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Khalil Lhamidi

Univ. Lille, IMT Nord Europe, JUNIA, Univ. Artois, ULR 4515 - LGCgE

Jamal El Khattabi

`jamal.elkhattabi@univ-lille.fr`

Univ. Lille, IMT Nord Europe, JUNIA, Univ. Artois, ULR 4515 - LGCgE

Malek Sibai

Univ. Lille, IMT Nord Europe, JUNIA, Univ. Artois, ULR 4515 - LGCgE

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## Research Article

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**Posted Date:** October 15th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-11105169/v1>

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**Additional Declarations:** No competing interests reported.

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**Title**

Lithostratigraphic Control of Vertical Water Fluxes in Chalk Aquifer Systems: An Integrated Geophysical and Sedimentological Approach

Khalil Lhamidi, Jamal El Khattabi (\*), Malek Sibai

Univ. Lille, IMT Nord Europe, JUNIA, Univ. Artois, ULR 4515 - LGCgE, Laboratoire de Génie Civil et géo-Environnement, F-59000 Lille, France

(\*) Corresponding author: [jamal.elkhattabi@univ-lille.fr](mailto:jamal.elkhattabi@univ-lille.fr)

ORCID Khalil Lhamidi : 0009-0009-4451-0997

ORCID Jamal El Khattabi : 0000-0002-9046-4399

## **Abstract**

Chalk aquifers represent a major groundwater resource in northwestern Europe, yet the role of superficial formations in controlling recharge processes remains poorly constrained. This study investigates how lithostratigraphic successions, at the loess–chalk interface, regulate vertical water fluxes in the Senonian-Turonian chalk aquifer of northern France. An integrated approach combining electrical resistivity surveys (Vertical Electrical Soundings and Electrical Resistivity Tomography), sedimentological analyses, and hydro-mechanical characterization was applied across an urbanized sector of the Artois–Picardie Basin. Results identify three main lithostratigraphic successions controlling subsurface hydrological connectivity: loess over Senonian chalk (LSC), loess-tuffeau-chalk (LTC), and loess over Upper Turonian chalk (LUT). These successions influence the development of perched water bodies within the loess cover and regulate vertical transfers toward the regional chalk aquifer. Weathered interface facies “marnettes”, formed by the periglacial reworking and admixture of chalk debris with loessic sediments, locally act as semi-permeable layers that reduce hydraulic conductivity and promote water retention in the superficial formations. These findings highlight the key role of lithostratigraphic architecture and weathered interfaces in controlling groundwater recharge pathways in loess-covered chalk systems and emphasize the need to integrate these features into hydrogeological models under increasing hydroclimatic variability.

## **Keywords**

Loess, Chalk, Weathering, Electrical resistivity, Hydrosystems, Groundwater

## **Area of Focus**

Groundwater systems, deep sub-surface reservoirs, geological and water resources engineering, environmental impact assessment from a geological perspective, and research tools

## **Article Type**

Research

## 1. Introduction

Chalk aquifers of the major European sedimentary basins, particularly those of the Paris Basin, constitute one of the most strategic groundwater reservoirs in Europe (Nilsson et al. 2023). Their high matrix porosity, combined with dense fracturing and well-developed karst networks, confers substantial storage capacity and high productivity (Bell et al. 1999; West et al. 2023). These aquifers supply a significant proportion of drinking water, sustain agricultural irrigation, and support low-flow conditions in rivers, while playing a critical role in the functioning of wetlands and groundwater-dependent ecosystems (Maréchal and Rouillard 2020).

Although the intrinsic properties of chalk have been extensively investigated, the role of superficial formations in controlling recharge mechanisms remains insufficiently integrated into regional hydrogeological models. In northern Europe, chalk aquifers are commonly overlain by a thick cover of Quaternary loess deposits (Bertran et al. 2016). These deposits form a transitional unsaturated zone between the land surface and the water table and exert a major control on vertical water and solute fluxes (Wang et al. 2023). They also provide temporary storage, physico-chemical filtration, and regulation of transfer times toward the underlying chalk aquifer (Baran et al., 2007; Fan et al. 2024). Their silt-dominated texture, clay mineralogy, and vertical heterogeneity influence water retention capacity, infiltration dynamics, and percolation times to the chalk substratum (Valdes et al. 2014). The loess–chalk association thus forms a composite hydrogeological system in which recharge depends not only on the hydraulic properties of the chalk, but also on the lithostratigraphic architecture of the superficial cover and the nature of the interface between these two units (Bernard et al. 2008). At this interface, a distinctive weathering facies, locally termed “marnettes” may develop from the mixing of chalk granules and loessic material through periglacial processes (Sommé 1975). Although frequently observed in the field, its hydraulic role remains poorly quantified and is rarely incorporated into conceptual recharge models.

In the context of climate change and increasing anthropogenic pressures, this knowledge gap becomes critical. The intensification of extreme rainfall events, combined with prolonged drought periods, is altering the timing and efficiency of recharge processes (Baulon et al. 2025). Climate change is expected to profoundly modify system functioning (Yang et al. 2021; Gründemann et al. 2022; Disasa et al. 2025). These changes may lead to more irregular and seasonally concentrated recharge, promote rapid transfer of diffuse contaminants derived from runoff (Qui et al. 2023), increase surface runoff risks, and potentially reduce effective recharge. Land-use change and soil sealing further exacerbate these dynamics by disrupting surface water balances (Artmann 2016; Gabriels and Willems 2022). Such hydrological alterations represent a major challenge for both the quantitative and qualitative management of groundwater resources, particularly in ensuring secure drinking water supply (Barbieri et al. 2023; Ashofteh et al. 2024). Understanding how lithostratigraphic successions control vertical transfers is therefore central to sustainable groundwater management.

Geophysical approaches, particularly electrical resistivity methods, provide a valuable opportunity to characterize these processes across multiple spatial and temporal scales and to refine the assessment of aquifer recharge dynamics (Perzan et al. 2023). Sensitive to variations in water content, porosity, and lithology, electrical resistivity imaging enables the detection of hydric contrasts and structural discontinuities that govern subsurface flow (Brunet et al. 2010; Verdet et al. 2020). When coupled with sedimentological and geotechnical analyses, it constitutes a powerful framework for linking lithostratigraphic architecture to hydrological dynamics (Watlet et al. 2018).

Within this framework, we hypothesize that the lithostratigraphic succession of the loess–chalk interface exerts a primary control on vertical hydraulic continuity and, consequently, on the efficiency of recharge in chalk aquifers. The objectives of this study are to identify and characterize the main loess–chalk lithostratigraphic successions in a setting representative of northwestern European basins, quantify their geophysical signature through spatio-temporal analysis of electrical resistivity data acquired using vertical electrical soundings (VES) and electrical resistivity tomography (ERT), and evaluate their influence on vertical water transfers and on recharge conditions of the Senonian–Turonian chalk aquifer. The study further discusses the hydrological and ecological implications of these successions under increasing climatic variability.

By proposing an integrated approach that combines geophysics, sedimentology, and geotechnics, this work aims to advance the mechanistic understanding of recharge processes in chalk aquifers and to provide transferable conceptual insights for other loess-covered hydrogeological systems in Europe and beyond.

## 2. Background information

The study site is located in northern France, within a region characterized by extensive outcrops of post-Paleozoic formations largely mantled by Quaternary loess deposits (Antoine et al. 2003). The Mesozoic and Cenozoic sequences rest eastward against the Paleozoic formations of the Ardennes Massif, while they dip southward toward the Paris Basin and northward toward the Brussels Basin (Porel 1988). The region has been affected by both

primary and secondary tectonic phases. Within the Paleozoic basement of northern France, two structural domains can be distinguished, separated by a set of faults trending approximately NW–SE. These faults led to the uplift of the southern block during the Alpine orogeny of the Cenozoic.

The regional stratigraphic succession extends from the Paleozoic to the Quaternary, as described by Dufrenoy et al. (2010), Ferry (1992), and Porel (1988), and records a complex geological evolution marked by diverse lithological formations (Figure 1). The oldest units belong to the Paleozoic, notably the Dinantian (Carboniferous), which consists predominantly of massive limestones. This carbonate succession underlies and supports the overlying coal-bearing formations. The Mesozoic begins with sandy and clayey deposits, followed by a thick chalk succession. The latter starts in the Cenomanian with a sandy marl rich in glauconite. During the Turonian, thick chalky marls precede a coarse-grained chalk rich in flint nodules. The series culminates in the Senonian with a soft, fine white chalk, whose base is marked by a distinctive hardground level (“tun”). The Cenozoic is represented by Eocene formations of Ypresian and Landenian age. The Lower Landenian corresponds to a complex of tuffeau and/or the “Louvil” clay, described as a sandy, black, plastic, and impermeable clay. The Upper Landenian is composed of the Ostricourt sands, characterized as fine-grained, greenish, glauconitic quartz sands. The Ypresian is represented by the Flanders Clay, a blue-black plastic clay that may locally contain gypsum crystals. The stratigraphic series is capped by Quaternary formations, mainly composed of continental deposits. These include clayey-sandy and gravelly fluvial alluvium within the major valleys, locally containing peat layers, as well as an extensive loess cover formed by the aeolian accumulation of fine siliceous, clayey, and calcareous particles (Sommé 1975). This loess mantle, widespread across northern France, constitutes the dominant superficial formation. It comprises two main units, the recent loess of Weichselian age (Upper Pleistocene), typically 3–4 m thick and composed predominantly of very fine siliceous particles, and the older loess deposits, mainly of Middle Pleistocene age (Sommé and Tuffreau 1971). During the Holocene, pedogenetic processes including leaching and decalcification led to the development of a brownish surface horizon referred to as “lehm” overlying a more calcareous loess unit known as “ergeron” (Sommé 1975).

