Tracer Studies for the Modelling of Sedimentation Tanks

Etudes de traceurs pour la modélisation de bassins de décantation

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RÉSUMÉ

L'écoulement dans les bassins de rétention des eaux pluviales a des conséquences majeures sur leurs performances de traitement. Une méthode de mesure et une méthode d'évaluation ont été développées pour identifier les conditions d'écoulement défavorables dans les bassins de sédimentation existants. La base de données est alimentée par des mesures d'hydrogrammes, liées à des évènements, établies à partir de traceurs. L'analyse est basée sur les fonctions de transfert connues dans la théorie des systèmes. Les paramètres du modèle permettent d'élaborer des conclusions sur les conditions d'écoulement dans les bassins. La méthode peut être utilisée pour évaluer les bassins de décantation et pour fournir des informations sur les dysfonctionnements. Elle peut également être utilisée pour tester l'efficacité des réamémagements mis en œuvre.

MOTS CLÉS

Systèmes d'assainissement, modèle d'écoulement, distribution du temps de rétention, bassin de sédimentation, étude traceur

ABSTRACT

The flow in stormwater tanks has a major impact on their treatment efficiency. A measurement method and an evaluation method was developed to identify unfavourable flow conditions in existing sedimentation tanks. The data base is provided by mobile, event-controlled measurements of tracer-based hydrographs. The analysis is based on transfer functions known in system theory. The model parameters allow conclusions about the flow conditions in the tanks. The method can be used to evaluate sedimentation tanks and to provide information on malfunction. It also can be used for testing the effectiveness of retrofitting measures that were undertaken.

KEYWORDS

Drainage systems, flow model, residence time distribution, sedimentation tank, tracer study

1 INTRODUCTION

Sedimentation tanks are used in combined and separate flow systems and road drainage. As sedimentation facilities they are suitable to reduce emissions of particulate and particulate bound substances into surface waters. The sedimentation efficiency depends to a great extent on the flow behaviour of the tanks. Tracer studies seem to be very appropriate to examine the flow behaviour of these tanks integrally. For that purpose a practical measurement and analysis method was developed.

2 LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Flow-through of tanks

The flow conditions in tanks can be described within the limits of two extremes (LEVENSPIEL [1999]). The plug flow reactor (PFR) is characterised by a dispersion- and diffusion-free flow. The transport of water particles only takes place by translation. A concentration impulse in the inlet leaves the tank only time-shifted without any other changing. A concentration impulse in a fully mixed tank (continuous stirred tank reactor, CSTR) is distributed in the tank completely right after entering the tank. Because of the increasing mixing of the tank volume with the later entered „clean“ inflow the concentration in the tank decreases exponentially.

Tracer studies to examine the flow-through conditions or to determine the residence time of flow-through tanks and wetlands were carried out inter alia by KADLEC [1994], MATTHEWS et al. [1997], THIRUMURTHI [1969], ALKHADDAR et al. [2001] and STAMOU/ADAMS [1988]. All examined systems showed deviations from ideal conditions like death zones, preferential flow and well mixed parts in the tanks. MATTHEWS et al. [1997] used their results to optimise the uniform flow-through by using baffles. The realisation was checked by tracer studies successfully after the retrofitting measure.

An ideal plug flow does not exist in sedimentation tanks. The flow in the inlet area has to adapt to change in cross-section and flow conditions very quickly. Inlet constructions should help to achieve a uniform flow (DWA-A 166 [1999]). Flow disturbances also occur in the outflow area. The deviation between the real flow and the ideal plug flow can give information about the sedimentation performance of a tank.

Several models have been used to describe the hydraulic performance of tanks and ponds. Dispersed flow models (e.g. NAMECHE/VASEL [1998],THIRUMURTHI [1969]) or tanks-in-series model (TISM) (HIGGINS et al. [1999]) were widely-used. Not all flow conditions can be described by a dispersion model or TISM. Therefore KADLEC [1994] developed a network model for wetlands. It consists of well mixed sections in series and a plug flow component.

