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EVALUATION OF THE HYDRAULIC CHARACTERISTICS AND FLOW PATTERN IN A CONSTRUCTED WETLAND BY MEANS OF TRACER STUDIES

Part 1

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SUMMARY

Hydraulic parameters were studied in a free water-surface vertical flow constructed wetland plant. The coefficients of hydraulic permeability of a typha-planted and a scirpus-planted unit were determined at different loading rates. Fluorescent dyes (uranine, pyranine and eosin) were examined for their capability to determine the mean residence time in comparison to bromide. Bromide, eosin and pyranine yielded a slight retention of approx. 10% and 15 % compared to the theoretical residence time, whereas uranine was accelerated, as our results suggest.

Key words: constructed wetlands, hydraulic conductivity, fluorescent dyes, residence time

INTRODUCTION

The effectiveness of macrophyte based biological treatment systems depends on the contact between the pollutants and the microbial population attached onto the surface of the soil particles [1]. A sufficient time of residence is required to achieve a high purification. In this study transport phenomena of pollutants passing a constructed wetland plant were examined. The objectives of our research focus on the size-characterization of the applied filling material and the behaviour of several fluorescence dyes injected into the wetland plant in comparison with bromide as a conservative tracer.

The free water-surface wetland plant located in Munich, Germany, consisted of five cascade-like arranged steel tanks planted with *Typha* ssp. (tank 1 - 3) and *Scirpus lacustris* (tank 4 and 5). The

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wetland plant (AQUAPLANT™) was supplied by the Umweltschutz Nord company in Germany. Water was fed into the first most elevated tank and passed the cascade by gravity. The total area of the cascade was approx. 27 m^2.

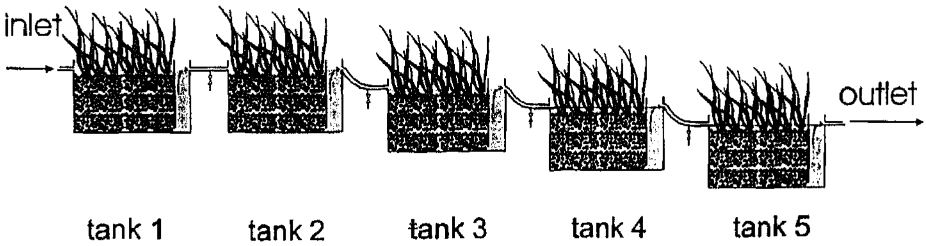

Fig. 1: Schematic view of the constructed wetland plant

RESULTS AND DISCUSSION

Hydraulic permeability

Filling material applied as substratum in the wetland plant was a coarsely graded porous lava with a nominal diameter of 2-8 mm. The particle size distribution curve (Fig. 2) exhibited a small size variability. The characteristic diameters obtained from the curve were: $d_{[10]}$ = 3.4 mm, $d_{[50]}$ = 5.1 mm and $d_{[60]}$ = 5.5 mm. The mean diameter of the lava was approx. 5 mm. The uniformity coefficient as obtained from U= $d_{[60]}/d_{[10]}$ was 1.6.

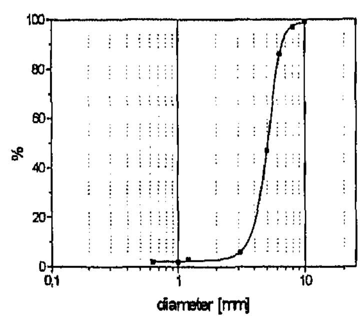

Fig. 2: Particle size distribution curve of the applied lava material

Due to a study of Beyer the coefficient of permeability can be derived from the Hazen-formula [2] as k_f= 1.34 x 10^{-1} m s^{-1}. This value coincided well with that of coarse gravel as reported by Hölting [2]. Data derived from the size distribution curve indicated a high permeability of the coarse lava material. In practice however, the hydraulic conductivity can be affected by spreading of the plant roots and soil clogging. Experiments were performed in two separated series at different hydraulic loading rates in a *typha*- and a *scirpus*-planted unit of the pilot plant to estimate the k_f-value. The experimental coefficient of permeability [m s^{-1}] using the Darcy Equation [2] is given by:

$$k_f = Q * l * A^{-1} * \Delta h^{-1}$$

Q: flow rate [m^3 sec^{-1}]
l: length [m]
A: cross-sectional aera [m^2]
Δh: difference in elevation of the water level [m]

Depending on the hydraulic loading rate and the permeability of the filling material an elevation of the water level in the planted unit against the oulet device was observed. Experimental data are given in Tab. 1.

