# LARGE SCALE TRACER STUDY OF MIXING IN A NATURAL LOWLAND RIVER

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## ABSTRACT

Large scale tracer test along 90 km river reach was performed in a natural river in the North-East of Poland – Narew River. It was a crucial method for the evaluation of the impact of the retention reservoir on the protected areas of the river downstream and for the evaluation of the threats caused by potential catastrophic releases of toxic substances to that river. The study consisted of the detailed recognition of hydrological and morphometric state within the river channel and actual tracer test. At the crucial cross-sections, streamwise velocities were measured and volumetric flow rates evaluated. 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 this experiment consisted of the instantaneous injection of a known quantity of Rhodamine WT into the stream and the observation of the variation in concentration of the tracer as it moved downstream.

*KEYWORDS:* tracer experiments, natural rivers, water velocity measurements, longitudinal dispersion

## 1 INTRODUCTION

Tracer tests constitute a commonly recognized method for the evaluation of transport and mixing processes in rivers. It is a relatively simple experiment in case of small streams but its logistical difficulty increases with the length and time scale of the study. Therefore there is paucity in literature with respect to tracer studies performed over long distances. Most large scale tracer tests were performed in the seventies (e.g. Nordin and Sabol, 1974; Yotsukura et al., 1970). Very often the concentrations were recorded at a limited number of sites and insufficient readings in the tails of concentration distributions were taken. Among recent studies, the one from Hudson River (Ho et al., 2002; Caplow et al., 2004) and the tests performed in the Rhine river (Van Mazijk and Veling, 2004) should be mentioned. In this respect, tracer tests in natural non-engineered rivers, with limited pressure from the human population, are of great interest. One such river, the Upper Narew river (Poland) was selected as a case study.

Narew is an example of a relatively undisturbed river in a landscape rich in nature, and hence it allows the study of mixing processes present in a channel with almost no engineering construction along its course. This reach was also selected due to the practical problems that are of crucial importance for that region, namely, the impact of the Retention Reservoir Siemanówka on water quality in the Narew River and particularly on its reach within Narew National Park. A tracer test in that multichannel river system itself was performed in 2001 (Rowiński et al., 2003a, 2003b) and it facilitated the analyses and quantification of the transport and mixing processes in that complex environment. That study extended over almost a 17 km river reach. This time a challenging 90 km tracer test in the reach between

Siemianówka Reservoir and Narew National Park has been undertaken. This study also fulfilled a part of another objective, i.e. the construction and calibration of an alarm model prepared for the Upper Narew river, the tool that could be helpful for decision makers to mitigate the effects of possible accidental spills (Rowiński, 2006).

## 2 DESCRIPTION OF STUDY AREA

The Narew River is one of few remaining natural river systems in Europe. The valley of the Upper Narew is localized in the north-east part of Poland. The study area includes 90.2 km long reach that begins from the bridge in Bondary 400 m downstream from the Siemianówka Water Reservoir outflow and ends on the river gauge in Suraż, located in the buffer zone of the Narew National Park exactly 500 m before its border. Between those two locations, the river flows from the east to the west – the general alignment of the study reach is given in Fig.1. In principle, except areas close to the reservoir dam, this part of the river is not channelized. The valley is about 1 - 2 km wide and 7 - 10 m deep, it was shaped by a meandering river channel and presents a natural form of lowland river systems, with relatively small slope values, at the level of 0.24 per mille bed. The Upper Narew River, considered here, has a drainage area of approximately 3376 km$^2$. Discharges at the upstream Bondary site, are directly dependent on the management of the Siemianówka Reservoir – this influence decreases with increasing distance from the Reservoir.

Nearly 90% of the valley is occupied by reach wetland ecosystems, mostly by marshes (55%) and peat lands (31%). Remaining 10% is covered by postglacial mineral soils and sand dunes. Additionally, an important role for local ecosystems is played by mud soils which fill old riverbeds. Such conditions lead to extensive agriculture. This semi-natural character and environmental conditions of the region cause this part of the Narew valley to have great ecological value and it favours this region for landscape protection, tourism and agriculture. Recently more and more studies have been initiated to understand the hydrological conditions and to identify relevant water management strategies there but still the data and the information is rather scarce. One should mention a recent study of Kubrak et al. (2005) in this respect, an independent in-situ study has been performed at the time of the experiment.