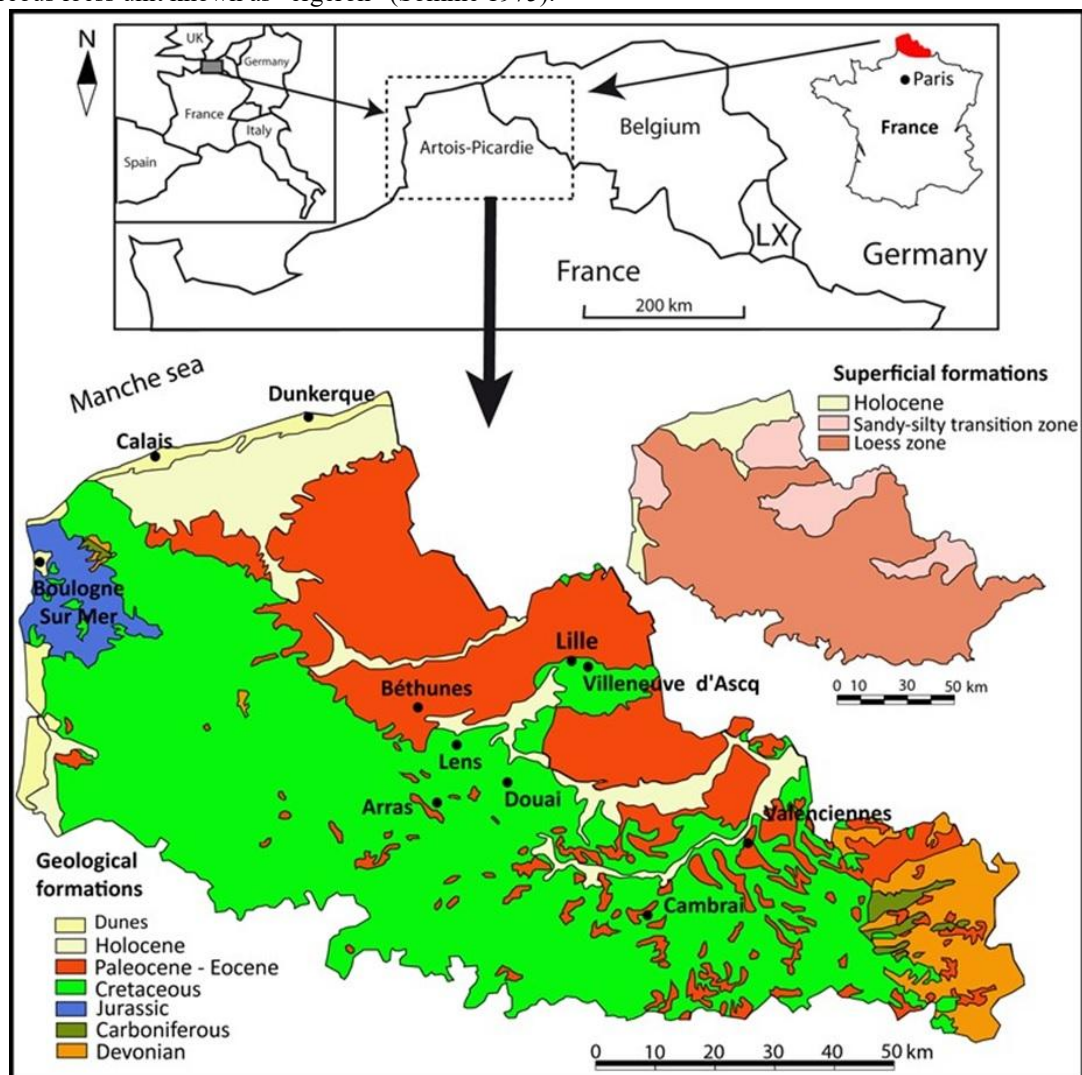


Figure 1 : Geological Map of Nord-Pas-de-Calais



Three representative sub-sectors were selected to incorporate a gradient of land artificialization and stormwater management practices: the Cité Scientifique district in Villeneuve-d'Ascq (Area A), the urbanized sector of Lezennes (Area B), and the Haute Borne business park in Villeneuve-d'Ascq (Area C). These areas exhibit marked contrasts in land use, thickness of superficial formations, and infiltration infrastructure, thereby providing a relevant experimental framework for analyzing the interactions between lithostratigraphic successions, hydrodynamic properties, and groundwater recharge.

### 3.2. Electrical resistivity surveys

The geophysical survey was designed to map the spatial distribution of electrical resistivity to identify lithological horizons, constrain the stratigraphic architecture through integration with geological and geotechnical borehole data and detect aquifer levels and characterize saturated or partially saturated zones controlling subsurface flow. Measurements were carried out using a multi-electrode Terrameter LS resistivity meter coupled with an ES1064C electrode selector. Two complementary approaches were implemented: Vertical Electrical Soundings (VES) combined with Electrical Resistivity Tomography (ERT) surveys. VES surveys were conducted using the Schlumberger array, selected for its sensitivity to vertical resistivity variations and its depth of investigation, which is well suited to chalk aquifer settings. In parallel, ERT surveys were performed using both Schlumberger and Wenner successions to optimize the vertical and lateral resolution of geo-electrical contrasts. The apparent resistivity ( $\rho_a$ ) curves obtained from the VES were inverted in one dimension (1D) using the IX1D software, as a function of half the current electrode spacing ( $AB/2$ ). The ERT profiles were processed and inverted in two dimensions (2D) using X2IPI and RES2DINV (Geotomo Software 2019). The inversion procedure was performed over five successive iterations, with convergence defined by a root mean square (RMS) error below 5%, thereby ensuring the robustness and reliability of the resulting resistivity models. The conceptual model incorporates up to four main lithological units: loess, tuffeau, Senonian chalk, and Turonian chalk. Two aquifer systems are considered: a perched water table within the loess deposits and the regional Senonian-Turonian chalk aquifer. To discriminate contrasts associated with lithology and saturation state, the VES data were interpreted using a multi-layer model comprising up to seven geo-electrical horizons. Acquisition parameters and detailed survey characteristics are provided in Table 1.

Table 1 : VES and ERT surveys succession

| Site   |        | Survey | Succession   | Electrode spacing (m) | Lenght (m) | Reached depth (m) | Software          | RMS error threshold |      |
|--------|--------|--------|--------------|-----------------------|------------|-------------------|-------------------|---------------------|------|
| Area A | Site 1 | VES1   | Schlumberger | Protocole             | 104        | 17                | IX1D              | 5 %                 |      |
|        |        | ERT1   |              | 2                     | 45         | 8                 | X2IPI<br>RES2DINV |                     |      |
|        |        | ERT2   |              | 1                     | 50         | 9                 |                   |                     |      |
|        |        | ERT3   |              | 0.60                  | 21         | 4                 |                   |                     |      |
|        | Site 2 | VES3   | Protocole    | 280                   | 46         | IX1D              |                   |                     |      |
|        |        | VES4   |              | 280                   | 46         |                   |                   |                     |      |
|        |        | ERT5   | Wenner       | 1.5                   | 189        | 31.5              | X2IPI<br>RES2DINV |                     |      |
|        |        | ERT6   |              | 3                     | 252        | 42                |                   |                     |      |
|        |        | ERT7   |              | 3                     | 380        | 63                |                   |                     |      |
|        |        | ERT8   |              | 2                     | 128        | 21.5              |                   |                     |      |
|        |        | Site 3 | VES5         | Schlumberger          | Protocole  | 200               | 33                |                     | IX1D |
|        |        |        | VES6         |                       |            | 380               | 63                |                     |      |
|        | VES7   |        | 380          |                       |            | 63                |                   |                     |      |
|        | VES8   |        | 280          |                       |            | 46                |                   |                     |      |
|        | ERT4   |        | Wenner       | 2                     | 128        | 21.5              | X2IPI<br>RES2DINV |                     |      |
| Area B | Site 1 | VES9   | Schlumberger | Protocole             | 380        | 63                | IX1D              |                     |      |
|        |        | VES11  |              |                       | 380        | 63                |                   |                     |      |
|        |        | VES12  |              |                       | 144        | 24                |                   |                     |      |
| Area C | Site 1 | VES2   |              |                       | 144        | 24                |                   |                     |      |
|        |        | VES10  |              |                       | 200        | 33                |                   |                     |      |

### 3.3. Sampling and physico-mechanical characterization

#### 3.3.1. Sampling strategy

A targeted sampling campaign was conducted to characterize the physical, mineralogical, and mechanical properties of the superficial formations and the loess–chalk interface. Loess samples were collected using a hand

auger within the municipality of Villeneuve-d'Ascq chalk. Samples were collected from various regional outcrops, notably along the A1 motorway and the cliffs of Cap Blanc-Nez (Escalles, Sangatte), as well as from former quarries at Coquelles. A tuffeau sample from loess backfill was also analyzed. Interface levels, the so-called marnette (loess–Senonian and loess–Upper Turonian), were sampled along a roadside embankment of the A1 motorway and at the bottom of an infiltration basin at the Cité Scientifique (Figure 3).

