FLOW AND TRANSPORT IN A CONSTRUCTED INFILTRATION SYSTEM FOR WASTEWATER TREATMENT AS CHARACTERISED BY ELECTRICAL RESISTIVITY AND 2D NUMERICAL UNSATURATED ZONE MODELLING

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ABSTRACT

Disposal of domestic sewage effluents in soil has been used for several decades in Norway and more than 100000 constructed systems for wastewater purification have been built with capacities between 5 and 8000 pe (person equivalent). However, the infiltration of wastewater effluents into soils and the estimation of application rates for a given system design and environmental setting are extremely complex and often poorly understood and oversimplified (Siegrist, 2004). The infiltration system presented here consists of 26 horizontal distribution pipes separated by 1.25 m over an area of 1100m^2. The distribution pipes are placed in a coarse stone/gravel distribution layer at about 1m depth. A pump ensures regular injection of wastewater into the system. Below the distribution layer there is a 20 cm thick layer of local natural soil, which is a coarse gravely sandy soil, followed by a 25 cm thick layer of light weight aggregates (LWA). Below the LWA layer there is natural soil and the water drains freely to the groundwater at about 5m depth. Hence the retention time and flow pattern are key factors determining whether phosphates are retained and organic components are degraded before water leaves the filter system or enters the phreatic level. In this study a combination of time lapse electrical resistivity (ER) measurements and numerical modelling of an unsaturated system have been performed in order to examine the wastewater distribution and its potential effect on flow and transport in a 2D unsaturated layered profile. Measurements were performed in June 2005. In addition to the ER measurements, an inactive tracer was applied and the breakthrough curve monitored at three depths below the constructed filter. Changes in electrical resistivity with time revealed a distribution of water coinciding with the distribution pipes. The re is some consistency between measured changes in resistivity and changes estimated from unsaturated numerical simulations. Although a forward modelling based on the simulations were not done for this paper. The difference between the simulations and the field measurements indicate that the flow and transport in the system may be non uniform over the area, hence causing preferential flow paths in the filter system.

1. INTRODUCTION

In Norway approximately one-third of the population lives in sparsely populated areas, and conventional sewer systems and treatment plants are expensive. The use of alternative treatment systems such as constructed filter systems based on saturated or unsaturated flow are often preferred. More than 100000 systems have been built for wastewater treatment in Norway. The capacities are between 5 and 8000 pe (person equivalent). The underlying processes determining flow and transport in these systems are extremely complex and are and often poorly understood and oversimplified in the designing procedures (Siegrist, 2004).The efficiency of these systems with respect to degree of purification is not always well known. The monitoring is often limited to a few sampling points. In a closed system this may be sufficient to know the overall efficiency. In an open system, however, more monitoring points are required. In an infiltration system, an unsaturated flow regime is typically a design objective as this can yield higher treatment efficiency due to aerobic conditions and larger retention times than in a saturated flow system. Although the treatment efficiency not only depends on hydraulic characteristics (Cooper, 2004), a good knowledge of wetting front advance and its spatial distribution can improve the design of filters. Overall features, such as the retention time, aren't sufficient because they don't describe the repartition of water and pollutants in soil (Molle, 2003).The presence of preferential pathways may limit the volume active in the treatment process, thus control of flow pattern is important.

In this paper we have studied the flow and transport of sewerage effluents in a typical Norwegian infiltration system designed for a small rural community of 250 person equivalents (pe). Three suction cups are installed below the studied filter system in order to monitor its efficiency, soil water samples are collected about 4 times a year, i.e. no continuous monitoring. The objective of the design, is to ensure uniform distribution of wastewater effluents over the area, however it is not possible to ascertain whether this is the case based on the installed suction cups (French et al., 2000). Time-lapse electrical surveying has proven to be useful for studying hydrogeological processes non-invasively (e.g. French et al., 2000). In this work we want to explore the possibility of using different field methods in combination with unsaturated flow and transport modelling to improve the understanding of the flow pattern in this system.

