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Transport of passive admixture in a multi-channel river system - the Upper Narew case study. Part 2. Application of dye tracer method

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Abstract

The paper presents information related to conducted tracer test to study hydraulic transport in unique multi-channel Narew river system. The motivation of the experiment was the evaluation of the threats to the Narew National Park by an accidental release of the pollutants at the upstream locations. The study is concerned with one-dimensional longitudinal transport of the dye described by means of so-called dead-zone model. It is shown that the temporary storage of the admixture plays a crucial role in the analyses of the pattern of its spread in the multi-thread river system. A special procedure based on the frequency response function and the reverse Fourier transform was elaborated for the identification of respective storage-zone parameters and the dispersion coefficients. Despite high complexity of the river system under consideration good agreement between modeling and experimental results has been attained.

Key words: ananstomosing river, tracer test, longitudinal dispersion, dead-zone model, passive pollutant.

1. Introduction

Very broad knowledge exists concerning the mechanisms of solute transport in streams. Literature review reveals that interest has focused on relatively geometrically simple streams, for which both the experimental and modeling work is easier (e.g. Rutheford 1994; Deng *et al.* 2001). 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 at downstream stations and fitting appropriate models. The present paper is aimed at the discussion of the tracer test performed in a unique multi-channel river system present within the Narew National Park in the northeast of Poland. The characteristics of flow and morphology of the selected river reach are provided in the Part 1 of this two-part series of papers (Rowiński *et al.* 2003 this issue). The study has been motivated by the demand 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. The experimental study has been preceded by a large debate, which resulted in the consensus among experts about the necessity of the performance of the field test in the area under consideration (Rowiński, Napiórkowski 2001). The modeling framework for the respective analyses has been proposed by (Rowiński 2001).

2. Materials and methods

A tracer experiment was carried out in a meridional part of the Upper Narew River (Rowiński *et al.* 2003 this issue). What makes the Upper Narew in this area particularly, and perhaps uniquely, interesting is the fact that its topographic configuration facilitates creation of excellent nature preserves and on the other hand side makes the interpretations and predictions of physical processes extremely complex. The experiment was carried out at relatively low water levels and therefore only a few channels were active, i.e. hydraulically coupled with the main Narew stream. Hence this extremely complex anastomosing river system was slightly simplified and easier for analyses.

There are numerous options in the selection of the tracer for the constituent transport studies. Since the experiment was carried out in the area of the national park the main requirement for its selection should be its harmlessness for the environment and the sense of safeness of the local communities. Although it is commonly recognized that an application of isotope tracers is most useful in terms of providing new insights into hydrologic processes (Kendall, McDonnel 1998), there was no agreement for their use in this particular case. Therefore another frequently used tracer, Rhodamine WT dye, meeting strong environmental criteria, has been selected (Holley 2001). Other options could embrace Rhodmaine B (Czernuszenko 1975), uranine (Höttges *et al.* 1994; Szpilowski *et al.* 1994), tritium (Johansson *et al.* 2001), lithium chloride (LiCl), sodium bromide (NaBr) (Broshears *et al.* 1993), sodium chloride NaCl (Sukhodolov *et al.* 1997) and many others.

Pre-conditions for the proper run of tracer test contain sufficiently detailed recognition of hydraulic conditions. Holley (1986) names the following desirable field data: stream discharges, stream stages, plan-form geometry, cross-sections and velocity profiles, slopes of the energy grade line, observations of bed material and bed forms and possibly storage zones. The above requirements have been fulfilled and are described in details in (Rowiński *et al.* 2003 this issue).

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 general alignment of the study reach, which was 16.83 km long, is shown in Fig. 1. 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 concentra-

