Hydraulic characteristics of constructed wetlands evaluated by means of tracer tests

Przemyslaw Wachniew[1], Piotr Czuprynski[1], Piotr Maloszewski[2],

[1]AGH University of Mining and Metallurgy, Mickiewicza 30, 30-059Krakow, Poland; wachniew@ftj.agh.edu.pl [2]GSF-Institute of Hydrology, Neuherberg, Germany

Use of tracers and mathematical modelling for evaluation of hydraulic characteristics of constructed wetlands is presented for two case studies representing two most common in Poland types of treatment wetlands: subsurface-flow system with *Phragmites* in Nowa Slupia *australis* and *Lemna* pond in Mniow. Instantaneously injected bromide and tritium were used to obtain residence time distributions (RTD) of wastewater in those wetlands. Flow components were identified and their hydraulic characteristics were derived from RTDs by fitting of the analytical solution of one-dimensional advection-dispersion equation to the experimental data.

1 Introduction

Knowledge of hydraulic properties is a prerequisite for studies of constructed wetlands functioning (WACHNIEW & ROZANSKI 2002). Hydraulic processes influence contaminant removal in wetlands in many ways and some aspects of these relationships remain undescribed. Efficiency of contaminant removal in wetlands is primarily related to the extent of contact between wastewaters and the reactive surfaces (substratum, plants, detritus) on which purification processes occur. Zones of stagnant flow as well as preferential and bypassing flows limit the opportunity for this contact. Apparent dispersion of solutes in wetlands is connected with various mixing and transport phenomena which can also influence wetland performance through redistribution of contaminants, oxygen and other gases and heat. In sub-surface flow systems mixing is related to physical phenomena that are specific for flow in porous medium while in ponds mixing is due to heat and momentum transfer and water density changes. Tracer technique is a valuable tool used to gain insight into wastewater flow phenomena in constructed wetlands. Examples of use of tracers to study hydraulics of constructed wetlands concern: mixing in wetlands (KADLEC 1994), influence of substratum clogging on transit times in gravel cells (TANNER ET AL. 1998), influence of pond properties on flow patterns (NAMECHE & VASEL 1998), testing of flow models (WERNER & KADLEC 2000). Residence time distribution (RTD) obtained as a breakthrough curve of a non-reactive tracer carries synthetic information on wetland hydraulic properties. Quantitative wetland characteristics are derived with help of an assumed model of wastewater flow. Use of tracers in studies of constructed wetlands is generally discussed by WACHNIEW & ROZANSKI (2002) and this work presents evaluation of hydraulic properties based on RTDs obtained in case studies representing two most commonly applied in Poland types of constructed wetlands: subsurface flow (SSF) systems and free water surface systems (FWS). The former type is represented by a gravel bed with common reed and the latter by a duckweed pond.

2 Study sites

2.1 Nowa Slupia

The constructed wetland system is located in the region of the Holy Cross Mountains (21°05' E - 50°52' N) at 250 m a. s. l. with an annual mean temperature of 8 ^{o}C and annual precipitation of 700 mm. It was built in 1995 in order to treat municipal wastewaters from both the Nowa Slupia sewage system and from septic tanks that are not connected to the sewage system. The wetland serves about 1500 inhabitants. The designed average diurnal flow rate to this system is 325 m^3/l and peak diurnal flow rate is 449 m^3/l.

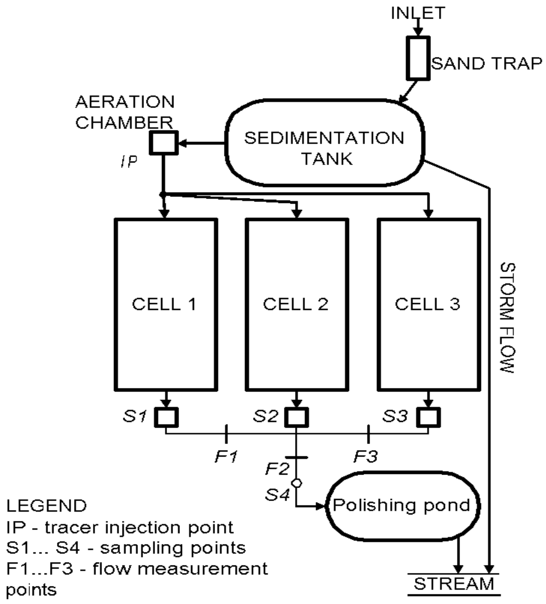

Figure 1: Constructed wetland system in Nowa Slupia.

