# An Interdisciplinary Framework for Evaluating Urban Soil Transformation

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In the field of urbanism, the question of the soil is being recognised over the last years as a key to the transition toward more resilient cities. This paper presents a methodology to analyse the impacts and constraints of soil transformation, by classifying soils according to their unsealing constraints and to the improvement of the water cycle potentially achieved by their transformations. This methodology calls upon different disciplines, such as urbanism, hydrogeology and pedology, to allow a decompartmentalised and 'hybrid' analysis of soils in the urban system.
Urban soils are analysed as a three-dimensional system, composed of different strata: (a) the soil cover, defining if the soil is sealed, built-up or unsealed ; (b) the soil itself, the stratum filling the function of hosting life if this function is not threatened by human activity; (c) the subsoil, the hydrogeological structure and its role in many urban functions. Based on the existing literature, the interactions between these strata are then studied to highlight different categories of urban soils, according to the constraints and impacts of their transformation.
The case of the Brussels-Capital Region is studied, as this region is facing multiple challenges related to its soil: from pollution inherited from its industrial past to major water dysfunctions resulting from urbanisation and increasingly revealed by climate change. Soil remediation, projects of green spaces and soil unsealing are also multiplying in Brussels, but generally without any monitoring of their environmental benefits and often at a high environmental cost: using energy intensive remediation technic, requiring the reconstruction of artificial soils (technosols), generating exports of polluted soil…
The purpose of this paper is to explore a classification of Brussels' urban soils, based on a three-dimensional approach, to favour transformations based on soil assessment. Thus, this work aims to draw attention to repercussions of urban soil transformation, both from an operational point of view and from an environmental perspective.

## Introduction

The question of soils in urbanism is a growing field, as shown by the numerous publications on this subject [fig. 1]. This interest stems from a better understanding of the nonrenewable nature of soils – at least on a human time scale – and of the many crucial ecosystem functions performed by soil (European Commission and European Soil Bureau, 2005; Hazelton, Murphy, and CSIRO Publishing Staff, 2009; Cavalieri, 2019; Vialle, 2021; Viganò and Guenat, 2022). These functions are strongly threatened by soil consumption which remains important: the artificialisation of soil represents 711km2 on average per year in Europe, between 2012 and 2018 (European Environment Agency, 2019).
A better understanding and consideration of urban soils therefore seem essential to address environmental issues and enable cities to cope with ongoing climate change. To address the complexity of urban soils, a hybrid approach between several disciplines – such as pedology, hydrology, life sciences, etc. – is necessary. This paper proposes to further explore these interdisciplinary links, with the aim of better understanding the interactions between the soil, the soil cover and the underlying geological strata.
This interdisciplinary understanding of urban soils aims to address the gap in the assessment of the positive and negative impacts of soil transformation at a district and city scale. The presented evaluation framework is designed to promote a more comprehensive consideration of soil in urbanism and urban projects, in line with the vision of a city adapting to nature, and not controlling it (McHarg, 1969; Barles, 2010). The need for such an approach is grounded in the analysis of the existing literature.
Within the structure of a PhD thesis, this article is an exploration of the existing literature ('Hybrid Approach of Soil') and an attempt to highlight the contributions of the various disciplines to the question of urban soils ('At the Crossroad of Different Disciplines'). This paper also goes further by trying to represent through mapping these disciplinary contributions, and their interrelations, in the Brussels-Capital Region Territory ('A Complex and Interrelated System').
The research presented in this paper was conducted within the context of the 3Dcit-is research project, funded by Innoviris. The PhD thesis is therefore taking this research as a starting point to further explore urban soil and underground questions.

**Hybrid Approach of Soils**

The need for a better consideration of the complexity of the soil system in urban projects has recently a particular echo in the face of environmental concerns. Understanding urban soils, and their complexity, requires a hybrid approach, gathering knowledge from various fields. This chapter aims to examine the existing literature in urbanism related to soil and to position this article within the current knowledge base. To achieve this, we have conducted a review of publications on this topic and categorised them into seven themes or approaches, which we will elaborate on in the following sections.

*Review and categorization of relevant urbanism literature on soils*

Aligned with Bernardo Secchi's observations (Secchi, 1983), the disconnection between soil and the city has been highlighted more recently by Dehaene and Vandermaelen (2022). There is therefore an urgent need to valorise urban soils and to adapt urban projects – and architecture – to the soil (Meulemans and Labat, 2016; Viganò and Guenat, 2022). This approach is in line with the concept of a nature-based urbanism, working with nature and not against it (McHarg, 1969; Barles, 2010). An increased emphasis on soil can also lead to the reestablishment of links between elements of the fragmented city (Secchi, 1983) through the continuity in soil and in green infrastructure (Galí-Izard *et al.*, 2022).

This disconnection between cities and their soils is especially problematic in the face of climate change and our entry into the Anthropocene (Mantziaras, 2016). The ecosystem functions (or services) of urban soil and the consequences of their dysfunction on the city are the basis of the work of many authors [fig. 1]. Cities are now compelled to rethink their approaches to soil functions, such as vegetal production, climate regulation, carbon storage, water management and biodiversity preservation (Havlicek, 2016; Cavalieri, 2019). The soil's crucial function of regulating the water cycle and storing rainwater through infiltration is particularly significant in dealing with extreme weather events that are becoming more frequent with global warming (De Bondt and Claeys, 2008; Kuzniecow Bacchin and Recubenis Sanchis, 2022). The concept of living soil – soil that can support life and fulfil its ecosystem functions – is therefore becoming increasingly important in urbanism (Barcelloni Corte and Boivin, 2022).

Many of these ecosystem functions of soil are currently being relegated outside cities (Dehaene and Vandermaelen, 2022). Food and plant production are being pushed outside of urban areas, as is the function of the soil as a recreational space. This renders the city heavily reliant on its hinterland for soil functions as well as soil itself, as soil fluxes to and from the city are significant. To enhance urban resilience, it is therefore necessary to rethink these relationships and to envision a more circular system (Meulemans and Labat, 2016).

This analysis raises important questions about urban development models. 'Inward urbanisation', which aims to build the city on itself to avoid urban sprawl, has the side effect of increasing the pressure on urban soils which are not yet urbanised (Vialle, 2021; Barcelloni Corte and Boivin, 2022; Dehaene and Vandermaelen, 2022; Viganò and Guenat, 2022). Therefore, the externalisation of soil functions (food production, carbon sequestration, water infiltration, …) outside the city increases, endangering the urban ecosystem. The compact city model is therefore criticised for its lack of consideration for urban soils.