2.2 Theoretical sedimentation efficiency

An ideal plug flow is assumed to be optimal for the sedimentation process. In this case, it is possible to calculate the efficiency η depending on the settling velocity u_s and surface load q_A of the tank according to the theory of Hazen (HAZEN [1904]):

$$\eta = \begin{cases} u_s/q_A & \text{für } u_s/q_A \le 1 \\ 1 & \text{für } u_s/q_A > 1 \end{cases}$$

Also in the second case, the CSTR, a theoretical efficiency can be calculated (FELDHAUS [1993]):

$$\eta = \frac{1}{1 + \frac{1}{u_s/q_A}}$$

Plug flow indicates considerable higher efficiency values than the well-mixed CSTR for particles with settling velocities in the same range as the surface load

3 MATERIALS AND METHODS

3.1 Concept

The sedimentation efficiency of tanks is influenced by the settling velocity of the solids and the flow field in the tanks to a great extent. The flow field can be described integrally by hydrograph of a dissolved tracer at the tank outlet. The tracer hydrograph can be measured as response of an injected tracer impulse at the inlet of the tank. The response signal of the tracer at the outflow and consequently, the tank behaviour can be described and analysed by system theoretical models.

However, it is not possible to identify the spatial distribution of the often complex flow pattern with this integral view of the tracer studies being presented in this paper. If the flow distribution within the tank is identified to be unfavourable by the tracer studies, CFD can be used for a detailed analysis of spatial flow conditions and the origins of irregularities. The results of the tracer study can be used for validation of numeric flow models as well.

3.2 Measurement Devices

Stormwater tanks are loaded corresponding to the rainfall events rather rarely. For that purpose an online measurement station with an automatically working dosing feeder and measuring system was developed. The station consists of the following components:

- Dosing feeder into the tank inlet for fluorescence tracer
- Bypass tracer measuring pipe with online probes for the tank outlet
- Control system of the measuring system

The dosing feeder consists of an opaque reservoir for the powdery tracer (fluorescein) and an event-controlled injection pump. The tracer in the reservoir is dissolved by pumped water and is then injected as pulse into the inlet stream. The tracer must be homogeniously mixed with the inlet stream. This must be tested in first studies. The tracer feed can be divided into several places in the inlet depending on the local situation.

The event-controlled bypass pump is situated at the tank outlet and is connected with the tracer-measuring pipe. The fluorescence is measured by the fibre-optic fluorometer MKT-2 (Sommer Mess-Systemtechnik, Austria). This device is equipped with excitation and emission filters for the fluorescein sodium (uranine) detection and has two fibre-optic probes. Temperature, pH-value and turbidity are measured simultaniously because these parameters have an influence on the fluorescence. The compensation of disturbances is undertaken by a specially developed, online-capable method. The tracer measuring pipe is constructed as culvert due to saving the probes against desiccation.

The measurement station is activated event-dependent by a water level sensor at the outlet. The control strategy normally includes one or two tracer measurements per event. Data management takes place on the spot. The measurement station can be monitored by online data transfer. The reservoir for the tracer is filled again with a previously precisely weighted amount of tracer after each event.

3.3 Analysis method

3.3.1 Residence time distribution (RTD)

Tracer studies of steady-flow systems can be analysed with the theory of the residence time distribution (RTD). The RTD theory is introduced in LEVENSPIEL [1999]. The RTD is the distribution of times that exiting tracer molecules have spent in a tank. However, there are generally non-steady-flow conditions in sedimentation tanks. Therefore, WERNER/KADLEC [1995] developed an approach that allows qualitative and quantitative comparisons of steady and non-steady systems. This volume based RTD included a dimensionless description of concentration and time.

A dimensionless concentration C´ can be defined as:

$$C' = \frac{C}{C_0}$$

where C is the measured tracer concentration in the outlet of the system and C_0 is a pseudo initial concentration

$$C_0 = \frac{M}{V_{sys}}$$

with M being the total mass of tracer added to the system and V_{sys} being the volume of the fluid system.

During tracer studies at non-steady conditions the theoretical residence time of the tracer is not constant due to the variable flow rate. If the flow rate declines the theoretical residence time of the tracer in the system will decrease and vice versa.

