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Original Research

Hydraulic Characteristics of a Wastewater Treatment Pond Evaluated through Tracer Test and Multi-Flow Mathematical Approach

P. Małoszewski[1]*, P. Wachniew[2], P. Czupryński[2]

[1]GSF-Institute of Groundwater Ecology, D-85764 Neuherberg, Germany
[2]AGH-University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland

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Abstract

Use of tracers and mathematical modelling to evaluate of hydraulic characteristics of constructed wetlands is presented for a duckweed pond in Mniów, Poland. Instantaneously injected bromide was used to obtain residence time distribution (RTD) of wastewater in that wetland. Flow components were identified and their hydraulic characteristics were derived from tracer concentration curve measured in the outflow by partial fitting of the analytical solution of one-dimensional advection-dispersion equation to the experimental data. The modelling has shown that the wastewater flows along three different flow-paths to the exit. The mean weighted transit time obtained from modelling of tracer data combined with measured mean flow rate of waste water yields the volume of wastewater in the pond.

Keywords: duckweed pond, tracer test, constructed wetland, mathematical modelling, multi-flow dispersion model.

Introduction

Duckweed (Lemna) ponds are an example of wastewater treatment solutions which become increasingly popular worldwide as cost-effective alternative to traditional treatment plants. Wastewaters are purified in these ponds through the combined action of physicochemical and biological processes with an essential role of free-floating duckweeds which cover whole pond surface. However, many aspects of duckweed ponds functioning are not fully understood (see review in [1]). Efficiency of contaminant removal depends primarily on the time the wastewater spends in the treatment system and during which has the opportunity to undergo purification. The theoretical, or expected, wastewater transit time defined as a ratio of pond volume to wastewater flow rate is often significantly different from the actual transit time which can be evaluated by means of tracer tests. Such a discrepancy may be due to retardation of wastewaters in zones of stagnant flow and to the occurrence of preferential and bypassing flows. Pond performance depends also on internal redistribution of contaminants, oxygen, other gases and heat which in turn is influenced by various mixing and transport phenomena related to heat and momentum transfer and to water density changes. Synthetic information on hydraulic properties of the pond both in terms of the efficient use of its volume and of mixing patterns is represented in the wastewater residence time distribution (RTD), which can only be obtained in the field test, as a breakthrough curve of a non-reactive tracer instantaneously injected into the entrance and observed in the outflow from the treatment system. Derivation of flow patterns and hydraulic parameters from an RTD must be based on an adequately chosen model which has to properly describe the solute transport.

*Corresponding author; e-mail: maloszewski@gsf.de

Table 1. Results of modeling the bromide concentration curve using multi-flow (MFDM) single-flow (DM) dispersion model. Fitting parameters for each flow-path (i) were: the mean transit time (t_{oi}); the dispersion parameter (P_D)$_i$ and the relative portion of the volumetric flow rate (p_i). The relative tracer mass recovery (RR) calculated until the 75th day was 96%.

	MFDM			DM	
	t_{oi} [d]	$(P_D)_i$ [-]	p_i [-]	t_o [d]	(P_D) [-]
Flow-path 1	15.9	0.34	0.80		
Flow-path 2	22.8	0.03	0.12	15.8	0.37
Flow-path 3	64.0	0.01	0.08		
Mean value of the transit time	20.6			15.8	

Tracer tests are commonly used to derive hydraulic properties of treatment ponds and in most cases these studies use modelling approaches and terminology developed in the chemical engineering field (e. g. [2-5]) which not always satisfactorily describes reality. The aim of this study was to evaluate hydraulic properties of the Lemna pond in Mniów based on an adequate model and to discuss the results obtained within the context of pond purification performance. One should note that duckweed ponds comprise one third of all constructed wetlands in Poland and there are significant controversies about the usefulness of this type of treatment system in Polish climatic conditions [6].

Tracer Test

The wastewater treatment system in Mniów (20°29' E - 51°01' N) consists of two ponds in series. After mechanical pretreatment municipal wastewater flow to the first aerated pond and then, through the coagulant dosing chamber, to the second pond with free-floating plants of the *Lemnaceae* family. Aluminium sulphate coagulant is used in winter periods in order to enhance phosphorous removal. 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. The duckweed pond is divided into three compartments of approximately equal volumes by floating plastic barriers. Diagram of Mniów wastewater treatment plant showing points of discharge measurements, tracer injection and sampling is presented in Fig. 1.