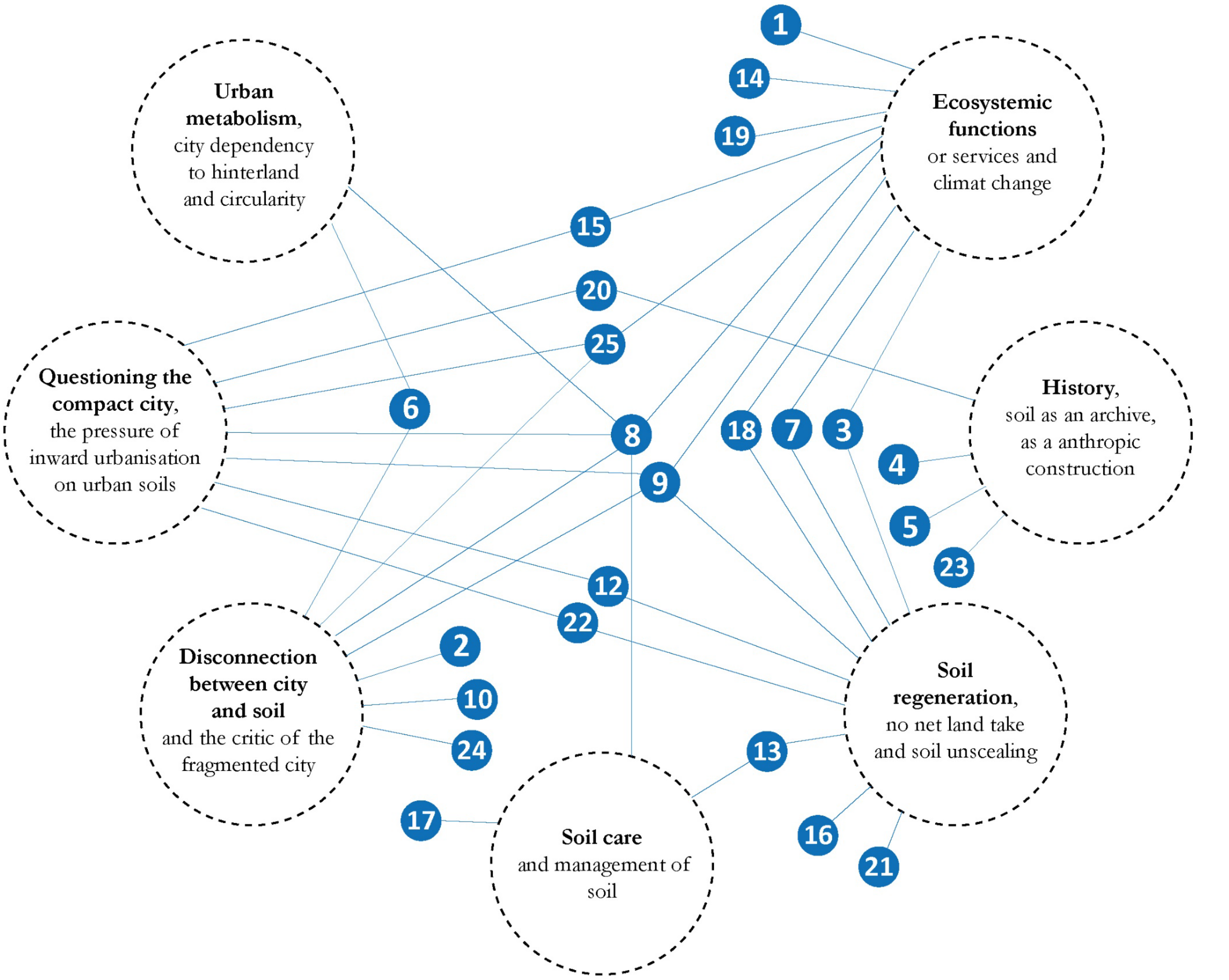
Preserving the living soils that still exist in cities and rehabilitating dysfunctional soils through unsealing is seen as a solution by many authors [fig. 1]. Unsealing does not necessarily require major intervention to rebuild artificial soils (technosols) as life can reinvest soils autonomously (Bee and Clément, 2022). However, unsealing cannot replace soil preservation, as natural soils are the result of a very long process of pedogenesis (Mantziaras and Viganò, 2016). The European no net land take policy, which aim to end soil consumption in Europe by 2050 (European Commission, 2011, 2021), is in line with this goal, as are the '*Stop Béton*' and '*Bouwshift*' movements at the Belgian level (Labo XX+I, 2021).

The preservation of living soil goes hand in hand with soil care, as soil is a dynamic element in perpetual transformation (Vialle, 2022). Soil care practises – as well as soil care actors, such as farmers – have been overlooked in cities. Giving more importance to the voice and expertise of soil care actors in urbanism therefore enables a better consideration for living soils (Dehaene and Vandermaelen, 2022). Soil care could also consist of a minimal intervention, emphasising care rather than control of the soil, allowing for a more autonomous natural development (Bee and Clément, 2022). This approach is in line with the criticism of the priority given to heavy technological solutions (Barles, 2010), which often lead to side effects, requiring in turn another technological response. This effect is perfectly illustrated in water management, where *"plus de tuyaux signifie donc plus de tuyaux"* [more pipes means consequently more pipes] (Barles, 2010). The relationship to soil is a complex issue of "social relations and regulations" (Raffestin, 1989). Projects such as Super Terram (BRAL, ULB and 51N4E, 2023) investigate this relationship by exploring urban soil management and

governance practices through participatory experiments. Such initiatives have the potential to provide insights into effective soil care practises and to promote sustainable soil management in urban areas.
Finally, soil also serves as a valuable historical archive of the city by preserving traces of past constructions and land uses, while revealing the continuity between these historical elements and the contemporary city (Pinon, 2016). The study of the evolution and transformation of urban soils (Barles, 1993; Ripoll, 2016; Vialle, 2021) allows a better understanding of the impact of human activities on soils, which in turn can be used to improve soil management strategies.

*Positioning the current study within the existing literature*

This paper aims to address the gap in the assessment of the positive and negative impacts of soil transformation at a larger scale, the scale of the Brussels-Capital Region. This objective is derived from the literature review presented above. Thus, ecosystem functions, especially the role of soil in water management, are studied in an attempt to identify where unsealing would have the most significant impact. This approach is also inspired by McHarg's vision that "the distribution of open space [as well as urban planning in general] must respond to natural process" (McHarg, 1969, p. 65). This author also highlights the work performed by nature for humans, pioneering the concept of ecosystem services (McHarg, 1969, p. 55).
In regard to unsealing, the approach of a limited intervention in the transformation of soils is preferred, to avoid environmental side effects that may result from overly intrusive and technical transformation. This choice is also based on the need to rethink the interactions between the city and nature: moving away from a strategy based on the control of nature with the help of technology, which has shown its limits (Barles, 2010). This approach is also in line with the objective of circularity and the aim to minimise the dependence and impact of the city on its hinterland.
With the emphasis on the interdisciplinary nature of the soil issue, we will now move beyond urbanism literature to explore what other disciplines can contribute to the understanding of soils.

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[fig. 1] Mapping of the literature, elaborated by the author.

## At the Crossroad of Different Disciplines

To evaluate more concretely the constraints and benefits of soil transformations enabling the increase of living soil in the city, this study seeks a better understanding of soils in various disciplines. The objective is therefore very concrete: to develop an analysis which will help with the development of soil-sensitive urban projects and urban planning, while not denying the needs of the city (in terms of housing, productive spaces, etc.) and the constraints which soil transformation represents.

### *Disciplinary terms*

Soil is an ambiguous term (Havlicek, 2016; Vialle, 2021). Its meaning differs depending on the discipline or profession: for example, the farmer considers the soil as a source of nutrients for crops, the engineer considers it as an element of support or stability (European Commission and European Soil Bureau, 2005) and the ethnologist will study the cultural representations associated with the soil (Vialle, 2021). We will focus here on the main disciplines studying soil in order to understand the different vocabularies used and attempt to highlight the interrelations between the different approaches.