2. MATERIALS AND METHOD

The work consists of two parts, modelling and field work. Independent simulations of unsaturated flow and transport in a two dimensional transect of the infiltration system were conducted based on a priory knowledge of soil properties and the design lay-out of the system. The field work included a tracer experiment using bromide as an inactive tracer monitored by three suction cups at three different depths in order to estimate retention time and dispersivity. Time-lapse electrical resistivity (ER) measurements were conducted in order to examine the spatial distribution of waste water effluents from the distribution pipes. The results of the simulations were used to compare with the ER profiles. The tracer experiment is not reported in detail in this paper, but was used as a second dataset to verify the model.

1.1 The field site.

The field experiments took place in Åbogen, 150 km north-east of Oslo, in June and August 2005 (Forquet, 2005). It had been raining heavily for several days prior to the June-experiment. The Åbogen wastewater treatment plant was built in 1998 and was designed for 250 inhabitants with a loading rate of 50 $l/m^2/day$. At the moment, 110 persons are connected to the system and the loading rate is 12 $l/m^2/day$. The width of the infiltration system is about 25 m. The depth to the groundwater is 5 m below the surface. A groundwater well a few meters downstream from the infiltration bed is used to monitor potential releases of nutrients and organic carbon. The infiltration system consists of two infiltration beds with different filter materials. Only one of the infiltration beds is examined here. A vertical section through the filter bed has layers of different soil properties and placement of distribution pipes and suction cups is shown in Figure 1. The exact horizontal location of the suction cups is not known, but the depth beneath the filter is 0.3 m, 0.5m, and 2m accordingly. The filter consists of local gravely sandy soil, with 70-80% gravel, and a d_{10} (grain size at which 10% of particles by weight are smaller) of 0.5 to 1, the hydraulic conductivity estimated from Hazen's equation (is somewhere between 0.0058 ms^{-1} to 0.01 ms^{-1}. There are no specifications of permeability or unsaturated properties of the next layer, the distribution layer (Fig. 1). The layer consists of gravel and stones. The distribution layer is followed by a new layer of local soils, underlain by a layer of light weight aggregates (LWA), which has grain size diameters ranging from 0.5 to 4 mm.

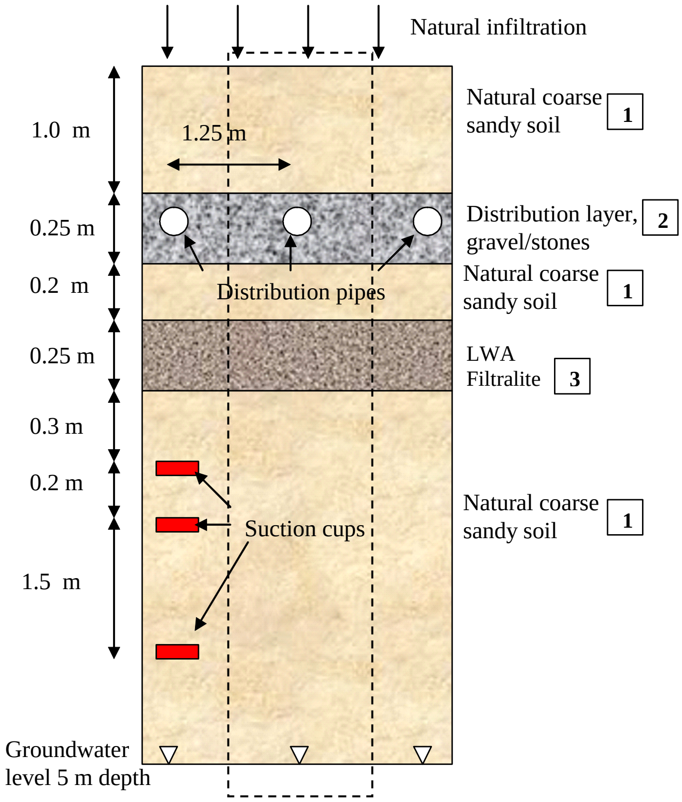

FIGURE 1. Vertical section through part of the infiltration system, with layers of different soil properties (bold), stippled part was used for verification of numerical model.

TABLE 1. Hydraulic properties of the different layers used in the numerical simulations.

