution transport in similar river systems.

Table 2. Statistical moments of the admixture concentration.

Moments	2-N	3-N	5-N	6-N	7-N
Avr [hours]	7.582	10.084	13.259	18.343	23.324
Var [hours^2]	1.062	1.025	30.885	110.600	122.700
asymmetry [-]	2.595	1.946	5.010	3.312	3.121

Observed visa modeling results

To describe the pattern of the pollution transport in the river reach under consideration some modeling concept has to be adopted. A proposed model will be successively fitted to the observed breakthrough curves on the reach-by-reach basis and reach-specific model parameters will be obtained. It constitutes the main idea for the analyses of the results of the present paper. More detailed analyses will be given elsewhere. The highly asymmetric shape of the concentration-time curves precludes from the application of the simplest Fick-type model (Sukhodolov et al., 1997). Therefore as the first approximation a variant of the dead-zone model will be applied (see Czernuszenko, Rowiński, 1997 and the references given there). Different methods of the interpretation of such model in respect to multi-thread channels have been given in Rowiński (2001). For the purpose of the subsequent analysis the following formulation of the model will be adopted. This model is traditionally developed by deriving the one-dimensional mass balance equation with source term in the form:

$$\frac{\partial \overline{C}^a}{\partial t} + \overline{U}^a \frac{\partial \overline{C}^a}{\partial x} - E_L \frac{\partial^2 \overline{C}^a}{\partial x^2} = \frac{\varepsilon}{T}(C_d - \overline{C}^a) \qquad 1$$

where $\overline{C}^a$ is the area-averaged concentration in the main stream, $\overline{U}^a$ is the area averaged mean stream velocity which is assumed to be constant along the given sub-reach, C_d is the concentration in the dead-zone, E_L is the constant dispersion coefficient, T and ε are additional constant coefficients. The latter represents the ratio of volume of stagnant areas (dead zones) to volume of mainstream for length unit of a river reach. The former will be explained below equation 2. Both concentrations $\overline{C}^a$ and C_d are normalized by the total mass of the solute discharged into the river, i.e at any time t>0 $\int_{-\infty}^{\infty} \overline{C}^a(x,t)dx = 1$, and at any x>0 $\int_{-\infty}^{\infty} \overline{U}^a \overline{C}^a(x,t)dt = 1$. On the left hand side of equation 1 the one-dimensional mathematical representation of basic processes governing the spread of passive admixture in flowing surface waters is given. These processes include advection, i.e. the downstream transport of solute mass at a mean velocity and dispersion - the spreading relative to the depth-averaged or cross-section averaged velocity due to movement with different velocities in different parts of the flow. The right side of equation 1 expresses the rate of concentration change due to mass-exchange between the mainstream and dead zones. Taking into account the complexity of the river geometry in the area we may assume that various sets of constant coefficients represent the described situation in each subsection. The mentioned parameters are interpreted as "lumped" parameters that represent a spectrum of storage processes that occur simultaneously in multiple types of storage zones. Depending on the sign, the rate term represents the growth or the decrease of concentration in the main stream of the river. Assuming that the admixture is completely mixed within the dead zones, the mass-exchange balance between the dead zones and the main stream gives:

$$\frac{\partial C_d}{\partial t} = \frac{\overline{C}^a - C_d}{T} \qquad 2$$

The parameter T may be interpreted as the penetration time of tracer into (or out) the storage zones and it is called a time constant of the system described by equation 2. It is easy to see that equation 1 and equation 2 converge to the Fickian equation when $\varepsilon \to 0$ and $T \to \infty$. The considered model has to be complemented with a set of initial and boundary conditions specific for the described situation.

For the estimation of parameters in the present study the use is made of the frequency response function derived for the system of equations (1-2). This function is the imaginary part of the transfer function, defined as the ratio of the Laplace transform of the output to the Laplace transform of the input under the assumption that the initial conditions are zero. The results of the described estimation procedure are given in table 3. Application of those parameters to the computations of temporal variations of concentrations at the given cross-sections lead to similar results as the ones experimentally observed. Fig.4 presents relevant examples of such computations. Computations were performed on the reach-by reach basis with the use of the frequency response function and the reverse FFT transform.

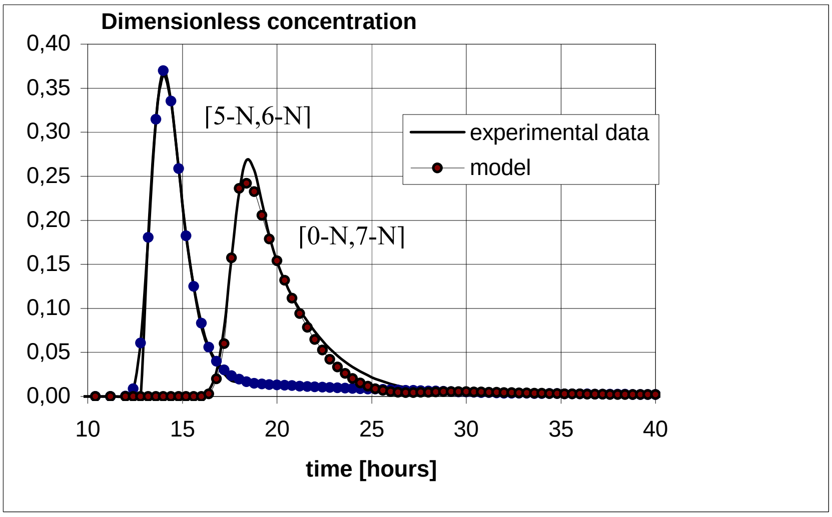

Fig.4 Comparison of measured concentration with that obtained by the dead-zone model