Pedology, which is the science of soils, is more specifically interested in the process of soil formation – pedogenesis – , soil functioning and soil classification (Blake et al., 2008; Séré et al., 2010; Vialle, 2021; IUSS Working Group WRB, 2022). In this discipline, soil is considered as an accumulation of layers, called horizons, resulting from the interaction between the atmosphere, the biosphere and the geosphere (European Commission and European Soil Bureau, 2005). Soil horizons are used to define soil classifications and, although the definitions of horizons may vary in different parts of the world [see fig. 2], the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2022) provides a globally standardised soil classification.

Geologists are mainly interested in the parent materials, i.e. the consolidated strata beneath the soil [fig. 2]. The classification used by geologists is based on the age of the different strata – chronostratigraphy – which are thus classified according to their era, epoch, age, etc. (Cohen, Harper and Gibbard, 2022). A lithologic classification – based on the nature of the rocks – also provides information about the structure of the strata (Devleeschouwer et al., 2018): strata could be formed by clay or by sand, for example. These lithologic properties have an important impact on the groundwater system, as sand strata are generally permeable, allowing a better water circulation than clay strata (De Bondt and Claeys, 2008).

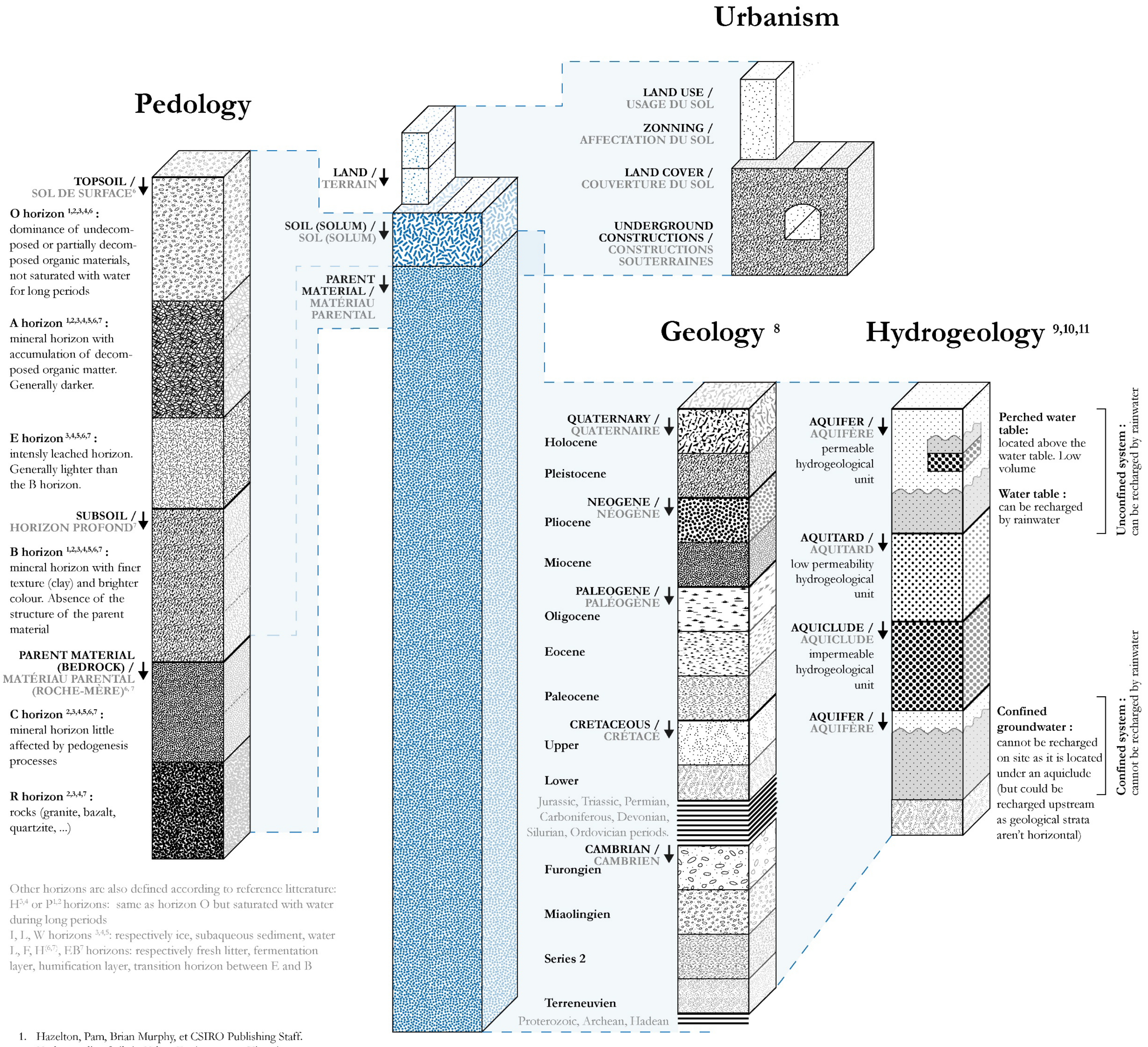
The links between these strata and groundwater are studied by a branch of geology: hydrogeology. This branch provides a classification of geological strata according to their permeability: (1) aquifers, permeable geological layers where water can therefore circulate easily, (2) aquitards, low-permeability strata where water circulation is difficult, and (3) aquicludes, which describes impermeable strata (Sethi and Di Molfetta, 2019; Bruxelles Environnement, 2020b). The position of groundwater in the superposition of geological strata is also analysed: groundwater could be confined, i.e. located between two impermeable strata and therefore cannot be recharged on site by rainwater, or, conversely, unconfined (Peeters, 2010; Nakić et al., 2017).

The study of urban soils requires a hybrid approach between these disciplines. Indeed, concepts such as soil composition (pedology) or groundwater cycle (hydrogeology) cannot be dissociated in an urban environment from the issue of land use (urbanism).

### *Soil cover impact*

Soil sealing is described as one of the main threats to soil in Europe (Commission of the European Communities, 2002) as well as in Brussels (Centre d'Ecologie Urbaine et al., 2020) and its impacts are transversal to the disciplines mentioned above. Soil sealing leads to irreversible soil degradation and dysfunction (Groupement d'intérêt scientifique sur les sols, 2011; Cavalieri, 2019). The water cycle is critically altered by soil sealing, leading to flood risks and pollution of surface and groundwater (Labo XX+I, 2021), as well as heat island phenomena (Poelmans, Van Rompaey and Batelaan, 2010).

The hydro(geo)logical balance is destabilised as sealed soils increase runoff and prevent infiltration, consequently affecting the recharge of aquifers [fig. 4, top]. The groundwater system is also impacted in the opposite direction by the decrease of evapotranspiration, and thus the lowering of water extraction from the underground by vegetation (Poelmans, Van Rompaey and Batelaan, 2010; Ungaro et al., 2014). The buffer function of the soil of absorbing water during heavy rains and releasing it during drier periods is therefore compromised.





