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### ► **To cite this version:**

Geoffroy Séré, Stéphanie Ouvrard, Vincent Magnenet, Benjamin Pey, Jean Louis Morel, et al.. Predictability of the Evolution of the Soil Structure using Water Flow Modeling for a Constructed Technosol. *Vadose Zone Journal*, 2012, 11 (1), pp.1-13. 10.2136/vzj2011.0069 . hal-02173862

**HAL Id: hal-02173862**

**<https://hal.science/hal-02173862>**

Submitted on 4 Jul 2019

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Soil hydrodynamics can be used to predict the pedogenic evolution of soil architecture. Technosols are valuable experimental models because their pedogenesis are fast and intense. The comparison between the monitoring of water flow in a technosol and its modeling with HYDRUS-1D highlighted an evolution of hydraulic parameters with time.

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Vadose Zone J.  
doi:10.2136/vzj2011.0069  
Received 21 June 2011.

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# Predictability of the Evolution of the Soil Structure using Water Flow Modeling for a Constructed Technosol

This paper focuses on the relation between the structure of a constructed Technosol and its hydraulic characteristics during its early pedogenesis. The method is based on a 3-yr comparison of, on one hand, experimental measurements from an in situ gravitation lysimeter and, on the other hand, a modeling approach with HYDRUS-1D. The change of water flow patterns with time was described. It was consistent with previous results for constructed Technosol aggregation. Apart from seasonal variations, the specificity of the hydraulic functioning of the constructed Technosol was shown to be due to the nature of its technogenic parent materials. The in situ evolution of the hydrodynamics has been established and partly linked to external factors (climate, vegetation). The direct modeling and the optimization of the parameters over first a 3-yr period and then three 9-mo periods accurately represented global water flow trends at the pedon scale. However it failed to simulate precisely the main events, such as massive leachate outflow. An evolution with time of some of the hydraulic properties was shown, expressing the structuring of the soil. The existence of two distinct time-scales (slow and steady/fast and cyclic) of the evolution of hydraulic parameters was then formulated as a new hypothesis.

Abbreviations: Hz, horizon; TDR, time domain reflectometry.

## Hydraulic Properties Evolution as an Indicator of Technosol Pedogenesis

The pedo-engineering approach aims to reclaim derelict lands by constructing soils able to fulfill basic soil functions (i.e., biomass production, habitat and gene reservoir, and filtering, buffering, and transformation) (Séré et al., 2008). The goal is especially to find a satisfying level of ecosystem functions in terms of land requalification and preservation of groundwater quality (Urbanska et al., 2004). Some previous results not only underlined the fact that soil construction could lead to the restoration of soil functions (Séré et al., 2008), but also showed that constructed Technosols (IUSS Working Group WRB, 2006) are submitted to a fast and intense early pedogenesis (Séré et al., 2010; Pey et al., unpublished data). In particular, dramatic changes in soil architecture have already been observed under the influence of climate, plant cover, and biological activity during the first months and years following the soil set up. Obviously the soil structure closely influences soil water balance (Kutilek, 2004). The assessment of the impact of fast structure evolution of constructed soils is then essential to determine its capacity to fulfill filtering and buffering functions and, then, the sustainability of the soil construction process.

Soil pore distribution is submitted to external soil stresses, such as seasonal variations (wetting and drying) and human activities (e.g., agricultural management practices, earthwork, irrigation). Pore distribution directly affects water flow and soil hydraulic characteristics, such as soil water retention curves (Täumer et al., 2006; Strudley et al., 2008; Pires et al., 2008). The study of Technosols and Anthrosols is recent, but has already highlighted the impact of their original properties (high organic matter content, coarse texture) and characteristics (heterogeneity, predominantly basic) on their hydraulic behavior, including water repellency and soil water availability (Wessolek et al., 2009; Hartmann et al., 2010; Arye et al., 2011; Ojeda et al., 2011).

Only a few studies have focused on the evolution of hydraulic parameters with time or land use due to the huge spatial heterogeneities of these soils (Hu et al., 2009). The variations of saturated and unsaturated soil hydraulic conductivities have been successfully

illustrated, not only under the influence of soil management, but also within a soil chronosequence (Hu et al., 2009; Das Gupta et al., 2006; Farkas et al., 2006). Some comparison of soil structure measurements (bulk density, total porosity) and soil hydraulic properties have highlighted differences in structure for contrasting land uses (i.e., forest, grass, or crops) (Bhattacharyya et al., 2006; Mubarak et al., 2009). Kodešová et al. (2011) even compared micromorphological image analysis with parameters like soil water retention curve or saturated hydraulic conductivity. They demonstrated the relevance of linking these characteristics to describe the impact of soil management. The interplay of both structure observation and water flow data has also been explored, focusing mainly on transport processes in soils, and has shown the strong impact of the relations between soil use, soil structure, and hydrodynamics (Kodešová et al., 2009).

Lin (2010) initiated a discussion on how to link pedogenesis with water flow regimes. Interestingly, he suggested that both soil and hydraulic properties (hydrologic feature and saturated hydraulic conductivity) would evolve continuously and in steady state. Thus, soil hydrodynamics during its pedogenic evolution would evolve continuously, also undergoing some abrupt changes. This emerging approach, founded on hydropedology (Lin, 2003, 2010), seems highly relevant in light of the above theoretical basis. Yet, the relation between soil structure evolution and hydraulic parameters has been relatively poorly studied. Indeed, this is particularly difficult to assess, given the slow genesis of natural soil in relation to biological time. Consequently, the studies that deal with this subject are either based on toposequence or on seasonal variations (Sobieraj et al., 2002, 2004; Schwen et al., 2011). A recent work has highlighted the significant influence of land use on hydraulic and hydrological properties of two soils, a Podzol and Stagnosol (IUSS Working Group WRB, 2006), but has failed to demonstrate any effective relation inside the toposequence (Bormann and Klaassen 2008).

The objective of this paper is to highlight the changes in the structure of a young constructed Technosol by studying its hydrodynamic behavior—focusing on water flow on the pedon scale—during its pedogenic evolution. Indeed, pedological observations of similar soils have already revealed significant evolutions in both the macrostructure, the microstructure, and the bulk density over a 3-yr period (Séré et al., 2010). This demonstrates the relevance of studying early pedogenesis on a relatively short period of time for a constructed Technosol. The

work here was based on the comparison, on one part, of the continuous data-monitoring (soil moisture, drainage water) in a gravitation lysimeter and, on the other part, of the modeling of water flow indirectly estimated by a one-dimensional model of Richards' equation (Selle et al., 2011). HYDRUS-1D was used to model the hydrodynamics and, further, to solve an inverse problem to estimate the parameters of the used model of Richards' equation. The comparison of experimental lysimetric data with HYDRUS-1D simulations has been examined by different authors (Abbaspour et al., 1999; Mertens et al., 2006), but mostly as a way to strengthen the modeling approach. The main goal of our work was to highlight significant changes with time in the hydraulic properties of a constructed Technosol and then to link them to the evolution of soil architecture. Our secondary objective was to approach the problem as tool-users and thereby to assess the suitability of existing models for testing our hypothesis.

The methods are first presented, focusing on the experimental devices and on the modeling approaches (i.e., hydraulic parameter estimation, direct modeling, and optimization procedure). The lysimeter monitoring is presented along with a description of the evolution of the hydrodynamics with time. Then, the results of the different simulations are discussed, focusing on their potential use to express the evolution of the soil structure. Finally, considerations about the relevance of further examination of hydropedology concepts are mentioned.

## Materials and Methods

### Constructed Technosol

The constructed soil studied was a Spolic Garbic Hydric Technosol (Calcaric) (IUSS Working Group WRB, 2006; Séré et al., 2010). It is made of three technogenic parent materials. Green-waste compost, paper mill sludge, and thermally treated industrial soil were stacked into layers forming three initially distinct horizons (Hz) from bottom to top: 45 cm of pure paper mill sludge (Hz 2), 125 cm of treated soil and paper mill sludge mixture (1:1 volumetric ratio) (Hz 1), and 15 cm of pure green-waste compost (Hz 0). The materials were analyzed following methods commonly used for natural soils, by a certified laboratory (Laboratoire d'Analyse des Sols–INRA Arras, France) (Table 1). The bulk density was estimated from the volume and weight of the total soil material placed into the gravitation lysimeter.