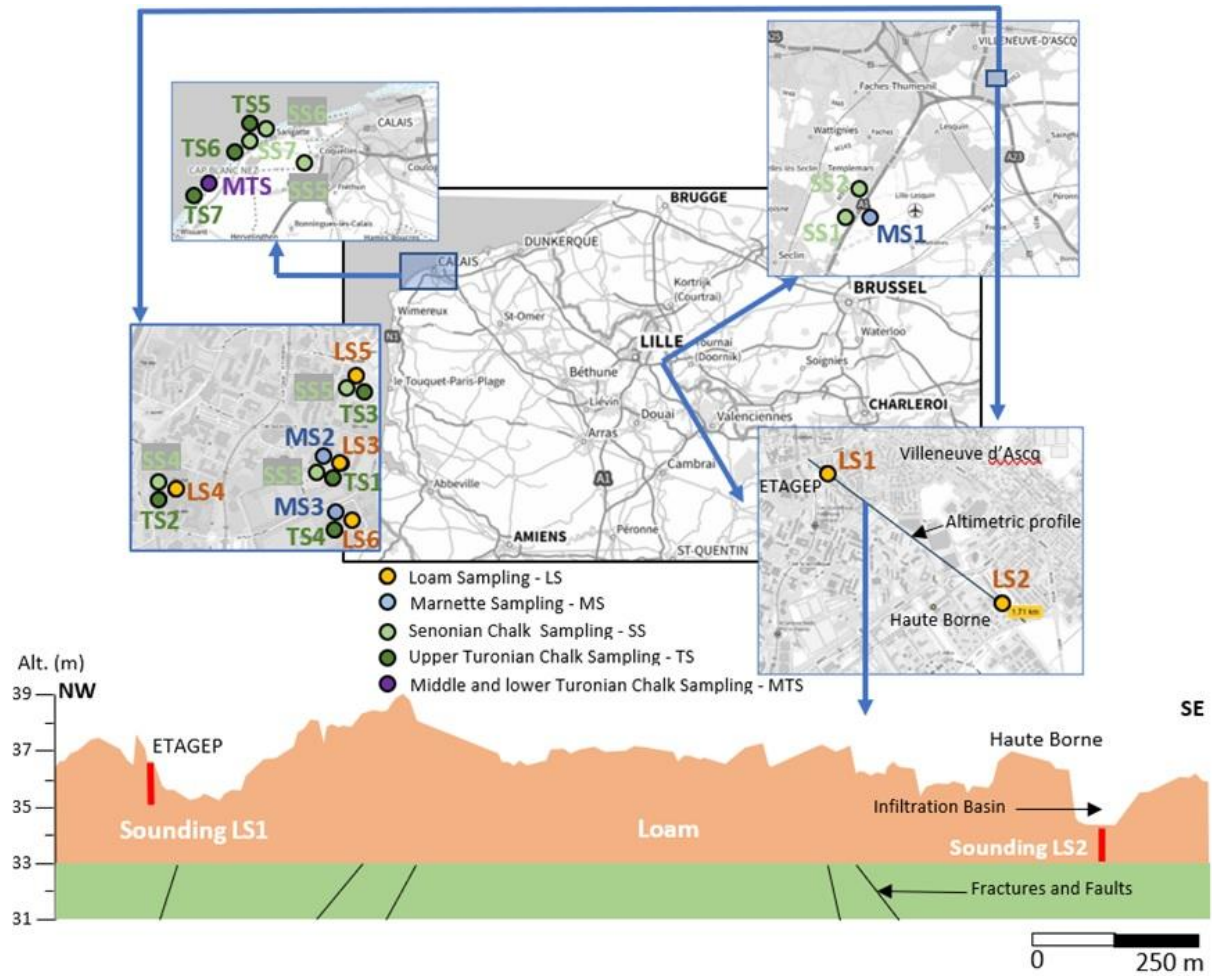


Figure 3 : Location of sampling sites and synthetic cross-section between area A and area C

### 3.3.2. Laboratory testing

Loess and tuffeau samples were subjected to particle size analysis using laser diffraction, mineralogical characterization by X-ray diffraction, and calcimetry measurements. Geomechanical characterization was carried out through pressuremeter testing conducted at the Cité Scientifique site, enabling determination of key pressuremeter parameters ( $p_f$ ,  $p_l$ ,  $E_M$ ), porosity, uniaxial compressive strength ( $R_c$ ), and Young's modulus ( $E$ ). These parameters serve as critical variables for constraining vertical transfer models and estimating equivalent hydrodynamic properties.

### 3.3.3. Hydraulic conductivity characterization

The hydraulic conductivity of the marnette layers was determined in the laboratory using variable-head oedometer tests. Three oedometer cells equipped with graduated tubes were employed. Synthetic loess–Senonian chalk mixtures were prepared to assess the influence of chalk content on hydraulic conductivity. The tested proportions of chalk (by mass) were 0%, 10%, 30%, 50%, 70%, and 100%. The saturated hydraulic conductivity,  $K$  ( $m s^{-1}$ ), was calculated using the standard expression for variable-head tests :

$$K = \frac{a \times L}{A \times t} \times \ln\left(\frac{h_1}{h_2}\right)$$

where  $K$  is the hydraulic conductivity ( $\text{m s}^{-1}$ ),  $a$  is the cross-sectional area of the graduated standpipe ( $\text{m}^2$ ),  $L$  is the length (height) of the specimen (m),  $A$  is the cross-sectional area of the sample ( $\text{m}^2$ ),  $t$  is the elapsed time between hydraulic head measurements (s), and  $h_1$  and  $h_2$  are the initial and final hydraulic heads (m), respectively.

This experimental approach enables quantification of the hydraulic role of marnettes interface levels as potential hydraulic barriers and allows assessment of their influence on vertical fluxes governing recharge of the underlying chalk aquifer.

## 4. Results

### 4.1. Physical and geomechanical characterization of superficial and chalky formations

#### 4.1.1. Vertical distribution of Pleistocene silt properties

Grain-size, mineralogical, and calcimetric analyses of eleven loess samples highlight a pronounced vertical structuring of physical properties within the Pleistocene cover (Table 2). Laser granulometry indicates a very low clay fraction ( $< 2 \mu\text{m}$ ), not exceeding 2.74%, whereas the silt fraction ( $2\text{--}63 \mu\text{m}$ ) overwhelmingly dominates the sedimentary matrix. Silt content is lower near the surface but increases with depth, reaching 84.92% in sample L150 and 81.14% in the Middle Pleistocene loess (L305). The sand fraction ( $> 63 \mu\text{m}$ ) averages 22.51%, with localized enrichments in certain Middle Pleistocene horizons and in backfill deposits. According to the USDA textural classification, the backfill and Ergeron correspond to silt loam, whereas the Weichselian Lehm is classified as silt.

Clay mineralogy reveals a strong dominance of smectites, with proportions varying significantly with depth. Within the 50–80 cm interval, smectite reaches approximately 83%, accompanied by minor amounts of illite (9–11%), kaolinite (5–6%), and chlorite (1–2%). Between 100 and 150 cm, the smectite fraction decreases (20–50%) in favor of a marked increase in illite (24–51%). In deeper levels corresponding to the Middle Pleistocene (Ergeron), smectite becomes again largely dominant, averaging 94.4%. Quartz remains a consistent accessory mineral across all samples (Table 2).

Table 2 : Mineralogy and carbonate content of silt samples

| Samples          |               |                                  | % Clay<br><2 $\mu\text{m}$ | 2 $\mu\text{m}$ <<br>% Silt<br><63 $\mu\text{m}$ | % Sand<br>>63 $\mu\text{m}$ | Smectite<br>(%) | Illite<br>(%) | Kaolinite<br>(%) | Chlorite<br>(%) | CaCO <sub>3</sub><br>(%) |
|------------------|---------------|----------------------------------|----------------------------|--------------------------------------------------|-----------------------------|-----------------|---------------|------------------|-----------------|--------------------------|
| Site             | Depth<br>(cm) | Stratigraphy                     |                            |                                                  |                             |                 |               |                  |                 |                          |
| Area A<br>Site 1 | L50           | Backfill                         | 1,11                       | 69,04                                            | 29,85                       | 83              | 9             | 6                | 2               | 5,72                     |
|                  | L80           |                                  | 0,98                       | 76,58                                            | 22,44                       | 83              | 11            | 5                | 1               | 5,63                     |
|                  | L100          | Upper<br>Pleistocene<br>Lehm     | 0,766                      | 72,05                                            | 27,18                       | 20              | 51            | 20               | 9               | 3,06                     |
|                  | L120          |                                  | 0,829                      | 77,22                                            | 21,95                       | 26              | 39            | 27               | 8               | 2,93                     |
|                  | L140          |                                  | 1,43                       | 83,88                                            | 14,68                       | 36              | 31            | 23               | 6               | 3,13                     |
|                  | L150          |                                  | 1,05                       | 84,92                                            | 14,03                       | 50              | 24            | 19               | 7               | 3,13                     |
| Area A<br>Site 2 | L235          | Middle<br>Pleistocene<br>Ergeron | 1,77                       | 66,28                                            | 31,95                       | 95              | 4             | 1                | 0               | 8,81                     |
|                  | L255          |                                  | 2,54                       | 76,33                                            | 21,13                       | 95              | 5             | 0                | 0               | 16,45                    |
|                  | L280          |                                  | 1,31                       | 76,59                                            | 22,10                       | 95              | 4             | 1                | 0               | 15,70                    |
|                  | L305          |                                  | 2,74                       | 81,14                                            | 16,12                       | 95              | 4             | 1                | 0               | 15,28                    |
|                  | L320          |                                  | 1,90                       | 79,72                                            | 18,38                       | 92              | 6             | 2                | 0               | 16,03                    |

Calcimetry also reveals a pronounced vertical differentiation. The surficial horizons exhibit low carbonate contents (around 3.9%), whereas deeper levels show average values around 14.5%, with maxima exceeding 16%. This vertical organization is consistent with regional observations reported by Sommé (1969; 1971; 1975), who noted the distinction between surface-decalcified Weichselian loess and older, carbonate-enriched loess (Table 2).

Principal component analysis (PCA) further confirms this vertical structuring, identifying four statistically distinct groups: superficial loess backfills (E1), brown Weichselian Lehm loess enriched in illite-kaolinite-chlorite (E2), deep, carbonate-rich loess dominated by smectite (Ergeron) (E3), and sandy tuffeau with predominant smectite (E4) (Figure 4).