The volume V_{out} which has exited the system since the tracer was added in the inlet can be calculated with consideration of the flow rate Q:

$$V_{out}(t) = \int_0^t Q(t) \cdot d(t)$$

A normalized form of V_{out} is defined as the flow weighted time Φ

$$\phi = V_{out} / V_{sys}$$

and

$$d\phi = dV_{out} / V_{sys} \ .$$

Therefore, the flow weighted time Φ depends on the flow rate. The time is normalized according to the existing flow. As a result, concentrations of effluent at low flow rates are not overweighted. The volume based RTD using the dimensionless concentration is accordingly:

$$C'(\phi) = \frac{C(\phi)}{C_0}$$

A cumulative RTD can be defined similarly to the familiar cumulative distribution function of statistics.

$$F(\phi) = \int_0^\phi C'(\phi) \cdot d\phi$$

F(Φ) values represent the probabilities that a part of the liquid in the tank has a residence time less or equal than Φ. Conservation on mass demands $F(\Phi \rightarrow \infty) = 1$.

The volume based RTD allows comparisons between various tracer study results. The method can be used to compare tracer studies with different flow rates and tanks with different volumes. These comparisons are not influenced by fluctuations of flow rates. It can be shown that for the steady-flow case this function is transferred to the classic RTD for steady flow.

3.3.2 System theoretical flow model

Flow characteristics in tanks can be analyzed by models based on systems theory. The linear tanks-in-series model (TISM) is defined by the number of tanks N in series and the mean dimensionless residence time per tank $\overline{\theta}_i$. This model enables a very variable modelling of the system response of RTD. A one-tank-model with N=1 represents a continuous stirred-tank reactor (CSTR). On the other hand $N \rightarrow \infty$ represents a plug flow reactor (PFR). Intermediate forms of the system behaviour are represented by tank numbers $1 < N < \infty$. Ideal plug flow can also be calculated as deformation-free time shift of the input impulse (pure translation).

Real tanks can have several zones with different flow through characteristic. This system behaviour can be modelled with parallel tanks-in-series models which included two or more parallel tank series.

In figure 1 is displayed the compartment model which was used in this study to analyse the RTD. The corresponding equations are given in table 1. Five parameters are available to enable a flexible fitting of the model to a measured tracer response signal or RTD. It is advisable to use the RTD for calibration. The parameters were optimized with the software KALIMOD (LWW; Muenster University of Applied Sciences). KALIMOD uses the shuffled complex evolution (SCE) algorithm. The target function is to minimise the sum of least squares between the measured and modelled RTD.