Table 1. Physico-chemical characteristics of the parent materials.

	Granulometric fractions			Bulk density	pH	Organic carbon	C/N	CaCO <sub>3</sub>
	<2 μm	2–50 μm	50–2000 μm					
	g kg <sup>-1</sup>			g dm <sup>-3</sup>		g kg <sup>-1</sup>		g kg <sup>-1</sup>
Green-waste compost	202	326	472	0.45	8.4	176	17	124
Treated soil–paper mill sludge mixture	113	272	625	1.17	8.2	85.2	38	402
Paper mill sludge	179	495	326	0.86	8.4	102	28	484

## Experimental Set Up

### Lysimeter Device and Soil Profile

A 2-m-deep and 1-m<sup>2</sup> surface area lysimeter of the GISFI experimental station (<http://www.gisfi.fr>, Homécourt, North-Eastern France, supplied by Umwelt-Geräte-Technik, Müncheberg, Germany) was filled with the parent materials in September 2007. A 15-cm sand bed was put at the bottom to ensure homogeneous drainage. Then the technogenic materials were added gradually and manually compacted every 30 cm to reach a given bulk density (Fig. 1). The lysimeter was equipped at three depths (50, 100, and 150 cm) with time domain reflectometry (TDR) probes, suction probes, and temperature sensors (Fig. 2). No water table was applied. The soil was initially unplanted until March 2008 when ryegrass (*Lolium perenne* L. ‘Tove’) was sown at a density 240 kg ha<sup>-1</sup>. A net was set up above the lysimeter to prevent any colonization by soil fauna. The lysimeter was submitted to natural rain and continuously weighed at a 0.1-kg precision. At the bottom, a tipping counter measures the drainage flow (Fig. 1b and 1c). All data were continuously monitored on an hourly basis using a data logger.

### Experimental Plot

A 1-ha in situ experimental plot was constructed with the same parent materials and settled at the same time in the vicinity of the lysimetric station and was used for the sampling of soil materials.

### Climatic Conditions

Climatic conditions were recorded with a weather station (rain gauge, wind gauge, energy sensor; WS STD1 from Delta-T Devices) located at a distance of 50 m from the lysimeter (Fig. 3).

### Water Balance and Real Evapotranspiration Calculation

Actual evapotranspiration was calculated using the monitored mass variation (including changes in water storage capacity,  $\Delta S$ ), drainage flow ( $D$ ), and precipitation ( $P$ ).  $\Delta S$  and  $D$  values were recorded by the lysimeter data logger, and  $P$  was given by the *on-site* weather station. The actual evapotranspiration ( $E_t$ ) was derived using the following equation:

$$E_{t_a} = P - D \pm \Delta S \quad [1]$$

The global evolution of mass  $\Delta M$ , based on the difference between initial mass  $M_0$  and actual mass  $M_a$ , gave global variation of the constructed soil moisture:

$$\Delta M = M_0 - M_a \quad [2]$$

### Soil Hydraulic Characteristics Measurements

Different measurements were conducted to assess soil hydraulic parameters. Soil materials were sampled in September 2007 on the

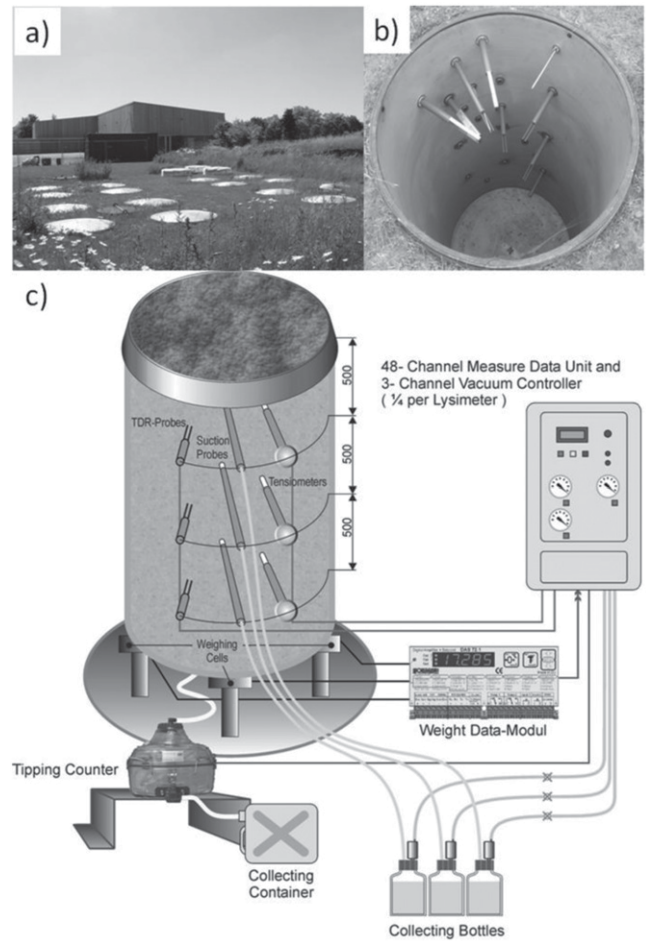


Fig. 1. Lysimeter station and gravitation lysimeter device: (a) general view, (b) empty equipped, (c) diagram of the experimental device (courtesy of UGT).

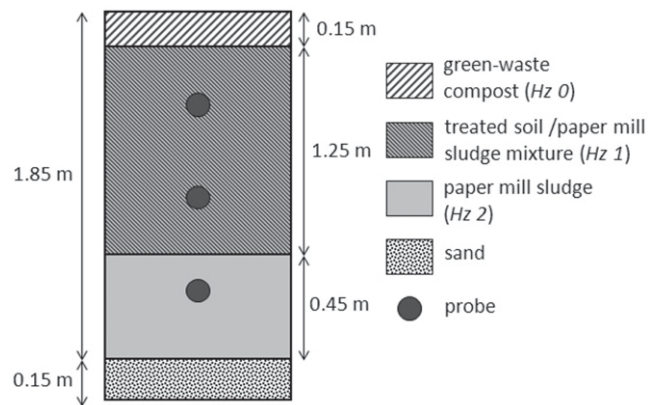


Fig. 2. Constructed Technosol solum in the lysimetric column.

experimental plot to avoid disturbing the lysimeter water flow. A pit was dug, and nine replicates were taken at 0.6 m depth, into the Hz 1, and nine replicates were taken at a 1.6 m depth, into the Hz 2. The samples were collected from 250-cm<sup>3</sup> cores and saturated for 2 d using the capillary rise method (Pires et al., 2008).

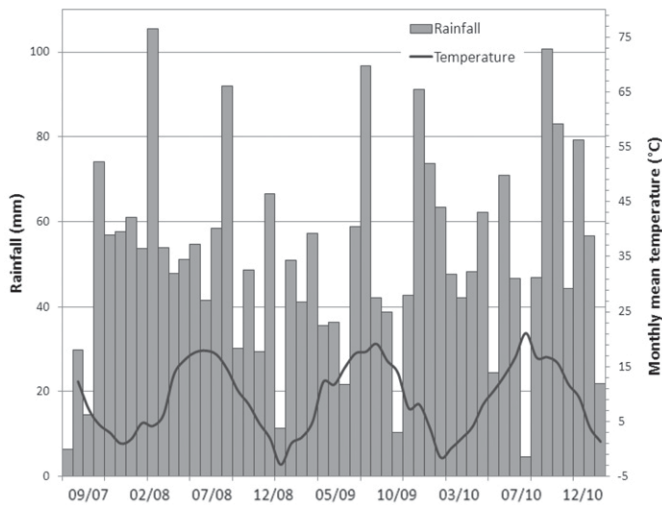


Fig. 3. Climatic data (rainfall and monthly mean air temperature at 2 m) measured with the meteorological station over the 3 yr.

### Pressure Plate Method

Water retention data were determined on three replicates for both horizons using the drying method on pressure plate apparatus for two water potentials (0.33 and 15 kPa) according to the methods described by Bruand et al. (1996).