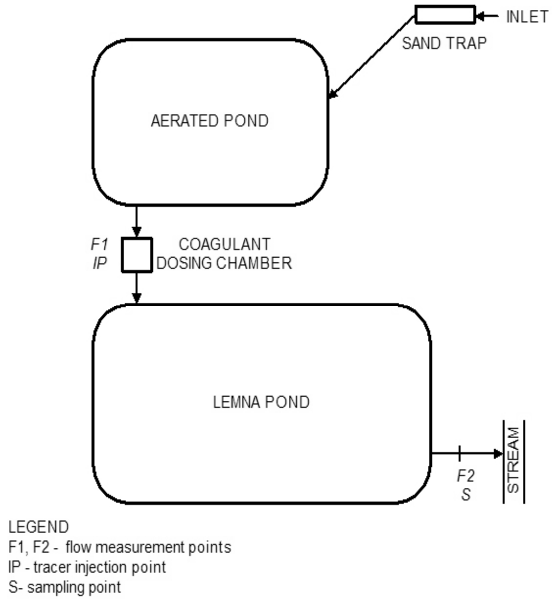

Figure 2: Wastewater treatment system in Mniow.

This subsurface horizontal flow system consists of three parallel gravel cells (78 m x 24 m x 1.2 m each), overgrown with common reed (*Phragmites australis*). Wastewaters are distributed across the width of each cell through perforated pipes. The cells have slope of 1% and are lined with 1 mm polyethylene. The wetland is flooded every spring to prevent growth of plant species other than *Phragmites australis*. The reeds are not harvested after the vegetation period. A sedimentation pond and an aeration tank provide primary treatment. Polishing pond (volume of 750 m^3) is used as a final treatment stage. Diagram of Nowa Slupia constructed wetland showing points of discharge measurements, tracer injections and sampling is presented in Fig. 1.

2.2 Mniow

The wastewater treatment plant is located west of the Holy Cross Mountains (20°29' E - 51°01' N) at 264 m a. s. l. with an annual mean temperature of 8 ^{o}C and annual precipitation of 700 mm. It was built in 1993 in order to treat municipal wastewaters from both the Nowa Slupia sewage system and from septic tanks that are not connected to the sewage system. The designed average diurnal flow rate of this system is 150 m^3/l and peak diurnal flow rate is 200 m^3/l. The treatment system consists of two ponds in series. First pond is aerated, second pond is free water surface constructed wetland with free-floating plants of the *Lemnaceae* family. The aerated pond and the duckweed pond have areas of 0.2 ha and 0.26 ha and depths of 3 m and 2.4 m, respectively. Floating plastic barriers are used in the second pond for control of duckweed. In order to remove phosphorous, especially in winter period, coagulant dosing chamber was constructed between the two ponds. Wastewaters leave the chamber through a pipe whose outlet is below the water surface in the duckweed pond. Diagram of Mniów wastewater treatment plant showing points of discharge measurements, tracer injection and sampling is presented in Fig. 2.

3 Tracer tests and estimation of hydraulic characteristics

Bromide ions (Br^-) injected in form of KBr solution were used as a tracer in all tests. In two cases tritium was used simultaneously with Br^-. Bromide is a commonly used tracer of water flow in environmental studies, including studies of constructed wetlands (WACHNIEW & ROZANSKI 2002) but there is some evidence of its nonconservative behaviour in wetland environment. Some studies suggest that bromide is taken up by plants (KUNG 1990; WHITMER et al. 2000). The question of bromide conservativity was addressed in this study by simultaneous use of bromide and tritium what allowed for comparison of their behaviour in the studied wetlands (see discussion below). Tritium constitutes a part of water molecule and as such is an ideal tracer of water flow. Tritiated water is generally not taken up selectively in any of physical, chemical

Table 1: Characterisitics of tracer tests in Nowa Slupia wetland.

Test	**Amount of KBr (Br-) in kg**	**Average outflow from cells (1; 2; 3) in l/s**	**Test duration in hours**	**Number of samples from each cell**
I - July 2001	30.0 (20.2)	1.6; 1.2; 1.4	94	36
II - November 2001	24.9 (16.7)	0.8; 0.6; 0.4	369	45; 45; 47
III – June - July 2002	24.0 (16.1) 25 mCi of ^3H	0.9; 0.7; 0.3	1013	39; 39; 38 50; 51; 53 (^3H)

Table 2: Characteristics of tracer tests in Mniow wetland.