Tab. 1: Experimental coefficients of permeability at different loading rates

tank 1 (typha)		tank 5 (scirpus)	
Q [L min^{-1}]	k_f [m s^{-1}]	Q [L min^{-1}]	k_f [m s^{-1}]
27	0.032	60	0.019
83	0.028	160	0.015
mean	**0.030**	**mean**	**0.017**

The different values within each unit (Tab. 1) at different loading rates were probably caused by misreadings of the water levels since the drop of the water level at the outlet of the tanks was fluctuating by several mm. The experimental k_f-values of approx. 3 x 10^{-2} resp. 1.7 x 10^{-2} m s^{-1} were much lower than the theoretical value obtained from the particle size distribution, indicating additional solid accumulation. As shown in Tab. 1, the permeability observed in the *scirpus*-planted unit (tank 5) was approx. 57% of that of the *typha*-planted unit (tank 1). These data confirmed our observation that in the *scirpus*-planted unit a compact root mesh was developed, creating a zone of higher hydraulic resistance. Similar effects were reported from Waters *et al.* [3] and Fisher [4].

Comparison of fluorescent dyes and bromide as tracers

In general, tracer compounds used for hydraulic experiments require a stability towards the environmental conditions in a wetland plant. Analytical methods yielding high sensitivity favor the application of dye stuffs as tracers. Fluorescence dyes are reported to be accessible to photo–

degradation, microbial attack [5] and both reversible and irreversible sorption phenomena [6]. Hence studies were carried out with bromide as a conservative tracer and three commonly used fluorescent dyes: uranine, pyranine and eosin.

The dyes were purchased from Simon und Werner, Bad Schwallbach. Fluorescent tracers were determined by spectrofluorometry using a Perkin-Elmer LS 5B fluorimeter. The analytical methods were described elsewhere [7,8]. Bromide was determined by means of ion chromatography. The tracer experiment was started in April and lasted for about 18 days. The average water temperature was approx. 11 °C. The following amounts of the tracer substances were used: Sodium bromide (10g), eosin (1g), uranin (0.5g) and pyranine (1g). Tracers (1 L aqueous solution) were applied simultaneously as pulse injection during 20 min at the inlet (tank 1) of the wetland plant. Samples were taken after defined time intervals at the outlet of tank 1 and tank 5 of the cascade by means of two autosamplers. Transit curves from tank 1 represent the time of residence in a single unit; the curves from tank 5 give the transit times of the whole cascade.