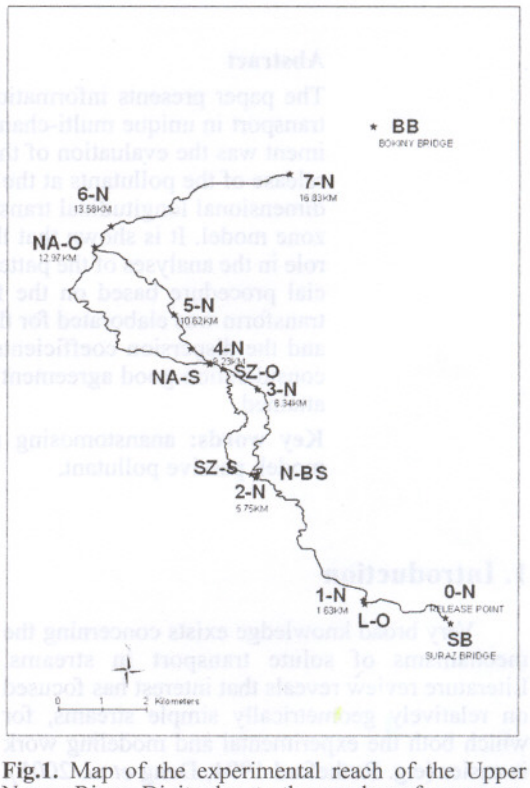

Fig.1. Map of the experimental reach of the Upper Narew River. Digits denote the number of cross-section, SB-Suraż Bridge, BB-Bokiny Bridge, N-Narew River, NA-Napiórka River, LO-Lisa outlet, SZ-Szołajdzianka River. The distances in km from the release point marked.

Fig.2. Spreading of Rhodamine WT at the early stage where lateral mixing occurs.

tions of the tracer. The dye release consisted of 20 dm^3 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, at cross-section 0-N. Concentrations were measured in Narew River at five transects 2-N, 3-N, 5-N, 6-N, and 7-N corresponding to flow distances of 5.75 km, 8.34 km, 10.62 km, 13.58 km, and 16.83 km respectively (Fig. 1), and in Szołajdzianka river at the transect close to the outlet. First cross-section 1-N 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. Fig. 2 shows the spreading of rhodamine still at the stage where lateral mixing occurs, while Fig. 3 presents the view of the Narew River at a long distance from the release point, i.e. at the stage where the tracer is mixed across the entire cross-section. There are usually small but detectable concentration differences across the channel even in the far field and therefore the tests of lateral degree of mixing were performed twice during the routing of the plume. The maximum differences in concentration did not exceed 2.5% and therefore 1D conditions could be assumed. Two methods of dye concentration measurements were applied. 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 and profile 5. 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. Instrument readings for fluorescent dyes are proportional to concentration from the lowest detectable levels up to a certain concentration (beyond the measured range in our case). Therefore further analyses, where the shapes of breakthrough curves are crucial, are rather straightforward.

Samples were collected to the glass bottles with Teflon-lined caps to prevent adsorption and were protected from sunlight. It is due to the fact that tracers are lost in transit due to adhesion on sediments and photochemical decay. Rhodamine WT dye has been shown to decay photochemically about 2-4% per day (Tai, Rathbun 1988). The dye concentration curves were registered until the complete decay of fluorescence, i.e. until the background concentrations were achieved. Good radio communication between field parties was assured to safeguard a smooth course of the entire experiment in this difficult terrain.

Fig.3. The view of the Narew River at a long distance from the release point, i.e. at the stage where the tracer is mixed across the entire cross-section.

3. 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. 4. 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 outlet of Szołajdzianka River (Fig. 5), where the bimodal temporal variation of concentration was recorded. 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.

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. It is worth mentioning that the concept of multiple storage zones has been recently proposed but such method introduces additional parameters which is much more data consuming (Choi *et al.* 2000). Depending on the sign, the rate

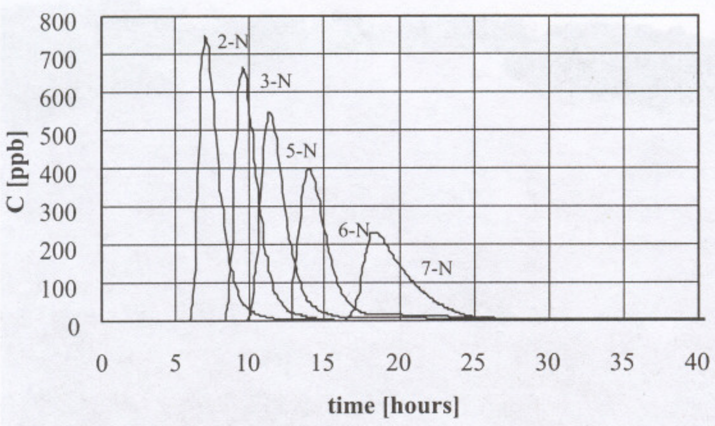

Fig.4. Variation of concentration with time at the cross-sections downstream of the injection.