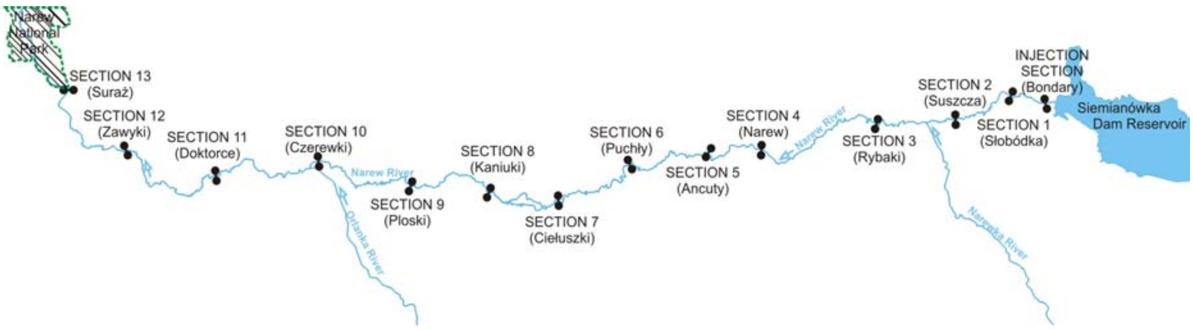


Figure 1. Study reach of the Upper Narew River between Siemianówka Reservoir and Narew National Park.

It is significant that water conditions change along river reach. In the Siemianówka neighbourhood, the terrain is rather dry and the share of wetland ecosystems is low, but in the downstream direction, the soil moisture content increases considerably. The reach between Siemianówka Reservoir and the Narewka tributary is covered by mineralised peat soils. Below the Narewka tributary the first complex marshy ecosystem appears. Near Narew town marshes transform into wet grasslands which dominate the valley until the Ploski village. Marshy cover appears again, which changes into grasslands below Doktorce village. Near

Zawyki, the soil moisture increases significantly and marshes peat lands exist, which cover nearly the whole River Liza estuary and surrounding areas, forming so-called Filipy Swamp.

## 3 HYDROLOGICAL RECOGNITION

Hydrological measurements were made at the end of June 2006. The conditions of river flow and ground supply were stable. There was no rainfall during the entire experiment and no increase of water level was observed. Initial choice of the measuring cross-sections was based on GPS readings and then slightly modified in the field to secure relatively convenient access during the actual tracer test.

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 electromagnetic sensors *Valeport 601* were utilized for the determination of point velocities. Examples of point velocity distributions at the selected verticals are given in Figure 2. 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 flow rate and its spatial variation in the period of measurements as well as other hydraulic and topographic characteristics are shown in Table 1.