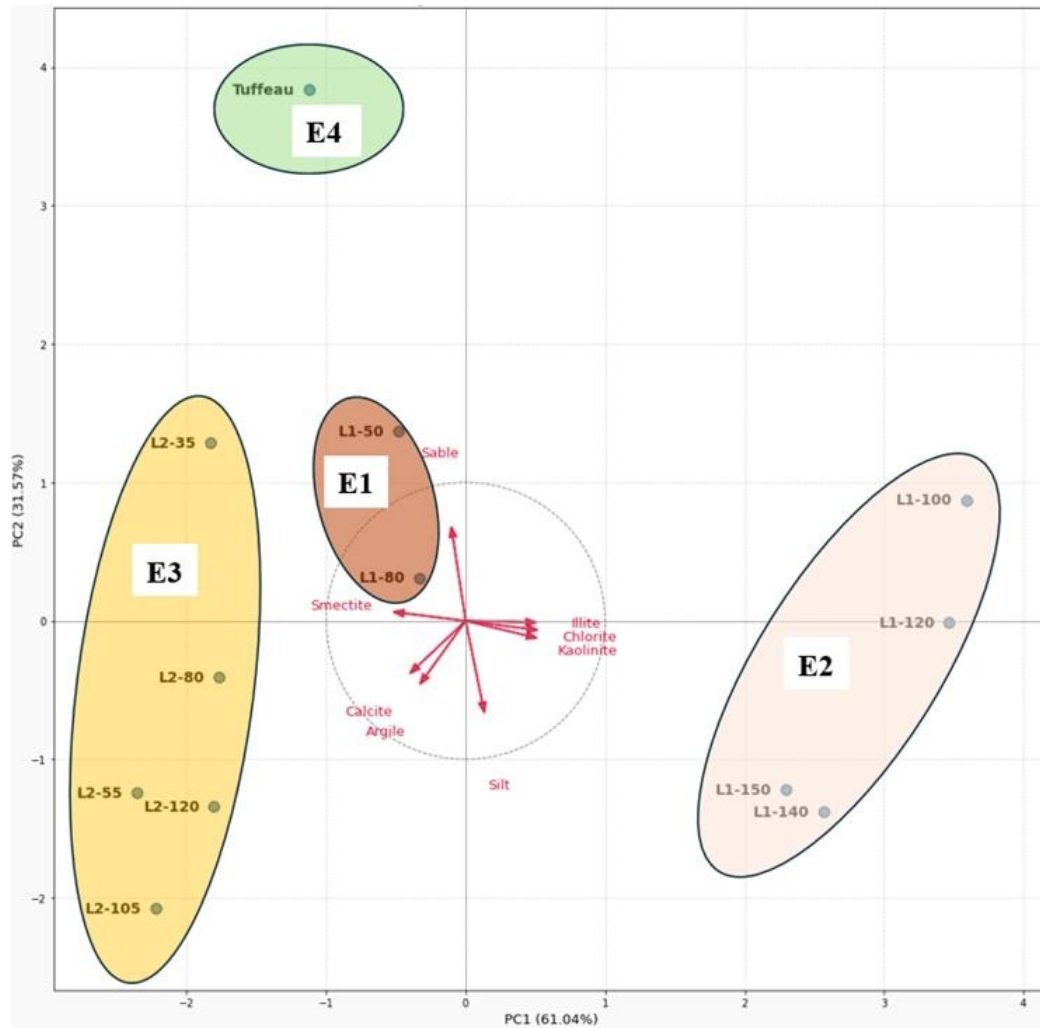


Figure 4 : PCA of sample properties and lithological units (E1: Backfill, E2: Lehm, E3: Ergeron, E4: Tuffeau)

Pressuremeter parameters (EM) range from 2.1 to 31.2 MPa, reflecting the combined influence of water content, texture, and mineralogy on the mechanical behavior of the loess. The deepest smectite-rich horizons exhibit particularly high sensitivity to these factors.

#### 4.1.2. Tuffeau physical properties

The tuffeau identified in the superficial fringe exhibits a physical signature distinct from that of the overlying loess. Its carbonate content remains low (around 1.98%), while the sand fraction reaches approximately 42%, indicating a markedly coarser texture. The silt fraction is around 59%, and the clay fraction is dominated by smectite (around 93%), with a minor contribution from illite (around 7%). Quartz and opal are the main accessory minerals. This composition imparts to the tuffeau an intermediate hydrodynamic behavior, situated between the loess cover and the underlying chalk formations.

#### 4.1.3. Chalk physical and geotechnical characteristics

Geotechnical analyses focused on the Senonian white chalk (Coniacian-Santonian) and the Upper Turonian grey chalk. From a calcimetric perspective, the Senonian chalk exhibits  $\text{CaCO}_3$  contents close to 100%, whereas the Upper Turonian chalk reaches approximately 90%, consistent with regional data (Doremus 1978; Hazebrouck and Duthoit 1979; Mortimore 1986; Siwak 1994; Lord et al. 2002; Nguyen 2009; Lafrance 2016).

The two formations differ in their poro-mechanical properties. Senonian chalk shows higher porosity (40–46%) than Turonian chalk (35–42%) but lower mechanical strength, with uniaxial compressive strength ranging from 7 to 10 MPa and a Young's modulus of 8–11 MPa. In contrast, the Upper Turonian chalk exhibits compressive strengths between 7.5 and 14.7 MPa and a Young's modulus of 10 to 15 MPa. This difference in mechanical behavior plays a critical role in the development of weathering facies observed at the loess–chalk interface.

## 4.2. Geophysical surveys and hydro-lithostratigraphic framework

### 4.2.1. Area A surveys

A total of eight Vertical Electrical Soundings (VES) were conducted, covering nearly the entire study area (Figure 2). Three principal lithostratigraphic successions were identified. Among these, a loess-over-Senonian chalk succession (LSC type) was recognized at VES 1, 3, 4, 5, and 8.

Interpretation of VES1 indicates that the subsurface is composed of backfill and loess deposits reaching a maximum thickness of approximately 4 m, overlying Senonian (Coniacian) chalk. This stratigraphic arrangement is consistent with that described in borehole BSS000BLVM (Figure 5). Within the loess unit, three distinct resistivity values reflect different hydric conditions. A moist loess horizon corresponding to superficial backfill extends to 1 m depth ( $36 \Omega \cdot \text{m}$ ), underlain by a very moist loess layer down to 2 m ( $22 \Omega \cdot \text{m}$ ). Below this, a saturated loess horizon extends to 4.80 m depth ( $15 \Omega \cdot \text{m}$ ). The two latter horizons correspond to a perched aquifer developed within the loess cover.

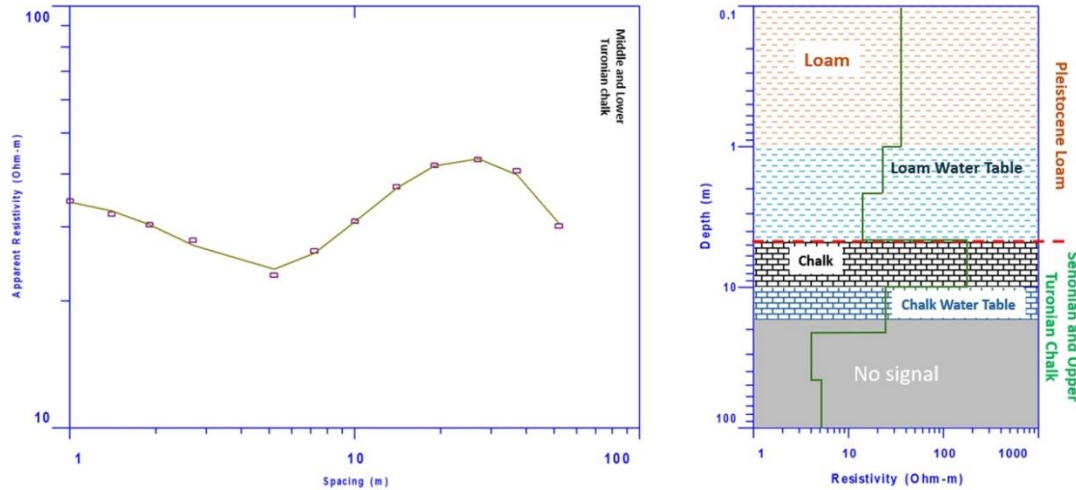


Figure 5 : VES1 signal - LSC succession

The underlying chalk sequence begins with a relatively dry chalk interval ( $\rho = 185 \Omega \cdot \text{m}$ ) between 4.80 and 10 m depth, followed by progressively increasing moisture content down to approximately 20 m, corresponding to the regional Senonian-Turonian aquifer. The saturated chalk level is characterized by an electrical resistivity of  $24 \Omega \cdot \text{m}$  (Figure 5 and Table 3).

In the southern part of Area 1, VES3 highlights the same LSC-type lithostratigraphic succession (loess over Senonian chalk). The loess thickness reaches 2.20 m, in agreement with the geological borehole BSS000BLJM. The upper meter of loess exhibits a resistivity of  $50 \Omega \cdot \text{m}$ , corresponding to a relatively low moisture content, whereas its deeper, water-saturated portion shows a value of  $14 \Omega \cdot \text{m}$ , indicating the presence of a perched aquifer within the loess.

The transition to the Senonian chalk occurs progressively and is marked by a gradual increase in resistivity. Values reach  $53 \Omega \cdot \text{m}$  down to 4.60 m depth, then increase to  $130 \Omega \cdot \text{m}$  at approximately 10 m. Below this depth, the Senonian-Turonian aquifer is identified by a marked decrease in resistivity, reaching  $17 \Omega \cdot \text{m}$  (Figure 6 and Table 3).

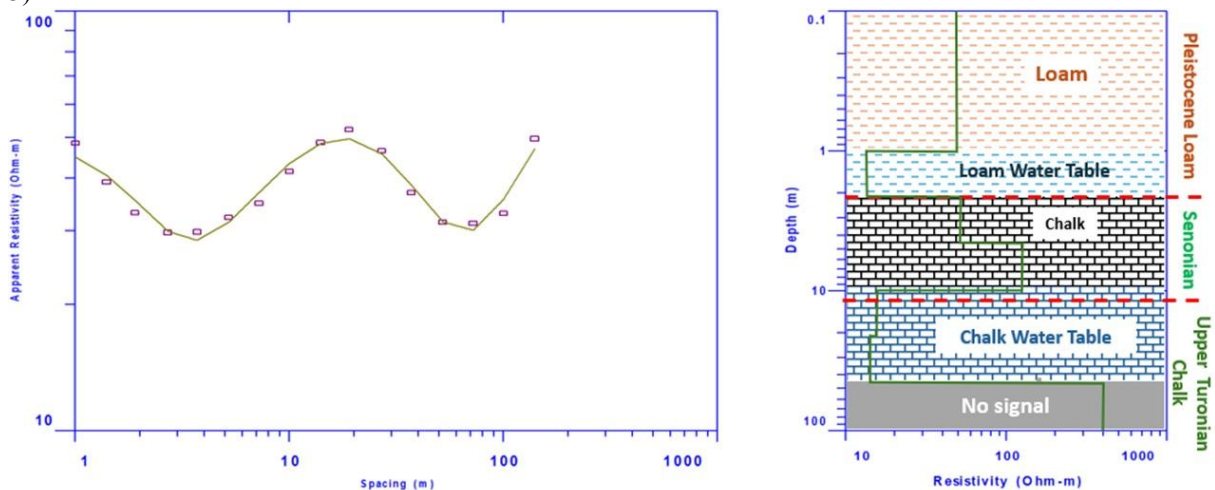


Figure 6 : VES3 signal - LSC succession

In the central-western part of Area 1, VES 5, 6, and 7 reveal a lithostratigraphic succession consisting of Pleistocene loess, underlain by Lower Landenian tuffeau, and subsequently by Senonian chalk (LTC succession). This interpretation is consistent with geological boreholes BSS000BLMR and BSS000BLNF (Figure 7).

