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Utilisation de méthodes géophysiques pour caractériser les bassins d'infiltration d'eaux pluviales.

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Use of geophysical methods to characterize stormwater infiltration basin.
Utilisation de méthodes géophysiques pour caractériser les bassins d'infiltration d'eaux pluviales.

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RESUME
Les bassins d'infiltration d'eaux pluviales sont généralement construits sur des formations à forte conductivité hydraulique moyenne. C'est le cas des formations alluvionnaires quaternaires, dont les formations fluvioglaciaires. Deux méthodes d'investigation géophysique, le radar géologique (GPR) et la tomographie électrique, ont été testées sur un bassin d'infiltration construit sur un dépôt fluvioglaciaire. Une première étape a consisté à calibrer les réponses géophysiques sur des structures sédimentaires. Une typologie de facies géophysique a ainsi établi. Cette typologie a permis l'interprétation d'une seconde zone dont la stratigraphie n'était pas connue. Ces deux méthodes géophysiques, complémentaires, ont permis d'élaborer un modèle stratigraphique du dépôt fluvioglaciaire. Cette caractérisation montre le haut degré d'hétérogénéité sédimentaire du dépôt. Un modèle simple d'évaluation des conductivités hydrauliques saturées a permis de quantifier les hétérogénéités hydrodynamiques. Cette étude montre que l'hétérogénéité sédimentaire doit être prise en compte dans les modèles d'écoulements non-saturés sous-jacents aux bassins d'infiltration. L'investigation géophysique préalable permet de disposer d'un modèle hydrostratigraphique réaliste.

ABSTRACT
Stormwater infiltration basins (SWIB) are generally built on geological formations with large values of hydraulic conductivity. Such is the case for the quaternary glaciofluvial deposits underlying the Django-Reinhart infiltration basin in Lyon (France). Two geophysical investigation methods, namely ground-penetrating radar (GPR) and electrical tomography, were tested on this an infiltration basin built on a glaciofluvial deposit. A first stage constituted to calibrate the geophysical answers on sedimentary structures. A geophysical typology of facies was thus established. This typology allowed the interpretation of a second area which stratigraphy was unknown. These two geophysical methods, complementary, made it possible to work out a stratigraphic model of the deposit fluvioglaciaire. This characterization shows the high degree of sedimentary heterogeneities of the deposit. A simple model of evaluation of the permeabilities made it possible to quantify hydrodynamic heterogeneities. This study shows that sedimentary heterogeneity must be taken into account in the unsaturated flow models subjacent to infiltration basins. The preliminary geophysical investigation makes it possible to have a realistic hydrostratigraphic model.

MOTS CLES
GPR, electrical resistivity, glaciofluvial deposit, stormwater infiltration

1 INTRODUCTION
Stormwater infiltration is frequently used in urban areas in France. However, their long-term evolution is not clearly understood and the pollutants contained in stormwater may lead to a contamination of the underlying soils and groundwater resources (Dechesne et al., 2005). It is also important to assess the long-term sustainability of such infiltration systems. This assessment requires an understanding of the subsoil hydrostratigraphy. In France, a large part of urban areas are located on quaternary sediments: for example, within southwest France, 72% of the population is living on surficial deposits (e.g. alluvial deposits, glacial and glaciofluvial sediments, loess), which cover approximately 25% of this area. This urban concentration, coupled with a localized infiltration, leads to an increasing exposure of the underground media underlying infiltration basin to diverse anthropogenic contaminations (e.g. heavy metals, hydrocarbons). Because of their large mean hydraulic conductivity, alluvial deposits constitute a large part of the geological formation underlying infiltration basins.

The design of stormwater infiltration systems was initially done by considering a homogeneous hydrogeological formation underneath the basin. However, alluvial deposits present sedimentary heterogeneities which may generate preferential flow paths contributing to a rapid, non-uniform transport of contaminants at depths greater than expected from the hypothesis of a homogeneous deposit. For example, Winiarski et al. (2004) show that the natural sedimentary heterogeneities of a glaciofluvial alluvial deposit underlying an infiltration basin have an impact on unsaturated water flow. An enhanced understanding of the sedimentary and hydraulic heterogeneities within alluvial deposits is also important to assess the impact of infiltration systems on the underground media.