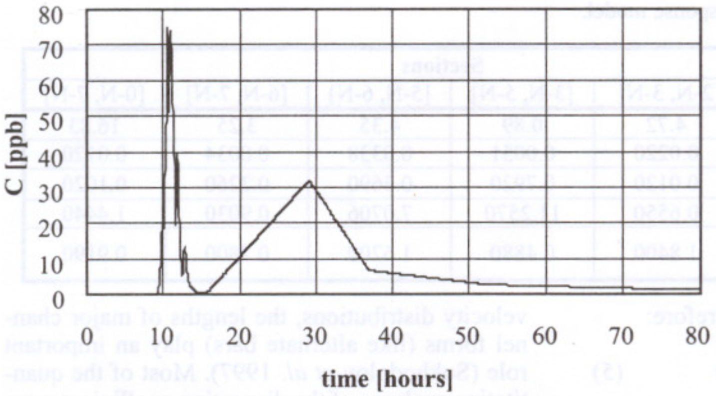

Fig.5. Breakthrough curve at the outlet of Szołajdzianka River.

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.

An estimation of the model parameters constitutes a basic difficulty in the application of the dead-zone model. A number of estimation methods have been elaborated in literature such as physically based empirical method of Pedersen (1977); fitting of the theoretical slope of the Laplace transformed solution for the concentration of the flow zone to the observed slope (Czernuszenko *et al.* 1998), moments matching procedure (Lees *et al.* 2000) or even visual determination of the set of parameters yielding the best fit to the concentration data (Bencala, Walters 1983). 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 frequency response function, as derived in (Czernuszenko, Rowiński 1997), reads:

$$H(x,i\omega) = \exp\left[\frac{\overline{U}^a}{2E_L}x - \frac{x}{2E_L}\sqrt{\overline{U}^{a2} + \frac{4E_L\varepsilon T\omega^2}{T^2\omega^2+1} + i\frac{4E_L(T^2\omega^3+\omega+\varepsilon\omega)}{T^2\omega^2+1}}\right] \qquad (3)$$

where:
i - imaginary number, ω - frequency. This function, when written in a polar form:

$$H(x,i\omega) = M(x,\omega)e^{i\Theta(x,\omega)}$$

(M is the magnitude and Θ is an angle) has clear physical meaning. If we have sinusoidal input to our system then the output is also sinusoidal with the same frequency as the input, an amplitude is $M(x,\omega)$ times that of the input and the phase is $\Theta(x,\omega)$ plus the input angle. An important fact is that the frequency response function defines the classical Fourier transform and therefore its inverse will represent the solutions of the model (1-2) in the original domain. Therefore the inverse of the Fast Fourier Transform (FFT) will be applied to the function $H(x,i\omega)$ and it will be denoted as $FFT^{-1}H$. The idea of the parameter estimation is to fit the theoretical results by means of $FFT^{-1}H$ function with the experimentally obtained breakthrough curves. Since reach-by-reach variation of parameters is used in the simulations, the investigated reach of the Upper Narew river [0-N,7-N] is divided into corresponding sections between the transects at which the breakthrough curves were measured. To simplify the notation these sections will be denoted as [k,l] where k,l are the numbers of the consecutive profiles with the given concentration curves, i.e..0-N, 2-N, 3-N, 5-N, 6-N, and 7-N. Here we concentrate on migration of the tracer in Narew and problems involved Szołajdzianka, profile SZ-O, are to be discussed in separate paper. In case of the river reach starting at the initial cross-section where the tracer was injected, the respective objective function J is defined as follows:

$$J(p^*) = \min_p \frac{\sum_{i=0}^{N-1}\left|C_{kl}(i) - Out_{kl}(p,i)\right|}{\sum_{i=0}^{N-1}C_{kl}(i)} \qquad (4)$$

where:
p is the parameters vector $p=[E_L, \varepsilon, T, \overline{U}^a]$, p^* is the optimal value of the vector p, subscript kl denotes the considered river reach,

$$Out_{kl}^p = FFT^{-1}H_{kl}^p(x,\omega)$$

is the inverse image of the frequency response at the outlet of the section [k,l], N is the number of the samples, $C_{kl}(i)$ is the concentration curve registered at the output of the considered section [k,l]. In case of the further sections [2-N,3-N], [3-N,5-N], [5-N,6-N], [6-N,7-N], the convolution of the function representing concentration time profile at the beginning of the considered reach $C_k(i)$ and the frequency response for the reach has to be