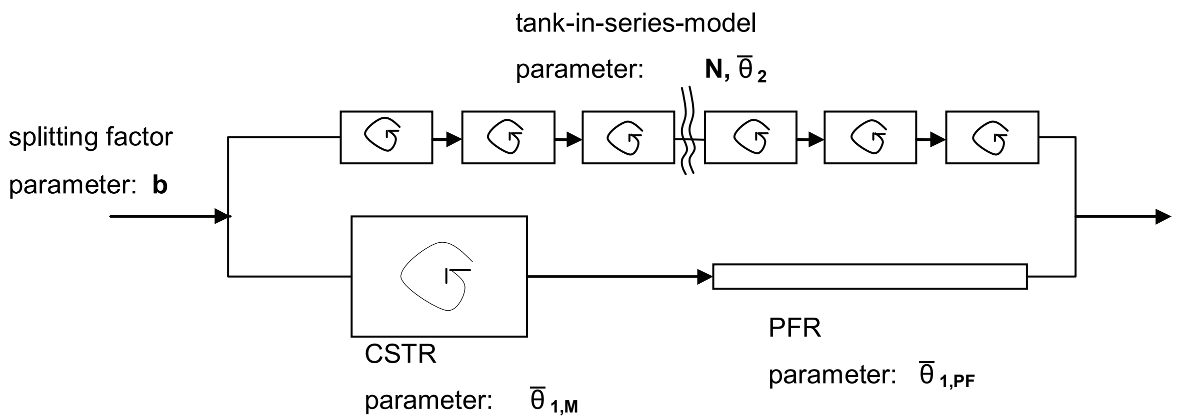

Figure 1: Developed model for tanks in series

model	equation	parameter
complete model	$C'(\phi) = C'_1(\phi) \cdot b + C'_2(\phi) \cdot (1-b)$	b splitting factor
TISM	$C'_2(\phi) = \frac{1}{\overline{\Theta}_2} \cdot \frac{N^N}{(N-1)!} \cdot (\phi/\overline{\Theta}_2)^{N-1} \cdot e^{-N \cdot \phi / \overline{\Theta}_2}$	N number of tanks $\overline{\theta}_2$ mean dimensionless residence time of TISM
CSTR + PFR	$C'_1(\phi) = \begin{cases} 0 & \text{for } \phi < \overline{\Theta}_{1,PF} \\ \frac{1}{\overline{\Theta}_{1,M}} \cdot e^{-(\phi - \overline{\Theta}_{1,PF})/\overline{\Theta}_{1,M}} & \text{for } \phi \geq \overline{\Theta}_{1,PF} \end{cases}$	$\overline{\theta}_{1,M}$ mean dimensionless residence time of CSTR $\overline{\theta}_{1,PF}$ mean dimensionless residence time of PFR

Table 1: Model equations

3.3.3 Flow indicator

The compartment model allows an analysis of the tank volume in respect to different hydraulic characteristics. The parameters of the compartment model as well as characteristic values derived out of it are used as indicator for the behaviour of tanks.

The splitting factor b shows the flow rate portion to each compartment type in the tank. Q_1 refers to the flow rate of the CSTR + PFR compartments and Q_2 to the flow rate of the TISM.

- flow rate fraction TISM $Q_2/Q = b - 1$
- flow rate fraction CSTR + PFR $Q_1/Q = b$

The arithmetical volume portions of the single element in the tank result from the flow rate portion and the mean dimensionless residence time.

- volume fraction TISM $V_2/V = (b-1) \cdot \overline{\Theta}_2$
- volume fraction CSTR $V_{1,M}/V = b \cdot \overline{\Theta}_{1,M}$
- volume fraction PFR $V_{1,PF}/V = b \cdot \overline{\Theta}_{1,PF}$

The calculated volume portions can be considered as estimation for the tank volume portion of the respective compartment type.

The mean dimensionless residence times give information about the translation and retention effect of the corresponding compartment type.

- TISM $\overline{\theta}_2$
- CSTR $\overline{\theta}_{1,M}$
- PFR $\overline{\theta}_{1,PF}$

A high number of tanks and a high residence time of the tank-in-series model clearly indicate plug flow. On the other hand low parameter values indicate short circuit currents and high dispersion. High residence times in the single tank cause a long tailing of the tracer signal. These indicate a high dispersion effect and therefore considerable secondary currents. The residence time of the translation element corresponds to the residence time which a tracer needs to be transported through the volume portion of the plug flow compartment. Low residence times point to an extensive short circuit in the tank.

The plug flow reactor offers the best conditions for high sedimentation efficiencies. A high splitting factor b, a minimum residence time $\overline{\theta}_{1,M}$ of the single tank and a high residence time $\overline{\theta}_{1,PF}$ in the translation element as well characterise good conditions for sedimentation.

3.4 Field Studies

Tracer studies were carried out on two sedimentation tanks during several months.

Tank 1 is a bypass sedimentation tank without permanent water level for treatment of rainfall runoff in a separate system. The circular shaped tank (diameter 30 m, average depth 2.45 m, volume 1730 m³) has an axial inflow with two screw pumps. The maximum surface load is 6.5 m/h. The 24 m long overflow weir is situated opposite the inlet. This construction does not meet the current state of the art in Germany and it is therefore interesting to detect hydraulic malfunctions.

Tank 2 is a CSO in bypass. The total tank volume of 10.000 m³ is divided into four compartments with same dimensions (length 52 m, width 12 m, average depth 4 m). Screw pumps are feeding the 4 chambers via a common distribution channel with a maximum surface load of 7.5 m/h. Horizontal slots in the sidewalls of the channel serve as inlets to the chambers. The clarified outflow is a free overflow weir with a scum board in front of it. The studies were only carried out on one tank at the end of the distribution channel. It was supposed that this tank has considerable disturbance of the current due to the inlet construction.