### Constant Head Method

Saturated hydraulic conductivity was estimated using the constant head method (Bagarello et al., 2009) on three replicates for both horizons. A Mariotte bottle was used, applying three different pressure gradients (−1, −2, and −3 cm), and the measurements were performed during 30 to 40 min.

### Evaporation Method

The ku-pf instrument (Umwelt-Gerate-Technik, Müncheberg, Germany) was used for the evaporation experiment according to the method described by previous authors (Minasny and Field, 2005; Bormann and Klaassen, 2008) and adapted from the previous work of Wind (1968). This method is based on the monitoring of the changes in water potentials inside a soil core at 1.5 and 4.5 cm using two tensiometers and the regular weighing of the soil core. The measurements were conducted on undisturbed soil core cylinders (250 cm<sup>3</sup>), on three replicates for each horizon, in a room at a constant 20°C temperature and for 8 to 9 d. Results were obtained for water potentials ranging from −50 to −600 cm.

### Modeling

Hydraulic parameters, based on the van Genuchten equation (Eq. [3]) (van Genuchten, 1980) in combination with the Mualem model for hydraulic conductivity curve (Eq. [4]) (Mualem, 1976), were determined to obtain a robust analytical expression of water potential  $h(\theta)$  and hydraulic conductivity  $K(\theta)$  as a function of soil moisture  $\theta$ . These expressions could be used in mechanistic water flow models (Mermoud and Xu, 2006).

$$\theta(b) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha b|^n\right]^m} b < 0 \\ \theta_s \end{cases} \quad [3]$$

$$K(b) = K_s S_c^1 \left[ 1 - \left( 1 - S_c^{\frac{1}{m}} \right) \right]^2 \quad [4]$$

where

$$S_c = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad [5]$$

and

$$m = 1 - \frac{1}{n}, \quad n > 1 \quad [6]$$

### Soil Hydraulic Characteristics Modeling

Three distinct methods were applied to determine a set of hydraulic characteristics for the soil materials: (i) direct measurements ( $K_s$  and saturated soil moisture), (ii) exploitation with RETC code (van Genuchten et al., 1991) of the evaporation method experimental measurements (ku-pf), and (iii) computation with the ROSETTA code (Schaap et al., 2001) with the physical properties of the materials (Table 1) and the water retention data (pressure plate method).

### Hydrodynamics Inverse Modeling

The HYDRUS-1D model (Šimůnek et al., 1998), which includes a parameter optimization module, was used to solve the water flow in the lysimeter based on methods similar to previous works (Kelleners et al., 2005; Durner et al., 2008; Vrugt et al., 2008).

The time-variable boundary conditions were specified as follows. The upper and lower boundary conditions were settled on “atmospheric boundary conditions with run-off” and “seepage face” ( $b = 0$ ) according to Šimůnek et al. (2008). The precipitations were measured from the weather station and the real evapotranspiration was calculated from Eq. [1]. The van Genuchten–Mualem soil hydraulic model was applied without taking any hysteresis into account. The lysimeter was described as a two-layered 1.85-m-deep soil profile consisting of Hz 1 from 0 to 1.4 m and Hz 2 from 1.4 to 1.85 m. The compost layer (Hz 0) was neglected since its contribution to hydrodynamics was expected to be low considering its thickness, its position in the soil profile (surface horizon), and its highly saturated hydraulic conductivity (100 cm d<sup>−1</sup>; results not shown). The potential hydrophobicity of the compost and its influence on the incoming water flow were not taken into account but will be discussed later. In HYDRUS-1D, the vertical domain was discretized into 186 equidistant nodes. The initial conditions were set at the water content values measured by TDR probes at  $t_0$ .

Four distinct objective functions were computed: daily boundary flux at the bottom of the lysimeter and the three soil moisture measured with TDR at 0.5, 1, and 1.5 m deep. The parameter estimation process described by Šimůnek et al. (2008) was applied only to soil hydraulic parameters (i.e., saturated soil water content  $\theta_p$ , residual soil water content  $\theta_s$ , saturated hydraulic conductivity  $K_s$ , parameters  $\alpha$  and  $n$  in the soil water retention function, and tortuosity parameter  $l$  in the conductivity function) without any internal weighing, but with a maximum of 20 iterations.

### Goodness of Fit Estimation

The root mean square deviation (RMSD) was used as an indicator of the accuracy of the model (Köhne et al., 2011). The differences between observed ( $X_1$ ) and simulated ( $X_2$ ) values for the different parameters (TDR values at different depths, water flow) were calculated according to

$$\text{RMSD}(X_1, X_2) = \sqrt{\frac{\sum_{i=1}^n (x_{1,i} - x_{2,i})^2}{n}} \quad [7]$$

The RMSD was then normalized, nRMSD, to account for magnitude differences and variability between the different objective functions

$$R_{p_i, p_j} = \frac{\overline{s_{p_i} s_{p_j}} - \overline{s_{p_i}} \overline{s_{p_j}}}{\sqrt{(\overline{s_{p_i}^2} - \overline{s_{p_i}}^2)(\overline{s_{p_j}^2} - \overline{s_{p_j}}^2)}} \quad [8]$$

$$\text{nRMSD} = \frac{\text{RMSD}}{x_{\max} - x_{\min}}$$

Thus, the smaller the nRMSD value, the better the fit between simulated and experimental data (0% would correspond to a perfect fit).

### Sensitivity Analysis

The sensitivities of the 12 estimated hydraulic characteristics were also estimated from the observable quantities. The sensitivity of the parameter  $p_k$  on the modeled quantity  $X(t, \vec{p}_{\text{ref}})$  around the set of reference parameters  $\vec{p}_{\text{ref}} = (p_{\text{ref}}^1, \dots, p_{\text{ref}}^{12})^T$  was defined as

$$s_{pk} = p_k \frac{\partial X(t, \vec{p}_{\text{ref}})}{\partial p_k} \quad [9]$$

in which the factor  $p_k$  made the sensitivities to be homogeneous and comparable for different parameters. In practice, the derivative appearing in the expression of  $s_{pk}$  was calculated by central difference by perturbing only the parameter  $p_k$

$$s_{pk} \approx p_k \left[ \frac{X(t, \vec{p}_{\text{ref}} + \Delta p_k \vec{e}_k) - X(t, \vec{p}_{\text{ref}} - \Delta p_k \vec{e}_k)}{2\Delta p_k} \right] \quad [10]$$

with  $\vec{e}_k$  the  $k$ th vector of the canonical basis of  $\mathbb{R}^{12}$ . The variation  $\Delta p_k$  was of the form  $\varepsilon p_k$ , with  $\varepsilon \ll \text{<< sufficiently small >>}$  (a value of 0.01 was considered for the calculations), leading to

$$s_{pk} \approx p_k \left[ \frac{X(t, \vec{p}_{\text{ref}} + \Delta p_k \vec{e}_k) - X(t, \vec{p}_{\text{ref}} - \Delta p_k \vec{e}_k)}{2\varepsilon} \right] \quad [11]$$

Once the sensitivities were obtained, the correlations between parameters were calculated by using the well-known expression of linear correlation coefficient

$$R_{p_i, p_j} = \frac{\overline{s_{p_i} s_{p_j}} - \overline{s_{p_i}} \overline{s_{p_j}}}{\sqrt{(\overline{s_{p_i}^2} - \overline{s_{p_i}}^2)(\overline{s_{p_j}^2} - \overline{s_{p_j}}^2)}} \quad [12]$$

where the symbol  $\bar{x}$  denoted the mean value of the quantity  $x$  over the time increments.

## Results and Discussion

### Hydrodynamic Description of the Technosol Lysimeter

#### Water Balance

The water balance of the lysimeter was first examined through the mass variation of the device, representing the overall water content variation with time, from September 2007 to February 2011 (Fig. 4). The mass variation presented a cyclic pattern of increases and decreases, mostly following seasonal variations.