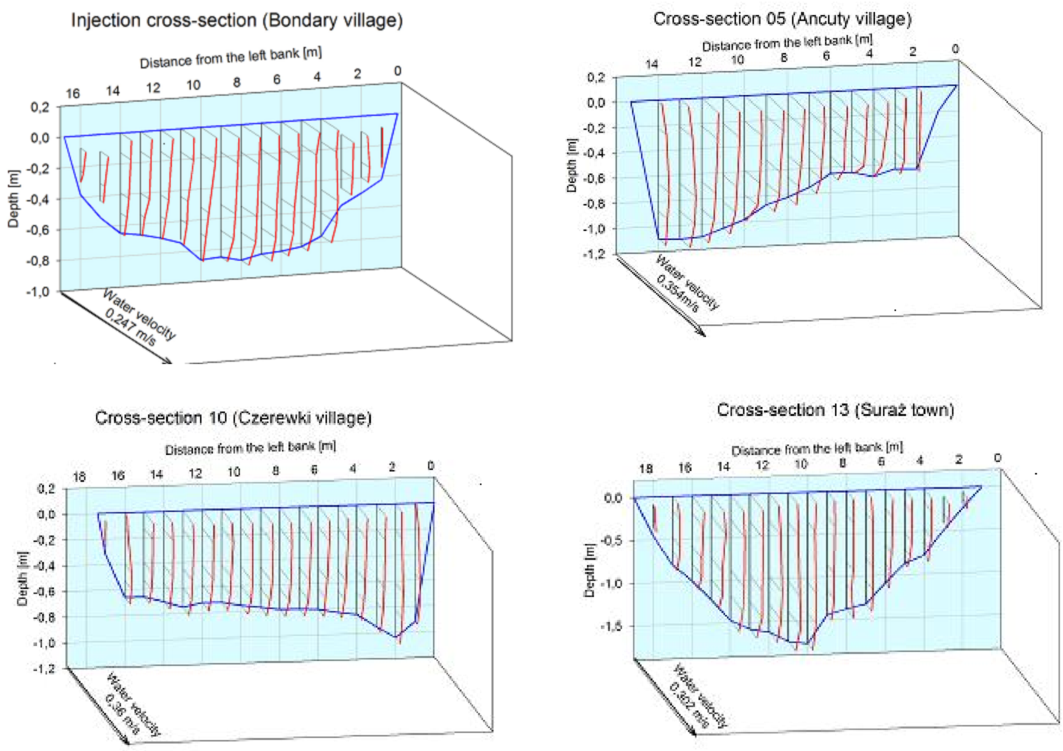


Figure 2. Examples of streamwise velocity distributions at the selected verticals within experimental cross-sections.

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

| River/ site | Cross-section/ distance from release [km] | **Wetted area** | **Width** | **Average depth** | **Maximum depth** | **Average velocity** | **Flow rate** |
|---|---|---|---|---|---|---|---|
| | | **A [m$^2$]** | **B [m]** | **$T_m$ [m]** | **$T_{max}$ [m]** | **$V_m$ [m/s]** | **Q [m$^3$/s]** |
| Narew/ Bondary village | Release point | 10,950 | 16,6 | 0,66 | 0,88 | 0,247 | 2,701 |
| Narew/ Słobódka village | 1/ 3.3 | 7,769 | 9,4 | 0,83 | 0,96 | 0,343 | 2,667 |
| Narew/100 m below bridge in Suszcza village | 2/ 9.2 | 7,255 | 9,7 | 0,75 | 0,85 | 0,378 | 2,739 |
| Narewka (tributary of Narew) | | 6,643 | 6,4 | 1,04 | 1,18 | 0,118 | 0,782 |
| Narew/ Rybaki village | 3/ 15.7 | 9,148 | 11,6 | 0,79 | 0,95 | 0,397 | 3,628 |
| Narew below the bridge in Narew village | 4/26.6 | 10,692 | 12,8 | 0,84 | 1,10 | 0,373 | 3,989 |
| Narew/ Ancuty village | 5/31.2 | 11,405 | 15,2 | 0,75 | 1,11 | 0,354 | 4,035 |
| Narew/ Puchły village | 6/37.6 | 10,981 | 13,2 | 0,83 | 1,41 | 0,374 | 4,109 |
| Narew/ Ciełuszki village | 7/43.9 | 12,433 | 11,4 | 1,09 | 1,40 | 0,355 | 4,414 |
| Narew/ below Kaniuki village | 8/50.9 | 15,399 | 17,7 | 0,87 | 1,09 | 0,283 | 4,355 |
| Narew/ bridge in Ploski village | 9/57.7 | 15,949 | 16,9 | 0,94 | 1,66 | 0,293 | 4,670 |
| Narew/ Kożany village | 10/65.9 | 12,924 | 17,4 | 0,74 | 1,04 | 0,360 | 4,655 |
| Orlanka (tributary of Narew) | | 1,704 | 5,8 | 0,29 | 0,40 | 0,301 | 0,513 |
| Narew/ below Doktorce village | 11/73.4 | 15,930 | 17,0 | 0,94 | 1,35 | 0,317 | 5,050 |
| Narew/ Zawyki village | 12/82.6 | 17,788 | 19,9 | 0,89 | 1,16 | 0,289 | 5,135 |
| Narew/ bridge in Suraż | 13/90.2 | 19,270 | 18,0 | 1,07 | 1,77 | 0,302 | 5,823 |

## 4 TRACER TEST

A tracer test has been designed to study longitudinal transport of a solute in the Upper Narew River. Most of the river is subject to special protection measures therefore high ecological standards have had to be fulfilled. A fluorescent dye, Rhodamine WT has been selected as a tracer fulfilling those strong environmental demands. Due to their excellent detectability, fluorescent dyes are used in low concentrations and as such, they do not cause strong negative influences on the natural environment (e.g. Smart and Laidlaw, 1977; Field et al., 1995; Rowiński et al., 2006).