4 RESULTS

Eleven successful tracer measurements were carried out at tank 1. Eight events had constant flow rates during the main tracer flow because of the screw pumps. The surface load during these events was 6.5 m/h. By means of these events it was possible to prove the good reproducibility of the measured results. The other events had slightly lower surface loads.

Seven tracer measurements were carried out during variable inflow conditions at tank 2. The average surface loads amounted to between 2 and 4 m/h. The duration of the measurements depended on the duration of the overflow and in this case amounted to in this case between the 0.5 to 5 times of the theoretical residence time.

The recovery rate of the added tracer mass was up to 98% for sufficiently long overflow duration. During shorter overflow events the tracer doesn’t leave the tank completely so that the recovery rate is therefore lower

Figure 2 shows for example for both tanks hydrographs of the tracer and the flow.at the outlet. The graphs vary depending on overflow duration and –intensity. The system characteristics can be more appropriately described by the normalised residence time distribution (figure 3). The volume based RTD enables a better comparison of different events. Particularly, in this case the early and sharp increase of the RTD from tank 1 becomes obvious.

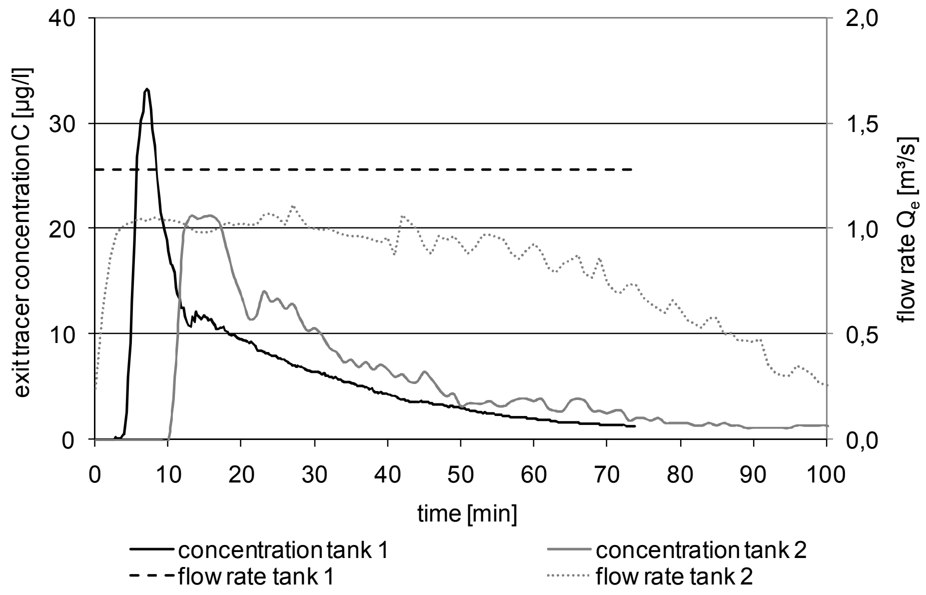

Figure 2: Exemplary tracer flow-through curves and flow rate for the two examined tanks