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[fig. 2] Glossary of disciplinary terms. Terms used in pedology, geology, hydrogeology and urbanism are described and illustrated here in a schematic and simplified way. The order, thickness and horizontality of the different strata are only for ease of understanding: in real situations, not all layers are present nor horizontal. Elaborated by the author.

*Urban Soils*

Urban soils are highly anthropised. These anthroposols, which are composed of varying thickness of artificial backfill, cover all cities that are several centuries old (Barles, 1993, p. 49). The importance of the transformation of these soils, as well as past soil uses, can be the cause of contamination (Région Bruxelles-Capitale, 2020). The state of soil pollution and the suspicion of contamination are documented in Brussels (Bruxelles Environnement, 2020c). Depending on the parcels' contamination, different studies and treatment processes are required (Bruxelles Environnement, 2010, 2021).

*Influence of geological strata*

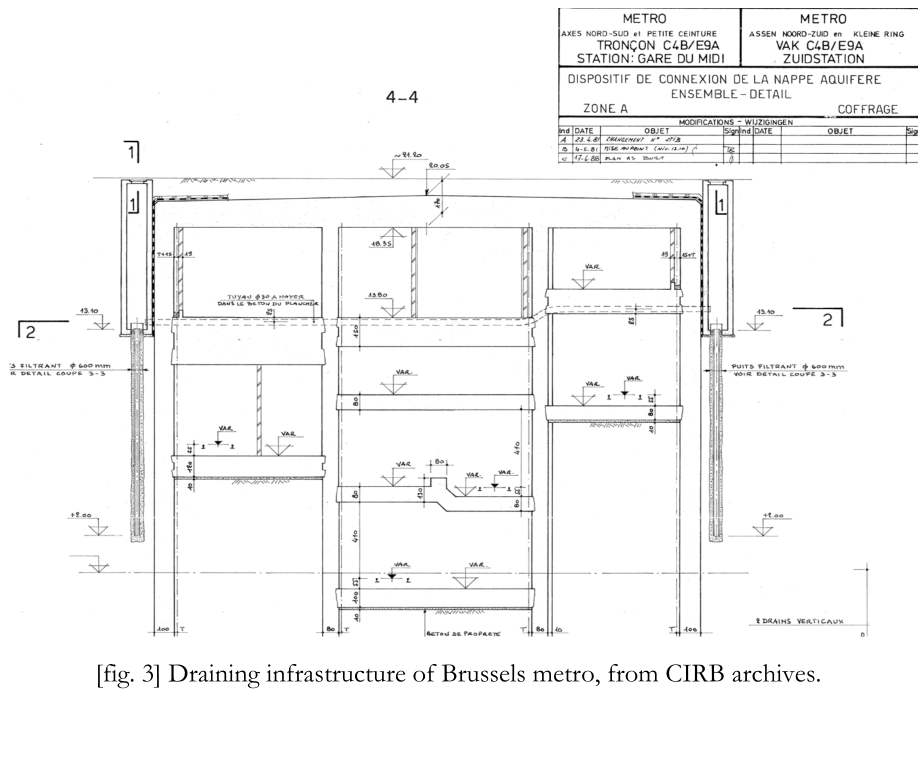
Urban soils are supported by geological strata, which structure influences the rainwater infiltration and retention capacity (Brito et al., 2006; De Bondt and Claeys, 2008). Indeed, an impermeable clay stratum close to the soil surface represents a barrier to water infiltration [fig. 4, center]. The presence of a shallow water table is also an obstacle to infiltration, as water saturated strata cannot absorb additional rainwater (D'Aniello et al., 2019).

Aquifer vulnerability study – a branch of hydrogeology investigating the risk of contamination of aquifers by surface pollution (Foster, Hirata and Andreo, 2013) – highlights the influence of soil cover and geological strata permeability on the dispersion of contaminants (Palmer and Lewis, 1998). The risk of groundwater contamination and pollutants dispersion increases in parallel with the water recharge capabilities of aquifers, i.e. the more permeable soil cover, soil itself and geological strata are, the higher the dispersion risk is (Machiwal et al., 2018). The geological structure therefore plays a role in the risk of pollutant dispersion [fig. 4, center]. Low permeability clay strata (aquicludes) tend to block the vertical dispersion of pollutants, while permeable strata (aquifers) facilitate the transport and dispersion of contaminants (Santi, Mccray and Martens, 2006).