The periods from September 2007 to December 2007 (P1 and P2) corresponded to the initial hydric equilibration of the constructed soil inside the lysimeter (Séré et al., 2010). At first (P1), only a small

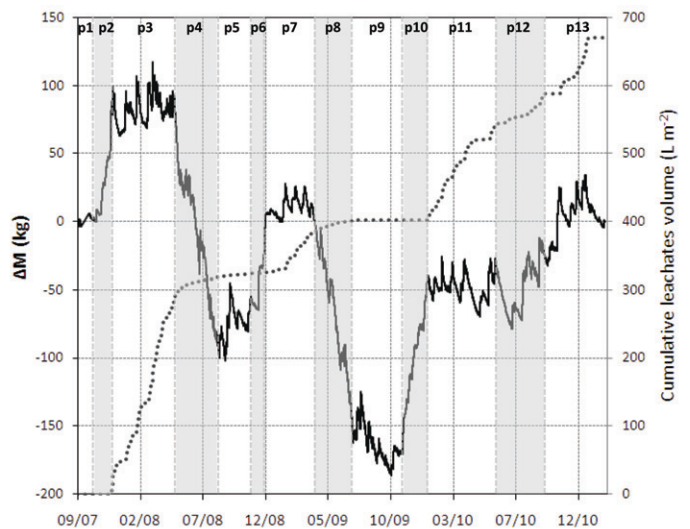


Fig. 4. Mass variation  $\Delta M$  (plain line) (left axis) and cumulative leaching water (dotted line) (right axis) of the lysimetric column filled with constructed Technosol. Vertical areas noted P represent time period that are referred to in the text.

increase in  $\Delta M$  was observed due to a rather dry period (only 10 mm of rain). With massive rainfall (P2),  $\Delta M$  increased by about 100 kg until reaching the water holding capacity of the whole soil profile and the beginning of water drainage, i.e., leaching.

Afterward, over winter periods and saturation of water holding capacity of the device (P3 in 2007–2008, P7 in 2008–2009, P11 in 2009–2010, P13 in 2010–2011), the  $\Delta M$  varied only slightly, around an average value of +80 kg for P3, +10 kg for P7, –50 kg for P12, and +10 kg for P13. These periods also corresponded to the highest leaching periods with respectively 70, 40, 50, and 15% of incoming rain drained through the lysimeter.

Transitory periods of increase and decrease of  $\Delta M$  were observed over springs (P4 and P8) and autumns (P6 and P10) with a remarkable exception in 2010 (P11, P12, and P13). Indeed, after the increase in  $\Delta M$  in autumn 2009 (P10), there was a plateau from winter through to summer 2010 (P11 and P12) followed by a slight increase in autumn 2010 (P13). The absence of no significant decrease in  $\Delta M$  over the spring or summer could be partly explained by a rainy summer (263 mm) (Fig. 3) and, possibly, a poor development of the vegetation. Consequently, there was a continuous drainage of water with only short interruptions. Other summer periods (P5 and P9) were characterized by slightly decreasing or steady  $\Delta M$  at low values around respectively –75 kg for P5 and –170 kg for P9 and by an absence of leaching.

Water content values in the profile displayed patterns similar to the overall mass variation, but with variable intensity depending on the position and material in the profile (Fig. 5). Values at 0.5 m measured in the treated soil–paper mill sludge mixture (Hz1) presented the highest variations, fully representative of the global variation described above (Fig. 4). Measurements in the same

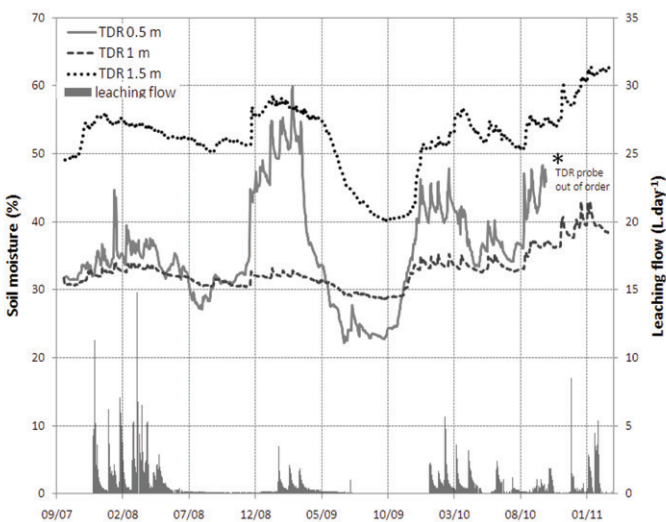


Fig. 5. Soil moisture measured with TDR probes at three different depths (curves) (left axis) and leaching flow (histogram) (right axis) in the lysimetric column filled with constructed Technosol.

horizon at a 1-m depth gave similar trends but with much smaller amplitude. Water content in the paper mill sludge horizon (Hz2) at 1.5 m was systematically higher than at the two other depths due to the high water holding capacity of this material.

Most variations were explained by rain events and evapotranspiration intensity, as already described. The moisture in the upper part of Hz1 (0.5 m) was lower than that of the lower part (1 m) during the summers of 2008 and 2009. This was consistent with the high and long evapotranspiration period (Fig. 6) associated with few rainfall events. In fact, the TDR measurements at 1 m remained almost constant. This was especially noticeable during the dry period (P9) in the summer and fall of 2009 when the TDR at 0.5 m decreased from 54 to 23%, as well as the TDR at 1.5 m that dropped to 40% when the TDR at 1.0 m evolved only slightly. Conversely, the following period (P10) led to a massive increase in the moisture in the upper part of Hz1 (0.5 m) that was not reflected at 1.0 and was delayed at 1.5 m.

As far as drainage was concerned, this occurred when the soil moisture in Hz2 exceeded 53%, which seemed to be the “field” water holding capacity of the material.

### External Factors: Climate and Vegetation

The calculated evapotranspiration,  $E_t$ , along with the incoming light are presented in Fig. 6. Over fall 2007, evapotranspiration values were low due to the absence of vegetation cover (sowing was done in March 2008), which is consistent with other observations on the lysimetric station (data not shown). Bare soils have low evapotranspiration due to the strongly filtrating conditions set by the lysimetric device. The  $E_t$  pattern was of course strongly influenced by the seasonal variations. The shape of the curve was similar in 2008 and 2009. In 2010, a cloudy and rainy month of May (indent in the light curve) led to a slight drop in  $E_t$ . The yearly cumulative real evapotranspiration decreased from 104 cm in 2008 to 90 cm in 2009 and 2010. However, globally the ratio rainfall/yearly cumulative evapotranspiration was lower in 2008 (0.85) and 2009 (0.88) than in 2010 (0.98). This indirect information was exploited here to describe the vegetation development (no experimental data acquired). It appeared that the biomass production was certainly high in 2008 due to recent direct sowing, optimal climatic conditions, and a warm and rainy spring. The plant growth was more limited in 2009, when there was a dry spring, and in 2010, with less light in May. The water balance (rain – evapotranspiration) was similar in 2008 and 2009 and significantly negative. In 2010, it was approximately null.

### Discussion

The first important result of the monitoring of the in situ lysimetric column was the fact that the constructed Technosol could fulfill its function of filter/buffer as far as water was concerned. Indeed there was retention and drainage of the water similarly to a natural soil. Moreover, a specific hydraulic