Layer	no.	Reference	Porosity	Permeability	van Genuchten parameters	
			ϕ	k_s, m^2	(n)	(α) m^2/N
Natural soil	1	French et al., 2001	0.2	1.0 x 10^{-10}	2	0.0002
Gravel/stone	2		0.1	1.0 x 10^{-7}	2.95	0.00035
LWA	3	Suliman et al., 2005	0.4	3.0 x 10^{-10}	1.16	0.058

The estimated hydraulic properties, based on measurements of grain size or literature values, of the different layers are shown in Table 1, these parameters were used in the simulations.

1.2 Numerical simulations.

The finite element model SUTRA (Saturated Unsaturated TRAnsport model) by Voss and Provost (2003) was used for the numerical simulations. Parameters in Table 1, were used to define the hydraulic properties of the soil. The van Genuchten equation was used to describe the unsaturated properties and a fitting routine based on pF measurements of the similar soil types were used, as there were no values determined for this particular system. These values are reported in Table 1. To verify the numerical simulations a small section of the infiltration system was simulated (see fig. 1). Observations were made at the same depths as in the field and compared with tracer experiments (not shown). The parameters of this model were used in the wider less discretised model. The width of the large 2D vertical transect was 24 m, same as the length of the electrical resistivity measurements. The depth was 5 m, equivalent to the measured ground water level, and 0 pressure was defined along the bottom boundary of the system. The element size was 0.125 m by 0.125 m in the top 1.7 m, below the elements were 0.125 m wide and 0.25 m in the vertical direction. A longitudinal dispersivity of 0.08 m, and a transversal dispersivity of 0.008 m was defined for the whole profile. Along the top boundary and infiltration rate of 2 mmday^{-1} was defined based on meteorological data collected in the same area. At each location of the pipes, a flux boundary lasting 2 minutes, with total rate of 0.083 lsec^{-1} was defined. The relative electrical conductivity of the wastewater effluent compared to the natural soil water was used as the concentration of the injected water. The conductivity of the sewage effluent was 500 μS/cm, while the background conductivity of soil water was approximately 30 μS/cm, hence a concentration of 17 was used for the steady state injection solute. After the pulse injection a resting period of 16 hours followed. A cycle of pulse and resting periods was run until a steady state situation was realised. In order to simulate the tracer experiment, a pulse with the tracer solution which had a different electrical conductivity than the normal waster water effluent was injected (7). The simulation results were used to compare with the ER measurements. For the comparison with the ER data, resistivity values (ρ_w) were estimated from the simulated concentrations. Archie's law (see e.g. Reynolds, 1997) relates the soil's resistivity (ρ_s) to the soil's saturation (S), porosity (ϕ), and pore fluid electrical conductivity (ρ_w) as follows:

$$\frac{\rho_s}{\rho_w \phi^{-m}} = S^{-n} \tag{1}$$

where the exponents m and n in equation (1) are empirically derived constants. As the porosity is constant in the simulated system, we can derive the following equation:

$$\frac{\rho_{s,t}}{\rho_{s,t=0}} = \frac{S_t^{-n}}{S_{t=0}^{-n}} \frac{\rho_{w,t}}{\rho_{w,t=0}} . \tag{2}$$

The subscripts t=0 and t indicate conditions before and after injection of solute in the pipes. The constant n=1.5 was used for time-lapse comparisons of simulated resistvities. The changes in resistivity at increasing number of time steps from the tracer pulse injection were found by normalising each time step by the simulation results at 0.5 hours which was most similar to the timing of the ER measurements. Because homogeneous filter layers are assumed for such systems, although other studies have indicated otherwise (Suliman et al., 2005) we have chosen to simulate the layers to have uniform properties.

1.3 Electrical resistivity surveys.

The electrical resistivity measurments were conducted with Syscal-Pro (Iris instruments). A line consisting of 48 electrodes with 0.5 spacing were distributed on the surface perpendicular to the direction of the distribution pipes. A Wenner survey was applied (see e.g. Reynolds, 1997). Measurements were carried out approximately once an hour, and the initial dataset for the time-lapse survey was collected just after diluted wastewater effluent was pumped into the distribution layer. Following measurements were normalised on the first dataset. The commercial software Res2Dinv, version 3.54 (Geotomo Software), was used to invert the collected datasets.