Test	**Amount of KBr (Br-) in kg**	**Average outflow in l/s**	**Test duration in days**	**Number of samples from each cell**
I – June -September 2001	20.1 (13.5)	3.0	74	52
II – June - October 2002	24.9 (16.7) 25 mCi of ^3H	3.4	111	37 46 (^3H)

and biological processes that occur in wetlands. It is lost from wetland through the evapotranspirative pathway but tritium fractionation associated with this process is negligible. Bromide tracer was injected after dissolution of KBr in 80 l of wastewaters. This volume was necessary to completely dissolve required amounts of KBr. Due to low flow rates and technical difficulties injection of this amount of tracer solution in a strictly instantaneous manner was not possible. Injections were completed over 10 minutes in Nowa Slupia and 30 minutes in Mniow wetland. Given water transit times in both wetlands (see below) this mode of injection can be considered as practically instantaneous. The effluent was collected manually and discharges were measured at the same time by means of a calibrated vessel and stopwatch. Samples were collected to 0.2 l plastic bottles and stored in ambient temperatures.

Bromide concentrations in effluent samples were determined in the laboratory by use of bromide ion selective electrode with AgBr/AgS membrane (WTW Br 501), reference Ag/AgCl electrode (WTW R 502) and temperature probe (WTW TFK 325/HC). Electromotive forces and solution temperatures were measured by pH/mV meter (WTW pH 340/ION-SET). Calibration of the electrode with solutions containing known concentrations of bromide was not possible because of different ionic compositions of wastewaters and standard solutions and because of the presence of interfering ions in wastewaters (e. g. NH_4, HS^-, Cl^-). $Ni(NO_3)_2$ solution was added before measurements to remove sulphide ions from samples. The double standard addition method (CAMMANN 1973) was applied to derive bromide concentrations from electromotive force measurements. In this method electromotive force is measured three times: firstly for the sample with unknown concentration of Br- and then after each of two additions of a standard solution containing known concentration of bromide. Concentrations of bromide were calculated on the basis of the Nernst equation. Reproducibility of the method was 15% for background concentrations of bromide (ca. 0,8 mg/l) and less than 2% for concentration of bromide at the peak of breakthrough curves (ca. 25 mg/l). Tritium activities were measured by liquid scintillation spectrometry following standard procedures.

3.1 Nowa Slupia

Three tracer tests were performed in July 2001, November 2001 and June-July 2002. Bromide was used in all tests and in June 2002 tritium was injected simultaneously with bromide. Tracers were injected through the outflow pipe from the aeration chamber (IP in Fig. 1). Discharges were measured during all tests at points F1, F2, F3 (Fig. 1). Flow rates measured at points F1 and F3 corresponded directly to discharges from the respective cells. Discharge from cell 2 was calculated by subtraction of discharges from cells 1 and 3 from the total flow rate measured at point F2. In July 2001 only composite samples of the effluent were collected at point S4 (Fig. 1). Those samples represented the total outflow from the wetland. During two other tests effluents from each cell were sampled at points S1, S2 and S3. Table 1 presents information on amounts of injected tracers, average discharges, tests duration and sampling frequency.

Table 3: Hydraulic characteristics of Nowa Slupia wetland based on results of July 2001 tracer test.

flow component	mean transit time [h]	dispersion parameter	water volume [m^3]
I	25	0.03	95
II	40	0.02	175
III	74	0.02	635

Table 4: Hydraulic characteristics of Nowa Slupia wetland cells based on results of November 2001 and June – July 2002 tracer tests.

November 2001				June - July 2002		
Mean transit time [h]	dispersion parameter	water volume [m^3]		mean transit time [h]	dispersion parameter	water volume [m^3]
65	0.17	95	Cell 1	71	0.06	130
177	0.05	140	components	156	0.04	95
339	0.01	190		390	0.07	200
69	0.12	65	Cell 2	82	0.09	65
156	0.05	150	components	244	0.06	245
339	0.01	140		709	0.04	530
98	0.18	70	Cell 3	43	0.06	10
195	0.04	55	components	130	0.08	55
325	0.01	110		520	0.15	355

3.2 Mniow

Two tracer tests were performed in June - August 2001 and June – September 2002. Bromide was used in all tests and in June 2002 tritium was injected simultaneously with bromide. Tracers were injected into the coagulant dosing chamber (IP). Flow rates were measured at inlet and outlet at points F1 (inlet) and F2 (outlet). Discharges, water level in the pond and precipitation were measured daily in the morning. Table 2. presents information on amounts of injected tracers, average flow rates at outflow, tests duration and sampling frequency.