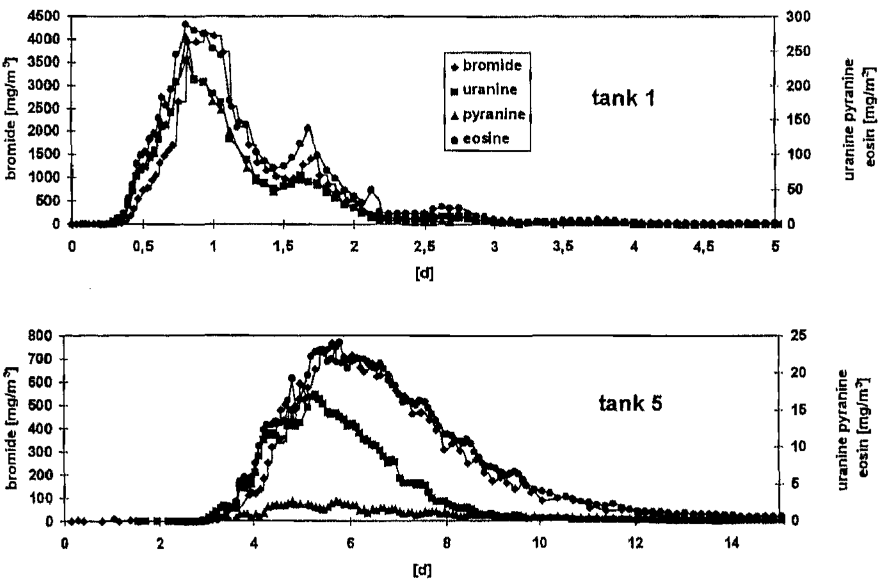

Fig. 3: Tracer response curves from tank 1 and tank 5

The tracer response curves from tank 1 exhibited no significant differences in the transit time of the injected compounds (Fig. 3). Secondary peaks as observed after approx. 1.7 days could be attributed to a slight retardation due to circulations in the flooded layer of the unit. Three days after injection the transit of all applied substances in the first tank was complete. The half-width of the curves was approx. one day, indicating a moderate dispersion.

Considering the tracer response curve at tank 5 (indicating the transit of the whole cascade) the breakthrough curves of all substances started nearly at the same time (after 3 days); but unlike bromide and eosin the maximum concentration of uranin was reached approx. one day earlier. The broadening of the tracer pulses resulted in a half-width of several days and the peak heights of the curves were considerably lower than those of the first tank.

The theoretical residence time can be calculated by dividing the net system volume by the flow rate. The porosity according to $\%P = V_p/V_t*100$ was obtained by weighing the mass difference of a defined volume of dry and water filled lava and was found to be 55%. (V_p pore volume, V_t total volume). The mean residence times were obtained from the centres of gravity of the tracer response curves. The amounts of the tracers, recovered after the passage were calculated by multiplying the area of the response curves by the flow rate.

Tab. 2: Recovery rates of the applied tracers and mean residence times in tank 1 and 5

	time of residence [d]					recovery rate [%]			
	bromide	uranine	eosin	pyranine	theoretical	bromide	uranine	eosin	pyranine
tank 1	1.19	1.15	1.3	1.13	1.2	87	49.6	75.3	51.34
cascade	6.82	5.85	7.27	6.84	6.2	78.7	13.4	29.1	2.81

With regard to a certain misreading of the experimental data no significant differences of the theoretical and experimental times of residence were observed in the first tank. In contrast, bromide and pyranine yielded a retention of approx. 10% after passage of the cascade (tank 5), for eosin the delay was at least approx. 15% of the theoretical value, whereas uranine seemed to be accelerated. The sorptive property of eosin was also reported by Netter [9], whereas no reference for an acceleration of dyes during the transit of a wetland plant was found in the literature. A marked retardation of uranine compared with bromide in a fine grading filter material was reported by Netter and Bischofsberger [10], whereas the difference was not as definite in a coarse grading material.

The low recovery rates of uranine and pyranine were assumingly due to microbial degradation [11]. A consecutive loss of approx. 50% in each of the five units would result in final recovery of approx. 3% in the outlet of the cascade. This assumption fits our finding in pyranine but not in uranine. For eosin the loss of 25% during the transit of the first tank should result in a total loss of approx. 24% and confirmed our experimental result. Recovery rates of only 87 resp. 79 % for bromide were also found during former experiments in horizontal flow wetland plants [9]. Since our hydraulic experiments were started early in the year (April) when plants were not developed an uptake of the tracer substances by the plants had not to be taken into account.

CONCLUSIONS

Our determinations of the hydraulic permeability in two different planted units confirmed some authors' statements, that a compact root mesh forming in the subsoil might decrease the hydraulic conductivity of a coarse grading soil material. A comparison of several fluorenscent dyes and bromide as a conservative tracer shows that the latter exhibited the highest recovery rate of approx. 80%. In contrast, the loss of the dyes was found between approx. 70 - 97 % after passage of the wetland plant and hence the dyes were not as suitable as bromide. On the other hand, bromide showed a slight retardation during the passage of the cascade (approx. 10%) and did not exactly reflect the time of residence of water.