Table I. 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]
Section length [km]	3.62	4.72	0.89	4.35	3.25	16.83
E_L [km^{2}h^{-1}]	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
$\overline{U}^a$ [kmh^{-1}]	0.5200	1.8400	0.4880	1.6200	0.7800	0.9190

considered as the output signal. Therefore:

$$Out_{kl}(p,i)=\sum_{j=0}^{i-1} C_k(j) I_{kl}(\Delta x,p,i-j)\Delta t \qquad (5)$$

where:
Δt - sampling interval (in our case Δt is equal to 0.08 h)
Δx - distance between cross sections k and l
$I_{kl}(\Delta x,p,i)=FFT^{-1}H^{p}_{kl}(\Delta x,\omega)$
$H^{p}_{kl}(\Delta x,\omega)$- frequency response for the reach [k,l].

The results of the described estimation procedure are given in Table I.

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.6 presents relevant examples of such computations. Computations were performed on the reach-by reach basis with the use of the frequency response function (3) and the reverse FFT transform.

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). 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^{-1}) and it assumes the highest values in the sub-reach [5,6], i.e. 0.0338 km^{2}h^{-1}.

Such big differences are the result of high variability of geometrical and hydraulic conditions along the stream. It is commonly accepted that the values of dispersion coefficients depend on mean water depths, average shear velocities, mean aspect ratio of the channel, channel curvature, river flow (Rutheford 1994; Deng *et al.* 2001), also the heterogeneity of the velocity distributions, the lengths of major channel forms (like alternate bars) play an important role (Sukhodolov *et al.* 1997). 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 by the fact 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

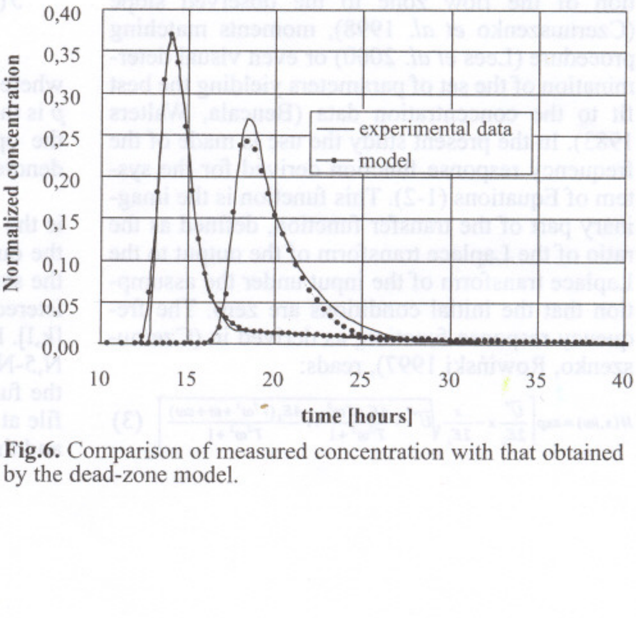

Fig.6. Comparison of measured concentration with that obtained by the dead-zone model.

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 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 Equation (1). 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).

Usually in the analyses of the experimental results of the dye tracer test the statistical characteristics, such as time of travel of peak concentration and the leading edge and the time of passage of pollutant; variance and skewness of the time-concentration distributions and their variability with distance are provided. Such results are discussed in (Rowiński, Napiórkowski 2002).

4. Conclusions

- The presented results are far from being conclusive. Various other modeling approaches should be tested against the obtained field data and a number of studies are carried out at the moment. There is no intention to prove the superiority of any of those approaches; each of them is to underline different aspects of the complex system under consideration. In the present study it is definitely shown that because of the asymmetric nature of all the observed breakthrough curves, the temporary storage of the admixture plays a crucial role in the analyses of the pattern of its spread in the multi-thread river system.
- A tracer test definitely facilitates the analyses and quantification of the hydrodynamic and also chemical processes in surface waters, particularly in such complex environment as the Upper Narew. 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 with a decision-supporting tool at the times of anticipated catastrophes. Also the experimental investigations performed in the Upper Narew would help in the understanding of the similar systems irrespective of their location.

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