3.3 Estimation of hydraulic characteristics

Analyses of the obtained RTDs were based on an assumption that transport of wastewaters in both systems can be described by one-dimensional advection-dispersion equation. Solution of this equation in case of instantaneous injection and detection in fluid flux is given by the following equation (KREFT & ZUBER 1978):

$$C(x,t) = \frac{A}{Q}\frac{x}{\sqrt{4\pi D t^3}}\exp\left[-\frac{(x-Ut)^2}{4Dt}\right] \qquad (1)$$

where: C - tracer concentration, A – amount of tracer, Q – discharge, x - distance from injection point, D- dispersion coefficient, t - time from injection and U – mean water velocity. RTDs obtained in tracer tests correspond to solution (1) for a fixed distance from injection point corresponding to the sampling point. Preliminary values of mean transit time of tracer $\tau = x/U$ and dispersion parameter $P_D = D/Ux$ are calculated for the outlet point by the method of moments. These estimates are used as starting values for the fitting procedure by which equation (1) is iteratively fitted to the experimental RTD. Finally the procedure gives values of: τ, U, P_D and volume of mobile water in the system $V_m = \tau Q$ which can be compared to the nominal volume of water in the system in order to check for the occurrence of zones of stagnant flow.

4 Results and discussion

4.1 Nowa Slupia

Tracer recoveries calculated for each cell are roughly proportional to the respective discharges so the three flow components can be identified with separate cells. Components I, II and III correspond to cells 3, 2 and 1, respectively. Total volume of mobile water in the wetland is 905 m^3 what corresponds to 13% of the total wetland volume.

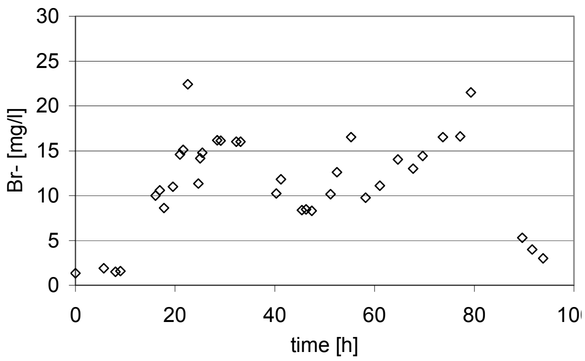

Figure 3: Bromide concentrations in outflow from Nowa Slupia wetland, July 2001.

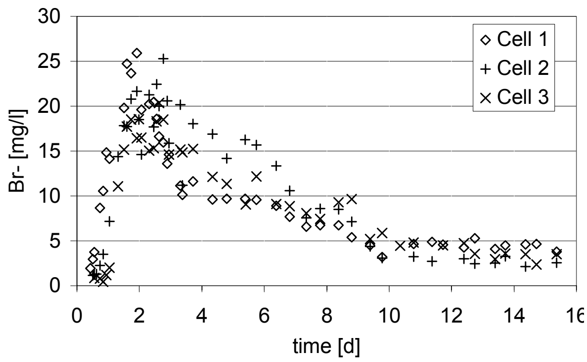

Figure 4: Bromide concentrations in outflow from Nowa Slupia wetland, November 2001.

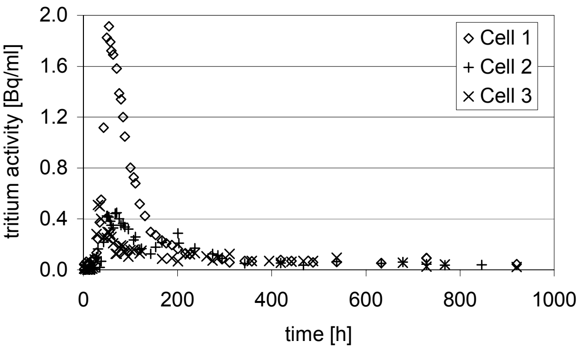

Figure 5: Tritium activities in outflow from Nowa Slupia wetland, June 2002.