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EVALUATION OF THE HYDRAULIC CHARACTERISTICS AND FLOW PATTERN IN A CONSTRUCTED WETLAND BY MEANS OF TRACER STUDIES

Part 2

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SUMMARY

Investigations of the flow distribution within a planted unit of a constructed wetland plant confirmed the expected vertical flow. During the first time after injection the tracer (bromide) mainly distributes in the flooded region (10 cm above the substratum surface) and afterwards was translocated downwards. However no uniform superficial distribution was observed. Approx. 65% of the withdrawn tracer soaked downwards in the region near to the system inlet indicating an inhomogenous load of the planted area.

Key words: constructed wetlands, residence time, tracer, flow distribution

INTRODUCTION

The gravel matrix in a constructed wetland plant provides an extensive surface area for microbial colonisation. Hydraulic short cuts as well as significant dead zones reduce the effectiveness of the biological treatment [1]. Hydraulic regime therefore has to be taken into account to avoid incomplete mixing. In part 1 of this paper the capability of several dyes and bromide as tracer substances were studied. As a result bromide was found to be a convenient tracer for investigations in wetland systems. Time dependent response curves of a tracer pulse give no full informations about the flow pattern within the subsoil of the plant. In this study the spatial distribution of a conservative tracer during transit of a single unit of a constructed wetland plant is examined.

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EXPERIMENTAL SETUP

The design of the free water-surface wetland plant was described elsewere [2]. The dimensions of a single unit are 2.5 x 2.3 x 1.2 m (length x width x height). The water is flooded up to 10 cm above the soil surface. Water enters the system at the filling level and is prompted to travel vertical downwards to the bottom of the tank where collector drains are installed. One single unit of the cascade is given in Fig. 1.

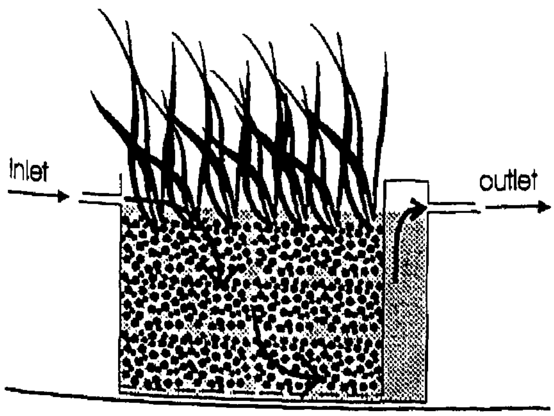

Fig. 1: Diagrammatic longitudinal section of a single tank

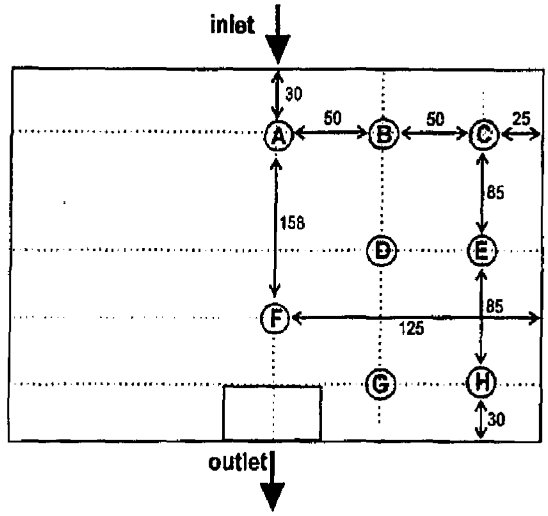

Fig. 2: Sampling scheme in the single unit; position of the sampling hosts

Sampling pipes were installed at 8 locations (superficial distribution) and in three depths (10, 50 and 90 cm) as vertical distribution and additionally in the outlet of the tank resulting in 25 sampling points. The sampling scheme with the 8 sampling hosts (A - H) each consisting of 3 steel tubes of different lengths is given in Fig. 2. Only one half of the system had to be equipped with the sampling pipes reflecting the symmetric construction of the unit.