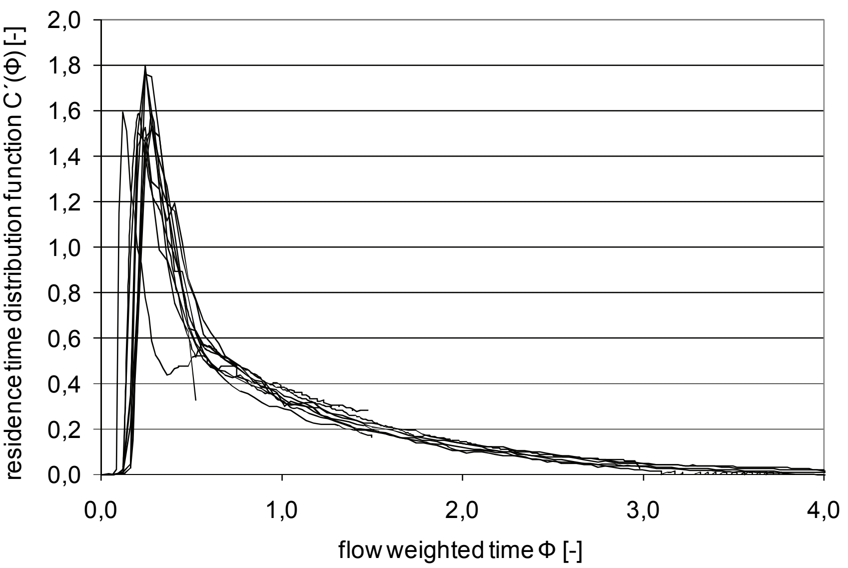

Figure 3: Volume based RTD for tank 1

5 ASSESSMENT OF THE FLOW CONDITIONS

The flow indicators derived from the flow model allows to conclude about the dominate flow characteristics of the tanks and the effective utilisation of the tank volume (figure 4).

Table 2 summarises the five calibrated parameters as well as the other flow indicators for each event. All events were taken into consideration if the main tracer flow was measured completely at the outlet. The goodness of fit of the compartment model in reference to the RTD is very good for tank 1 ($R^2 > 0.95$). The goodness of fit regarding to tank 2 is with $R^2 > 0.90$ for four events good as well. One event cannot be modelled so precisely ($R^2 > 0.83$). Figure 4 shows examples for the measured and modelled RTD.

The normalised mean residence times in the CSTR part of tank 1 are higher than in tank 2 and in the plug flow and the tanks-in-series part of tank 1 lower than in tank 2. This combination indicates short circuit currents in tank 1.

The volume distribution of the different compartments indicated short circuit too. 60 – 70 % of the tank volume from tank 1 works like a CSTR. This part of the volume is lower in tank 2 for the measured events. The high volume parts are an indication for a high dispersion in the tank.

The hydraulic efficiency rate η_{hydr} is the mean dimensionless residence time of the tracer. It is calculated from the RTD in consideration of the 2.5 times from the theoretical residence time. This value is an indicator for the hydraulic efficiency of the tanks. The volume from tank 1 is used efficiently between 70 – 80 %. For tank 2 the hydraulic efficiency rate varies between 72 and 92 %.