In this study, we consider hydrogeological heterogeneities at the centimetric to decimetric scale of the hydrofacies. Hydrofacies are defined as homogeneous, isotropic or anisotropic units, hydrogeologically relevant for groundwater modelling and solute transport (Anderson, 1989). Hydrofacies are the smallest mappable hydrostratigraphic units, which may result in either pathways for fluid flow or flow barrier (Heinz and Aigner, 2003). A better understanding of unsaturated flow needs a relevant sedimentary characterization at the hydrofacies scale, i.e. a characterization of the lithofacies distribution. Because of their discrete nature, traditional techniques of core analysis are not adapted for this, neither are pumping tests, since they integrate information at the scale of the aquifer formation.

During the last decade, the use of subsurface geophysical methods for sedimentological and hydraulic applications has developed considerably. These methods have the advantage of producing continuous data, which are easily extrapolated into two and three dimensions. However, their resolution is limited, and the use of only one geophysical method is often insufficient to define a reliable stratigraphic distribution. The use of one or more geophysical methods, coupled with a localized knowledge of stratigraphy (i.e. from drilling or outcrop analysis), often allows a good characterization of sedimentary heterogeneities. Among the geophysical techniques most usually used in subsurface applications, Ground Penetrating Radar (GPR) and electrical resistivity can provide an image of the sedimentary structures of gravelly deposits with a resolution between the centimetric and the metric scales.

In this study, these two methods were tested to characterize sedimentary heterogeneities of a glaciofluvial deposit underlying a stormwater infiltration basin in the east of Lyon (France). This infiltration basin is one of the study sites of the multidisciplinary research federation O.T.H.U. (Field Observatory on Water Management), which works towards providing guidance on the management of various urban drainage systems. The aim of this paper is to show how geophysical methods can be used to improve the characterization of alluvial deposits in order to better understand how their sedimentary architecture affects unsaturated water flow underneath a stormwater infiltration basin.

2 METHOD

2.1 Site description

The Django Reinhardt stormwater infiltration basin is located in Chassieu, in the eastern suburbs of Lyon (France). It collects stormwater over an industrial watershed area of 185ha. Before entering the infiltration basin, stormwater first passes through a retention basin. The infiltration basin is 5 m deep and the infiltration area is 1 ha. The basin was dug in a 30 m deep quaternary glaciofluvial formation overlying tertiary molassic sands. The water table is located at a depth of 13 m from the bottom of the basin. According to a previous study, the mean saturated hydraulic conductivity of the glaciofluvial formation ranges from 7.10^{-3} to 9.10^{-3} $m.s^{-1}$ (BURGEAP, 1995).

2.2 Geophysical methods

The Ground-Penetrating Radar (GPR) method is based on the propagation of electromagnetic (EM) waves into the subsurface. A radio-frequency transmitter pulses the EM waves. Some EM energy is reflected by subsurface heterogeneities, due, for instance, to changes in grain size, water content, mineralogy, and grain packing. A receiver regularly records the reflected waves (traces). After processing, the result is a 2D section which represents successive recorded traces as a function of their two-way-travel time in nanoseconds. In our study, GPR measurements were performed with a GSSI (Geophysical Survey System Inc.) SIR 3000 system, with a 400 MHz shielded antenna operating in a monostatic mode (a single antenna for transmitting and receiving EM waves). Data processing was performed with the GSSI Radan 6 software. Our previous work showed that the 400 MHz antenna was a good compromise between high resolution and adequate penetration depth in glaciofluvial deposits (Goutaland et al., 2005). Moreover, Goutaland et al. (2005) translate two-way-travel times (in ns) to actual depth (in meters) by the calibration of GPR profiles on trench walls. The mean EM wave velocity was evaluated at 0,09 $m\ ns^{-1}$.

