Simulation of water flow and solute transport in intermittent sand filter

Mahmoud Bali and Moncef Gueddari

ABSTRACT

Water and solute transport in intermittent sand filtration was simulated with a modified HYDRUS 1D program. Field trials were performed through a 10 × 10 m infiltration basin located at Dissa agriculture area in the north of Gabes city (south-east Tunisia). Performance of the calibrated model has been statistically evaluated for its ability to predict water flow and solute transport. Comparisons between measured and simulated water content resulted in R^2 and root mean square error (RMSE) average values of 0.88 and 0.74 $cm^3\,cm^{-3}$ for the calibration period and of 0.86 and 0.78 $cm^3\,cm^{-3}$ for the validation period, respectively. Predicted water quality parameters were found to be in best agreement with the measured results. On average, the model predicted COD and NH_4-N concentrations well, with a RMSE of 1.06 and 1.26 mg L^{-1} respectively. However, it underestimated NO_3-N concentration. Similar corresponding values were computed for the validation period indicating that the model is able to predict water flow and solute transport with a reasonable degree of accuracy.

Key words | intermittent sand filtration, simulation, treatment, wastewater

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INTRODUCTION

Infiltration percolation of wastewater through an unsaturated sand bed is a very common technique aimed at eliminating organic matter, oxidizing ammonium and removing pathogens.

Intermittent infiltration through permeable soils or sand filters has been increasingly used for the treatment of primary or secondary wastewater effluents (Brissaud & Lesavre 1993; Stevik *et al.* 2004; Auset *et al.* 2005) because of its low energy and maintenance requirements. These systems represent a simple, low-cost method of wastewater treatment in developing countries and even in developed ones (Auset *et al.* 2005). These systems can also increase the recharge of groundwater aquifers, but there is concern about the impacts on water quality.

Intermittent sand filters behave as aerobic fixed biomass reactors, as long as the oxygen required to oxidize dissolved organic matter and nitrogen is available in the air phase of the porous medium. Drainage periods allow oxygen in the air phase to be renewed through convection and molecular diffusion (Bancolé *et al.* 2003). Alternation of operational and drying periods has always been considered essential to infiltration percolation and soil aquifer treatment; it is the only practical way to manage clogging at the surface and in the core of filtrating beds (Brissaud *et al.* 2003).

The technique of infiltration percolation is performed as an advanced treatment system for suspended solids, organic matter and nitrogen. However, it is less efficient concerning the reduction of phosphorus.

Research and field experiments have shown that intermittent filtration can provide high removal efficiency of bacteria if properly designed and operated (Brissaud *et al.* 1991; Guessab *et al.* 1993; Castillo *et al.* 2001; Ausland *et al.* 2002). Therefore filtered secondary treatment effluents can be used for unrestricted agricultural irrigation (Salgot *et al.* 1996), irrigation of public parks, lawns and golf courses (Faby *et al.* 1999) and groundwater recharge (Bouwer 1996).

Mathematical models, such as HYDRUS 1D, are now routinely used in research and management for predicting

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the movement of water and dissolved chemicals in the unsaturated zone. Models are convenient tools for analysing laboratory and field experiments involving unsaturated flow and/or solute transport. Also, HYDRUS is helpful for extrapolating information gained from specific field experiments to other sites involving different soil and climatic conditions, as well as for evaluating alternative soil and water management practices. It may be possible to use this model to predict the influence of kinetics on oxidation performances and biomass development on internal clogging. It may be used to establish the effect of the main construction and operation parameters on sustainability of infiltration percolation plants.

The aim of this work was to simulate water and solute transport in intermittent sand filtration with a modified HYDRUS 1D model. The model was calibrated and validated after real scale tests performed in a sand filter pilot plant.

MATERIALS AND METHODS

Sand filter pilot and experimental protocol

Experiments were conducted in 100 m^2 sand filter located at Dissa agriculture area in the north of Gabes city (south-east Tunisia). The filter is a trapezoidal basin 2.0 m in height and filled with 30 cm of coarse gravel and 1.5 m of sand. The mean grain size of sand (d_{50}) is 0.26 mm and the uniformity coefficient of the particle-size distribution (d_{60}/d_{10}) is 1.93. A polyethylene pipe was used drilled with 0.5 cm holes to drain filtrate out. The sand filter was fed with activated sludge effluents from Gabes treatment plant. Secondary wastewater effluents were applied according to a four days operating – three days drying schedule. During the operation phases, the daily hydraulic load was 0.27 m^3/m^2 of sand bed.