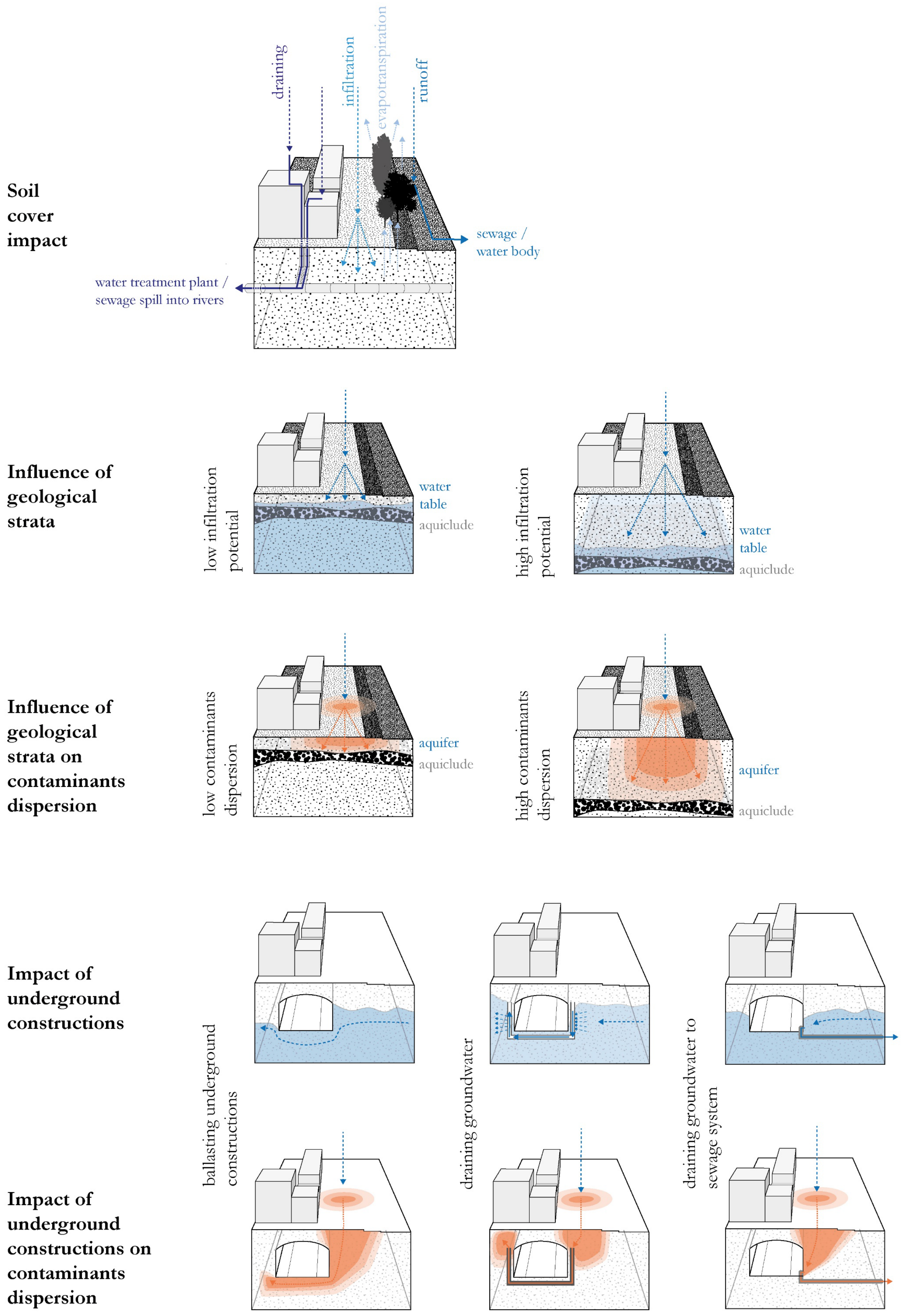
*Underground constructions impacts*

This hydrogeological system becomes more complex in urban areas due to the presence of many underground constructions. These constructions represent obstacles to infiltration and groundwater flows (Attard et al., 2017). Underground constructions are equipped with different technical solutions to deal with risks of flooding and pressure from groundwater [fig. 4, bottom], as the ballasting and waterproofing of underground structures or the draining of groundwater to avoid pressure (Attard et al., 2016). The Brussels metro is thus equipped with groundwater draining systems allowing groundwater to cross the constructions [fig. 3]. These technical solutions can alter groundwater levels, and also impact groundwater quality and temperature (Attard et al., 2017).

The modification of groundwater flows by underground constructions and their technical infrastructure can also results in the dispersion of contaminants [fig. 4, bottom]. Ballasted structures tend to lead to more local dispersion of contaminants, while draining infrastructure transports contaminants over larger distances (Attard et al., 2017). In addition, the construction materials used for these underground structures can also be a source of contamination (Chae et al., 2008).




[fig. 3] Draining infrastructure of Brussels metro, from CIRB archives.




[fig. 4] Diagrams describing disciplinary contributions, elaborated by the author.

## A complex and interrelated system

Based on the literature, a methodology to map the different interactions presented above has been constructed. The process presented in this chapter aims, in a first phase, to build different layers – a delayering of the system – and, in a second phase, to assemble these layers to highlight their interrelations as a three-dimensional system.

*Delayering of the system*

*A. Soil cover*

To identify unsealed soils, high-resolution data (2 m) from the vegetation map produced by Brussels Environment (Bruxelles Environnement, 2022b) is used. This data was constructed using infrared aerial imagery (NDVI) and provides information on the presence of vegetation rather than soil cover. Therefore, additional processing was carried out to filter out buildings, whose vegetated roofs could distort the results (Massy, Martin and Wyler, 2011), and roads, to limit the excessively large vegetated area due to the tree canopy. Although there might be some remaining inaccuracies, the results [fig. 6] allow for a sufficient level of detail on a large scale.

Concerning sealed soils, an additional categorisation between built and non-built seems necessary from a urban transformation perspective. Indeed, a project aiming to transform a non-built sealed surface, such as a car park or mineral square, is different from a building transformation project. To isolate the buildings, cadastral data (SPF Finances, 2021) was used. Non-built sealed soils were identified by elimination, i.e. soils that are not unsealed, are not built on, and not covered by water.

*B. Urban soil and unsealing constraints*

Data on soil pollution is published by Brussels Environment (Bruxelles Environnement, 2020c) and classify parcels into 4 (+1) distinct categories: (1) Non-polluted, (2) Slightly polluted without risk, (3) Polluted without risk, (4) Polluted parcels where soil studies or treatments are ongoing. A 5th category (category 0) groups parcels where pollution is suspected, given the risk generated by past activities.

These categories have regulatory implications related to soil. In the case of water infiltration, studies may be required before infiltrating water for the parcels in categories 3, 4 and 0 (Bruxelles Environnement, 2022a). These categories also determine the possible uses, as in the case of the vegetable gardens: risks are minimal in categories 1 and 2, prohibitions may exist in categories 3 and 4, and a soil evaluation is required for category 0.

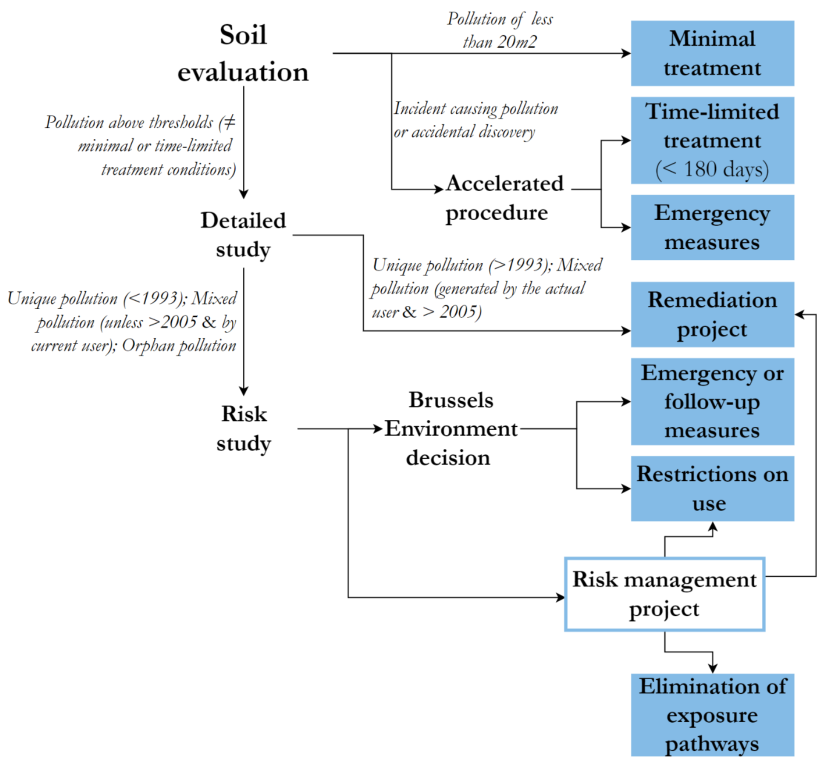
This categorisation of parcels also determines the required process regarding pollution in the case of soil transformation [fig. 5]:

1. Categories 1 and 2 (unpolluted or slightly polluted): remediation or risk management intervention is not necessary.
2. Parcels not included in the database: a soil evaluation (‘*reconnaissance de l’état du sol*’) is only needed if pollution is discovered or suspected. The soil evaluation is the starting point for the process described in [fig. 5].
3. Category 0 (suspected pollution): a soil evaluation is required. The same applies to category 0+1 and 0+2, as pollution is still or again suspected.
4. Categories 3 and 4 (polluted without risk or under investigation/treatment) as well as categories 0+3 and 0+4 (since in addition to the suspicion of pollution, pollution has actually been detected): a risk study (‘*étude de risques*’) or the intervention of the pollution expert are necessary, which may therefore lead to remediation or risk management projects.

These four points present an increasing need or likelihood for remediation or risk management, ranging from point 1, requiring no intervention, to point 4, where intervention is required. Points 2 and 3 represent a degree of probability of contamination and are not related to the extent of the pollution. For example, it is not impossible that serious pollution may be present, requiring major remediation measures, on parcels not included in the database (category 2), even if it is less likely.