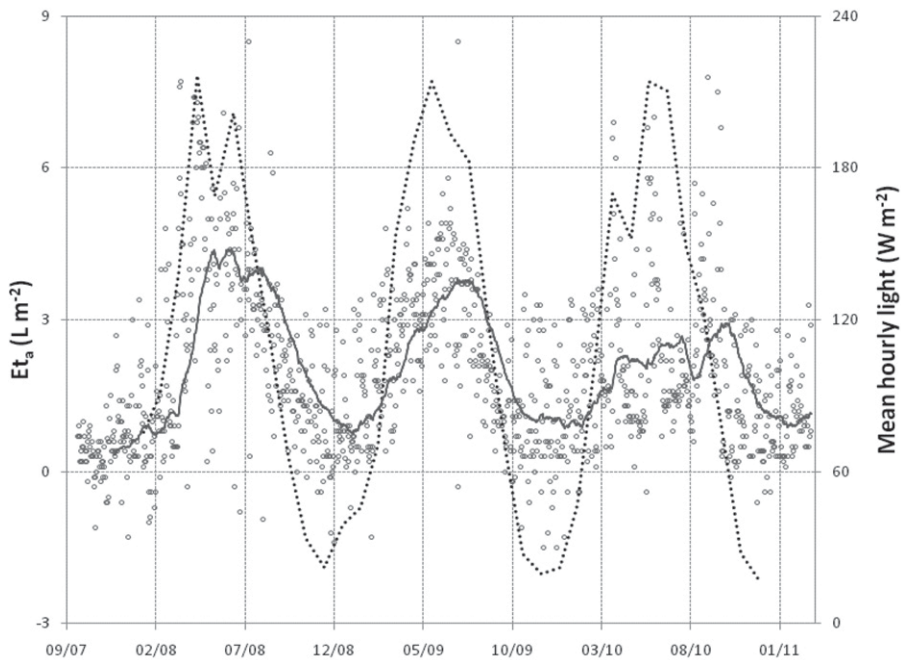


Fig. 6. Actual evapotranspiration  $E_{t_a}$  (gray round) and its mobile average (plain line) (left axis) of the lysimetric column filled with constructed Technosol; mean hourly light (dotted line) (right axis).

functioning of the constructed soil was observed. Indeed, the Hz2 of pure paper mill sludge behaved as a water supply for the upper horizon during dry periods and recharged itself during rainy events, as expected from its specific formulation.

The hydrodynamic behavior of the constructed Technosol was studied through the drained water volumes and the mass variations, i.e., global water content. Vegetation development and climate (rainfall, temperature, and light) were not the same over the 3 yr. These external factors contributed to the main variations of the water flow. The water balance results in 2008 and 2009 were consistent with the global water content decrease observed. In 2010, the balance was close to equilibrium, which logically led to a relative increase in the water content at the end of the December 2010.

A seasonal pattern (moisture increase in fall–winter period and decrease in spring–summer period) was observed. However, this pattern evolved between 2008 and 2009 with a time lag (the different events of the pattern happened at different times), variations of the intensity of parameters, and a decrease of the total mass. During the third year, the pattern changed drastically in its shape and length because no downward trend was observed. The external factors, especially climate conditions, controlled the global hydrodynamic evolutions of the system but failed to explain all the variations.

Other differences between the various measurements were visible. Indeed, there was a global decrease in the weight of the constructed Technosol profile with time. Yet that theoretical loss of water content

was not significantly visible on the TDR measurements of soil moisture at different depths. Thus, a potential deviation could exist in the TDR values that could be explained by modifications of several factors: bulk density, temperature, or simply contact surface could induce such variations (Jones and Or, 2002). In particular, a global compaction of 5 cm (equivalent to  $0.05 \text{ m}^3$ ) of the constructed Technosol profile was observed after its implementation over time. Yet, the global trend that was valid and representative of the hydric functioning was consistent with the reliable water balance results.

It is therefore clear that the hydrodynamic behavior of the soil column had evolved over the 3-yr period and could not be explained by external factor variations alone. This observation led us to the hypothesis that the soil hydraulic properties also significantly changed and could be linked to the evolution of structure previously described (Séré et

al., 2010). No direct physical measurements could be applied to the soil materials inside the lysimeter to assess this hypothesis without significantly disturbing the water flow. Consequently, the next step was to use a modeling approach of the system to try to evaluate the temporal variability of the hydraulic properties.

## Water Flow Modeling Soil Hydraulic Characteristics Estimate

The direct measurements led to robust values of  $\theta_s$  with small variations (<5%) between the replicates for both the treated soil–paper mill sludge mixture ( $\theta_s \text{ Hz1} = 0.59$ ) and the pure paper mill sludge ( $\theta_s \text{ Hz2} = 0.66$ ) (Table 2). These values were consistent with both the RETC exploitation and the ROSETTA simulation. The simulations of  $\theta_r$  gave significantly lower values with RETC than with ROSETTA. In addition, the  $\theta_r$  value given by ROSETTA for Hz1 was higher than some observed values on the TDR.

The saturated hydraulic conductivity ( $K_s$ ) measurements of the two materials were highly variable from one sample to another (up to 70%), which is a common observation (Carrick et al., 2010). Both simulation approaches were consistent for the Hz1 soil material (51.8 and  $64.6 \text{ cm d}^{-1}$ , respectively) but disagreed on the Hz2 (50.1 and  $2.6 \text{ cm d}^{-1}$ , respectively).

The values obtained for  $\alpha$  were low in all cases and calculations for the  $n$  parameter were rather similar with both models and for both materials (ranging from 1.3 to 1.7).



Table 2. Constructed Technosol hydraulic characteristics determined by (i) direct measurements, (ii) RETC exploitation, and (iii) ROSETTA simulation.

Parameters	Units	Direct measurements		Ku-pf measurements exploited with RETC		ROSETTA simulation		Selected values (Set 1)	
		Hz 1	Hz 2	Hz 1	Hz 2	Hz 1	Hz 2	Hz 1	Hz 2
$\theta_r$	–	–	–	$0.28 \pm 0.04$	$0.17 \pm 0.02$	0.07	0.12	0.17	0.14
$\theta_s$	–	$0.59 \pm 0.03$	$0.66 \pm 0.03$	$0.58 \pm 0.02$	$0.66 \pm 0.03$	0.50	0.62	0.59	0.66
$K_s$	$\text{cm d}^{-1}$	$179.5 \pm 123.4$	$22.97 \pm 15.66$	$51.8 \pm 6.23$	$2.6 \pm 1.75$	64.6	50.1	58.2	26.4
$\alpha$	$\text{cm}^{-1}$	–	–	$0.08 \pm 0.06$	$0.01 \pm 0.00$	0.02	0.002	0.05	0.01
$n$	–	–	–	$1.47 \pm 0.10$	$1.09 \pm 0.01$	1.27	1.66	1.37	1.37
$l$	–	–	–	–	–	0.07	0.30	0.07	0.30

Given the original and specific characteristics of the technogenic parent materials (i.e., low bulk density, high organic matter content, specific structure), such diverging results between methods was not surprising. Indeed, ROSETTA simulations are based on a natural soil database, and estimations rely mainly on particle-size distribution (Schaap et al., 2001). The composition, especially the high organic matter content and the structural arrangement, which led to the low bulk density of our materials for example, differ significantly from natural ones, and their hydraulic properties might therefore be governed by other parameters in natural soils. The ROSETTA estimates have therefore to be considered with caution.

Initial values for the hydraulic parameters were needed to run HYDRUS-1D model. To select these, a comparison was made between the different measurements and modeling approaches previously described. Then, measured values of  $\theta_s$  were used, whereas the other values were averaged between the RETC modeling and the ROSETTA simulation to get a robust set of values (Set 1) (Table 2).

### Water Flow Modeling over a Three-Year Period

The hydrodynamics of the lysimeter was first modeled over the 3 yr, using the initial parameters previously determined (Set 1) (Table 2). The model simulated the evolution of the soil moisture at different depths (0.5, 1.0, and 1.5 m, continuous line in Fig. 7a, 7b, and 7c, respectively). The goodness of prediction generally decreased with depth ( $R^2 = 0.09, 0.06,$  and  $0.03$  at 0.5, 1.0, and 1.5 m, respectively). Indeed, the plateau values were significantly overestimated at 1.0 and 1.5 m. The peak values were either not represented (1.5 m), shifted in time (0.5 m), or underestimated (0.5 m). The model did not fit the daily flow main events either ( $R^2 = 0.002$ ) (Fig. 7d), especially in the winter periods. The result of the cumulative leachate volume modeling was passable (nRMSD = 76%) while widely underestimating the experimental data. The different methods used to estimate the hydraulic properties and the way they were combined were certainly a major explanation of this deviation.