Wastewater was spread uniformly over the surface area through a distribution system of perforated pipes (3 mm diameter holes with a density of 20 holes/m).

For each wetting/drying cycle and before feeding of the filtration area, soil water content was measured at depths of 5, 10, 20, 30, 40 and 50 cm. Flow rates were monitored and percolating water was sampled at 0.5, 1 and 1.5 m depths during several feeding-drainage cycles. Chemical analyses were performed on secondary wastewater effluents and percolating water at three different depths along the unsaturated sand profile. Chemical oxygen demand (COD), ammonium (NH_4-N) and nitrates (NO_3-N) were analysed.

Simulation model

The mathematical model presented by Bancolé (2001) was used to simulate the transfer and oxidation of dissolved organic matter and nitrogen in unsaturated sand filters. The model was derived from the HYDRUS 1D code (Vogel *et al.* 1996).

The model allows simulation of biomass growth and its impact on the hydrodynamic characteristics of the sand filter. The code assumes that water flow in soil under isothermic condition can be described with the following form of Richard's equation (Bancolé 2001):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} - \cos\phi\right)\right] - S \quad (1)$$

where θ is the volumetric water content (L^3L^{-3}), h is the pressure head (L), S is the root water uptake rate (T^{-1}), x is the spatial coordinate (L), t is time (T), φ is the angle between the flow and the vertical axis ($\varphi = 0^\circ$ for vertical flow), K is the unsaturated hydraulic conductivity (LT^{-1}).

Porous media hydrodynamic characteristics, K *(h)* and θ *(h)*, with θ the volumetric water content are expressed through Van Guenuchten's functions (Bancolé 2001):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{(\theta_s - \theta_r)}{(1 + |\alpha\, h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (2)$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{l/m})^m]^2 \quad (3)$$

where θ_r and θ_s are the residual and saturated water content (L^3L^{-3}), respectively; K_s is the saturated hydraulic conductivity (LT^{-1}); α, n ($m = 1–1/n$) and l are empirical coefficients affecting the shape of the hydraulic function; and S_e is effective water content (L^3L^{-3}).

The effect of bacterial growth on the hydraulic conductivity is described with the following relationship (Bancolé *et al.* 2003):

$$K_s = a(\theta_{biof})^b K_{so} \tag{4}$$

where K_{so} is the hydraulic conductivity in the absence of any biological development; a and b are curve fitting parameters and θ_{biof} is the water content corresponding to the biomass.

The water content corresponding to the biomass is given by the following equation (Bancolé *et al.* 2003):

$$\theta_{biof} = \lambda\rho_{biof} \tag{5}$$

where ρ_{biof} is the biomass content and λ is the volume of the unit biomass.

The transport of dissolved organic matter, NH_4-N and NO_3-N, is described taking into account the division of the liquid phase into mobile and immobile regions. Exchanges between mobile and immobile water are diffusive. Thus, the transfer of a non-interactive tracer is described by the following equations (Simunek *et al.* 1998):

$$\frac{\partial(C_m\theta_m)}{\partial t} + \frac{\partial(C_{im}\theta_{im})}{\partial t} = \frac{\partial}{\partial x}\left[D_m\theta_m\left(\frac{\partial C_m}{\partial t}\right) - qC_m\right] \tag{6}$$

and

$$\frac{\partial(C_{im}\theta_{im})}{\partial t} = \alpha(C_m - C_{im}) \tag{7}$$

where C_m and C_{im} are the tracer concentration in the mobile and immobile regions respectively (ML^{-3}); θ_m and θ_{im} are water content in the mobile and immobile regions respectively (L^3L^{-3}); D_m is the longitudinal dispersion coefficient (L^2T^{-1}); q is the specific flow rate (LT^{-1}); and α is the exchange coefficient between the mobile and immobile regions.