3. RESULTS AND DISCUSSION

1.4 Results of numerical simulations

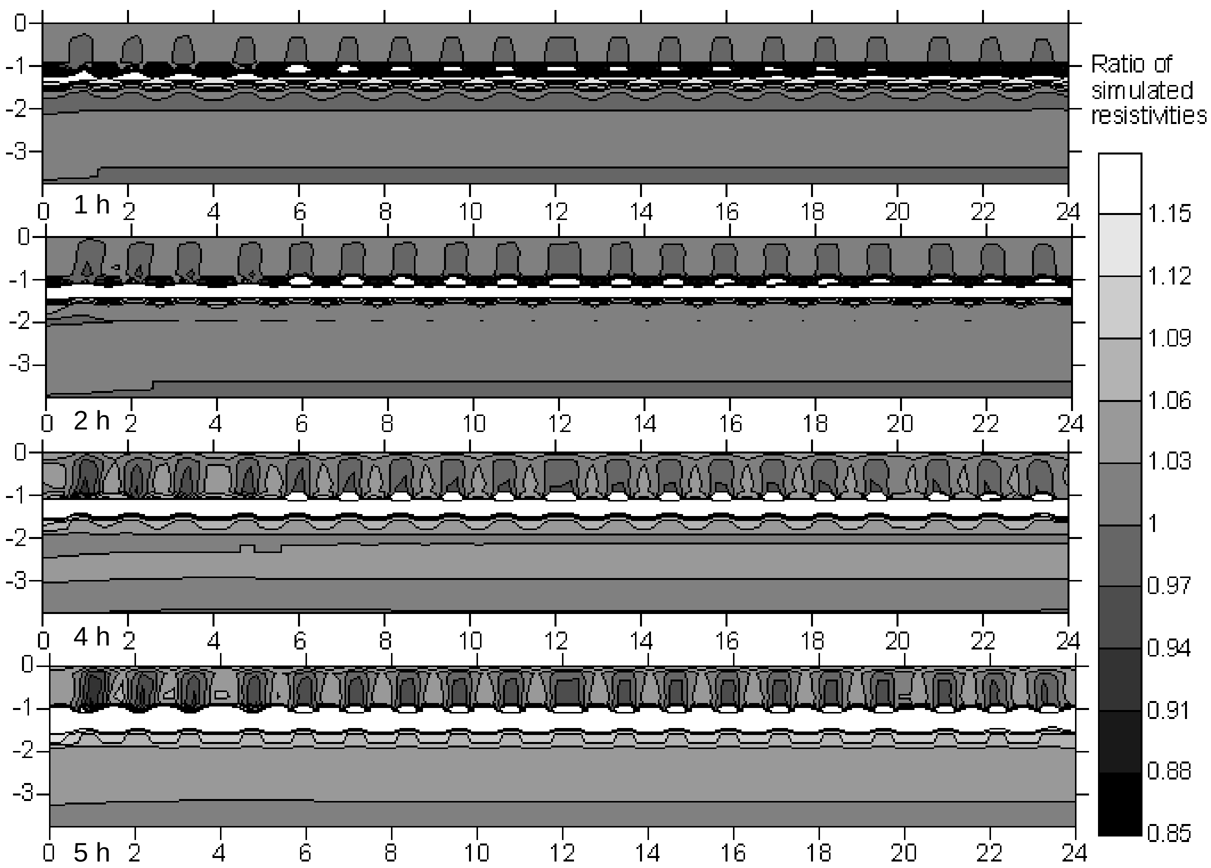

FIGURE 2. Values of ratio resistivities estimated from numerical simulations. Normalised on modelling results of 0.5 hours pipe injection. Time (hours) from pulse injection indicated.