In this study, the probability of soil pollution for parcels not included in the database – which are numerous in Brussels – as well as the public domain – also not covered by the database – is estimated according to the importance of the presence of artificial backfill. Data concerning the presence of backfill comes from the geotechnical maps of Brussels (Dam et al., 1990) and is determined through a comparison of the first elevation map of Brussels from 1860 with elevation data from the 1980s.

Through the study of pollution risks and the processes involved with soil pollution, this analysis of urban soils highlights the unsealing constraints related to contamination, ultimately enabling the mapping of these constraints [fig. 6].




[fig. 5] Diagram showing the process for soil contamination in Brussels, elaborated by the author.

*C. Geological strata, underground constructions, and infiltration potential*

The analysis of the geological strata is based on the BruStrati3D hydrogeological model (Bruxelles Environnement, 2020a). A categorisation of these strata is made according to their depth and their permeability (aquifer, aquitard or aquiclude). The classification of these different hydrogeological units makes it possible to identify the depth at which the first aquiclude or aquitard is located, and therefore the first barrier to water infiltration. In addition to this data, the water table also represents a limit to infiltration. Indeed, a subsoil already saturated with water has logically reached a limit in its capacity to absorb more water. A thick permeable strata and a deep water table therefore allows a large quantity of water to infiltrate and thus acts as a reservoir (De Bondt and Claeys, 2008). Conversely, a shallow impermeable stratum or a shallow water table limits water infiltration.

Underground constructions are an obstacle to water infiltration in the subsoil. They can represent a physical barrier to infiltration and can also limit the interest of infiltrating water, as in the case where a drainage infrastructure is present and diverts infiltrated water to the sewer system. Underground constructions also alter natural groundwater flows and water levels (Attard et al., 2017). Soil unsealing near underground infrastructure must therefore be conducted with care.

An analysis of the geological structure and the underground infrastructure can therefore assess the potential for water infiltration, by highlighting the depth of the first barrier to infiltration (Bossard, Cavalieri and Ska, 2022) and the presence of underground constructions.

**Soil cover**

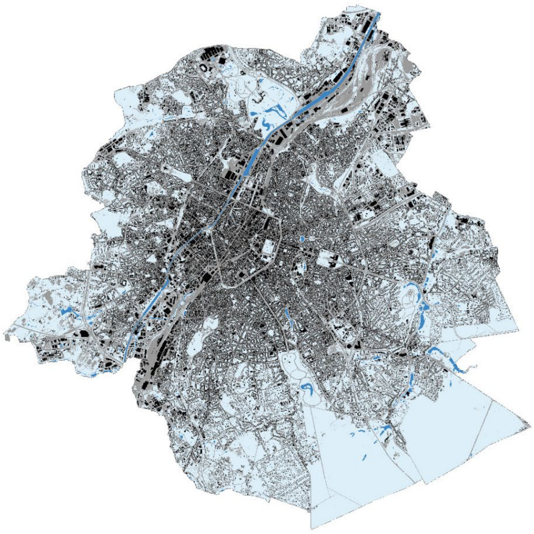
built

sealed

unsealed

water

Data : Bruxelles Environnement - vegetation_2020 (2020), water polygon ; SPF Finances - cadastre (2021) ; CIRB - Urbis (2021)



**Urban soil and unsealing constraints**

no intervention needed

observation

observation with suspicion of fill

Soil evaluation

Risk study

Data : Bruxelles Environnement - inventaire de l'état du sol (2022), remblais (1990) ; SPF Finances - cadastre (2021) ; CIRB - Urbis (2021)

**Geological strata, underground constructions and infiltration potential**

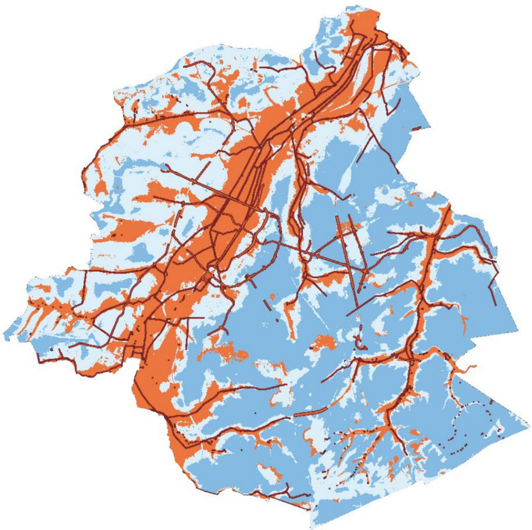
high infiltration potential

good infiltration potential

limited infiltration potential

close to an underground infrastructure (25m)

Data : Bruxelles Environnement - BruStrati3D (2018), Brussels Phreatic System Model (2019), remblais (1990), Exploitations souterraines (1990), River_cover (2022), Collectoren_AED (2020) ; BruFlow - Bassins d'orage (2020) ; Databank Onderground Vlaanderen - Geology stratigraphy ; CIRB - Urbis (2021) ; SPF Finances - cadastre (2021)



[fig. 6] Delayering of the system, elaborated by the author.

*Mapping interrelation of the three-dimensional system*

*A. sealed and built soil*

The diagram below [fig. 7] illustrates the different possibilities of interactions between the three previously presented layers and allows for the identification of different categories. This categorisation is based on two variables: infiltration potential and transformation constraints. The degree of geological permeability is a determining factor for assessing the infiltration potential, i.e. the role that these soils, once unsealed, could play in the water cycle. The second variable – transformation constraints – considers the probability and need for intervention regarding soil contamination and, if intervention is needed, its importance. The presence of underground constructions also influences the transformation constraints and is therefore also integrated into this variable.

The ecosystem potential and transformation constraints can be visualised in the form of a two-entry table [fig. 8, top], allowing these two variables to be crossed. The cells of this table represent the different cases emerging from the analysis that we will now detail.

Firstly, non-polluted or lightly polluted soils without risk have very low transformation constraints (as no remediation would be necessary) except when they are over or near important underground infrastructure. In the latter case, a study of these underground constructions is at least necessary. Infiltration potential depends, as previously presented, on the geological capacity for water absorption and the existence of underground infrastructure. Underground constructions could also counterbalance the positive effects of unsealing, for example if a draining infrastructure diverts infiltrated water to the sewer system.