The biological degradation of organic matter and nitrogen oxidation take place in the biofilm. Substrate consumption, biomass growth, endogenous respiration and oxygen consumption are described by modified Monod's equation (Molz *et al.* 1986):

$$P_{COD} = \left(\frac{\mu m_{COD}}{Y_{COD}}\right)\left[\frac{C_{im,\,COD}}{(K_{COD} + C_{im,\,COD})}\right] \times \left[\frac{C_{oxy}}{(K_{oxy} + C_{oxy})}\right]\rho_{biof,\,COD} \tag{8}$$

where μm_{COD} is the maximum specific growth rate of heterotrophic biomass, Y_{COD} the yield coefficient for COD, K_{COD} and K_{oxy} the saturation coefficients for COD and oxygen respectively, and $\rho_{bio,\,COD}$ the heterotrophic biomass content.

Loss of ammonia through nitrification process is given by the following equations (Bancolé *et al.* 2003):

$$P_{NH4} = \left(\frac{\mu m_{NH4}}{Y_{NH4}}\right)\left[\frac{C_{im,NH4}}{(K_{NH4} + C_{im,NH4})}\right] \times \left[\frac{C_{oxy}}{(K_{oxy} + C_{oxy})}\right]\rho_{biof,NH4} \tag{9}$$

where μm_{NH4} is the maximum specific growth rate of heterotrophic biomass, Y_{NH4} the yield coefficient for NH_4-N, K_{NH4} the saturation coefficients for NH_4-N, and $\rho_{bio,\,NH4}$ the heterotrophic biomass content.

Heterotrophic and autotrophic biofilms are modelled taking endogenous respiration into account (Horn & Hempel 1997):

$$\frac{\partial\rho_{biof}}{\partial t} = Y.P - Kd.\left[\frac{C_{oxy}}{K_{oxy+}C_{oxy}}\right]\rho_{biof} \tag{10}$$

where Kd is a microbial decay rate and $Y.P = [Y_{COD}.P_{COD} + Y_{NH4}.P_{NH4}]$.

Model application

Flow and wastewater quality data from the sand filter for the period of 24 March to 6 April 2008 were used for the calibration of the model. Data collected from 7 April to 20 April 2008 were used to validate the model.

In order to see if the model performs successfully for different loading conditions, it was validated for a long period with a different daily hydraulic load. The infiltration percolation of secondary treated effluent has been simulated for hydraulic load of 0.4 m^3 m^{-2} and bed depths of 0.5, 1.0 and 1.5 m. During several feeding-drainage cycles, samples were analysed for COD, NH_4-N and NO_3-N. These solutes were simulated keeping the values of the hydrodynamic and biological parameters taken from literature or resulting from the calibration procedure. This supplementary validation of the model took place from 28 April to 15 May 2008.

Boundary conditions

The upper water flow boundary condition at the surface ($x = L$) was specified as the atmospheric boundary condition with a surface layer (Bancolé 2001). This boundary condition imposed time-dependent conditions to specify the atmospheric conditions at the top of the sand filter. The lower water flow boundary conditions were set to free drainage (gravity dependent). As for solute (COD, NH_4-N and NO_3-N) transport, concentration flux boundary conditions were implemented at the upper boundary, and a zero gradient boundary condition was set at the lower solute boundary condition.

Statistical analysis

In this study, the accuracy of predicted values was evaluated by calculating the root mean square error (RMSE) between calculated and observed values:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (C_c - C_{obs})^2}{N}}$$

where C_c and C_{obs} calculated and observed value respectively and N is the number of measurements.

The RMSE ranges between 0 and plus infinity; a value of 0 indicates no difference between simulated and measured results; the smaller the RMSE the better the performance of the model.

Furthermore, to check systematic errors calculated values were regressed (R^2) against the observed values, and the slope (a) of the regression line. Nearer values to unity for both R^2 and (a) and low RMSE value suggested an acceptable prediction performance for the model.