Since the reach-specific parameters are obtained by means of the described procedure, each set of parameters should somehow reflect the geometrical features of each river sub-reach. It is important to remember that in such complex system as the Upper Narew the parameter representing the mean, cross-sectionally averaged velocity does not have a very simple interpretation and cannot be compared to the measured mean velocity in a single (even main) river channel (Rowiński, 2001).

Table 3. Parameters of the impulse response model

Parameters	Sections					
	[0-N, 2-N]	2-N, 3-N]	[3-N, 5-N]	[5-N, 6-N]	[6-N, 7-N]	[0-N, 7-N]
E_L [km^2/h]	0.0027	0.0220	0.0051	0.0338	0.0034	0.0120
ε	0.0920	0.0120	0.7920	0.3690	0.2260	0.1020
T [h]	0.4530	0.6550	11.2570	7.0706	0.9030	1.4440
$\overline{U}^a$ [km/h]	0.5200	1.8400	0.4880	1.6200	0.7800	0.9190

Therefore this parameter only carries some information about the advective mean velocity in the entire system limited by two considered cross-sections. Another parameter, namely the dispersion coefficient, is the smallest in the initial section (0.0027 km^2/h) and it assumes the highest values in the sub-reach [5-N,6-N], i.e. 0.0338 km^2/h. Such big differences are the result of high variability of geometrical and hydraulic conditions along the stream. Most of the quantitative analyses of the dispersion coefficient were conducted by means of the traditional Fick-type model and such results cannot be automatically transferred to the models that take into account the temporary storage of the admixture. Czernuszenko et al. (1998) showed that when natural rivers are considered, the dispersion coefficients obtained by means of the dead zone model are much smaller than the ones obtained with the use of traditional methods. It is caused that in the Fick-type models, the dispersion coefficient among others accounts for the non-uniformities and irregularities such as islands, rapids, deep pools, which obviously influence the pattern of the spread of pollution. On the other hand side the information on the dependencies of the dispersion coefficient on stream characteristics is not sufficient to derive any final conclusions and further studies should be conducted in this respect. It can be, however, noticed that in the considered case, the dispersion coefficient increases together with the growth of the mean channel velocity. The parameters that account for the temporary storage of the dye vary along the river stream considerably as well. In the first sub-reaches the parameter ε is less than 0.1 and such values have been often observed in relatively regular rivers (Sukhodolov et al., 1997). Such values already testify about the presence of numerous dead zones in which the dye has been trapped and the time of penetration is represented by parameter T. These dead zones occur in the main stream itself. Much higher values of ε below the station 3-N is caused by the migration of the part of the tracer to the river branch Szołajdzianka where the conditions for the transport of mass is much worse and therefore the concentrations curves at the station where the streams rejoin are characterized by long tails stretching upstream and this fact has to be reflected in the source term of equation1. Parameter ε and more exactly the ratio of ε ad T is decisive for the magnitude of this term. Note the extremely long time of penetration of the admixture in this river reach. Similar situation is observed when we deal with Napiórka and Napióreczka bifurcations. In this highly complicated part of the river the dead zone parameters and consequently the additional term in the advection-dispersion equation are responsible for the hindered transport of the dye through the slower (in comparison to the main stream) river branches. Those river branches were much more vegetated and the solute needed much more time to overcome them. In the light of the presented model the river branches can be treated as additional storage zones, which superimpose with traditional dead zones created by the irregularities of the riverbed. Existence of sand bars and shoal patches, variability in roughness conditions influenced the increase of storage zone parameters. Moreover, 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 last set of parameters provides an overview for the entire river reach under consideration and it gives averaged values determined for this highly changeable reach. The values of the storage-zone parameters are similar as the ones computed for many other rivers (Czernuszenko et al., 1998).

Conclusions

The presented experiment is one of the first attempts of the studies of the admixture spread in a multi-channel river systems. The Upper Narew River is classified as an anastomosing river system and the investigations performed in the Upper Narew would help in the understanding of the similar systems irrespective of their location. A tracer test definitely facilitates the analyses and quantification of the hydrodynamic and also chemical processes in surface waters Because of its complete safeness for the environment such method is recommended as a tool for the recognition of the system behavior. Further tests in different hydrological conditions should be performed to provide enough data to equip the managers of the Narew National Park in a decision-supporting tool at the times of anticipated catastrophes.

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