In summer (June-September) 2001 the tracer test with bromide injected in the form of KBr was performed. Bromide is a commonly used tracer of water flow in environmental studies, including studies of constructed wetlands [7]. Bromide tracer was injected after dissolution of 30.04 kg KBr in c. a. 80 l of wastewaters. This volume was necessary to completely dissolve the applied amount of KBr. The tracer solution was injected via the coagulant dosing chamber F1 (IP on Fig. 1) which is a concrete pool with outflow through a pipe located at the bottom. Taking into account that the total volume of the chamber F1 was of 5.5 m^3, the density increase of wastewater resulting from the injection of above mass of tracer was equal to 0.006 g/ml, which should not yield any density effects by tracer transport. Inflow of wastewaters to the duckweed pond is also located near pond bottom. Assuming that the whole volume of the chamber (F1) is well mixed the tracer needs about 30 minutes to be washed out from the chamber. Taking into account the transit time of waste water through the pond found to be about 20 days (see Table 1) the duration time of injection (less than 0.12% of the mean transit time) can be neglected and the instantaneous injection can be assumed. The effluent was collected manually at the outlet (F2 in Fig. 1) while the discharges were measured at the inlet (F1) and outlet (F2) daily at 8 a.m. by means of a calibrated vessel and stopwatch. Altogether 52 tracer samples were collected to 0.2 l plastic bottles and stored in ambient temperatures. The flow rate through the duckweed pond (Lemna Pond in Fig. 1) was controlled by the aerated pond and stayed practically constant during tracer test (Q=250m^3/d).

Another test with simultaneous injection of bromide and tritium was planned for summer 2002. The double tracer injection was performed but the test was not com-

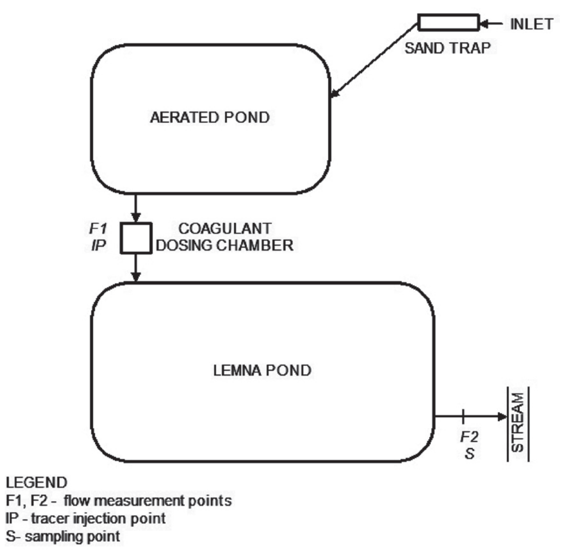

Fig. 1. Schematics of the wastewater treatment system in Mniów.

pleted because the injected tracers were retarded at the bottom of the pond due to density stratification. Density phenomena can influence results of tracer tests in ponds because flows are characterized by low Reynolds numbers [8]. Detention of tracer in the vicinity of wastewater inlet to the pond was confirmed by direct measurements of bromide concentration at six depth profiles. Bromide concentration in the inflow zone of the pond was 30 times higher at a depth of 2 m than at depths of 0 m and 1 m. We hypothesize that the tracer behaviour during the first test was not influenced by density phenomena because tracer injection was then performed during the passage of an atmospheric front which brought a significant drop in air temperature, rain and strong wind. Cooling of surface water layers could induce vertical mixing in the pond, preventing formation of stable salt solution layer.

Bromide concentrations 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 of known concentrations of bromide could not be performed due to the specific ionic composition of the wastewaters which was significantly different from ionic composition of available standard solutions. Moreover, the wastewaters contained ions interfering with Br^- at the electrode (e. g. NH_4^+, HS^-, Cl^-). The double standard addition method was applied to derive bromide concentrations from electrode electromotive force measurements. In this method the electromotive force is measured three times: first for the sample with unknown concentration of Br- and then after each of two additions of a standard solution with known concentration of bromide. Concentrations of bromide were calculated from the three measured values of electromotive force 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 peak concentrations of bromide (ca. 22 mg/l).