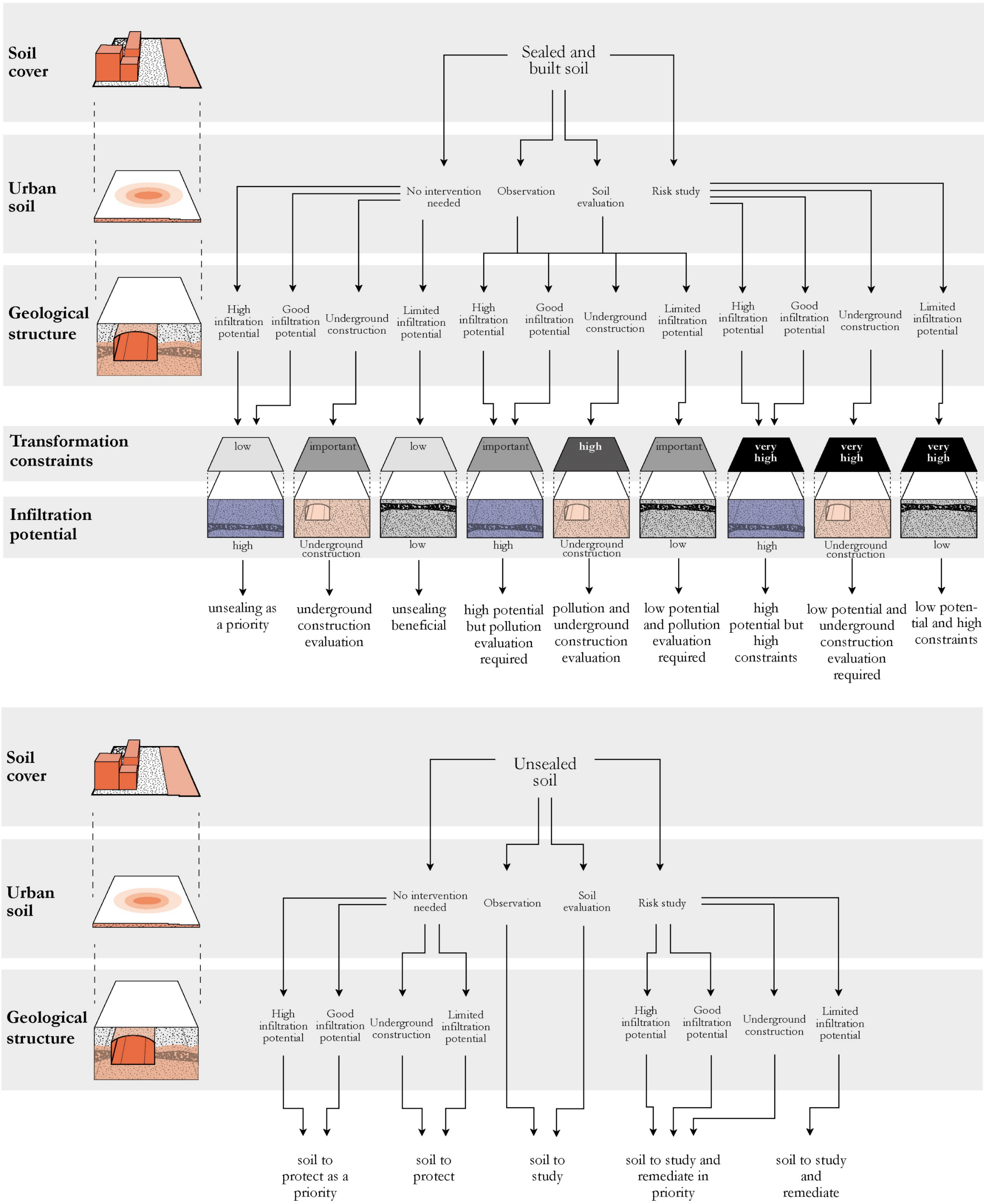
Soils with suspicion of contamination or not included in the soil database can generate transformation constraints in the event of pollution being detected. Therefore, the probability of constraints is increased, while the potential for infiltration remains unchanged from that of non-polluted soils. Finally, polluted soils always represent strong transformation constraints, as pollution management is necessary, especially if they are located on permeable geological structures with high infiltration potential, as the risk of pollutant dissemination is also higher.

This methodology enables the elaboration of a Brussels map [fig.8, top] revealing the constraints of soil transformation, ranging from light (low constraints) to dark (high constraints), as well as the potential benefits of unsealing, ranging from red-orange (low potential) to blue (high potential).

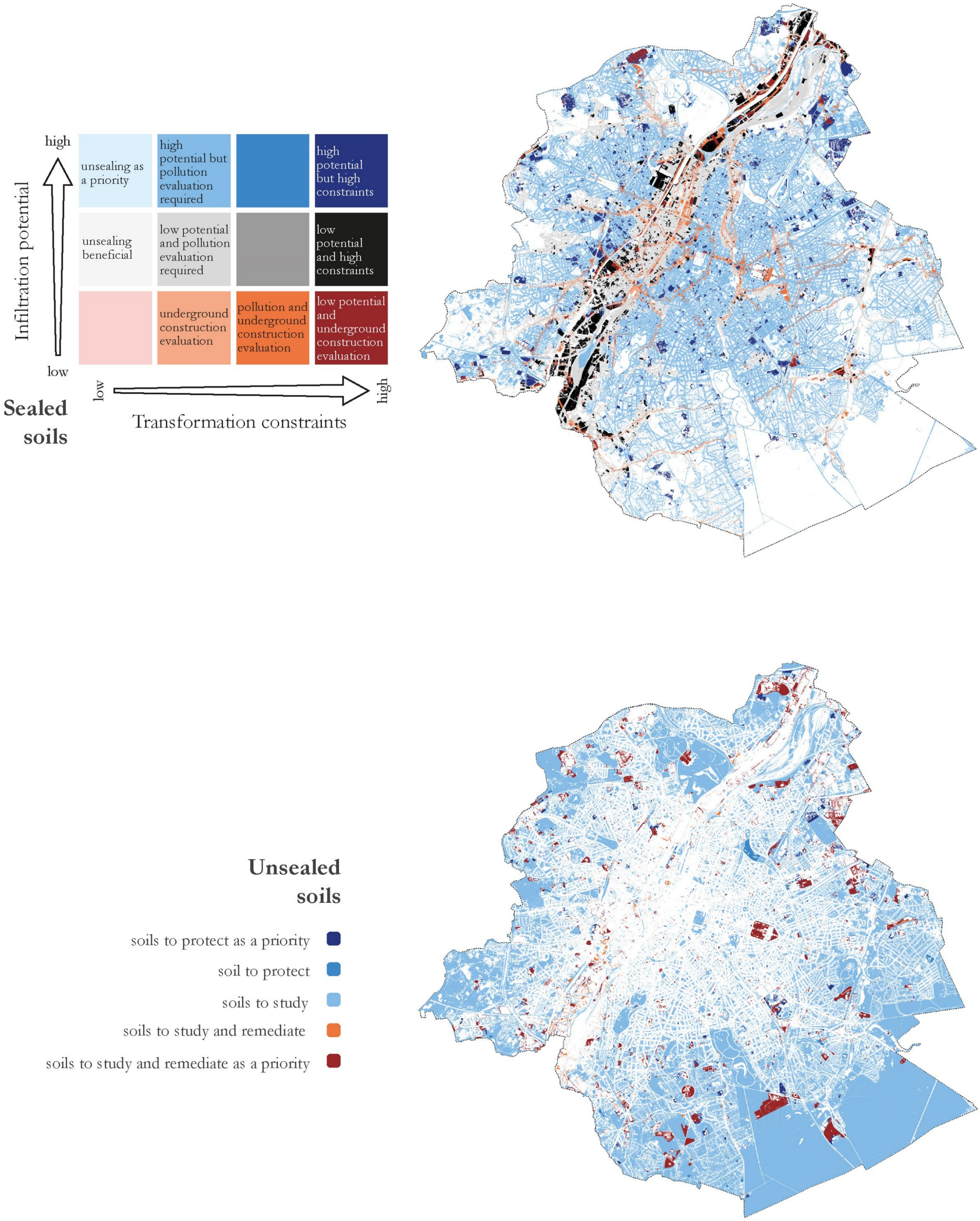
*B. unsealed soil*

Concerning unsealed soil, categories based on the need for intervention relative to pollution are constructed [fig. 7]. Unsealed soils where no intervention is needed (non-polluted or slightly polluted without risk) play an important role in the urban ecosystem, and their protection therefore seems necessary. When these soils are also located on a geological structure with high infiltration potential, their role in the city's water cycle seems even more crucial. Thus, these soils fall into the category of 'soils to protect as a priority'. Unsealed soils with a suspicion of pollution or not included in the soil contamination database fall into the category of soils to be studied, given the lack of information about them and the potential risk of contaminant dispersion.