Subsurface electrical resistivity is measured by applying an electric current through two current electrodes and measuring the resulting voltage difference between two potential electrodes. Electrical resistivity is a function of porosity, saturation, resistivity of the pore fluids and the solid phase, and the material texture (Meads et al., 2003). For this study, we used the ABEM Terrameter LUND Imaging System, with a SAS 4000 resistivity instrument. A dipole-dipole array was used with an electrode spacing of 1 m. Two- and three-dimensional inversions were performed with the Res2Dinv and Res3Dinv softwares, respectively. Profiles of apparent resistivity are mapped after processing.

2.3 Experimental procedures

A trench wall (15 m long, 2,5 m deep) was exposed by excavating the glaciofluvial deposit with a power shovel. Geophysical data were measured on an orthogonal grid covering a 15 m N-S x 8 m W-E area behind the trench wall. The line spacing was 1 m in each direction. The GPR investigation was conducted on the orthogonal grid, while electrical tomography was only performed on the N-S lines. GPR and electrical resistivity profiles corresponding to the trench wall were calibrated on the lithological units, water contents and the fraction of fine particles in each unit. Units characterized by geophysical methods were defined by changes in the dip of GPR reflections.

Geophysical profiles measured behind the trench wall were indirectly compared to the trench wall. To understand the three-dimensional distribution of structural and textural glaciofluvial units and thus interpolate geophysical data between survey lines, a sedimentological study was carried out. The sedimentological study of natural deposits allows the three-dimensional reconstruction of the palaeoenvironment, which can be used to interpret the genetically homogeneous distribution of structural units and associated lithofacies. A typology of GPR and electrical resistivity features associated to sedimentary structures (depositional elements, i.e. structural scale, and lithofacies, i.e. textural scale) was defined. Dry sieve analyses were performed on each lithofacies. The sedimentological code of Miall (1978), presented in table 1, was used for the identification of the lithofacies. Estimations of saturated hydraulic conductivities were performed using the Kozeny-Carman expression proposed by Chapuis and Aubertin (2003), which requires lithofacies grain-size distribution (measured) and void ratio (estimated from literature data on analogous lithofacies).

The typology defined in the previous step was used to interpret the glaciofluvial stratigraphy of another area of the basin of unknown hydrostratigraphy. The GPR measurements were carried out on a 15 m W-E x 6 m N-S orthogonal grid, with line spacing of 1m in each direction. Electrical tomography was carried out on a single W-E line corresponding to the northern side of the GPR grid. A conceptual stratigraphic model of lithofacies distribution was defined. Finally, estimations of saturated hydraulic conductivity were assigned to each lithofacies, to define a hydrostratigraphic conceptual model of the glaciofluvial deposit, which was discussed compared with the infiltration basin functioning.

3 RESULTS AND DISCUSSIONS

3.1 Geophysical methods

Figure 1a) summarizes the main stratigraphic features of the trench wall, and the corresponding GPR and apparent resistivity profiles. The investigation depth is 3 m with GPR and 4,6 m with electrical resistivity. Unit 1 corresponds to continuous parallel GPR reflections dipping northward. Corresponding resistivity values are ranging from 1000 to 1400 Ω.m. This unit corresponds to unsaturated sands and gravels mixture with a major gravel fraction. Unit 2 is relatively thin, it corresponds to subparallel, high-amplitude GPR reflections dipping southward. This structure is not clearly identifiable on the resistivity profile, but resistivity values are high (1000 Ω.m). Such are related to thin gravel beds on the trench wall. Unit 3 is characterized by oblique (dipping northward) and curved reflections at depths between 1 and 2 m. The upper part of unit 3 is characterized by subparallel higher amplitude reflections dipping northward. The curved shape of unit 3 is observable on the resistivity profile. Resistivity values decrease in the curved shape, ranging from 500 to 1000 Ω.m and corresponding to a change in the lithology (sand lens). The upper unit (unit 4) is characterized by continuous subhorizontal high amplitude reflections. Resistivity values of the first meter are low, they range from 200 to 500 Ω.m. Due to the proximity with the basin surface, this unit a higher quantity of fine particles (Ganaye et al., 2007), leading to high water content, and explaining accentuated high amplitude GPR reflections and low resistivity values. At depths between 3 and 4,6 m, where only resistivity data are available, the resistive lobe in the middle is interpreted as a large quantity of coarse gravel. This calibration shows that the main structural and textural features of the trench wall are characterized by both geophysical methods. GPR and electrical resisitivity methods are complementary. GPR reflections give details which are easier to correlate with stratigraphic units (dip). However, a better understanding of the spatial distribution of the stratigraphic units is needed to define a realistic model of lithofacies geometry.