At the start of the experiment a solution of sodium bromide (15 g in 1 L water) was injected instantaneously at the inlet of the tank during 20 min. The water flow was kept at 1 L min^{-1}. The average water temperature was 10 °C during the experiment.

From each sampling pipe water was drawn continuously by multi-channel peristaltic pumps (flow rate: 0.5 mL min^{-1}). Samples were collected after defined time intervals (20 - 60 min.) over a total period of 5 days. Altogether 2700 samples were taken in the experiment. By means of this device the spatial motion of the applied tracer within the subsoil should be observed and preferred flow paths or stagnant regions could be discovered.

RESULTS AND DISCUSSION

The tracer response curves of 9 of the 25 sampling points are given in Fig. 3. Similar transit curves were observed at the resting points, but data are not shown here.

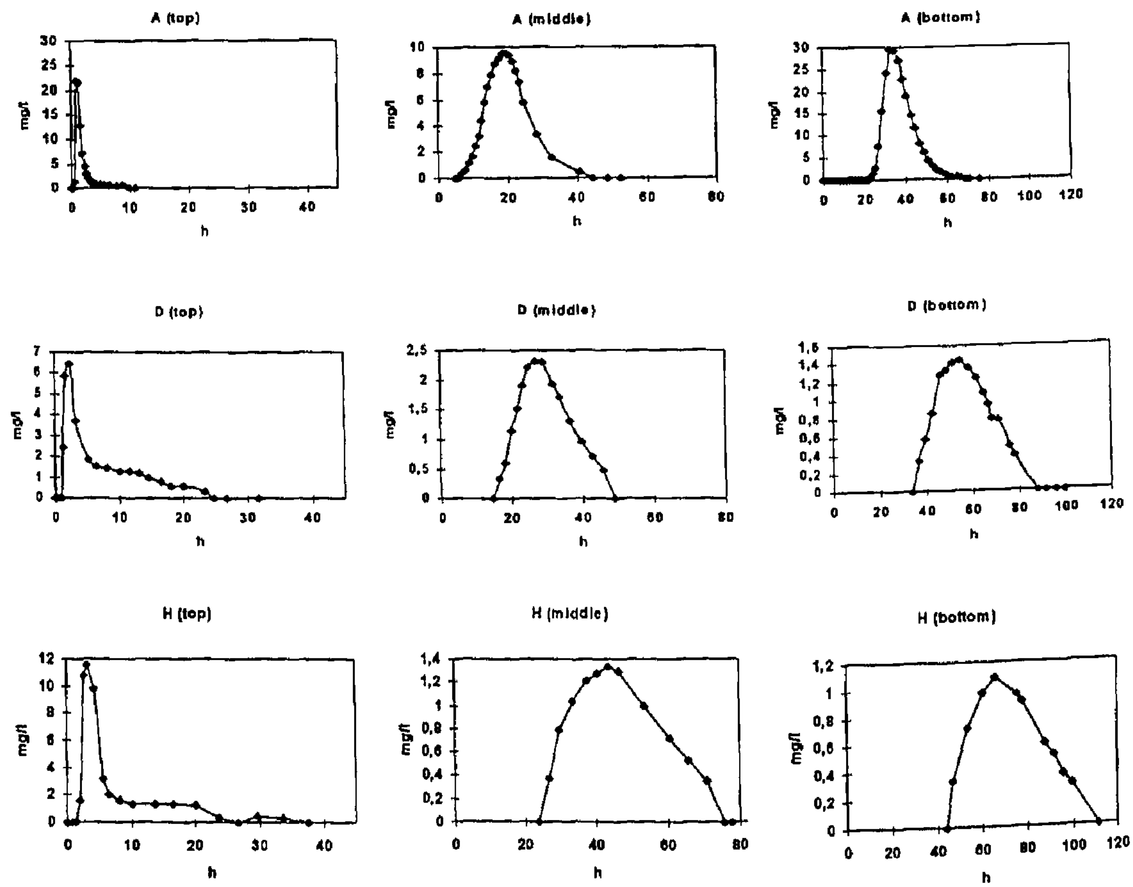

Fig. 3: Tracer response curves of 9 selected sampling sites

The observed tailing of several tracer response curves (D (top) and H(top)) might be basing on any algae or root material resting on the surface of the soil layer and by any inhomogeneity in the subsoil, for instance in the top layer (i.e. plant stems or roots) [3]. In addition wind was reported to play an important role in creating circulation patterns in open water bodies [4].