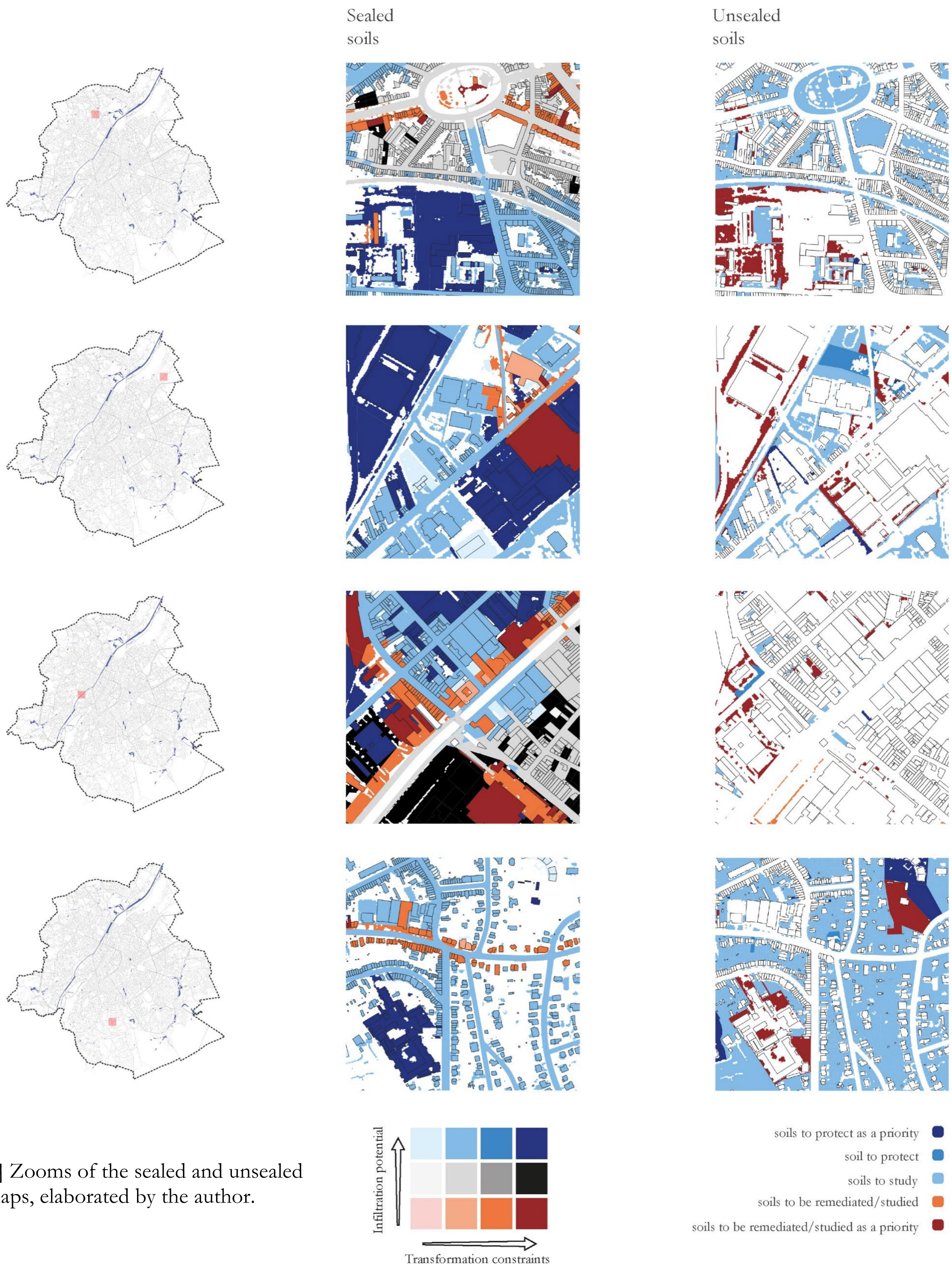
Unsealed soils that are contaminated pose a significant risk of pollutant dispersion, particularly when situated above a geological formation with high infiltration potential or above underground infrastructure. This combination of unsealed soil cover, soil pollution, and permeable geological strata presents a significant risk and falls into the category of 'soils to study and remediate as a priority'. When the permeability of the subsoil is lower, the risk of pollutant dispersion is reduced (but still present). The corresponding category is therefore 'soils to study and remediate'.




[fig. 7] Diagram of interrelations, elaborated by the author.




[fig. 8] Sealed soil and unsealed soil mapping, elaborated by the author.




[fig. 9] Zooms of the sealed and unsealed soil maps, elaborated by the author.

**Conclusion**

These maps [fig. 8 and 9] seek to synthesise the interrelation between soil cover, soil and geological strata, thereby facilitating a more comprehensive understanding of the complex soil system. A parallel analysis of sealed and unsealed soils offers a new perspective on urban transformation. The third zoom [fig. 9] reveals a district predominantly characterised by sealed soil, which is heavily impacted by soil contamination and traversed by underground constructions. This zoom offers a new perspective for envisioning the transformation of this district by identifying areas where an increase in unsealed living soil would be significantly beneficial without requiring disproportionately extensive remediation efforts. Conversely, unsealed soils are predominant in the area shown in the last zoom [fig. 9]. However, some of these soils are contaminated, and given the underlying permeable geological structure increasing contaminant dispersion risks, remediation appears necessary. Thus, this mapping enables a new gaze on the urban fabric, highlighting the environmental potentials and constraints of urban transformation.

This paper emphasises the importance of incorporating soil and underground dynamics, both visible and invisible, within the urban diagnostic phase, the urban planning strategy, and the decision-making process. Integrating these soil and underground dynamics into existing frameworks will contribute to a more comprehensive understanding of urban environments, enabling an urban transformation toward a more resilient city able to face the complex challenges of climate change. An approach that is sensitive to soil and underground dynamics aligns with the concept of "design with nature" (McHarg, 1969), highlighting the necessity of harmonising the city with its natural environment.
In line with this paper, explorations of various scenarios have been carried out (Bossard *et al.*, 2023, forthcoming). The focus of these scenarios is the Heyvaert District in Brussels, which serves as a case study for envisioning a transformation taking into account soil and geological strata. This study also integrates Brussels urbanism regulations and addresses the question of the practical implementation of these transformations, identifying both limits and paths toward a transformation of the soil enabling a more resilient district and city.

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