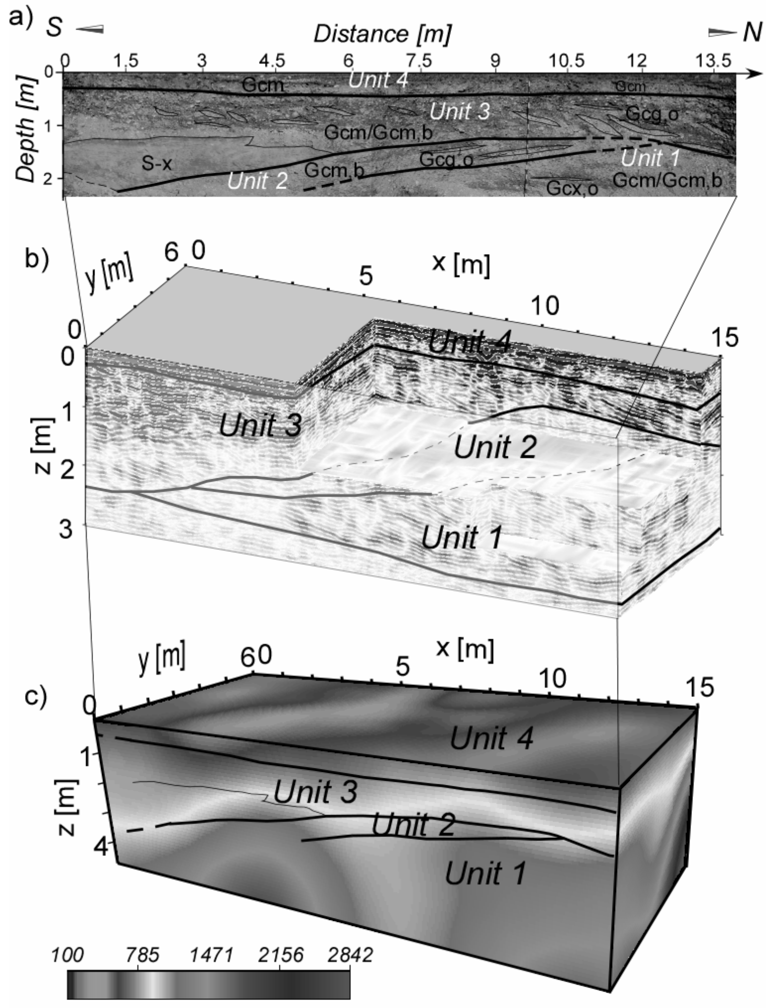


Figure 1: cross interpretation of the trench wall (a) and the surrounding geophysical investigation [GPR pseudo-3D bloc (b) and apparent resistivity maps (c)].

3.2 Typology of geophysical features

We relate the different geophysical features outlined above to a sedimentological description, in order to set up a typology of geophysical features linked to sedimentological description. The sedimentological study described below organizes the structural (metric scale - architectural elements) and textural (decimetric scale – lithofacies) heterogeneities into genetically related depositional units.

Four lithofacies were described. They are summarized in table 1, with their associated estimation of saturated hydraulic conductivity. Concerning the structural description, two main braided-stream palaeoenvironments were described:

- a lower structural unit corresponding to successive palaeochannels characterized by their structure dipping, composed of a channel fill S-x lithofacies (bottom of unit 3, figure1), and alternating Gcx,o and Gcm,b progradations (units 1,2 and top of unit 3, figure 1);
- an upper unit corresponding to a high current energy deposit, with a wide grain-size distribution (lithofacies Gcm), in which some Gcx,o beds are intercalated (unit 4, figure 1).