VES7 shows a surficial loess layer associated with backfill, characterized by a resistivity of  $28 \Omega \cdot \text{m}$  within the first meter, decreasing to  $20 \Omega \cdot \text{m}$  at the level of the perched loess aquifer, identified down to 1.90 m depth. The tuffeau unit occurs between 1.90 m and 3.80 m depth, with a lower resistivity of approximately  $15 \Omega \cdot \text{m}$ . Below 3.80 m, resistivity increases markedly within the Senonian chalk (3.80–7.20 m), reaching  $41 \Omega \cdot \text{m}$ . The transition to the Upper Turonian chalk is inferred from 7.20 m depth onward, with a resistivity of  $33 \Omega \cdot \text{m}$ . The Senonian-Turonian aquifer is detected at approximately 14 m depth, marked by a very low resistivity of  $3.2 \Omega \cdot \text{m}$  (Figure 7 and Table 3).

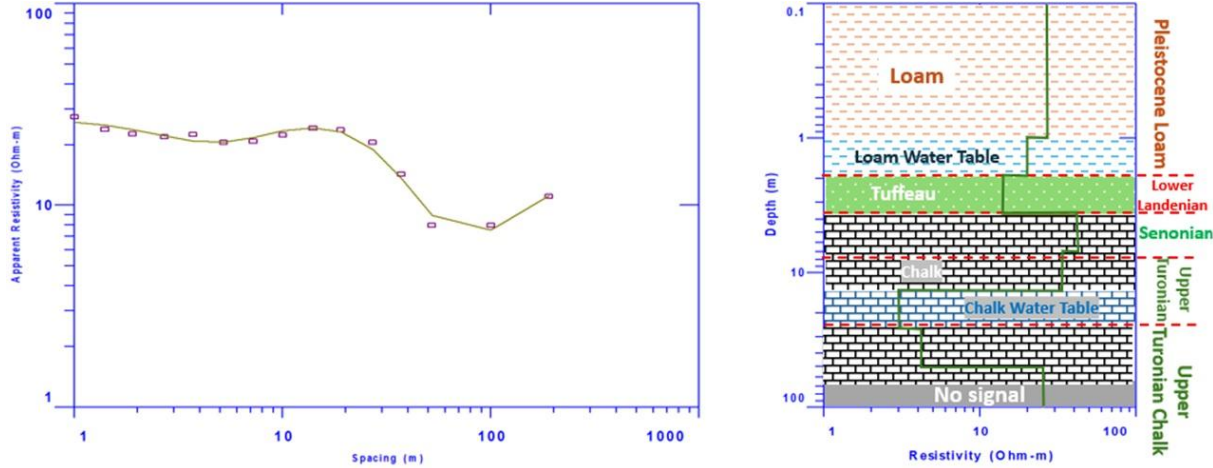


Figure 7 : VES7 signal - LTC succession

To complement the VES results and refine their interpretation, Electrical Resistivity Tomography (ERT) profiles were conducted in three key sectors displaying contrasting lithostratigraphic successions. In the eastern part, in the vicinity of VES1 (LSC succession), the geophysical investigation was designed to account for differences in stormwater management. Two ERT profiles were acquired on 06/19/2024, following a rainfall event of 16.2 mm recorded the previous day: ERT1 was performed on a grassed area near swales and served as a reference profile, whereas ERT2 was conducted across infiltration basins (infiltration swales) to evaluate the direct influence of infiltration devices on subsurface moisture distribution (Figure 8).

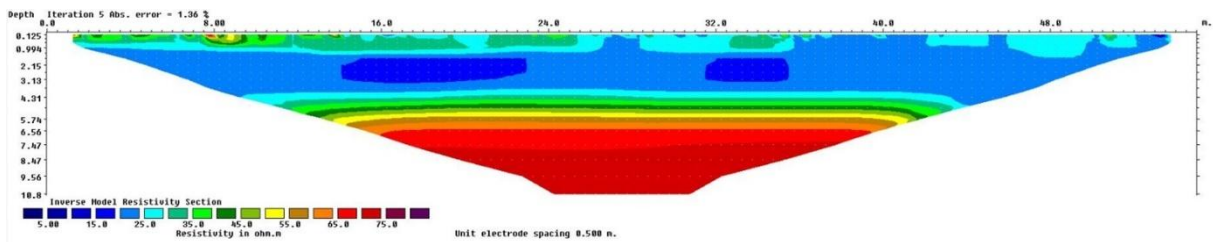


Figure 8 : ERT1 profile acquired on 06/19/2024 over the grass-covered field – LSC succession

In the grassed area, the ERT profile shows a root mean square (RMS) error of 1.46% between calculated and measured values, indicating excellent model fit. Observed resistivity values are low, ranging from 17 to  $21 \Omega \cdot \text{m}$ , reflecting infiltration of rainfall from the previous day. Below approximately 4 m depth, resistivity increases progressively, marking the transition to the chalk layer, consistent with the VES1 interpretation. Laterally, resistivity variations remain limited, except within the superficial horizons, where differences can be attributed to biotic and abiotic surface factors (Figure 8).

The profile acquired along the infiltration swales (ERT2) exhibits an inversion error of 2.8%, indicating satisfactory data quality. Vertically, the superficial layer down to 1 m depth displays local resistivity variations associated with the presence of concrete retaining structures and localized surface drying induced by evapotranspiration.

Within the loess horizon, between 1 and 3.50 m depth, resistivity values are lower than those measured on the ERT1 reference profile, with values below  $20 \Omega \cdot \text{m}$ . This decrease reflects enhanced moisture content directly beneath the infiltration swales. From approximately 4 m depth onward, a progressive increase in resistivity marks the transition to the underlying chalk horizon (Figure 9).

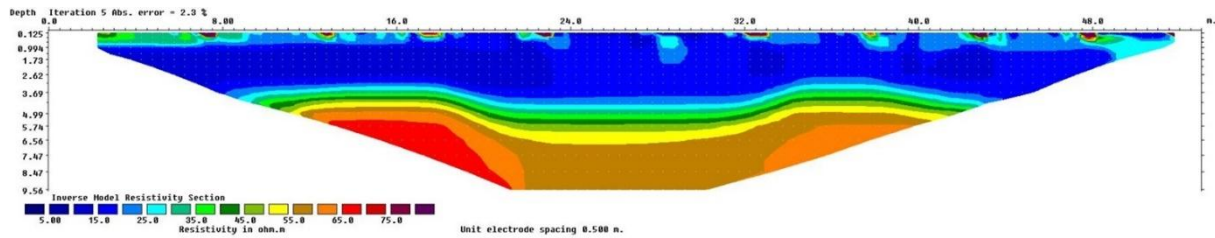


Figure 9 : ERT2 profile acquired on 06/19/2024 over the swales area – LSC succession

To further investigate vertical variations in electrical resistivity and their relationship with water flux transfer, a series of electrical resistivity tomography (ERT) profiles was acquired along the two transects between 06/21 and 07/01 (Figure 10). These repeated measurements enabled spatio-temporal monitoring of infiltrated water following rainfall events, highlighting soil moisture dynamics and the hydrological response of the different lithological horizons (Figure 10).

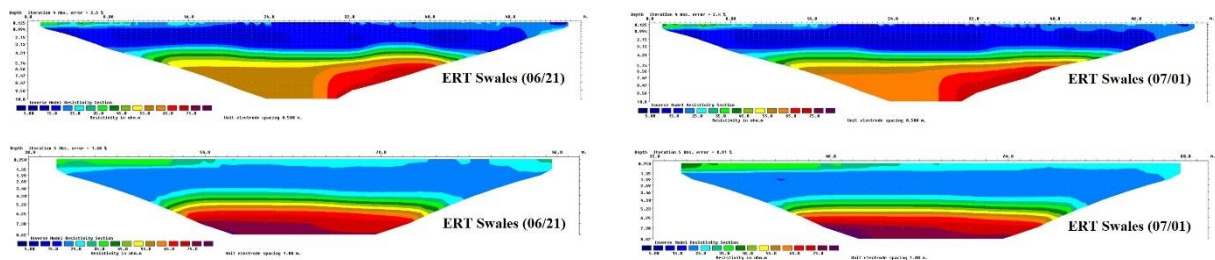


Figure 10 : Spatiotemporal evolution of electrical resistivity between 06/21 and 07/01

In the western sector, characterized by the LTC succession, an electrical resistivity tomography profile (ERT4) was acquired at the location of VES5 over a total length of 128 m (Figure 11). The profile reveals three main horizons. The uppermost horizon, extending to approximately 1 m depth, is characterized by low resistivity values. The second horizon, between 1 and 4 m depth, exhibits resistivities ranging from 10 to 30  $\Omega \cdot m$  and corresponds to the loess and underlying tuffeau. The deeper horizon, below 4 m depth, displays moderate resistivity values between 30 and 60  $\Omega \cdot m$ . Between 80 and 96 m along the profile, a localized increase in resistivity up to 90  $\Omega \cdot m$  is observed, separated by a zone of lower resistivity (10–30  $\Omega \cdot m$ ). This low-resistivity anomaly is interpreted as a preferential flow pathway, associated with the presence of stormwater inlets that collect and infiltrate a significant proportion of surface runoff in this sector.

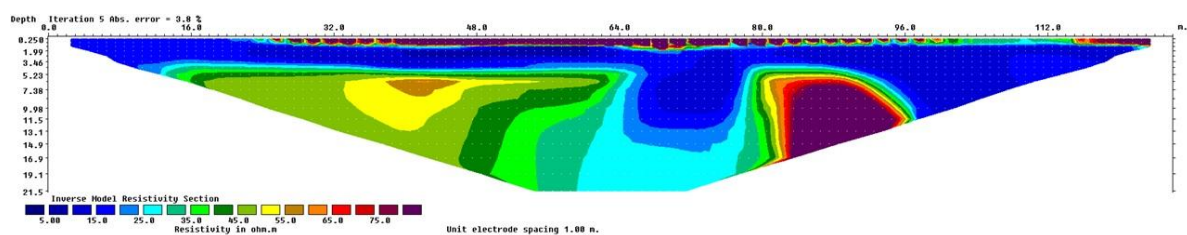


Figure 11 : ERT4 profile – LTC succession

In the southern sector, ERT8 was acquired. This area corresponds to the geological boundary between Senonian chalk outcrops to the west and Upper Turonian chalk to the east. ERT8, oriented along a northeast–southwest transect over a length of 128 m, clearly illustrates the lithostratigraphic succession through variations in electrical resistivity (Figure 12). The superficial loess layer, approximately 1 m thick, is characterized by relatively high resistivity values, locally reaching 100  $\Omega \cdot m$ . This upper horizon is underlain by a second loess unit exhibiting lower resistivities, ranging from 20 to 35  $\Omega \cdot m$ . The thickness of the loess increases westward, consistent with the westward dip of the Upper Turonian formations. The Upper Turonian chalk displays moderate resistivity values between 35 and 55  $\Omega \cdot m$ , locally reaching 65  $\Omega \cdot m$ . These values are consistent with those obtained from the VES investigations. The aquifer is identified at approximately 12 m depth (Figure 12).