For each sampling point the mean residence time was derived from the centre of gravity of the corresponding tracer response curve. The data as shown in Fig. 4 confirmed our expectation that during the first hours after injection the tracer was mainly distributed in the free-standing water body and afterwards traveled vertical downwards to the bottom. The temporal order for the passage of each layer downwards (10, 50 und 90 cm) was strictly found at each sampling point. A slight retardation with respect to the outlet of the system was discovered at the bottom region far remote from the inlet (D, E and H). Clearly local flow patterns may be different from the average, since preferential channels provide inhomogeneities in flow distribution [3]. Similar effects were reported by Netter [5]. In summary, the supposed vertical flow in our constructed wetland system was proved.

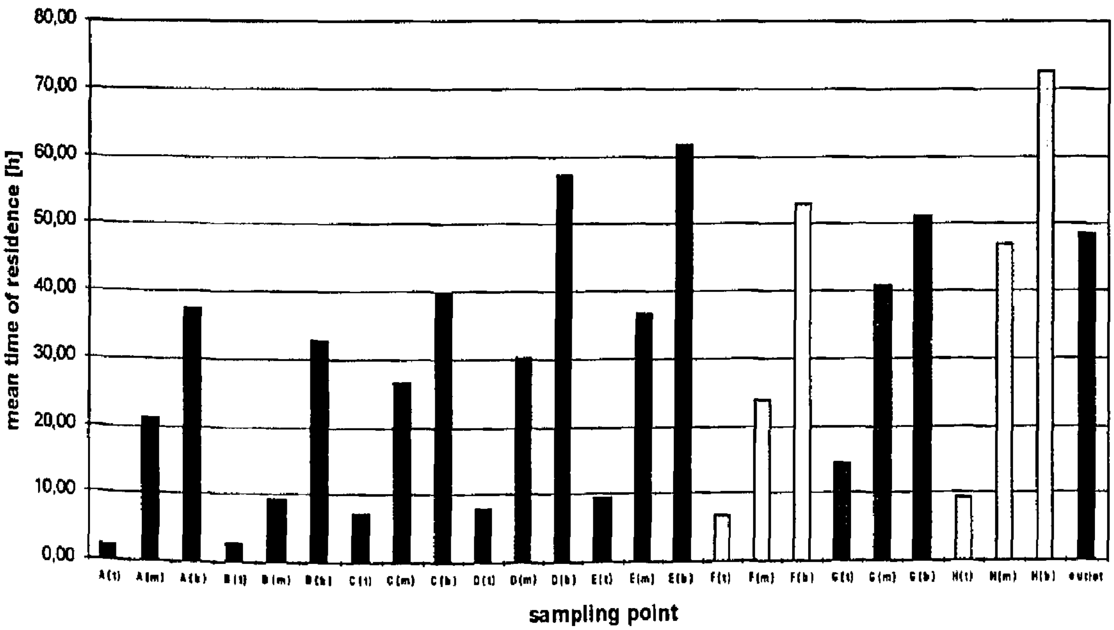

Fig. 4: Mean residence time of each sampling point of the unit (t = 10 cm, m = 50 cm, b = 90 cm)

The amounts of bromide obtained from the integrated concentration-versus-time curves indicated that approx. 65% of the withdrawn bromide was collected at the sampling points A and B near the inlet. In this region a preferred superficial pathway was discovered, probably due to the punctual inlet.