On June 28, 2006 at 5:40 a.m. 24 litres of 20% water solution of Rhodamine WT was released in a short period of time (to simulate pulse release) at a cross-section under the bridge in Bondary (see Fig.3).

Figure 3. Near instantaneous dye release at the initial cross-section at Bondary.

Dye concentration measurements were undertaken at 13 sections downstream of the injection point over a distance of 90km. Due to the size of the project, distances between sites (on gravel tracks) and relatively high financial implications of the project, it was decided to take simultaneous measurements at each site using both an in-situ electronic Turner Designs SCUFA fluorometer (Self-Contained Under-water Fluorescence Apparatus), as well as manual grab samples.

A fluorometer is a device used to measure dye concentration. Using suitable filters for different types of benzo-organic dyes, the instrument utilises the fluorescent properties of the tracer whereby the dye emits light of a different wavelength to that of the light striking it. The intensity of the emitted light is detected by a photo multiplier and the output measured as a voltage. From calibration of the instrument with known concentrations of dye, the voltages can be converted to concentration values. The SCUFA's are self contained, with their own data logging capabilities. They have the ability to measure turbidity on a separate channel, and also correct for temperature fluctuations, both of which influence fluorescence values. Both parameters were utilised during the experiment, temperature was corrected automatically within the electronics, and turbidity logged together with the tracer concentration. Figure 4 shows a typical raw data trace of dye concentration and turbidity from a SCUFA before data filtering (site 5), it is noticeable that around 15:00 hours the turbidity increases resulting in an increase in the fluorescence value. Use of an established technique allows these fluctuations to be isolated, quantified and removed.

Three SCUFA's were used during the experiment, each alternately moved from site to site during the passage of the tracer cloud. At each site, the SCUFA was positioned midstream, approximately 0.5m below the water surface, and concentrations were recorded every 30 seconds.

Discrete samples were also collected in special dark bottles and they were again measured in stable laboratory conditions - all samples were stored at the same temperature and light conditions for a couple of days. These readings were regarded as the most accurate. The dye concentration curves were registered until almost complete decay of fluorescence, i.e. until the background concentrations were achieved. These measurements were extremely labour intensive and logistically complex. The registered concentration distributions in all measuring cross-sections are given in Figure 6. In principle, this represents the response of the stream to slug injection of a tracer.

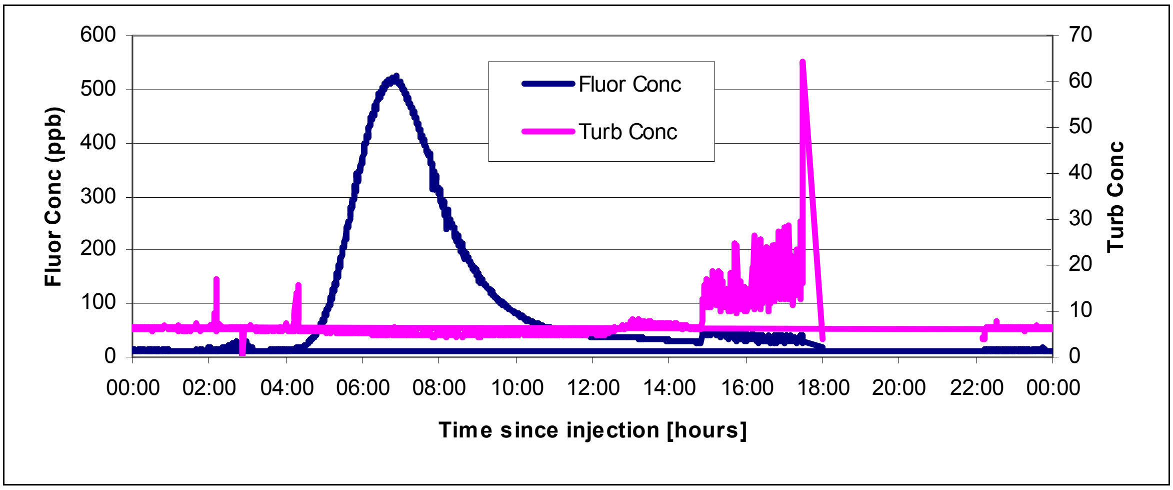


Figure 4. Example (site 5) of typical raw data of dye concentration and turbidity obtained from SCUFA before data filtering.