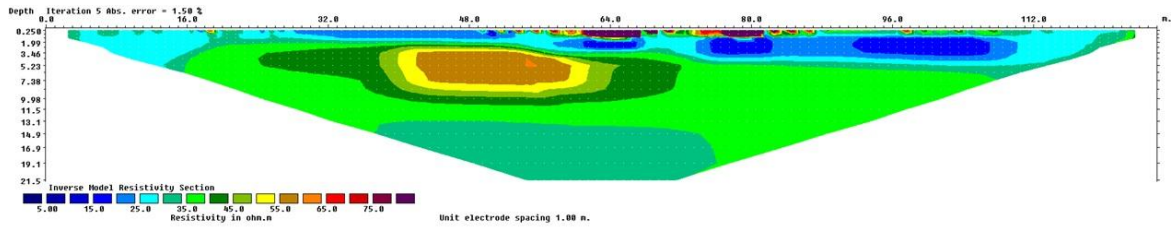


Figure 12 : ERT4 profile – LUT succession

#### 4.2.2. Area 2 surveys

In this sector, two VES soundings (VES2 and VES11) were carried out less than 50 m apart (Figure 2). VES2, validated by borehole BSS000BMKJ, reveals an LCS-type lithological succession (loess over Senonian chalk). The loess horizon is relatively thin, with a total thickness of 2.30 m. The upper meter exhibits a mean resistivity of  $70 \Omega \cdot m$ , which progressively decreases to  $13 \Omega \cdot m$  in its deepest part, corresponding to the perched aquifer with an approximate thickness of 1.20 m. The transition to the Senonian chalk is gradual, marked by an increase in resistivity to  $58 \Omega \cdot m$  at 3.5 m depth and up to  $130 \Omega \cdot m$  around 10 m depth. Below this level, the Senonian-Turonian aquifer is identified, with a resistivity of  $39 \Omega \cdot m$  (Figure 13 and Table 3).

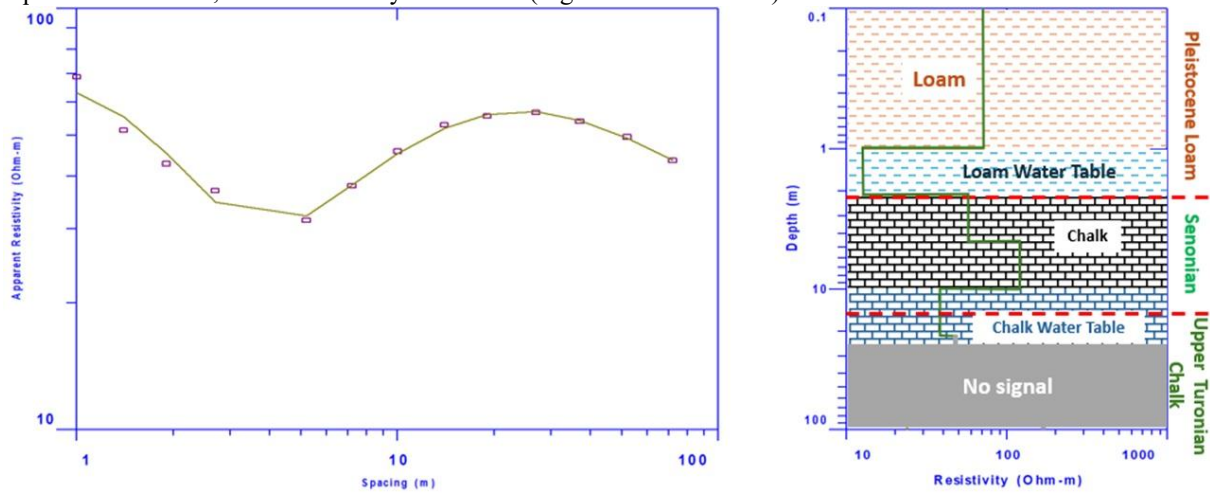


Figure 13 : VES2 signal – LSC succession

Despite its proximity to VES2, VES11 reveals a distinct lithological succession, characterized by the presence of tuffeau and corresponding to an LTC-type succession (loess–tuffeau–chalk). The loess horizon is relatively thin, with a total thickness of 1.70 m, and its saturated zone is limited to 0.70 m, exhibiting a resistivity of  $24 \Omega \cdot m$ . The tuffeau layer, approximately 2 m thick, is subdivided into two sublevels: the upper sublevel shows a resistivity of  $58 \Omega \cdot m$ , while the lower sublevel is much less resistive at  $19 \Omega \cdot m$ . The Senonian chalk appears from 3.70 m depth, with an initial resistivity of  $21 \Omega \cdot m$  that gradually increases to  $77 \Omega \cdot m$  between 5.5 and 8.7 m. Below this, the Upper Turonian chalk is present, with resistivities decreasing from  $61 \Omega \cdot m$  to  $38 \Omega \cdot m$  toward 14 m depth, marking the onset of the regional phreatic aquifer (Figure 14 and Table 3).

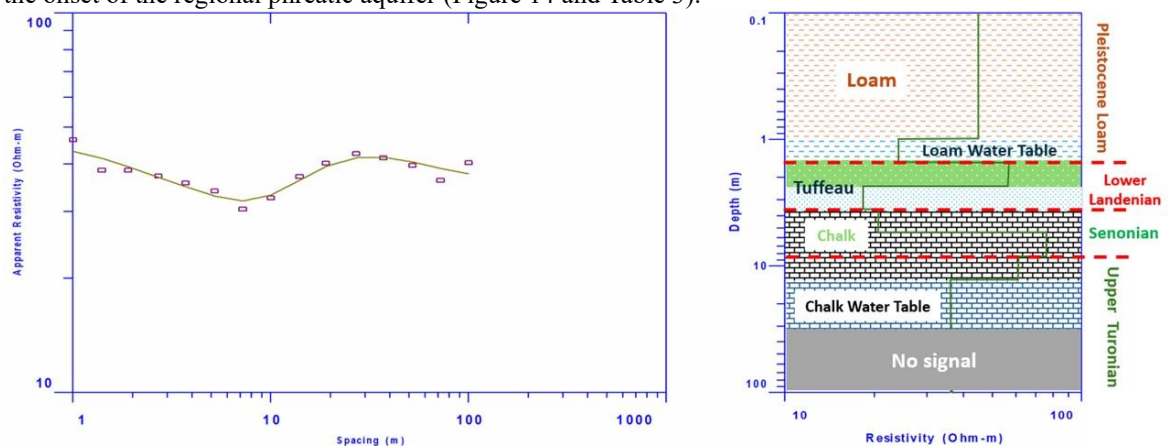


Figure 14 : VES11 signal – LTC succession

### 4.2.3. Area 3 surveys

In this area, 2 VES soundings (VES9 and VES12) were conducted (Figure 2). VES9 reveals the same LTC-type lithological succession, including the presence of tuffeau, which is not shown on the geological map but is confirmed by borehole BSS000BLPQ (Figure 15).

Within the loess, resistivity values reach  $105 \Omega \cdot m$ , indicating the presence of backfill over approximately 1 m thickness, before decreasing to  $28 \Omega \cdot m$  in the moist horizon corresponding to the perched aquifer, whose base lies at 2.50 m depth. Resistivity then increases moderately to  $38 \Omega \cdot m$  down to 5 m, corresponding to the tuffeau layer. The transition to the Senonian chalk is marked by a more pronounced increase in resistivity, reaching  $83 \Omega \cdot m$ . The Senonian-Turonian aquifer, located at approximately 17 m depth, is indicated by a resistivity drop to  $18 \Omega \cdot m$  (Figure 15 and Table 3).

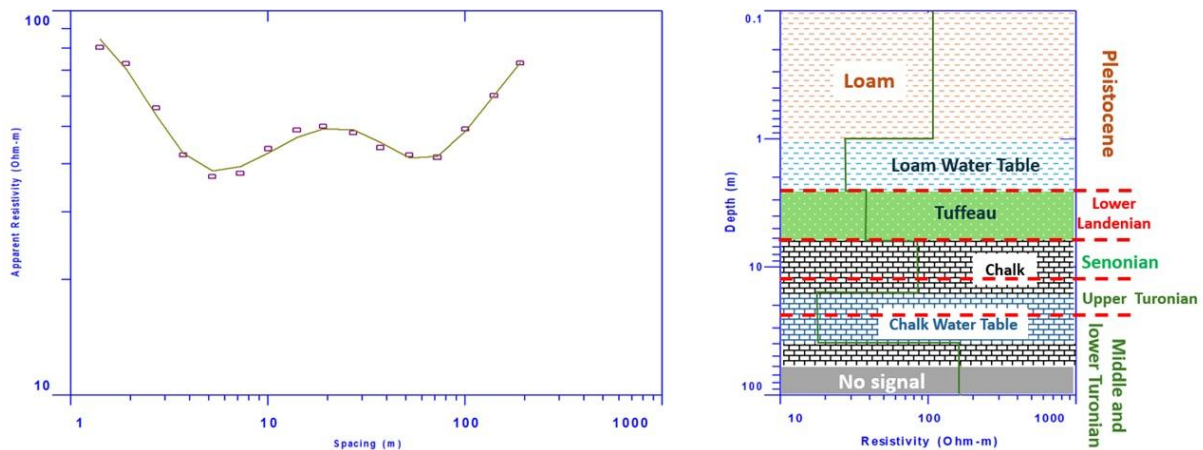


Figure 15 : VES9 signal – LTC succession

VES12 is distinguished by the absence of Senonian chalk. In this profile, the loess rests directly on the Upper Turonian chalk formations, defining an LUT-type succession (Loess–Upper Turonian), which is confirmed by borehole BSS000BNQR.