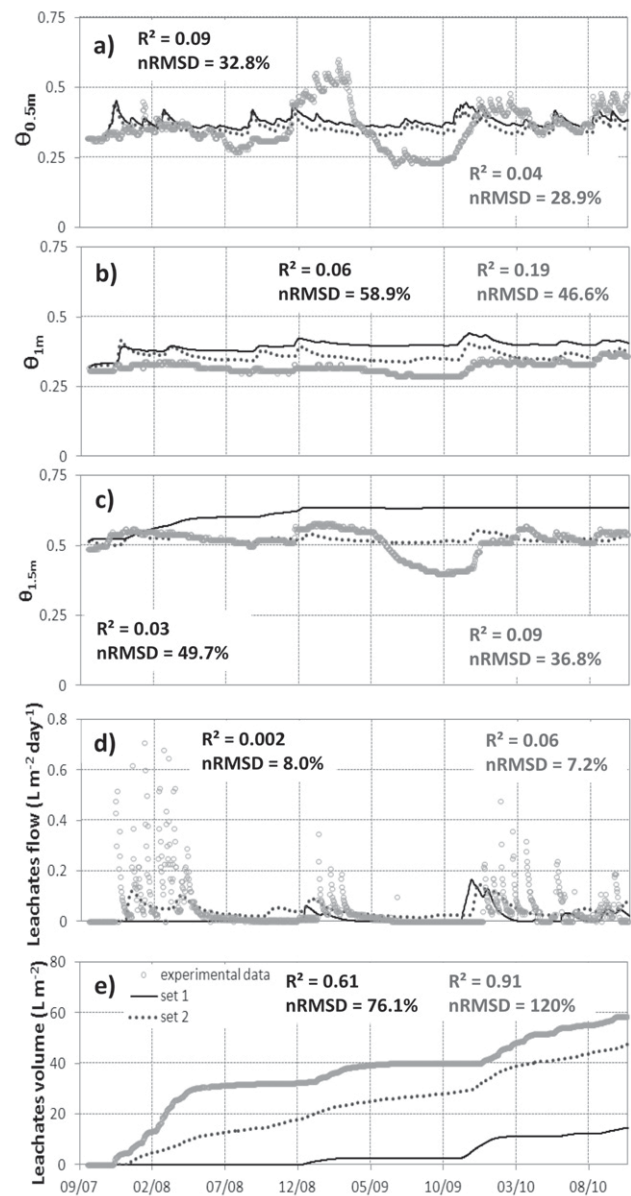


Fig. 7. Comparison between experimental measurements (light gray rounds), predicted values with Set 1 (black plain line), and predicted values with Set 2 (dark gray dotted line) of the hydrodynamic of a lysimetric column filled with constructed Technosol from September 2007 to October 2010 for (a) 0.5 m TDR, (b) 1.0 m TDR, (c) 1.5 m TDR, (d) daily leachate flow, and (e) cumulative leachate flow.

Therefore, an optimization process of all soil hydraulic characteristics was applied to the period using the four objective functions previously described. The process led to some significant changes in some of the optimized values of the parameters (Set 2) (Table 3). Both  $\theta_r$  values were smaller after the optimization. To the contrary,  $\alpha$  values increased for both horizons, as well as the  $l$  values that even reach its maximum for Hz2 ( $l = 1$ ). The optimized saturated hydraulic conductivities were only slightly adjusted ( $K_s\text{Hz1} = 49 \text{ cm d}^{-1}$ ,  $K_s\text{Hz2} = 10.5 \text{ cm d}^{-1}$ ), such as other characteristics ( $\theta_s, n$ ).

This inverse modeling and new set of parameters led to significant improvements in the soil moisture evolution at all depths (nRMSD < 47%) (dotted lines in Fig. 7). This time, the plateau values were generally in better agreement with experimental data (e.g., around 0.50 at 1.5 m). Yet, the intensity, the extent, and position of the main events (peaks and troughs) were still not very well explained, especially at 0.5 m, which had the worst  $R^2$ . The leachate daily flow was slightly improved, notably because the model did not fit the major water flow peaks during the winter periods. The simulated cumulative flow was noticeably better, as illustrated by the  $R^2$  that increased from 0.61 to 0.91; however, the shape of the curve remained different from the experimental data (nRMSD = 120%).

Globally, the relatively poor capacity of the model to estimate the different parameters highlighted the complexity of the modeling of the hydrodynamic behavior of the constructed Technosol. Indeed, the inverse modeling approach led to significant discrepancies between measurements and model. For example, the water-supply effect of the Hz2 made of pure paper mill sludge to Hz1 was poorly represented.

### Water Flow Modeling on Three Nine-Month Periods

To check for possible evolution of hydraulic properties of the materials over the 3-yr period of this experiment, simulations were performed on 9-mo periods using the soil moisture at 0.5 m as an objective function. Indeed, our hypothesis was based on the pedological observations that demonstrated the strongest pedogenic evolution of the upper part of the constructed Technosol. The periods (November 2007–July 2008, November 2008–July 2009, November 2009–July 2010) were chosen because they were the more water draining intervals. For each period, a simulation with the inverse modeling results for the entire 3-yr period (Set 2) (Table 3) was compared with the Hz1 optimized parameters for each 9-mo period. For the three selected periods, the cumulative rainfall differed only slightly (68 cm in 2007–2008, 52 cm in 2008–2009,

62 cm in 2009–2010), as well as the evapotranspiration (81 cm in 2007–2008, 69 cm in 2008–2009, 63 cm in 2009–2010) (Fig. 3 and Fig. 6). The results of the simulations were therefore of great interest.

With these conditions, the simulation with Set 2 systematically underestimated the soil moisture (Fig. 8). For all three periods, the inverse modeling approaches led to a better simulation of the average soil moisture, which explains the increases of the  $R^2$  values, but still failed to represent the peaks events, which is consistent with high nRMSD values (>26%). The optimization

Table 3. Soil hydraulic characteristics of a constructed Technosol before and after an inverse modeling optimization based on daily flow and TDR measurements.

Parameters	Units	Initial value (Set 1)		[Min., Max.]		Optional value (Set 2)	
		Hz 1	Hz 2	Hz 1	Hz 2	Hz 1	Hz 2
$\theta_r$	–	0.17	0.14	[0.01, 0.21]	[0.01, 0.30]	0.11	0.12
$\theta_s$	–	0.59	0.66	[0.50, 0.90]	[0.50, 0.95]	0.54	0.65
$K_s$	cm d <sup>-1</sup>	58.2	26.4	[10 <sup>-3</sup> , 10 <sup>4</sup> ]	[10 <sup>-3</sup> , 10 <sup>4</sup> ]	49.2	10.5
$\alpha$	cm <sup>-1</sup>	0.05	0.01	[0.001, 5.0]	[0.001, 5.0]	0.13	0.08
$n$	–	1.37	1.37	[1.0, 2.0]	[1.0, 2.0]	1.40	1.36
$l$	–	0.07	0.30	[0.0, 1.0]	[0.0, 1.0]	0.01	1.00

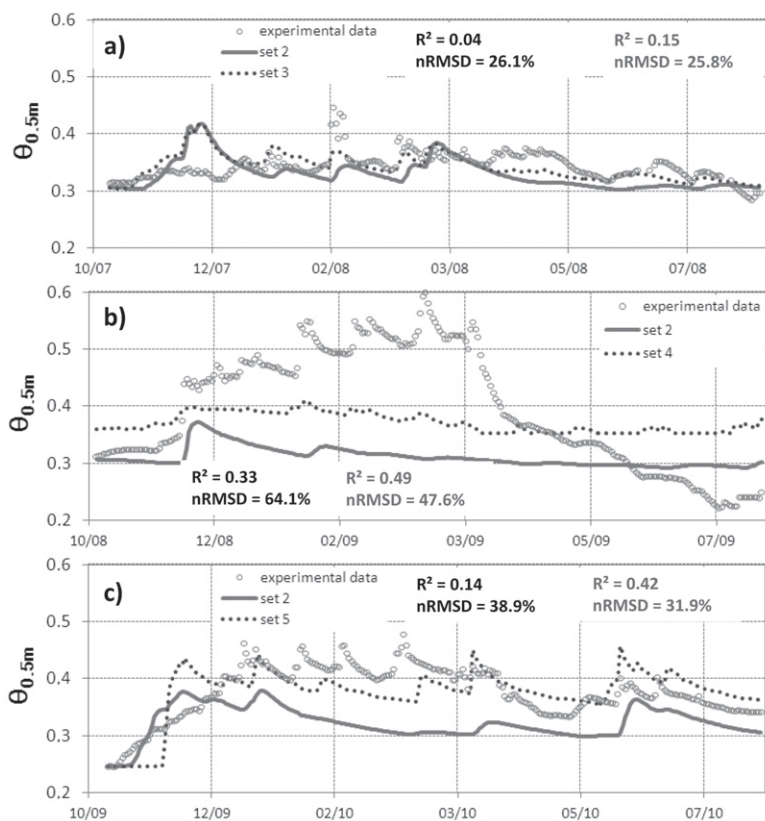


Fig. 8. Comparison between experimental measurements (light gray round), predicted values with Set 2 (black plain line) and predicted values after parameter optimization (dark gray dotted line) of the soil moisture at the 0.5-m depth of a lysimetric column filled with constructed Technosol for (a) November 2007–July 2008, (b) November 2008–July 2009, and (c) November 2009–July 2010.