RESULTS AND DISCUSSION

Model calibration

Soil water content and water flow

As a first step during the calibration, the saturated hydraulic conductivity parameter (K_{sat}) and the saturated moisture content (θ_s), characterized as the most sensitive parameters (Abou Nahra & Madraootoo 2005), were manually calibrated to ensure that the numerical solutions converged by comparing the moisture content at the end of each simulation and ensuring that the water balance error did not exceed 1%. Figure 1 shows observed and calculated water content at different depths for the calibration period. Observed and calculated results show the same general trend in water content in relation to depth. An average R^2 and RMSE values of 0.88 and 0.74 cm^3 cm^{-3} were obtained respectively. Data of observed and calculated water content were equally distributed along the 1:1 line. Linear regression through the origin gave 0.98 slope coefficient from the calibration indicating that the Van Guenuchten's equation was able to successfully describe the soil moisture variations. Figure 2(a) shows observed and calculated water flow at 50, 100 and 150 cm depth when the filter was flooded with 27 m^3 of secondary wastewater for the calibration period. Visual analyses of this figure showed that the

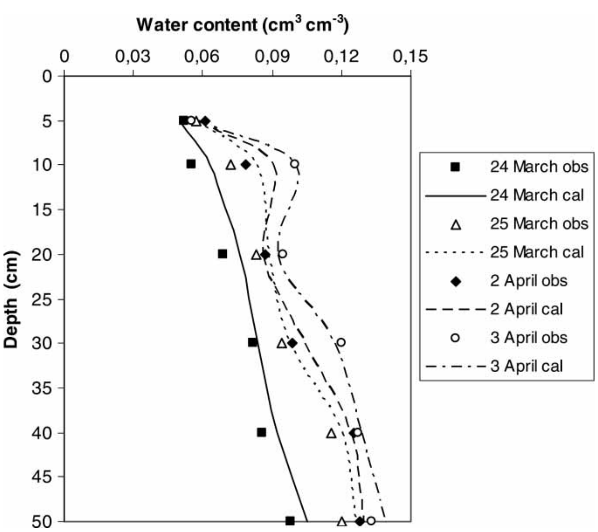

Figure 1 | Observed and calculated water content profiles during the calibration period.