The direct simulation results revealed a uniform distribution over the entire area (not shown), as could be expected based on the homogeneous layers of the system. The changes in estimated resistivity also revealed a horizontal pattern (Fig. 2), but there were however large changes observed near the surface of the profile. The pattern coincides with the distribution of the pipes. The simulations also indicate that the layer of natural soil above the distribution layer may be significantly affected by the injection of the pulse. The ratios of simulated resistivities are significantly larger than those shown in the figure, to be comparable with changes observed in the field ER measurements. Because information about the soil physical parameters of the system are poor, especially for the distribution layer, the results must be treated as an example outcome. Eventhough a numerical simulation of a tracer experiments was compared to the field experiment, the system only has three measuring points, and there is no guarantee that these are representative of the whole system.

1.5 Results of electrical resistivity surveys

The direct results of the inversion of the resistivity measurements clearly show the defined layering of the infiltration system. The most dominating layer is the distribution layer at approximately 1 m depth (Fig. 3).

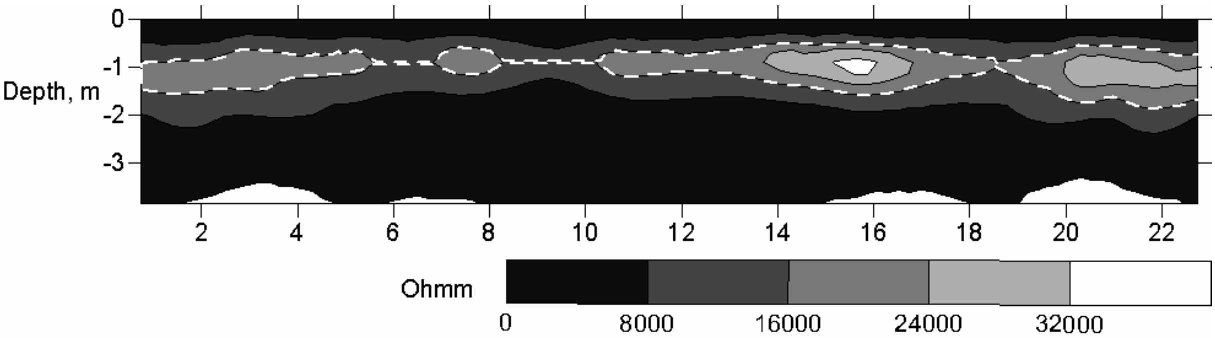

FIGURE 3. Electrical resistivities measured along a 24 m long line perpendicular to distribution pipes. White stippled lines indicate what is interpreted as the distribution layer.

The time-lapse measurements shown for selected times clearly show a pattern of changing resistivity which bares some similarity to the pipe distribution (1.25 m separation), although as can be expected less so than for the numerical simulations (Fig. 4). The resistivity changes are not extremely large, plus/minus 15 %. This is an expected result because of the averaging process implicit in the electrical resistivity measurement, and because of the coarser resolution of the electrode separation than the size of the elements in the simulations. The layer of high resistivity coinciding with the coarse gravel layer has been indicated in the time-lapse measurements. Similar to what was observed in the numerical simulations the fluid injection affects the soil volume above as well as below the distribution layer. In addition to the areas affected by the injection there is an increased resistivity occurring over time over the entire profile, which is not visible in the simulation. This could be an indication that the unsaturated properties defined in the simulations cause a slower drainage than what is the real situation. The vertical structures could indicate that there are preferential flow paths in the system, which also may cause the filter to drain faster. Another common feature with the simulations is that the pattern coinciding with pipe distribution seems to become clearer with time.