was conducted for each period with the same range of values as those presented in Table 3. The optimizations led to Set 3, Set 4, and Set 5 (Table 4). The main evolutions were visible on  $\theta_s$ ,  $\theta_r$ , and  $\alpha$  that could be considered as the most sensitive parameters. There was a decrease of  $\theta_r$  with time (from 0.25 to 0.2) at a significantly higher level than the Set 2 value (0.11). The optimized  $\theta_s$  increased with time (from 0.43 to 0.55), reaching at the end a value close to the Set 2 one (0.54). No logical evolution of  $\alpha$  value, which changed from one extreme to another ( $10^{-4}$  to 3.3), was observed. Moreover, some of those values were physically aberrant. The saturated hydraulic conductivity only changed abruptly in the 2008–2009 period, certainly to represent the major increase of the soil moisture.

### Sensitivity Analysis

The sensitivities of all parameters on the four objective functions modeled with HYDRUS-1D ( $X \equiv$  TDR soil moisture at the 0.5-, 1-, and 1.5-m depths, and leachate flow at the bottom of the lysimeter) for Set 1 of Table 2 are presented in Fig. 9. Below, a parameter is considered “sensitive” if its sensitivity was greater than approximately one-tenth of the maximal sensitivity. Figure 10 shows the correlations between the parameters on the same quantities

Table 4. Soil hydraulic characteristics of a constructed Technosol after inverse modeling optimization based on daily flow and TDR measurements for three different 9-mo periods for Hz 1.

Parameters	Units	Set 3 Nov. 2007–July 2008	Set 4 Nov. 2008–July 2009	Set 5 Nov. 2009–July 2010
$\theta_r$	–	0.25	0.25	0.20
$\theta_s$	–	0.43	0.52	0.55
$K_s$	cm d <sup>-1</sup>	49.2	2411	47.8
$\alpha$	cm <sup>-1</sup>	0.02	$10^{-4}$	3.30
$n$	–	1.40	1.40	1.40
$l$	–	0.01	0.01	0.01

and around the same reference set. To improve the readability, the correlation coefficients,  $R$ , greater than 80% have been filled in gray.

At first, it can be noticed that only the hydraulic characteristics  $\theta_s$ ,  $\theta_r$ ,  $n$  of Hz1 were sensitive for the two TDR soil moistures located in this soil horizon (0.5- and 1-m depths). For the TDR soil moistures of Hz2 (1.5-m depth), the same observation was made but only for the first 400 d. Afterward, only  $\theta_s$  of Hz2 seemed to be sensitive. Concerning the leachate flow, the sensitivities exhibited more complex evolution with time and would need to be studied more deeply. It was also interesting to notice that the number of correlations between parameters of Hz1 and Hz2

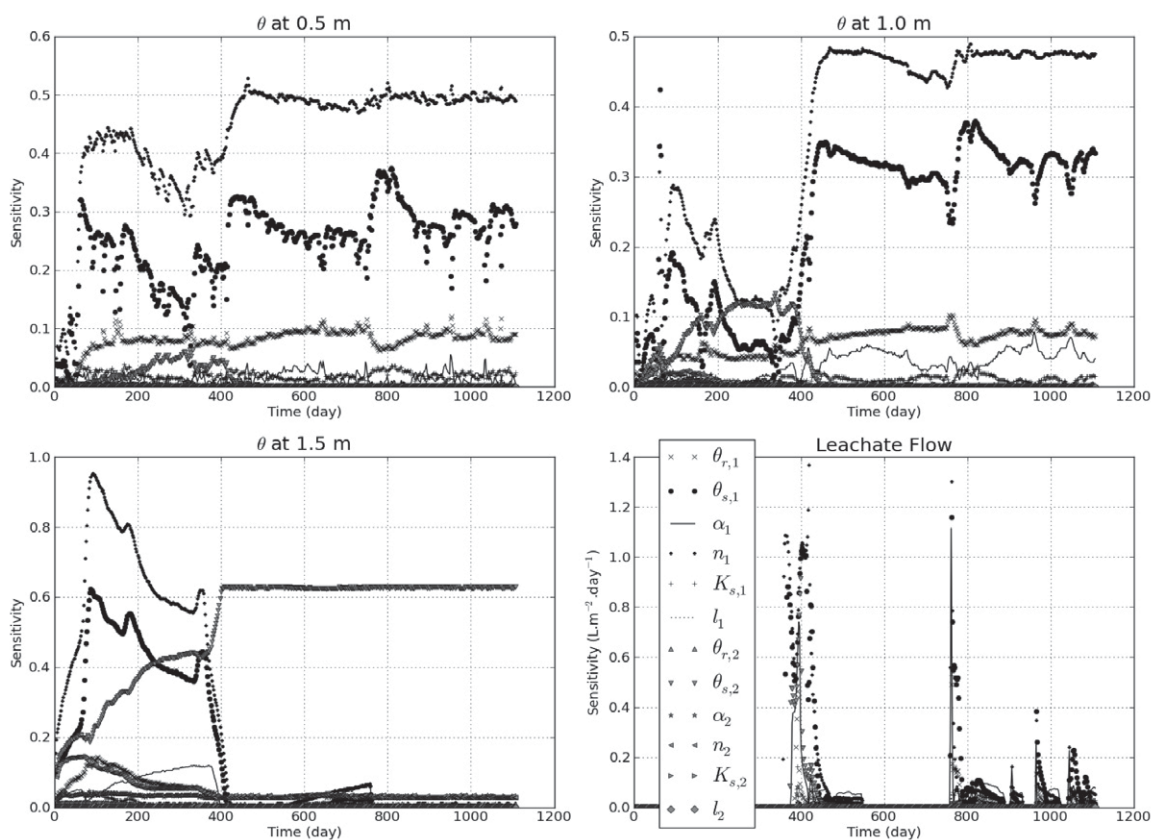


Fig. 9. Sensitivities of hydraulic characteristics on the four modeled quantities (TDR soil moisture at the 0.5-, 1-, and 1.5-m depths, and leachates flow at the bottom of the lysimeter) around Set 1 of Table 2. Subscripts 1 and 2 indicate the horizon number.