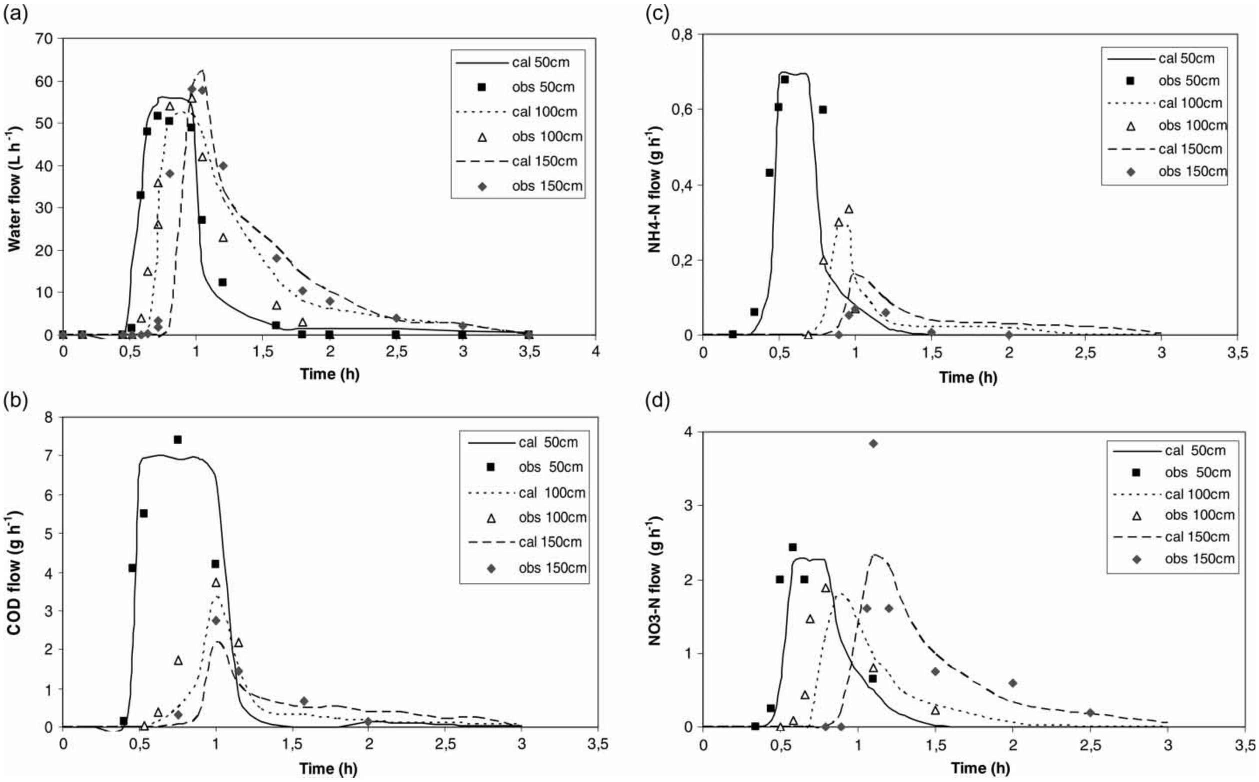

Figure 2 | Observed and calculated water flow (a), COD flow (b), NH_4-N flow (c) and NO_3-N flow (d) during the calibration period.

model fits well the observed water flow at different depths of the sand filter. The total time simulated by modified HYDRUS-1D to completely drain the sand filter was 3.36 h, while the experiment took 3 h on average.

Solute transport

Once the hydraulic parameters were calibrated, the solute transport parameters were then calibrated to fit outflow concentrations from the sand filter. Statistical fitting criteria between observed and calculated values are listed in Table 1. An example of comparisons between observed and calculated concentrations of COD, NH_4-N and NO_3-N at 50, 100 and 150 cm depth during the calibration period is shown in Figure 2(b–d). On average, the modified HYDRUS-1D model predicted COD and NH_4-N concentrations well, with a RMSE of 1.06 and 1.26 mg L^{-1} respectively (Table 1). However, it underestimated NO_3-N concentration. Computed R^2 and RMSE at the 150 cm depth were 0.77 and 2.41 mg L^{-1} respectively.

Model validation

The calibrated model was used to predict the water flow and solute with an independent set of data as a part of a validation test. Comparisons between the observed and calculated moisture resulted in R^2 and RMSE average values of 0.86 and 0.78 $cm^3\,cm^{-3}$ (Table 1). Similar comparisons are obtained for COD and NH_4-N, which reveal that HYDRUS tracked both indicators well. The R^2 and RMSE statistics for COD and NH_4-N were 0.87 and 1.04 mg L^{-1} and 0.89 and 0.98 mg L^{-1}, respectively, for comparisons between average observed and calculated values. In general, the statistics indicated that the predictions of COD and NH_4-N at the sampling depths corresponded well with the measured values. Again, the agreement between observed and calculated NO_3-N values was lower. Compared to the experimental results R^2 and RMSE of 0.74 and 2.84 mg L^{-1} were obtained in the validation period.

The simulation of COD and NH_4-N elimination with a hydraulic load of 0.4 $m^3\,m^{-2}$ was considered successful

Table 1 | Statistical fitting criteria between observed and calculated values

	Depth (cm)	Calibration				Validation			
		N	R^2	*a*	RMSE	*N*	R^2	*a*	RMSE
θ_r (cm^3cm^{-3})	5	10	0.91	0.97	0.72	10	0.90	1.01	0.66
	10	10	0.93	1.01	0.67	10	0.86	0.99	0.67
	20	10	0.87	0.94	0.75	10	0.85	1.02	0.83
	30	10	0.86	1.02	0.78	10	0.83	0.99	0.96
	40	10	0.85	0.96	0.72	10	0.87	1.02	0.68
	50	10	0.86	1.01	0.81	10	0.86	1.01	0.87
	Average		0.88	0.98	0.74		0.86	1.01	0.78
COD (mg L^{-1})	50	5	0.83	1.03	1.12	5	0.86	1.02	1.36
	100	5	0.92	1.02	0.98	5	0.92	1.00	0.84
	150	5	0.86	1.04	1.08	5	0.85	1.02	0.92
	Average		0.87	1.03	1.06		0.87	1.01	1.04
NH_4-N (mg L^{-1})	50	5	0.82	1.00	1.66	5	0.93	1.01	0.88
	100	5	0.92	1.01	0.92	5	0.89	1.02	1.09
	150	5	0.87	1.03	1.19	5	0.86	0.99	0.96
	Average		0.87	1.01	1.26		0.89	1.01	0.98
NO_3-N (mg L^{-1})	50	5	0.78	1.02	2.04	5	0.76	1.04	2.76
	100	5	0.85	1.04	1.96	5	0.81	1.01	1.75
	150	5	0.68	1.01	3.22	5	0.66	1.02	4.01
	Average		0.77	1.02	2.41		0.74	1.02	2.84