VES12 illustrates this succession: it begins with a highly resistive backfill layer ( $390 \Omega \cdot m$ ) over 0.75 m thickness, followed by an unsaturated loess horizon of 1 m thickness with a resistivity of  $100 \Omega \cdot m$ , and then a saturated loess horizon of 1.30 m showing a resistivity of  $14 \Omega \cdot m$ . The Upper Turonian chalk extends from 2.80 to 11 m depth and is subdivided into two sublevels: a moist portion with a resistivity of  $43 \Omega \cdot m$  and a saturated portion with  $19 \Omega \cdot m$ . The marly Middle Turonian, which forms the base of the aquifer, begins at 11 m depth with a resistivity of  $18 \Omega \cdot m$  and gradually increases to  $33 \Omega \cdot m$  at 21 m depth (Figure 16 and Table 3).

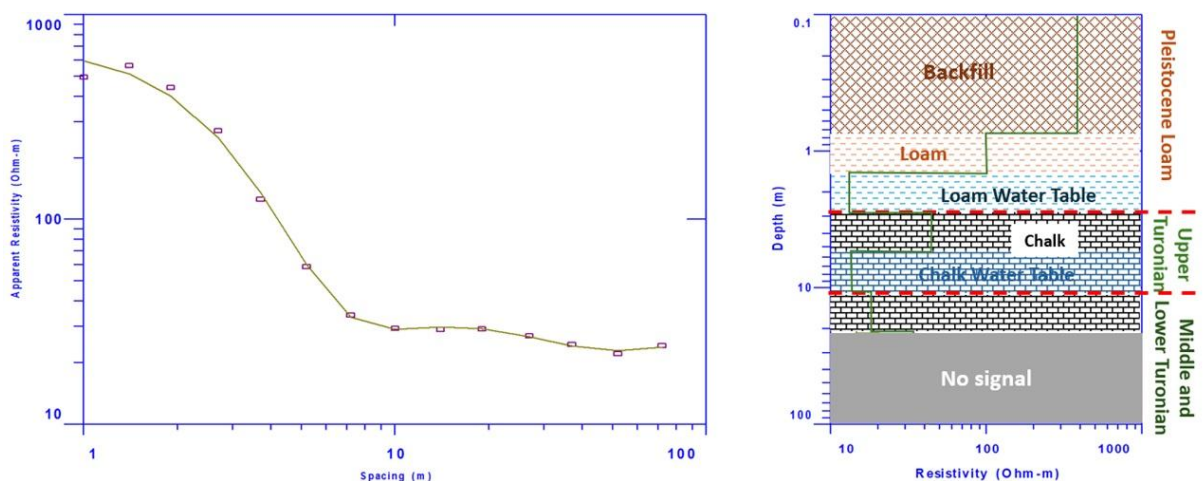


Figure 16 : VES12 signal – LUT succession

Table 3 : Resistivity results for Area A, B and C

| Area | VES survey | Borehole   | Lithostratigraphic succession | Layer                    | Depth (m)  | Resistivity ( $\Omega\cdot\text{m}$ ) |
|------|------------|------------|-------------------------------|--------------------------|------------|---------------------------------------|
| A    | VES1       | BSS000BLVM | LSC                           | Backfill (loam)          | 0 – 0.5    | 36                                    |
|      |            |            |                               | Saturated loam           | 0.5 – 4.8  | 15                                    |
|      |            |            |                               | Senonian chalk           | 4.8 – 10   | 185                                   |
|      |            |            |                               | Saturated Senonian chalk | 10 – 18    | 24                                    |
| A    | VES3       | BSS000BMKJ | LSC                           | Loam                     | 0 – 1      | 50                                    |
|      |            |            |                               | Saturated loam           | 1 – 2.2    | 14                                    |
|      |            |            |                               | Senonian chalk           | 2.2 – 10   | 53 – 130                              |
|      |            |            |                               | Saturated Turonian chalk | 10 – 17    | 17                                    |
| A    | VES7       | BSS000BLMR | LTC                           | Backfill (loam)          | 0 – 0.6    | 28                                    |
|      |            |            |                               | Saturated loam           | 0.6 – 1.9  | 20                                    |
|      |            |            |                               | Tuffeau                  | 1.9 – 3.8  | 15                                    |
|      |            |            |                               | Senonian chalk           | 3.8 – 7.2  | 41                                    |
|      |            |            |                               | Turonian chalk           | 7.2 – 14   | 33                                    |
|      |            |            |                               | Saturated Turonian chalk | Min 14     | 3.2                                   |
| B    | VES2       | BSS000BMKJ | LSC                           | Loam                     | 0 – 1      | 70                                    |
|      |            |            |                               | Saturated loam           | 1 – 2.3    | 13                                    |
|      |            |            |                               | Senonian chalk           | 2.3 – 17   | 58 – 130                              |
|      |            |            |                               | Saturated Turonian chalk | 17 – 27    | 39                                    |
| B    | VES11      | BSS000BMKL | LTC                           | Backfill (loam)          | 0 – 1      | 45                                    |
|      |            |            |                               | Saturated loam           | 1 – 1.7    | 24                                    |
|      |            |            |                               | Tuffeau                  | 1.7 – 3.7  | 19 – 58                               |
|      |            |            |                               | Senonian chalk           | 3.7 – 8.7  | 21 – 77                               |
|      |            |            |                               | Turonian chalk           | 8.7 – 14   | 61                                    |
|      |            |            |                               | Saturated Turonian chalk | Min 14     | 38                                    |
| C    | VES9       | BSS000BLPQ | LTC                           | Backfill (loam)          | 0 – 1      | 105                                   |
|      |            |            |                               | Saturated loam           | 1 – 2.5    | 28                                    |
|      |            |            |                               | Tuffeau                  | 2.5 – 5    | 38                                    |
|      |            |            |                               | Senonian-Turonian chalk  | 5 – 17     | 83                                    |
|      |            |            |                               | Saturated Turonian chalk | Min 17     | 18                                    |
| C    | VES12      | BSS000BNQR | LUT                           | Backfill (loam)          | 0 – 0.75   | 390                                   |
|      |            |            |                               | Loam                     | 0.75 – 1.6 | 100                                   |
|      |            |            |                               | Saturated loam           | 1.6 – 2.8  | 14                                    |
|      |            |            |                               | Upper Turonian chalk     | 2.8 – 11   | 19 - 43                               |
|      |            |            |                               | Middle Turonian chalk    | 11 – 21    | 18 – 33                               |

## 5. Discussion

### 5.1. Hydraulic properties of Pleistocene silts and lithostratigraphic constraints

Despite extensive research on hydrogeological systems in northern France (Manlay and Parmentier 2023) and on loess deposits (Ladrière 1875; Gosselet 1903; Sommé 1975), the hydrological and hydrogeological roles of loess horizons have been largely overlooked, with few exceptions from boreholes or local soundings. Most studies have focused on aquifers exploited for drinking water, such as the Senonian–Turonian and Carboniferous chalk aquifers, leaving the hydraulic function of loess largely unexplored, as well as its contribution to both surface and subsurface hydrosystems and ecosystems. Loess deposits are, however, globally widespread, particularly in Europe, where their distribution results from Quaternary glacial loess accumulation (Sommé 1966).

The geophysical survey (VES and ERT) carried out in this study helped identify the following lithostratigraphic successions across the three areas: LSC (Loess–Senonian Chalk), LTC (Loess–Tuffeau–Senonian Chalk), and LUT (Loess–Upper Turonian Chalk) successions (Figure 17).

Area A exhibits a dual lithostratigraphic succession, contrasting its eastern and western sectors. In the eastern part, the succession corresponds to an LCS-type succession (loess over Senonian chalk). The VES results show a marked increase in electrical resistivity within the chalk interval located between the base of the loess, corresponding to the lower boundary of the perched loess aquifer, and the top of the regional chalk aquifer. Resistivity values within the Senonian chalk consistently exceed  $120 \Omega\cdot\text{m}$  across all soundings, reaching  $185 \Omega\cdot\text{m}$  at VES1 and  $130 \Omega\cdot\text{m}$  at VES2 and VES3. These high values indicate the presence of a low-permeability transition zone between the loess and the chalk, limiting downward water fluxes. This transition zone, commonly referred to in the literature as marnettes, acts as a semi-impermeable barrier and forms the basal boundary of the perched loess aquifer, thereby promoting its persistence. In contrast, the western part of Area A is characterized by the

intercalation of Lower Landenian tuffeau between the loess and the Senonian chalk, defining an LTC-type succession (loess–tuffeau–chalk). Unlike the LSC succession, the LTC succession is associated with lower resistivity values within the chalk underlying the tuffeau (generally  $< 100 \Omega \cdot \text{m}$ ), reaching as low as  $11 \Omega \cdot \text{m}$  and  $33 \Omega \cdot \text{m}$  at VES7. These low resistivities reflect higher moisture content and indicate greater overall permeability. The presence of tuffeau between the loess and the chalk, combined with the absence of marnette interface, therefore enhances vertical water transfer toward the chalk aquifer (Figure 17).