Table 1 : typology of glaciofluvial lithofacies and associated hydraulic parameters (porosity n and saturated hydraulic conductivity Ks). The sedimentological code is that of Miall (1978): l_1, grain-size of the main components (G: gravel, S: sand); i_2, fabric (c: clast-supported, -: without matrix); i_3, sedimentary structure (m: massive, x: stratified); i_4 (optional), additional information (o: open framework, b: bimodal)

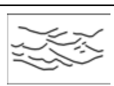
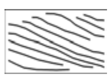
Lithofacies code ($l_1 i_2 i_3, i_4$)	Description	n*	Ks**
S-x	Poorly to moderately well sorted medium sands (D=385µm), with internal laminations	0,42	$7,0.10^{-4}$ m.s^{-1}
Gcx,o	Poorly to moderately well sorted clast-supported gravels, without sandy matrix, often prograding	0,36	$9,0.10^{-2}$ m.s^{-1}
Gcm	Poorly sorted clast-supported massive sands and gravels, wide grain-size distribution	0,27	$7,5.10^{-3}$ m.s^{-1}
Gcm,b	Poorly sorted clast-supported massive sands and gravels, bimodal grain-size distribution (a medium and coarse gravel mode, and a fine and medium sand matrix)	0,3	$1,8.10^{-3}$ m.s^{-1}

* Literature data, from Klingbeil et al. (1999)

** calculated using the Kozeny-Carman expression described in Chapuis et Aubertin (2003)

A typology of three “geophysical facies” relating sedimentary structures and corresponding geophysical features was defined in table 2. GPR reflections are easier to relate to sedimentary structures than electrical resistivity. The variability of electrical resistivity as a function of subsurface saturation is strong (for example, from Reynolds (1997), resistivity values in gravel range from 100 Ω.m in saturated gravels to 1400 Ω.m in dry gravels), no range of values were proposed in this typology. Only observations on qualitative changes of electrical resistivity were indexed.

Table 2: typology of GPR reflections and electrical resistivity features linked to lithofacies organisation, depositional elements and depositional events.

	Geophysical features			Sedimentary features
Facies	GPR reflection features		Electrical resistivity features	- Associated lithofacies - External shape of depositional elements - Associated depositional event
	Reflections	Internal structure		
f1	 High-amplitude, subhorizontal or slightly dip, continuous and parallel		Low resistivity values (high water content linked to a high quantity of fine particles)	- Gcm with Gcx,o intercalated, higher quantity of fine particles - Sheet or wedge shape - High current energy
f2	 Short, wavy or curved		Local decrease of resistivity values (higher sand fraction)	- Mainly Gcm or Gcm,b ; S-x and Gcx,o lenses - Channel shape - Channel-fill
f3	 Relatively high-amplitude, oblique, continuous, subparallel, sometimes short and curved		Local increase of resistivity values (desaturated macropores ; higher gravel fraction)	- Progradation of Gcg,o / Gcm,b alternance - Trough shape - Channel-fill

3.3 Hydrostratigraphic interpretation

3.3.1 Interpretation of geophysical data

Figure 2 shows the GPR pseudo-3D bloc and the W-E electrical profile corresponding to the northern side of the GPR grid for an area of the infiltration basin of unknown hydrostratigraphy. Interpretation of the geophysical data using the typology of table 2 enabled to propose a hydrostratigraphic conceptual model of the glaciofluvial deposit.

Four main units were identified. Considering the dipping and curved GPR reflections and the relatively low resistivity values, unit 5 is identified as a facies *f2*, which corresponds to a channel-fill deposit. Unit 6 is composed by a facies *f3*, corresponding to a progradation of Gcx,o in Gcm,b (parallel oblique high amplitude GPR reflections, local increase of resistivity). Unit 7 shape is characteristic of a palaeochannel (facies *f2*), composed of various lithofacies as S-x and Gcx,o (local increase of resistivity). Units 5, 6 and 7 were deposited in a braided-stream palaeoenvironment, in the same way as units 1, 2 and 3 of figure 1. Unit 8 is characterized by long continuous subhorizontal high-amplitude GPR reflections and low resistivity values, corresponding to the facies *f1*. This unit corresponds to a high energy event having led to a wide grain size distribution with some gravel beds intercalated, as Unit 4 of figure 1.