RMSE: Root mean square error; R^2: coefficient of regression; *a*: slope of the regression line; *N*: number of measurements.

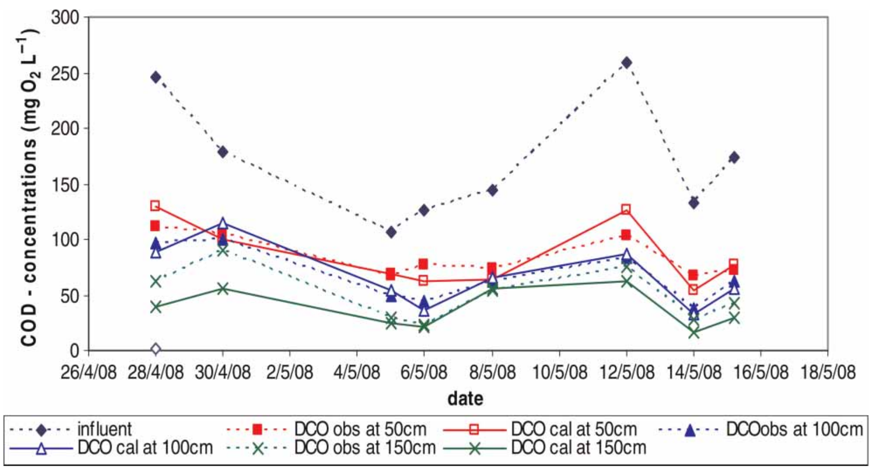

Figure 3 | Observed and calculated COD at 50, 100 and 150 cm depths.

(Figures 3 and 4). This result was considered a supplementary validation of the model.

CONCLUSION

The performance of the modified HYDRUS-1D model was tested by simulating water flow, COD, NH_4-N and NO_3-N transport in an intermittent sand filter. The numerical model was calibrated with the independently estimated soil hydraulic and reaction parameters. Simulated results were compared with experimental data. Both observed and calculated results show the same general trend in COD and NH_4-N transport in relation to depth. The computed values for RMSE, R^2 and (a) were found to be satisfactory to validate the

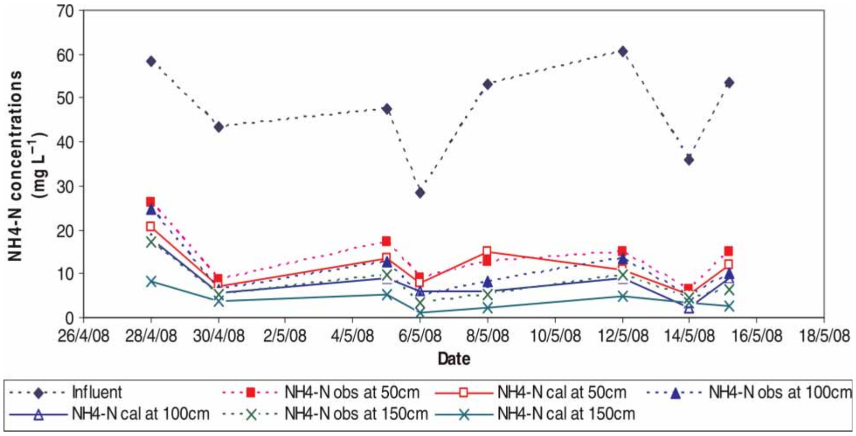

Figure 4 | Observed and calculated NH_4-N at 50, 100 and 150 cm depths.

simulation performance as successful with a reasonable accuracy.