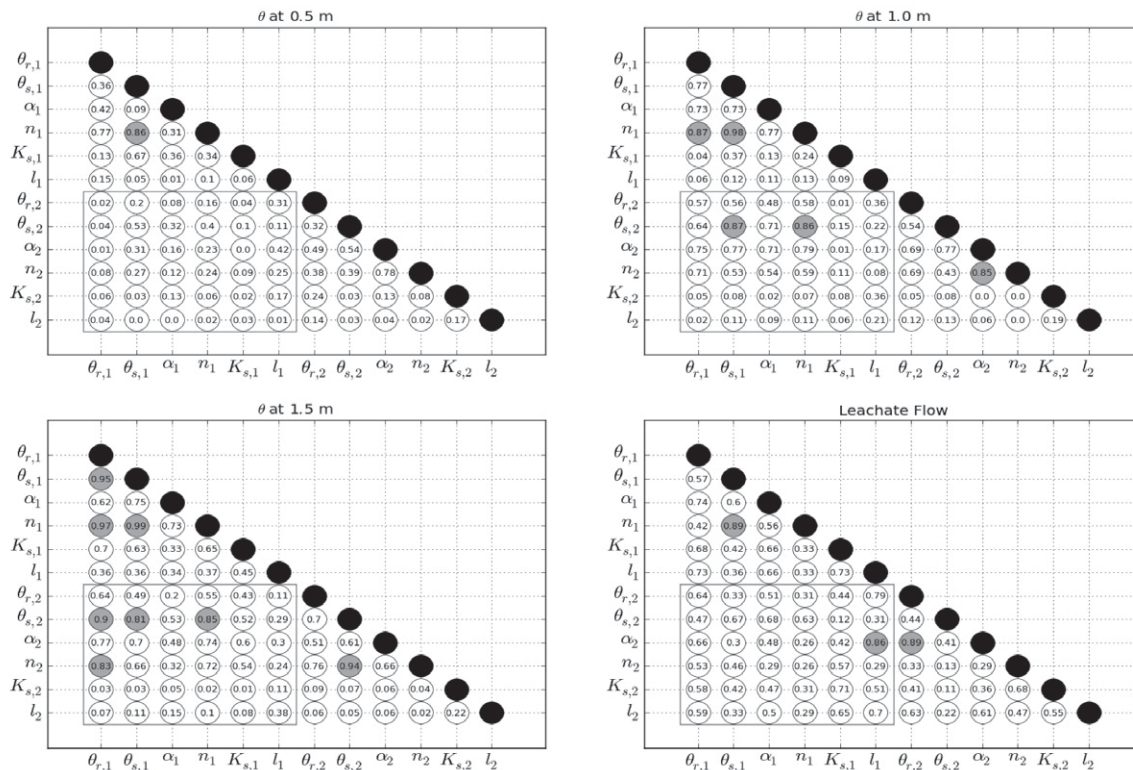


Fig. 10. Correlations between hydraulic parameters calculated with sensitivities of Fig. 9 (correlations > 80% are filled in gray). Subscripts 1 and 2 indicate the horizon number.

increased with depth (see the framed correlations in Fig. 10). The fact that these correlations are maximal at the 1.5-m depth may be explained by the great influence of the hydrodynamics of the low-depth soil layers on the soil located underneath. Thus, one may surmise that the present parameter estimation could be improved by considering objective functions associated with different experimental data sets, the latter being chosen to maximize the sensitivities of some parameters and minimize their correlations. Of course, one should keep in mind that the sensitivities and correlations calculated here may vary if the reference parameter set  $\vec{p}_{ref}$  were changed because of the high nonlinearity of the Richards equation solved by HYDRUS-1D. Consequently, a broader investigation should be performed to confirm or invalidate these first deductions.

### Discussion

Our modeling approach was based on previous pedological observations and measurements. An early pedogenesis of the constructed Technosol had already been described, leading notably to macro and microaggregation and subhorizons formation (Séré et al., 2010). Coherently, an evolution in the hydrodynamic behavior of the in situ constructed Technosol monolith was described above. We formulated the hypothesis that hydraulic parameters could steadily evolve with time expressing the changes of the soil structure. The results of the different simulations gave interesting perspectives on the hydraulic functioning of the constructed Technosol and its evolution with time.

different modeling results obtained on the constructed Technosol highlighted its originality in comparison to natural soils. For example, its technogenic parent materials had high values of saturated water content—explained by their low bulk density—that would be similar to a clayey soil, but a low value of residual water content like a loamy sandy soil. As a consequence, some of the hydraulic properties of the soil failed to be correctly represented by the model, as was the case for the water supply of the pure paper mill sludge.

Globally, the different estimations with HYDRUS-1D poorly fitted the experimental data (maximal  $R^2 = 0.6$ ). However, the inverse modeling over the 3 yr revealed valuable tendencies of the soil moistures at different depths. The leachate volume was also correctly simulated, whereas the peak events in winter were not represented. The model did not succeed in representing those major percolation events that led to a passable result on the daily flow. Consequently, it seemed obvious that parameter optimization could improve the adequacy of the simulation without leading to a much better fit. The relevance of the HYDRUS-1D model could be questioned. Our demonstration was based on the hypothesis that no preferential flow happened, which justified using HYDRUS-1D (Köhne et al., 2009). To support this hypothesis, a major argument was the low clay content of the constructed Technosol that induced no significant shrinkage or cracking process in the soil profile as well as the absence of soil macrofauna. However, the upper compost

layer and its potential hydrophobicity (Ojeda et al., 2011) may have had consequences on the flow that were not taken into account in this work. The absence of any intense water flow peak in the experimental data was considered here as evidence that no major preferential flows occurred. Further forecasts should therefore rely on a better use of the HYDRUS-1D tool. A single porosity model (van Genuchten–Mualem formalism) has been used, but other hydraulic models could be explored to improve the modeling results. A better fit could also be expected, considering, as mentioned above, the specificity of the soil materials, by taking into account hysteresis data for either retention curves or saturated hydraulic conductivity (Durner et al., 2008). In the same idea, a finer spatial discretization of the soil profile information around the transition between the two soil materials could be applied. Lastly, it would, of course, be necessary to conduct a deeper sensitivity analysis on the different hydraulic parameters (Montzka et al., 2011).

The study on the three 9-mo periods showed interesting trends on such parameters as saturated soil moisture, residual soil moisture and  $\alpha$ . The results—increase of  $\theta_s$  and decrease of  $\theta_r$ —were hard to link with our previously quoted results—decrease of the bulk density, increase of the macroporosity, and decrease of the available water storage—(Séré et al., 2010). Meanwhile, some trends were observed that were certainly the expression of an evolution of the soil structure. The variations of such an empirical parameter as  $\alpha$  could be related to the evolution of the pore geometry. This observation would now need to be confirmed by studying the lysimetric experiment on a longer term.

For now, the work on the early pedogenesis of a Technosol could contribute to the emergence of hydro-pedologic approach of soil evolution. What if the temporal variation of the soil hydrodynamic followed two distinct time scales: (i) a slow diachronic steady evolution driven by the soil pedogenesis (Lin, 2010) and (ii) a fast synchronic cyclic evolution driven by the seasonal or even microclimatic conditions (Hu et al., 2009)? The resolution of our measurements would therefore be inadequate to completely characterize their evolution. Future efforts should focus not only on the continuation of the measurements on the lysimeter device, but also on studies on a smaller scale, in the laboratory with simpler devices. Further developments could certainly take into account the biological activity (especially soil fauna) as a major factor that modifies the poral system during the evolution of the soil.

## Conclusions

The water flow of a lysimeter filled with a constructed Technosol was monitored over 3 yr. Apart from seasonal variations, an originality of the hydric functioning of the constructed Technosol (i.e., the water supply function provided by the pure paper mill sludge) was demonstrated due to the specific nature of its technogenic parent materials. The hydrodynamics of the system evolved with time, and it was only partly attributed to

external factors (climate, vegetation). This evolution could be linked with changes of the hydraulic parameters of the constructed Technosol and could be related to the early pedogenesis, particularly concerning the soil structure, which was consistent with previous observations.

A modeling approach was applied to highlight and to quantify the evolution of these parameters by conducting first a direct simulation of the water flow, then an inverse modeling. The estimations over a 3-yr period and 9-mo periods succeeded in representing the global trends of the water flow at the pedon scale but did not correctly simulate the main hydric events (e.g., massive leachate outflow, water supply function). Some evolutions with time of the hydraulic properties were demonstrated that are promising for future research.

The constructed Technosol is a valuable experimental model to study evolution at different time scales (slow and steady, fast and cyclic) of the soil hydraulic properties because its pedogenesis is faster than most natural soils. This work will continue with an effort to demonstrate the relevance of considering the coexistence of diachronic and synchronic evolutions of these parameters.

## Acknowledgments

This project is supported by the GISFI program ([www.gisfi.fr](http://www.gisfi.fr)). The authors wish to thank Jean-Christophe Renat (VALTERRA), Rémi Baldo, Lucas Charrois, Cindy Messana, Noëlle Raoult, and Frédéric Rees (GISFI) for their contributions. The questions and suggestions of the reviewers of this article significantly improved our work; we would sincerely like to thank them.

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