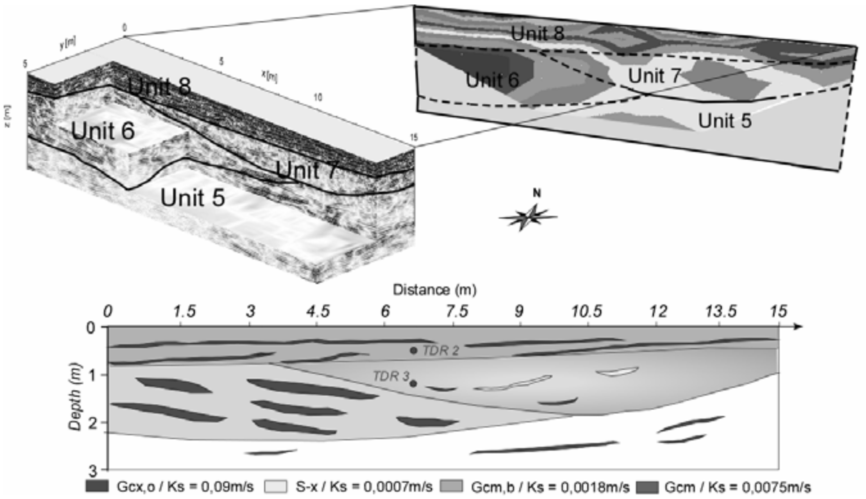


Figure 2: hydrostratigraphic interpretation of GPR pseudo-3D and resistivity map corresponding to glaciofluvial deposit bloc which stratigraphy is unknown. Affected conductivity values are taken from Table 1.

3.3.2 Hydrostratigraphic model and impact for stormwater infiltration

A hydrostratigraphic model is proposed by combining a stratigraphic interpretation with the estimated saturated conductivities found in table 1. The sedimentary heterogeneity induced a hydraulic heterogeneity, which may lead to preferential flow paths during stormwater infiltration. In fully saturated conditions, Gcx,o hydraulic conductivity is one to two orders of magnitude higher than other lithofacies. Gcx,o lithofacies may act as preferential flow path. If interconnectivity exists between the Gcx,o beds of units 6 and 8, fast flow paths through these facies may lead to a deep contaminant transfer (about 2m below surface according to the conceptual model). In unsaturated conditions, Gcx,o macropores may desaturate quickly while finer lithofacies (S-x or Gcm,b) remain more conductive. Capillary barrier effects may also occur.

4 CONCLUSION

In this study, we consider centimetric to decimetric sedimentary heterogeneities of a glaciofluvial deposit underlying an infiltration basin. We propose in this paper two complementary geophysical methods to investigate the stratigraphy of the deposit at this scale. These two methods are used to characterize the main structural and textural features of the glaciofluvial deposit. A sedimentological study was carried out to complete the geophysical investigation by interpreting the three-dimensional lithofacies distribution. A typology of geophysical features related to sedimentary characteristic was thus defined. This typology is used to build a conceptual hydrostratigraphic model, which can be used to perform a numerical modelling of unsaturated water flow in glaciofluvial deposits. This conceptual model shows that preferential flow paths may occur during stormwater infiltration in coarse gravels (lithofacies Gcx,o). The heterogeneity of alluvial deposits at the hydrofacies scale must be taken into account by managers, as preferential flow path may induce a long-term contamination at depths greater than expected.

These geophysical methods are of major interest for managers of stormwater infiltration basin. As sedimentary heterogeneities may generate differential contamination, they can be employed to assess the potentiality of a site to homogeneously infiltrate stormwater, or to evaluate the functioning of an existing basin by modelling the unsaturated flow underlying basins. Contaminants transfer have to be better understood (study of the different mechanisms depending on lithofacies, see Ganaye et al. [2007]) to perform this assessment.

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