The recovery rate of bromide at the outlet of the unit was found to be 88% and hence was nearly the same value as found during the former experiment (part 1). The total amount of bromide withdrawn from the 24 sampling pipes within the bed during the sampling period was approx. 0,5% of the applied bromide (15 g) and hence gave no significant rise of the tracer loss at the system outlet. The response curve from the system outlet is given in Fig. 5. The mean time of residence as obtained from the centre of gravity was approx. 2 d. This is in accordance with the theoretically expected value.

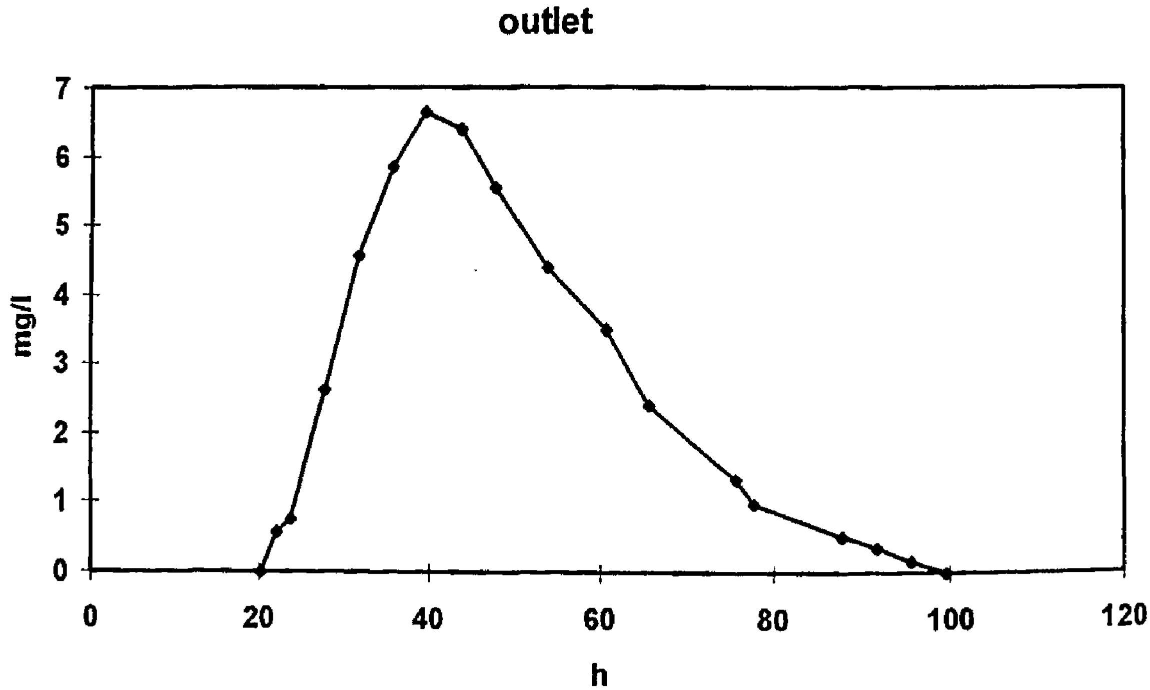

Fig. 5: Tracer response curve at the system outlet ([h] = hours)

The maximum interstitial velocities indicate that the tracer has passed the top layer within the first 2 h after injection. The time to reach the middle layer ranged from 1 up to 23 h depending on the flow distance. The average transit time to reach the bottom was found to be 15 - 42 h. Data obtained from Fig. 4 give an average interstitial velocity of approx. 2 cm h^{-1} basing on a porosity of 55%.

CONCLUSIONS

Bromide as a conservative tracer was used to examine the flow distribution and the mean flow direction in a single planted unit. The result confirmed our expectation of a vertical transport within the unit. However inhomogeneities in the superficial distribution were discovered, probably due to the point inlet. An optimized inlet system could make the biological performance more effective. Series of pipes with holes or gutters could distribute the flow more evenly.

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