The initial part of the stream where the solute mixed across the depth and the width of the river was ignored and the study is concerned with one-dimensional, longitudinal transport of the dye. First cross-section was established at a distance at which 1D conditions were assumed to be achieved – 3300 meters from the release point. During the early stages of a test, dye was visible to the naked eye, which facilitated sample collections (Figure 5).

Figure 5. Spreading of fluorescent dye a) at the early stage where 3D mixing occurred and b) at the stage where the tracer was mixed across the entire cross-section.

## 5. DISCUSSION OF RESULTS

The shapes of the tracer distributions 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. Due to this, it may be considered that the application of traditional Fickian mixing theory is just a first approximation but it will still provide some insight into the ongoing processes during the passage of the tracer wave through the Upper Narew river. This case study with use of the storage-zone model approach will be given in a separate publication. In spite of imperfect representation of all the processes by the traditional advection-dispersion equation, its simplicity ensures that it is the most often used approach in literature and as such its applicability to the given data is of interest.

Longitudinal advection-dispersion equation in its classical Fickian-type form is as follows:

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}=\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) \tag{1}$$

where

$C$ is cross-sectionally averaged concentration of admixture, $t$ – time, $x$ – distance from the point of release, $U$ – mean flow velocity (averaged in cross-section), $D$ – longitudinal dispersion coefficient. The solution of Eq. 1 for an instantaneous injection over the cross-section at x=0; t=0 is:

$$C=\frac{M}{2A\sqrt{\pi Dt}}\exp\left(-\frac{(x-Ut)^2}{4Dt}\right) \tag{2}$$

where $M$ is mass of released tracer and $A$ is the area of a cross-section.

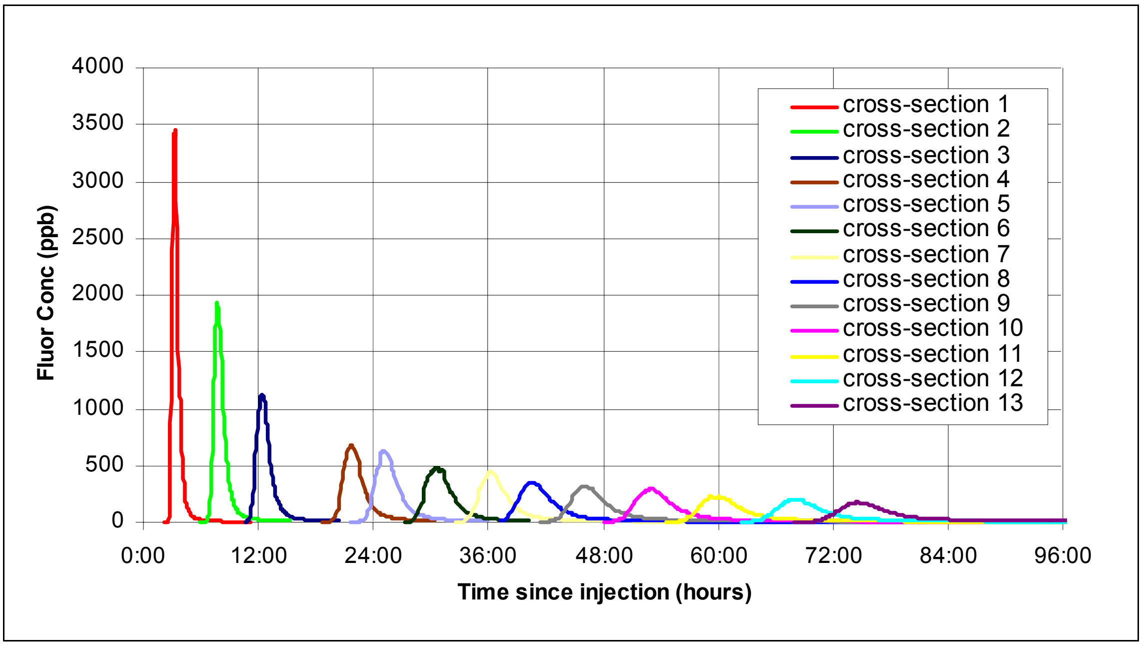


Figure 6. Temporal variations of tracer concentrations at all measuring cross-sections along 90.2 km river reach.