Evaluation of Tracer Test Results

Mathematical Model

Visual examination of the bromide concentration curve measured in the wastewater flowing out from the pond (Fig. 2) shows that the curve could be characterized by several peaks (maxima). Under quasi steady state hydraulic conditions during the experiment this effect suggests that the tracer is transported along different flow-paths. Physical meaning of this flow separation is discussed below. However, due to the fact that some apparent peaks are relatively small, one also has to consider the fact that the peaks might result from sampling and analytical uncertainties or from small unsteadiness of flow. This means that the transport along only one flow-path with or without diffusion of tracer into the dead water zones should also be taken into account. The relatively flat and confined tail of the curve as well as high recovery of bromide (about 96% after 74 days) suggest that the diffusion of tracer into the zones with stagnant water is neglectably small or the zones do not exist (e.g. [9-11]). Following the above consideration, two conceptual models shown in Fig. 3 were used for the interpretation of the tracer curve. The first, the Multi-Flow Dispersion Model (MFDM), describes tracer transport along several individual flow-paths (characterized by different water velocities and dispersivities), and the second, Single-Flow Dispersion Model (DM), assumes convective-dispersive transport along one flow path.

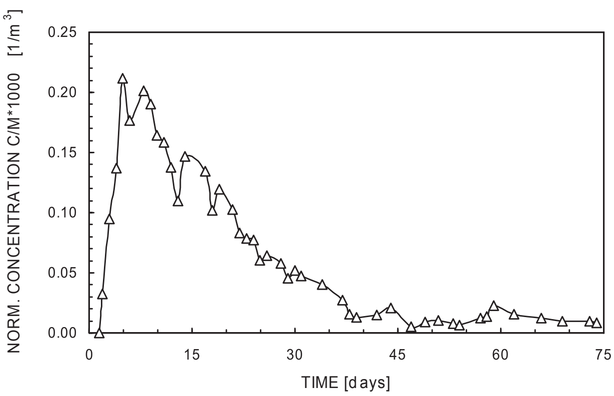

Fig. 2. Bromide concentration curve observed in the outflow from the pond in summer 2001.

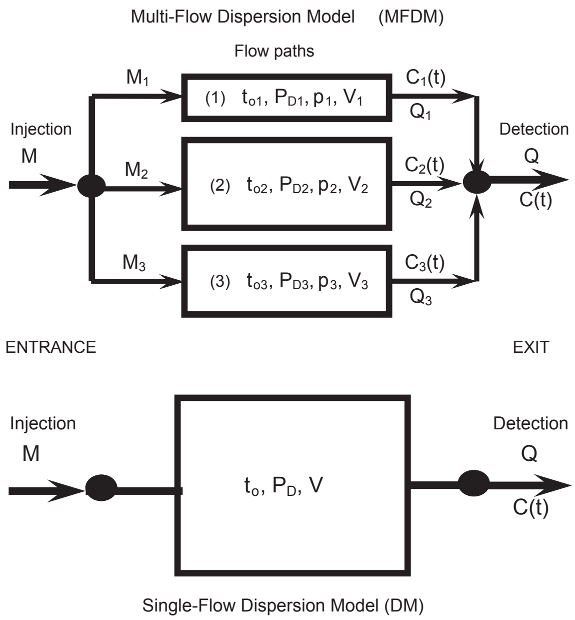

Fig. 3. The conceptual presentation of the Multi-Flow Dispersion Model (upper) and Single-Flow Dispersion Model (lower). Both models were applied for the modelling of bromide concentration curve measured during the tracer test.

The MFDM model assumes that the tracer transport between the entrance (injection site) and the exit from the pond (detection site) can be approximated by a parallel combination of 1-D dispersion-convection equations. Each flow-path is characterized by a specific volumetric flow rate (Q_i), mean transit time of water (t_{oi}) and dispersivity α_i (or dispersion parameter, P_{Di}). It is assumed that there are no interactions between the flow paths and that the whole injected mass of tracer is divided into several flow-paths proportionally to the respective volumetric flow rates. Then, the transport of an ideal tracer along the i[th] flow-path is described by the following 1-D dispersion equation [12]:

$$\alpha_{Li} v_i \frac{\partial^2 C_i}{\partial x^2} + v_i \frac{\partial C_i}{\partial x} = \frac{\partial C_i}{\partial t} \qquad (1)$$

where $C_i(t)$ is the concentration of tracer in the effluent from the i[th] flow-path, and, α_{Li} and v_i are the longitudinal dispersivity and the mean water velocity for the i[th] flow-path, respectively, x is the length of the flow-path and t is the time after injection.