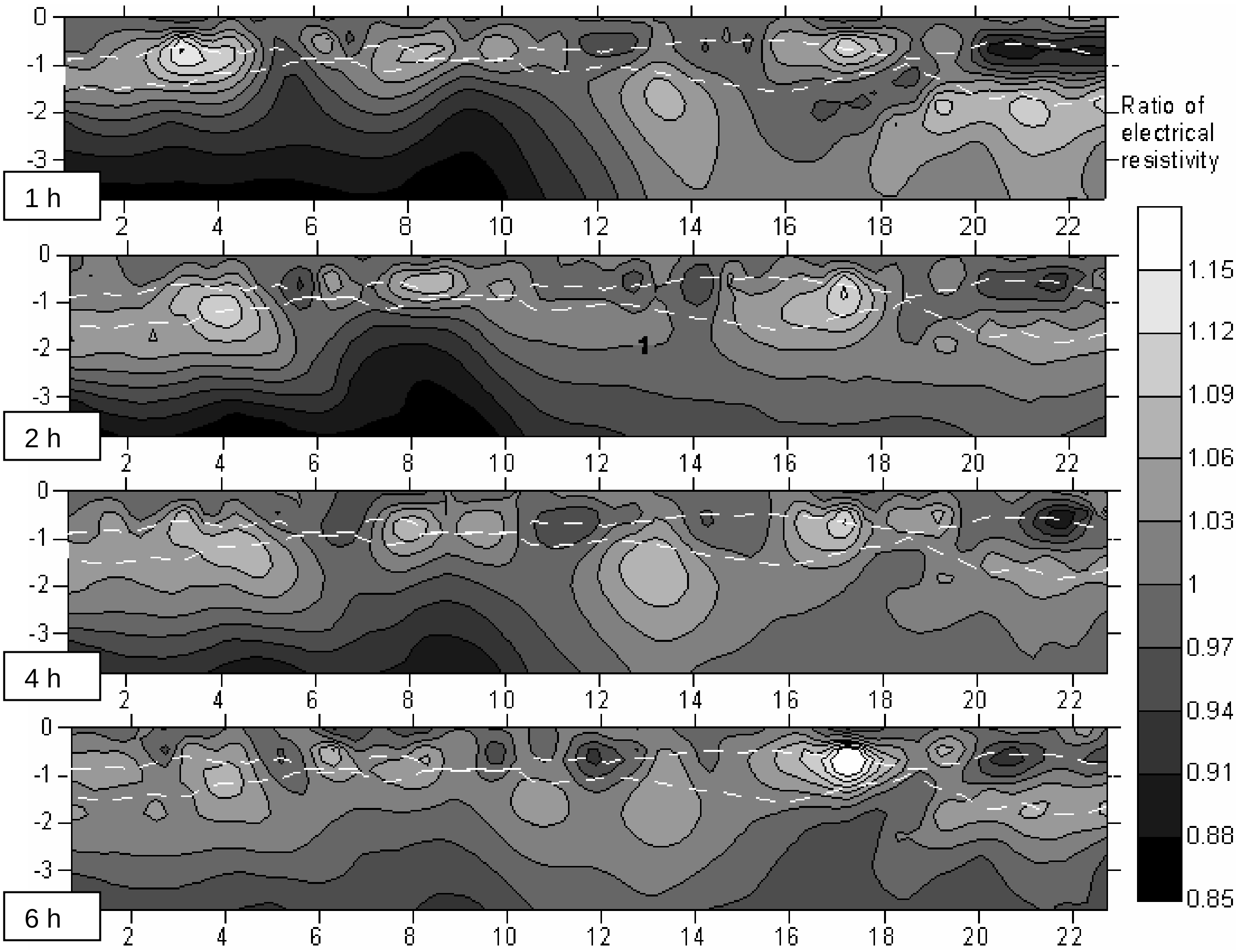

FIGURE 4. Values of electrical resistivities normalised on measurements conducted directly after injection in pipes. Numbers of hours from pulse injection indicated. White stippled lines indicate coarse layer interpreted from Fig. 3

4. CONCLUSION

The work in this paper shows promising results with respect to the use of electrical reistivity imaging as a method for monitoring functionality of constructed infiltration systems. Ideally the electrodes should be placed in the soil when the system is built, in order to follow the development of potential preferential pathways. Because we were conducting the survey in a system that had existed for several years, the presence of preferential pathways may not be clear just by monitoring changes following single pulses. This could however be solved by letting the infiltration bed dry out, and then conduct time-lapse measurement of a new pulse. Flow and transport simulations, as shown here, help improve our understanding of the constructed infiltration systems, and could in the future be helpful in the design of such systems. The work presented here will be continued, by doing a more thorough sensitivity analysis of the effect of unsaturated soil properties. We will conduct forward simulations based on simulated resistivities, in order to evaluate the expected electrical resistivity distribution using the same electrode configuration and type of survey.

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