It can be shown from Eq. (2) that maximum value of the concentration distribution $C_{max}(t)$ follows the relation:

$$C_{\max}(t)=\frac{1}{\sqrt{D}}\frac{M}{2A\sqrt{\pi t}} \tag{3}$$

Linear relation between $1/C_{max}$ and $t^{1/2}$ has been observed in a number of tracer tests, e.g. in Copper Creek (Holley and Jirka, 1986) and it is to a certain extent met in the field conditions of the Upper Narew River (Fig.7). One may distinguish three different areas with possible three different slopes in the mentioned relationship – each area starts with major tributary inflowing the Narew River.

A main question in the analyses of the pattern of pollution transport is the evaluation of longitudinal dispersion coefficient occurring in Eq. (1). An assumption about validity of the simple description by means of Eq. 1 introduces significant uncertainty, nevertheless evaluation of the dispersion coefficient is of practical importance. There are numerous methods that could be used for that task (see e.g. Sukhodolov et al., 1997; Wallis and Manson, 2004; Jirka and Weitbrecht, 2005) and their usefulness in this particular case is a topic of a separate discussion. Results of only two simple methods will be presented herein. The most obvious seems to be the method of moments, allowing for the calculation of dispersion coefficient based on pairs of observed temporal distributions of concentrations. Such methods are extremely sensitive to the measurements of the tail of the concentration distributions, but nevertheless it provides some information on the values of that coefficient.

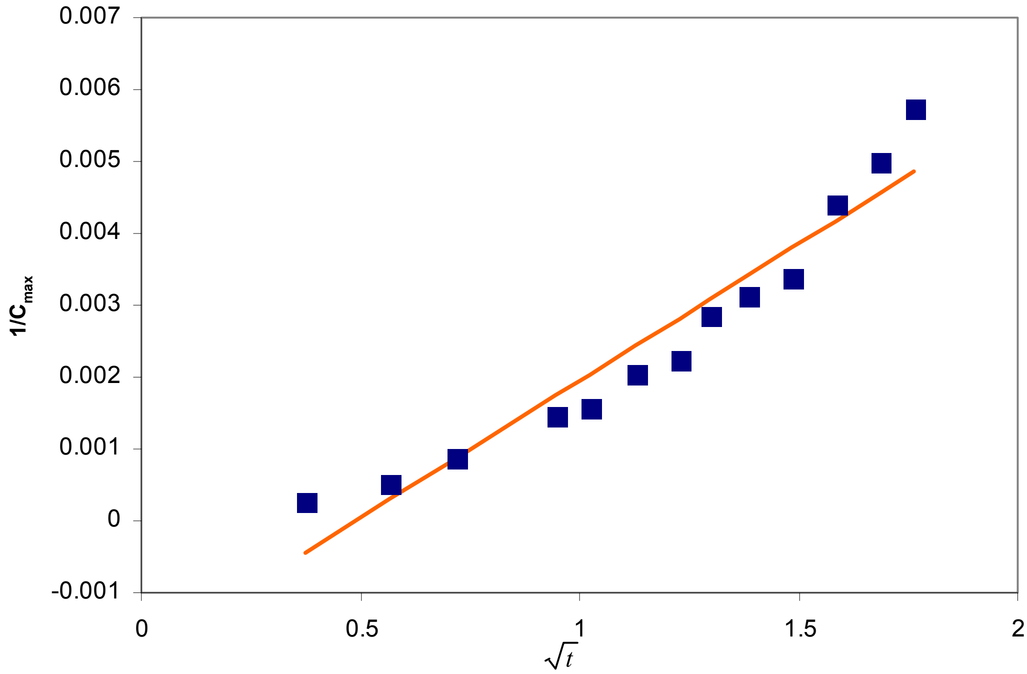


Figure 7. Peak concentrations as function of time (Upper Narew River).

To avoid the problems with the information introduced in the tails a method of Van Mazijk and Veling (2005) was utilized. That approximation is based on the assumption that the falling limb of the concentration distribution by a declining exponential function. As the falling limb plotted on semi-log scale was simply represented by a straight line, the dispersion coefficient value was obtained by means of linear regression with the application of the mean-square-root criterion. Dispersion coefficients based on that method are given in Table 2. Another set of dispersion coefficients is obtained by Fischer's routing procedure, fitting the analytical solution of Eq. (1) to experimental breakthrough curves (Rutherford, 1994). It is not surprising that various methods lead to different results and has been observed in many other studies. All methods implicitly introduce various assumptions and simplifications which influence the final results. The large value of dispersion within the river reach 7-8 is caused by river bifurcation occurring in that area (see Fig. 1) - water flows at different rates in river branches. An example of the agreement of data based on a routing procedure with experimental results is given in Figure 8.