The solution of (1) for an instantaneous injection (represented by Dirac-function δ(t)) in the case of the flux averaged injection and detection, which is applicable is the considered tracer test, was given by [13] and has the following form:

$$C_i(t) = \frac{M_i}{Q_i t_{oi} \sqrt{4\Pi (P_D)_i (t/t_{oi})^3}} \cdot \exp\left[-\frac{(1-t/t_{oi})^2}{4(P_D)_i (t/t_{oi})}\right] \qquad (2)$$

where Q_i is the volumetric flow rate measured in the outflow of each flow path and M_i is the mass of tracer transported along the i[th] flow-path. In the practice concentration $C_i(t)$ can not be measured. In the outflow from the system directly can be observed only the concentrations $C_i(t)_{out}$, equal to $C_i(t) \times Q_i/Q$, and the whole discharge Q, equal to $\sum_i Q_i$.

$$(P_D)_i = \alpha_{Li}/x \qquad (3)$$

while the mean transit time to [14]:

$$t_{o_i} = \frac{x_i}{v_i} = \frac{V_i}{Q_i} \qquad (4)$$

where V_i is the mean volume of water in the i[th] flow path.

The transit time for that model (MFDM, see Fig. 3) is the flux weighted mean described by the following equation:

$$(t_o)_{mean} = \sum_{i=1}^{N} p_i \, (t_o)_i = \frac{V}{Q} \qquad (5)$$

where N is the number of flow-paths, which has to be found in modeling procedure, and

$$p_i = \frac{\int_0^\infty C_i(t)_{out} \, dt}{\int_0^\infty C(t) \, dt} \qquad (6)$$

where C(t) is the concentration observed in the water flowing out from the treatment system and being the weighted sum of partial concentrations from all flow-paths:

$$C(t) = \sum_{i=1}^{N} p_i \, C_i(t) \qquad (7)$$

In equation (5) V is the whole waste water in the system equal to the sum of V_i:

$$V = \sum_{i=1}^{N} V_i \qquad (8)$$

where:

$$V_i = p_i \times t_{oi} \times Q \qquad (9)$$

The solution (7) combined with (2) and (6) is called the Multi-Flow Dispersion Model (MFDM). The fitting parameters of MFDM are: the mean transit time t_{oi}, dispersion parameter $(P_D)_i$, and the fraction of water flux (p_i) for each flow-path (i). The fitting procedure is performed stepwise by fitting one by one the partial concentration curves beginning with the earliest peak. In this way the number of flow-paths (N) will be also determined. In the present experiment N=3 was found and is shown in Fig. 4. After determining all fitting parameters the partial volumetric flow rates ($Q_i=p_i \times Q$) and the volume of wastewater in each flow-path (9) and in the whole system (8) can be easily found.

The second model, Single-Flow Dispersion Model (DM) applied here, can be easily found from equation (2), assuming one flow-path (i = 1):

$$C(t) = \frac{M}{Qt_o \sqrt{4\Pi (P_D)(t/t_o)^3}} \cdot \exp\left[-\frac{(1-t/t_o)^2}{4(P_D)(t/t_o)}\right] \qquad (10)$$

with $t_o=V/Q$.

Results and Discussion

Figure 4 presents the modelled curves fitted to experimental data according to both proposed transport models, the upper one using the MFDM and the lower one using the DM. Table 1 summarizes model parameters obtained via model calibration. The modelling accuracy was equal to $\delta_{MFDM}= 1.16 \cdot 10^{-5}$ [1/m^3] and $\delta_{DM}= 1.68 \cdot 10^{-5}$ [1/m^3], while δ/C_{max} to 0.058 and 0.084, for MFDM and DM respectively. Equation (9) combined with eq. (8) was used to derive water volume in the treatment system assuming the average flow Q equals 250 m^3/d. For the MFDM model the partial volumes of wastewater of three flow-paths are 3180, 685 and 1280 m^3, giving together the whole wastewater volume V equal to 5145 m^3. That volume represents the total hydraulically active volume of the pond. The DM model gives volume of the pond equal to V = 3950 m^3. This volume is about 25% smaller than that found by the MFDM approach. The real volume of the pond found from direct measurements of its geometry in June 2002 was 5160 m^3. The proper agreement between the geometrical volume and the result obtained from the tracer test with the MFDM model clearly supports the choice of this modelling approach. Application of the DM model with only one flow path leads to the loss of information contained in the fine structure of the breakthrough curve. Application of the inadequate model may result in serious underestimation of the mean wastewater transit time and of the hydraulically active volume of the pond. Results