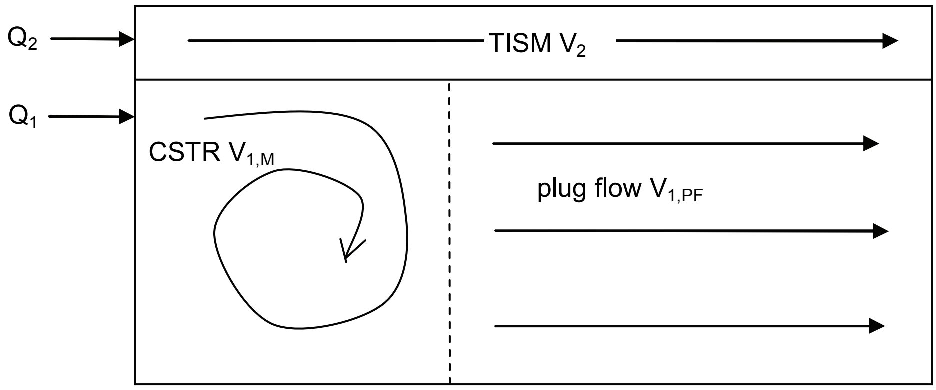

Figure 4: Mapping of volume fractions in tanks

	Q_1/Q	Q_2/Q	$V_{1,M}/V$	$V_{1,PF}/V$	V_2/V	$\overline{\theta}_{1,M}$	$\overline{\theta}_{1,PF}$	$\overline{\theta}_2$	N	$\eta_{hydr.}$	R^2
tank 1											
18.01.07	0,85	0,15	0,67	0,29	0,04	0,79	0,34	0,29	15	0,78	0,99
24.02.07	0,77	0,23	0,61	0,32	0,07	0,80	0,41	0,30	14	0,73	0,99
12.05.07	0,80	0,20	0,64	0,29	0,07	0,80	0,37	0,34	8	0,75	0,98
15.05.07	0,79	0,21	0,60	0,33	0,07	0,76	0,42	0,34	9	0,76	0,98
19.05.07	0,90	0,10	0,83	0,16	0,02	0,92	0,17	0,15	10	0,72	0,95
24.07.07	0,76	0,24	0,61	0,32	0,07	0,80	0,42	0,30	10	0,72	0,99
17.08.07	0,78	0,22	0,61	0,32	0,07	0,78	0,41	0,31	10	0,75	0,99
21.08.07	0,75	0,25	0,54	0,36	0,10	0,72	0,48	0,39	11	0,78	0,96
23.08.07	0,82	0,18	0,69	0,26	0,05	0,84	0,32	0,27	16	0,73	0,99
03.09.07	0,88	0,12	0,73	0,23	0,03	0,84	0,27	0,25	14	0,76	0,98
28.09.07	0,82	0,18	0,69	0,26	0,05	0,84	0,32	0,28	8	0,74	0,98
tank 2											
10.11.07	0,78	0,22	0,40	0,47	0,12	0,52	0,61	0,55	14	0,90	0,83
01.12.07	0,92	0,08	0,54	0,44	0,03	0,58	0,48	0,32	17	0,92	0,90
19.01.08	0,69	0,31	0,53	0,36	0,12	0,76	0,52	0,38	12	0,72	0,90
04.08.08	0,77	0,23	0,57	0,33	0,10	0,74	0,42	0,44	8	0,79	0,96
05.10.08	0,82	0,18	0,48	0,44	0,09	0,58	0,53	0,48	60	0,89	0,97

Table 2: Results of the flow model

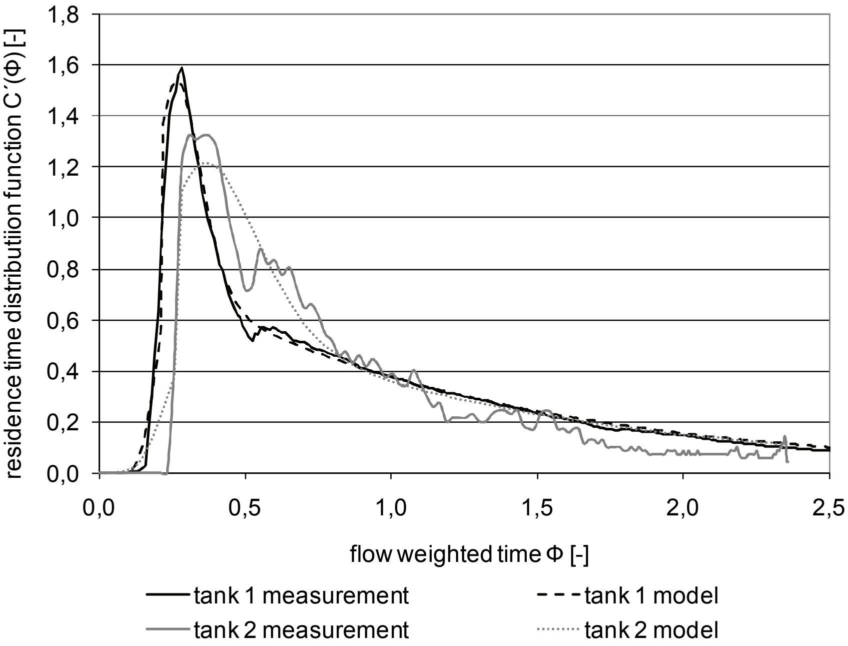

Figure 4: Comparison of experimental RTD and the fitted flow model

6 CONCLUSIONS

The presented measurement and analysis method enables a meaningful assessment of the integral flow conditions in tanks. The reliable measurement technique provided good tracer hydrographs when the overflow duration is sufficient. Requirements are a well-mixed location for the injection of the tracer and the precise measurement of the overflow rate.

The tracer hydrograph can be analysed by means of the volume based RTD. The RTD can represent the system behaviour of tanks also during non-steady conditions. The real system behaviour can be described by a systemtheoretical flow model which consists of different ideal flow models. The flow model is fitted to the measured RTD. From the resulting model parameters, conclusions can be drawn about the type and effects of the retention and flow-through processes.

The developed method is usefully applicable for the examination of existing sedimentation tanks and provides detailed information about malfunctions. Furthermore, it is suitable to test tanks after retrofitting.

7 ACKNOWLEDGEMENT

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