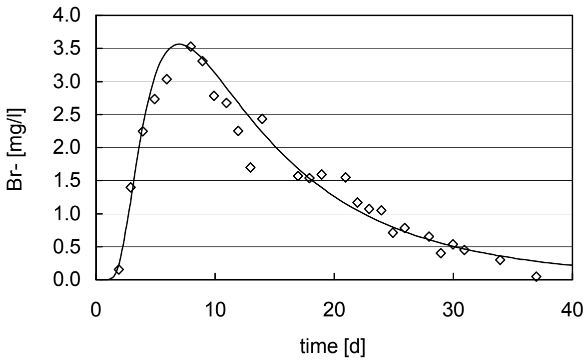

Figure 6: Bromide concentrations in outflow from Mniow wetland and the fitted curve, June – August 2001.

Figs 4 and 5 show breakthrough curves obtained separately for each cell in November 2001 and June – July 2002, respectively. Shapes of curves in Fig. 4 suggest that they might be a superposition of several components. Indeed, three flow components were identified in each of RTDs by sequential fitting of equation (1). Each of RTDs obtained during the 2002 test could be also separated in three components. Table 4 summarizes hydraulic characteristics derived from RTDs obtained during these two tests. Total volumes of mobile water vary between 235 to 840 m^3 what corresponds to 3 to 12% of the total wetland volume. Tables 3 and 4 show that three identical cells of the Nowa Slupia wetland reveal significant differences in their hydraulic properties. Moreover, hydraulic properties of each wetland cell changed over one year of observations. Differences between cells might result from differences in hydraulic loadings. Visual inspection of cell surfaces in summer 2002 revealed occurrence of bypassing flows and partial inundation of cells. These unfavourable from the viewpoint of wetland performance phenomena might be caused by clogging of the substratum with organic matter (TANNER ET AL. 1998; TANNER & SUKIAS 1998) and by operation practices (intentional flooding of cells). Correspondence between the above mentioned factors and quantitative hydraulic characteristics of wetland cells is, however, not obvious and requires further examination.

Results presented in Table 4 are arithmetic means of estimates based on tritium and bromide RTDs. It must be noted that tritium and bromide breakthrough curves have the same shapes and estimates of hydraulic characteristics based on both tracers agree within 10%. These findings suggest that behaviour of bromide tracer in the environment of constructed wetlands is similar to behaviour of tritium which is considered as the ideal tracer of water flow. Close correspondence of bromide and tritium breakthrough curves proves also reliability of the applied methodology of bromide concentration measurements by use of ion selective electrode.

4.2 Mniow

Fig. 6 presents results of the first tracer test performed in Mniow wetland in June – August 2001. Bromide concentrations are plotted together with a curve fitted to them. Following hydraulic characteristics were estimated: mean transit time – 15.8 days, dispersion parameter – 0.3, volume of mobile water – 3900 m^3. Actual volume of the pond is 5100 m^3 so 24% of pond volume was not active in throughflow. Second tracer test performed in Mniow with bromide and tritium in 2002 gave very flat breakthrough curves with low peak concentrations of tracers. This unexpected response of the system resulted from density effects associated with injection of high density solution of KBr to the pond. Fig. 7 presents plots of bromide concentration in three cross-sections three weeks after injections. These plots were obtained by extrapolation of bromide concentrations measured in six depth profiles. Locations of cross-sections and depth profiles are shown in the sketch. Cross-sectional activities of tritium show very similar picture with apparent vertical stratification of tracer in cross-section A. Tritium became attached to KBr solution because both tracers were injected simultaneously after dilution in the same volume of water. Development of density effects in constructed wetland ponds is favoured by flows characterized typically by low Reynolds numbers (SCHMID ET AL. 2003). Cross sections of bromide concentration presented in Fig. 7 show also general flow pattern in the pond and indicate possible zones of stagnant flow. Surprisingly the first test in Mniow was apparently not influenced by density effects despite the fact that KBr solutions of similar densities were injected in case of both tests. In June 2001 tracer was injected during passage of an atmospheric front which brought significant drop in air temperature, rain and strong wind. The meteorological phenomena could induce vertical mixing in the pond preventing formation of stable salt solution layer.