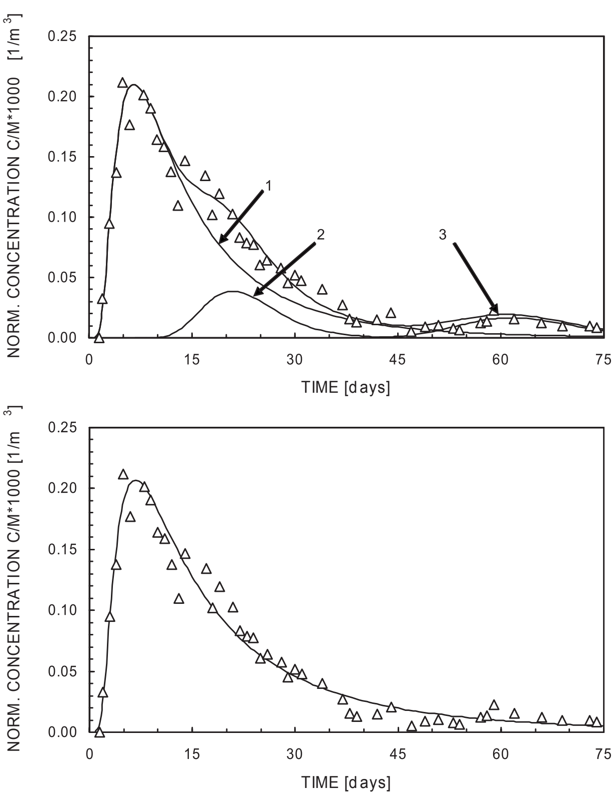

Fig. 4. The best fits of theoretical curves (heavy line) to the bromide concentrations (triangle) measured in the outflow from the pond (C/M) obtained by the calibration of the Multi-Flow Dispersion Model (upper) with three flow-paths (thin lines) and the Single-Flow Dispersion Model (lower). The concentrations (C) are normalized to the mass of tracer injected (M). The values of fitting parameters are summarized in Table 1.

of the DM model show that over 20% of pond volume comprises so-called dead zones, whose presence supposedly worsens purification capacity of the duckweed pond. However, the tracer concentration curve observed in the pond does not indicate the occurrence of dead zones because slow exchange of solutes between mobile and stagnant water zones would be reflected by the extended tail of the tracer curve and incomplete mass recovery.

Identification of three flow components through the pond might be considered surprising but one has to note that the pond is divided into three compartments by the floating barriers with relatively small apertures distributed in a manner that facilitates prolonged transit of wastewaters (Fig.5). The barriers are not tight-fitting, with the slopes of the pond creating additional contacts between the compartments. Fig. 5 presents three possible flow paths that result from the distribution of the apertures with respect to permeable barrier edges. One can suppose that flow separation at each barrier occurs between the aperture and the opposite edge of the barrier. There should be no observable separation between the aperture and the neighbouring barrier edge as they are close to each other. Significant difference between the transit times and dispersion parameters of the second and third flow components result from differences in inflow and outflow boundary conditions for each compartment. It is difficult to assign hydraulic parameters from Table 1 to the flow-paths shown in Fig. 5, except for the main flow component, without assessment of the actual velocity field. The main flow component corresponds probably to the pathway inlet – first aperture – second aperture – outlet. Existence of additional flow components in the studied duckweed pond is probably favourable from the viewpoint of pollutant removal. Generation of additional streamlines across the floating barriers improves circu-

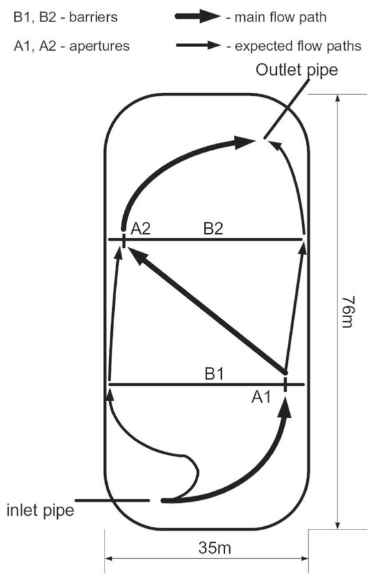

Fig. 5. Localization of apertures in the floating barriers and expected flow-paths in the duckweed pond.

lation and prevents stagnation of wastewaters in dead zones. As a result, pond volume is more efficiently used for wastewater purification.

High tracer recovery means that loss of water from the pond through seepage is negligible and that bromide can be considered a conservative tracer of flow in duckweed ponds. Tracer tests should be routinely performed in wastewater treatment ponds and in other types of constructed wetlands as they allow for relatively inexpensive evaluation of the actual hydraulic performance and its influence on purification capacity.

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