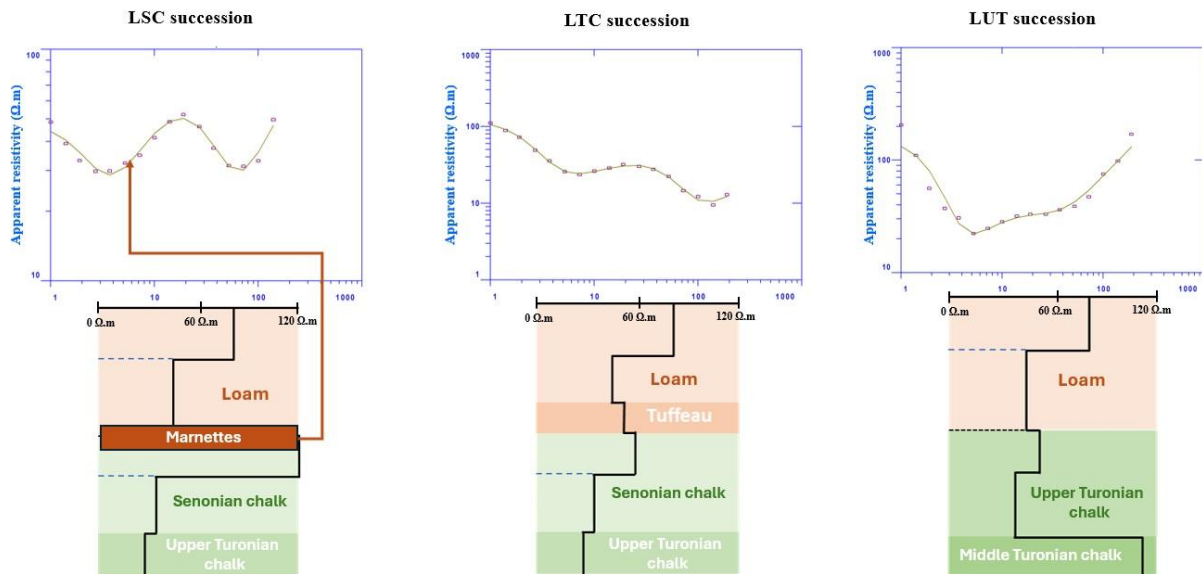


Figure 17: Geophysical results and lithostratigraphy of the LSC, LTC, and LUT succession

Area B illustrates the coexistence of two lithostratigraphic successions, LSC and LTC, with contrasting effects on the transfer of water fluxes toward the underlying chalk. In the LSC succession, two aquifers are present: a perched aquifer within the loess, maintained by the presence of the marnettes layer at the loess–chalk interface, and the regional Senonian–Turonian aquifer within the chalk. In contrast, within the LTC succession, the intercalation of tuffeau promotes the downward transfer of water fluxes toward the chalk horizon, thereby enhancing the circulation of infiltrated water and limiting the development of a persistent perched water table in the loess (Figure 17).

Area C is characterized by the local presence of tuffeau, indicating an LTC-type succession, but it is mainly distinguished by a third lithological succession, referred to as LUT, marked by the absence of both the Senonian white chalk and the Landenian tuffeau. In this setting, the Pleistocene loess is in direct contact with the Upper Turonian grey chalk. This arrangement results in significantly lower electrical resistivity values than those observed in the Senonian chalk zone, generally below  $50 \Omega \cdot \text{m}$ . These values indicate that marnettes layer is insufficiently developed, thereby facilitating the downward transfer of water fluxes toward the deeper horizons (Figure 17).

## 5.2. Genesis of marnettes and paleoenvironmental implications

The development of marnettes forms a transitional weathering horizon at the top of the chalk formation, significantly influencing water infiltration by locally reducing hydraulic conductivity and modifying near-surface flow pathways. Their formation is largely controlled by weathering processes and by contrasts in the geomechanical properties of the different chalk units.

Senonian white chalk is more brittle than Turonian grey chalk: it is more porous (40% to 46%) and exhibits lower mechanical characteristics than the less porous Turonian chalk (35% to 42%). The development of the weathering facies in the LSC succession can be attributed to the lower mechanical strength and reduced Young's Modulus of the Senonian chalk compared to the Turonian chalk. These properties make the white chalk more vulnerable to degradation by weathering agents or deformation under load.

Freeze–thaw cycles during the last Quaternary glacial period (Amédéo et al. 2023) accentuated the surface weathering of this more fragile chalk. During the subsequent post-weathering phase, loess deposition, compaction, and solifluction processes, driven by water infiltration and the silty overburden, contributed to the formation of marnettes, a weathering horizon composed of a mixture of Senonian chalk and silt. In contrast, Turonian chalk, owing to its superior geomechanical properties, was less susceptible to weathering, making the formation of marnettes less favorable.

Field observations confirm this hypothesis: the marnettes weathering facies reaches a thickness of approximately 1 meter in the Senonian chalk (A1 Motorway) (Figure 18), compared to only 0.2 m for the Turonian chalk (Area

1, southern part). Furthermore, the analysis of 320 boreholes in the study area shows that marnettes systematically appear in LSC successions with thicknesses between 0.5 and 1 meter, whereas they are rarely observed in LUT successions, and where they do occur, their thickness is less than 0.5 m.

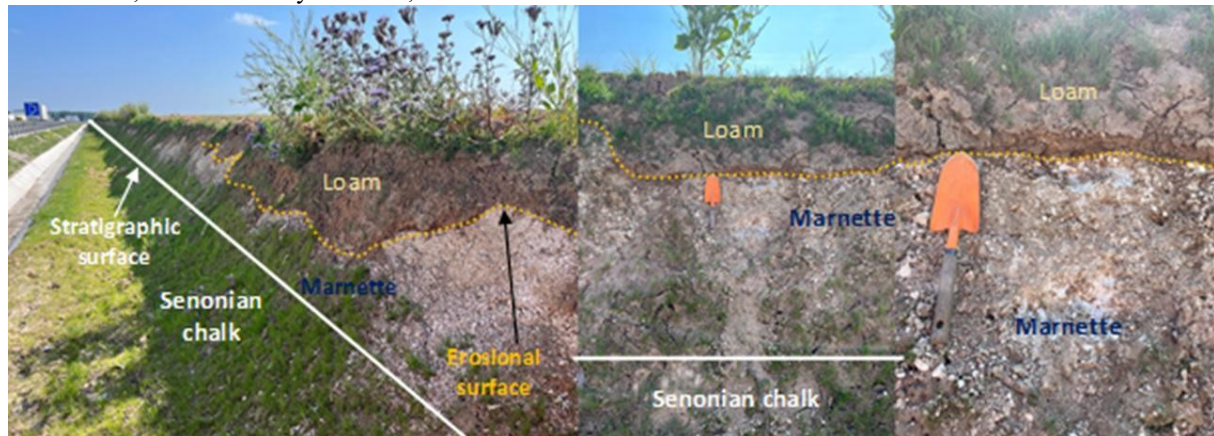


Figure 18 : The silt–Senonian boundary is marked by strong variations and the presence of marnettes

Where tuffeau is present, the Senonian chalk does not undergo significant weathering. The deposition of tuffeau during the Tertiary effectively provided local protection for the chalk against subsequent weathering agents that occurred during the Quaternary era. This protective cover explains the absence of marnettes in areas where tuffeau is intercalated between the silt and the Senonian chalk.

### 5.3. Influence of marnettes on groundwater circulation

To evaluate the role of marnettes as a hydraulic barrier, falling-head permeability tests were conducted. The investigated materials are granular geomaterials characterized by a connected matrix porosity that exerts primary control on fluid flow and transport processes (Carlier et al., 2006). Marnettes, corresponding to the Senonian chalk weathering facies, comprising chalk granules mixed with silt, exhibit lower hydraulic conductivity values than pure silt. The initial hydraulic conductivity of the two materials is on the order of  $3 \times 10^{-7}$  m/s for the silt and  $2 \times 10^{-7}$  m/s for the marnettes. Under a progressive loading protocol, the hydraulic conductivity of both materials decreases simultaneously. In terms of equivalent silt thickness, the marnettes displays hydraulic conductivities of  $1.44 \times 10^{-7}$  m/s for 1 m,  $9.6 \times 10^{-8}$  m/s for 2 m, and  $5.24 \times 10^{-8}$  m/s for 4 m. These tests were supplemented by measurements on mixtures of Senonian chalk powder and silt. For thicknesses equivalent to the silts surveyed in the field (0, 1, 2, and 4 m), the hydraulic behavior of the marnettes corresponds to mixtures containing 30% to 50% chalk. The decrease in hydraulic conductivities with an increasing chalk fraction is consistent with the experimental results of Cabalar and Omar (2023), which show that the permeability of a silt–carbonate mixture (50%) is twice as low as that of pure silt. This reduction is explained by the infilling of silt pores by chalk deposits, thereby restricting intergranular flow.

The quasi-permanent wet state of the silts, with variations across the three lithostratigraphic successions (LSC, LTC, LUT), is facilitated by their silty, low-permeability mineralogy and the presence of sand and smectites within the clay fraction. The marnettes also play a decisive role by limiting deep drainage, thereby contributing to the moisture retention of the silty horizon. These silty horizons do not constitute true aquifers but are rather quasi-saturated zones. However, in specific cases, such as with sandier silts, the presence of a water table may be considered. Nevertheless, the water held within the silts contributes to the functioning of hydrosystems and ecosystems and participates in the recharge of Tertiary and Secondary aquifers. Maintaining moisture levels near saturation raises questions regarding the potential role of silts in biodiversity preservation, as well as their medium and long-term contribution to aquifer recharge. These observations are particularly relevant for assessing the resilience of lithostratigraphic successions in the face of climate change and drought episodes.

## 6. Conclusion

This study, integrating sedimentological, geotechnical, and geophysical analyses, demonstrates that Pleistocene loess formations constitute quasi-permanent hydric horizons whose functioning is tightly controlled by the underlying lithostratigraphic succession. The loess is characterized by a persistently moist state, lacking a structured reservoir and exhibiting limited internal drainage. This quasi-permanent wetness results from its granulometry, the presence of sand fractions regulating pore architecture, and the mineralogical composition of its

clay fraction, particularly the abundance of smectites. In certain successions, this intrinsic water-retention capacity is further reinforced by the development of marnettes. This weathering facies, located at the interface with the Senonian chalk, acts as a semi-confining layer that restricts vertical transfers and promotes temporary water storage within the loess cover. Conversely, where this alteration facies is absent or where tuffeau is intercalated, hydraulic connectivity with the underlying chalk aquifers increases significantly, enhancing vertical fluxes and groundwater recharge. In the context of increasing hydroclimatic variability in Western Europe, these loess volumes perform a critical buffering function for regional hydrosystems and ecosystems. By storing and gradually releasing infiltrated water, they mitigate the effects of both excess rainfall and prolonged drought. Their potential contribution to hydrological resilience under intensifying climate extremes warrants further investigation at the catchment scale and across the different chalk units overlain by loess cover.

#### **Author Contributions**

**Khalil Lhamidi:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Jamal El Khattabi:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review and editing. **Malek Sibai:** Formal analysis, Investigation, Methodology, Validation

#### **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### **Acknowledgements**

This work was supported and funded by the *Agence de l'Eau Artois Picardie* (grant number 2021DRI00435), the *Métropole Européenne de Lille* (grant number 2021DRI00434) and the *Région Hauts-de-France* (grant number 2021DRI00140).

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