The model could be used as a tool for a better understanding of the process, to design infiltration percolation plants. Thanks to advances in knowledge and modelling of oxidation mechanisms, the predictability of organic matter and nitrogen removal by the infiltration percolation process is being significantly improved.

This research was carried out to predict changes in secondary wastewater quality through an intermittent sand filter. Consequently future simulation works should be undertaken to estimate water quality improvement as affected by the hydraulic loading rates and operation mode conditions (wetting-drying periods).

REFERENCES

Abou Nahra, J. & Madramootoo, C. A. 2005 Modelling phosphorus dynamics in tile drained fields. *Water News, Newslett. Canad Water Resour. Assoc.* **24**, 13–14.

Auset, M., Keller, A., Brissaud, F. & Lazarova, V. 2005 Intermittent filtration of bacteria and colloids in porous media. *Water Res. Res.* **41**, W09408.

Ausland, G., Stevik, T. K., Hanssen, J. F., Kohler, J. C. & Jenssen, P. D. 2002 Intermittent filtration of wastewater – Removal of faecal coliforms and faecal streptococci. *Water Res.* **36**, 3507–3516.

Bancolé, A. 2001 L'oxydation en infiltration percolation. Doctoral Thesis, Montpellier II University.

Bancolé, A., Brissaud, F. & Gnagne, T. 2003 Oxidation processes and clogging in intermittent unsaturated infiltration. *Water Sci. Tech.* **48**, 139–146.

Bouwer, H. 1996 Issues in artificial recharge. *Water Sci. Tech.* **33**, 381–390.

Brissaud, F. & Lesavre, J. 1993 Infiltration percolation in France: 10 years experience. *Wat. Sci. Tech.* **28**, 73–81.

Brissaud, F., Restrepo, M., Soulié, M. & Joseph, C. 1991 Infiltration percolation for reclaiming stabilization pod effluents. *Water Sci. Tech.* **24**, 185–193.

Brissaud, F., Tournoud, M. G., Drakids, C. & Lasarova, V. 2003 Mixing and its impact on faecal coliform removal in a stabilization pond. *Water Sci. Tech.* **48**, 75–80.

Castillo, G., Mena, M. P., Dibarrart, F. & Honeyman, G. 2001 Water quality improvement of treated wastewater by intermittent soil percolation. *Water Sci. Tech.* **43**, 187–190.

Faby, J. A., Brissaud, F. & Bontoux, J. 1999 Wastewater reuse in France: Water quality standards and wastewater treatment technologies. *Water Sci. Tech.* **40**, 37–42.

Guessab, M., Bize, J., Schwarzbrod, J., Maul, A., Nivault, N. & Schwarzbrod, L. 1993 Wastewater treatment by infiltration percolation on sand: results in Ben Sergao, Morocco. *Water Sci. Tech.* **27**, 91–95.

Horn, H. & Hempel, D. C. 1997 Growth and decay in an autotrophic/heterotrophic biofilm. *Water Sci. Tech.* **31**, 2243–2252.

Molz, F. J., Widdowson, M. A. & Benefield, L. D. 1986 Simulation of microbial growth dynamics coupled to nutrient and oxygen transport in porous media. *Water Resour. Res.* **22**, 1207–1216.

Salgot, M., Brissaud, F. & Campos, C. 1996 Disinfection of secondary effluents by infiltration-percolation. *Water Sci. Tech.* **33**, 271–276.

Simunek, J., Huang, K. & Van Genuchten, M. 1998 *The HYDRUS code for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media*.

Version 6.0. Research Report No. 144. U.S. Salinity Laboratory, Riverside, CA.

Stevik, T. K., Keller, A., Ausland, G. & Hanssen, J. K. 2004 Retention and removal of pathogen bacteria in wastewater percolating through porous media. *Water Res.* **38**, 1355–1367.

Vogel, T., Huang, K., Zhang, R. & Van Genuchten, M. 1996 *The HYDRUS code for simulating one-dimensional water flow, solute and heat movement in variably saturated media*. Version 5.0 Research Report n°140. U.S. Dep. of Agric. Riverside, CA.

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