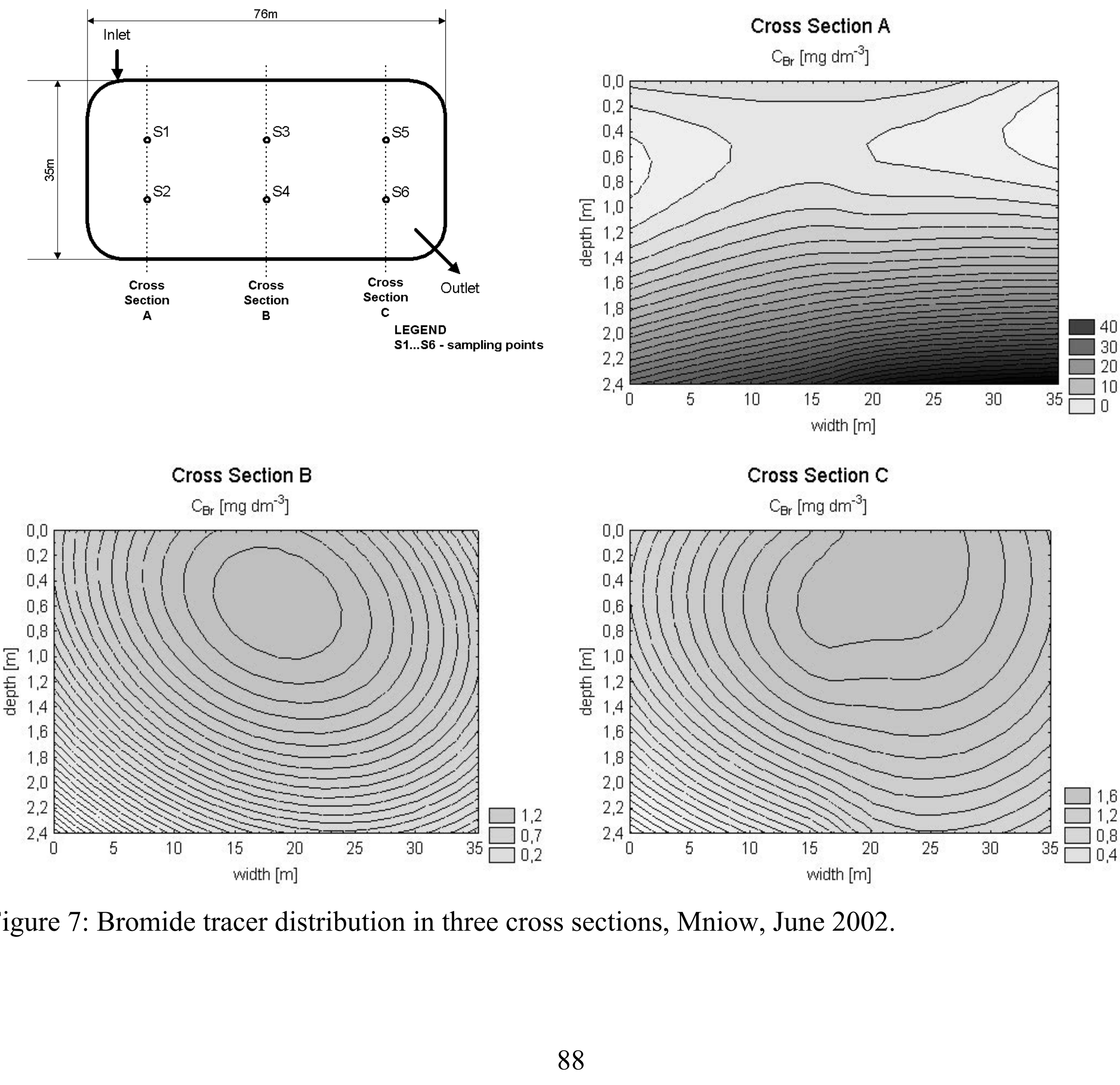

Figure 7: Bromide tracer distribution in three cross sections, Mniow, June 2002.

5 Conclusions

1. Bromide and tritium proved equally useful as tracers of wastewater flow in objects representing two types of constructed wetlands: the subsurface flow system with common reed and the free water surface system with duckweed.
2. Ion selective electrode can be used for reliable measurements of bromide concentrations in wastewaters.
3. Possibility of density effects must be considered when dissolved salts are used as tracers in ponds.
4. Wastewater flow through each of gravel cells of the Nowa Slupia wetland is apparently a superposition of three components. Their physical interpretation requires further studies.
5. Three identical cells of the constructed wetland reveal large degree of variability in quantitative hydraulic characteristics which might be related to uneven distribution of wastewaters between the cells and/or to other hydraulic phenomena like bypassing flows and inundation of cell surfaces with wastewaters.

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