**6. CONCLUSIONS**

A unique tracer test ("Beki" trace) in sense of its length, time scales and the number of measuring sites has been presented in the study. The experiment allows for the simulation of potential accidental releases of toxic substances upstream from environmentally protected areas. It provides additional arguments in an ongoing debate on the negative impacts of the retention reservoir located upstream the river reach under consideration. It will also facilitate the construction of an alarm model for that specific site.

Table 2. Reach-specific longitudinal dispersion coefficients evaluated on the basis of method of moments with "exponential smoothing" and on the Fischer's routing procedure.

| River reach | D from MOM [$m^2/s$] | D from Fisher routing procedure [$m^2/s$] |
|---|---|---|
| 1-2 | 11,6 | 8,5 |
| 2-3 | 12,8 | 12 |
| 3-4 | 14,8 | 9 |
| 4-5 | 30,0 | 21 |
| 5-6 | 23,2 | 15 |
| 6-7 | 20,8 | 15 |
| 7-8 | 120,7 | 70 |
| 8-9 | 37,9 | 21 |
| 9-10 | 26,6 | 19 |
| 10-11 | 62,5 | 29 |
| 11-12 | 34,4 | 18 |
| 12-13 | 63,6 | 30 |

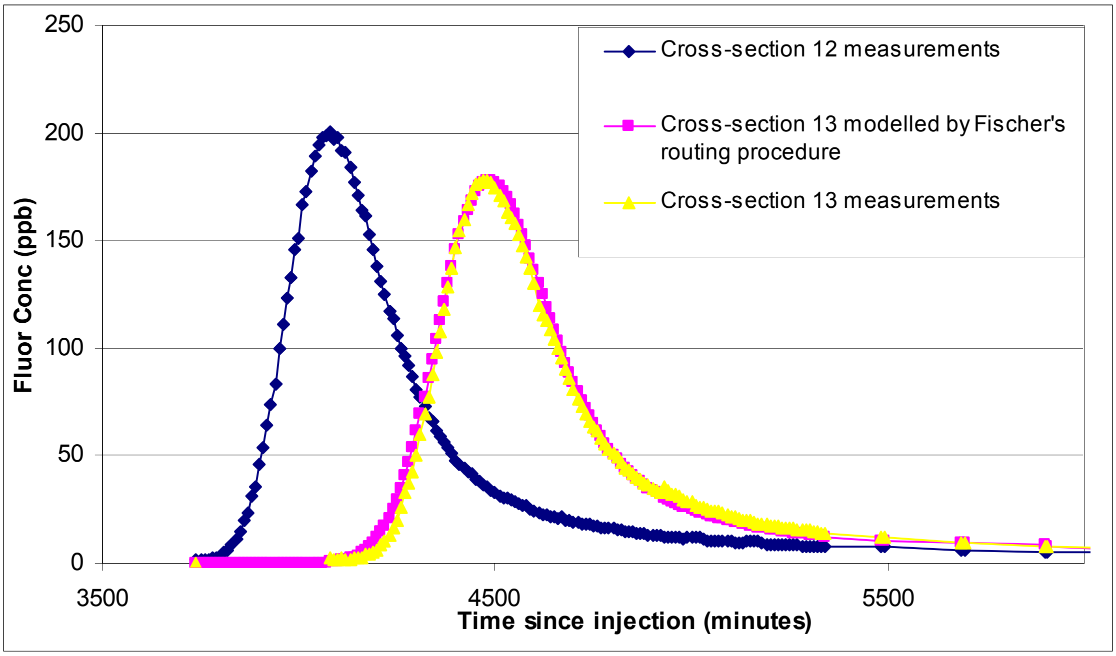


Figure 8. Performance of a routing procedure in the reach 12-13.


## ACKNOWLEDGEMENTS

This work was financially supported in part by The Ministry of Higher Education and Science Grant No. 2 P04D 026 29 and in part by The Sendzimir Foundation, USA. The authors are grateful to colleagues from the Institute of Geophysics of the Polish Academy of Sciences, Narew Society for Environmental Protection, Narew National Park, Department of Physics of University of Warsaw and Warsaw Agriculture University for their help in field studies.


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