JDU

Journal of Delta Urbanism
Delft University of Technology

Issue #06 Depletion

Fall | Winter 2025

Assessing urban soil unsealing constraints and potential for water regulation: a framework and case study of Brussels-Capital Region

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After a functional and immaterial reduction of urban soil to a two-dimensional surface, dominating the urbanism of the 20th century, over the last decades, soil has been progressively restored as a material, urban, and living element.

This study proposes a comprehensive framework for assessing soil thickness within urban environments, emphasizing its three-dimensional and multidisciplinary nature. The proposed framework conceptualizes soil as comprising three distinct strata: (1) the land surface, which underpins urban planning and zoning practices; (2) the living soil, a dynamic and biologically active stratum composed of various horizons and domains of pedology; and (3) the deep underground, comprising parent materials and geological formations typically studied by geologists. In urban contexts, these strata are subject to significant anthropogenic interference. In particular, the urban underground is often heavily constructed, accommodating basements, mobility networks, and technical infrastructure.

The proposed framework is applied to the case study of Brussels and aims to foster a soil-sensitive approach among urban designers and planners, thereby enabling site-specific unsealing and soil restoration practices. The application to Brussels reveals key insights into the benefits and constraints of soil unsealing, particularly concerning the soil's function in water regulation. This study underscores the importance of considering soil in urban planning and offers a model for assessing the potential effectiveness of soil unsealing projects, ultimately promoting more resilient and sustainable urban environments.

INTRODUCTION

Over the past few decades, there has been a substantial reevaluation of the significance of urban soil in the fields of urbanism and urban planning[1]. This shift in perspective arises from the growing recognition that soil is not just a structural support for urban projects, but rather an integral component of the public realm[2], accomplishing many ecosystem functions[3]. Several theories supporting a nature-based urbanism[4, 5, 6, 7, 8] serve as a lens for understanding the importance of soil in urban contexts and fostering greater cohesion and continuity within peri-urban and diffuse urbanization[9]. Despite this growing awareness, soil remains under severe threat, particularly in Europe, where urban expansion, land consumption, and infrastructure development contribute to substantial soil degradation[6].

One of the most critical threats to urban soil is soil sealing—the covering of soil with impervious materials, such as asphalt or concrete—which leads to the loss of soil functions[10]. Other significant threats, also highlighted by Stolte et al., include erosion, decline in organic matter, compaction, contamination, salinization, desertification, flooding, landslides, and loss of biodiversity. According to the European Environment Agency[11], almost 2% of Europe's total land area (and over 40% of its urban soils) have been sealed, with an average annual increase of 711 square kilometers reported[12]. In this context, urban soil refers to soils located within urban areas as defined by the DEGURBA categorization[13]. Soil regulates critical processes, such as the water and carbon cycles, supports vegetation growth, and serves as a resource for human activities, for instance, by providing materials for construction and as support for infrastructure, while also preserving historical and cultural heritage[14, 15, 16, 17, 18]. Impaired soil functions have significant consequences. For instance, dysfunction in the regulation of the water system can lead to reduced rainwater infiltration, diminished groundwater recharge, and heightened flood risks. These impacts are exacerbated by the increasing frequency of extreme weather events driven by global warming[19, 20].

Soil unsealing and soil ecosystem restoration have therefore become of paramount importance in urban transformation. However, it is imperative to recognize that while unsealing is vital, it cannot fully substitute for soil preservation, as natural soils are the result of very long pedogenesis processes[9]. In some situations, unsealing can cause issues related to the dispersion of contaminants[21] or requires significant and costly soil remediation efforts, potentially generating substantial greenhouse gas emissions[22]. Consequently, there has been a growing emphasis on weighing the social and environmental benefits of remediation, propelled by movements advocating for 'risk-based land management' or 'green remediation'[22, 23, 24, 25].

Therefore, a sensible approach to soil unsealing and rehabilitation depends on a systemic comprehension of urban soils. Existing frameworks such as the System Exploration Environment and Subsurface (SEES)[26] have advanced this perspective by integrating subsurface and surface systems—such as civil constructions, water, energy, and soil—into urban planning and design. Building on this systemic understanding, the methodological framework proposed in this study aims to enable case-specific

1 Meulemans, 2020
2 Secchi, 1986
3 Millennium Ecosystem Assessment, 2003
4 Barles, 2010
5 Corner, 1999
6 McHarg, 1969
7 Mostafavi & Doherty, 2016
8 Waldheim, 2006
9 Mantziaras & Viganò, 2016
10 Stolte et al., 2015
11 European Environment Agency, 2021
12 European Environment Agency, 2019
13 European Union et al., 2021
14 Blanchart et al., 2018
15 Cavalieri, 2019
16 De Bondt, 2017
17 Havlicek, 2016
18 Teixeira Da Silva et al., 2018
19 De Bondt & Claeys, 2008
20 Kuzniecow Bacchin & Recubenis Sanchis, 2022
21 Machiwal et al., 2018
22 Grifoni et al., 2022
23 Hou & Al-Tabbaa, 2014
24 Pedron & Petruzzelli, 2011
25 Song et al., 2019
26 Hooimeijer & Maring, 2018

assessment of the benefits and constraints of unsealing, promoting what we term “soil-sensitive urbanism”. This concept refers to urban design and planning practices that adapt to existing soil conditions rather than altering soil to fit urban projects and plans. The proposed framework focuses on the relationship between soil and water and the key urban soil functions of water cycle regulation using a multidisciplinary approach. Given the complex nature of soil, incorporating fields such as pedology, hydrology, and life sciences is indispensable for fostering a more holistic consideration of soil. This includes understanding soil connectivity, which emphasizes the importance of nurturing mutually beneficial soil-society relations to achieve soil security and sustainability[27].

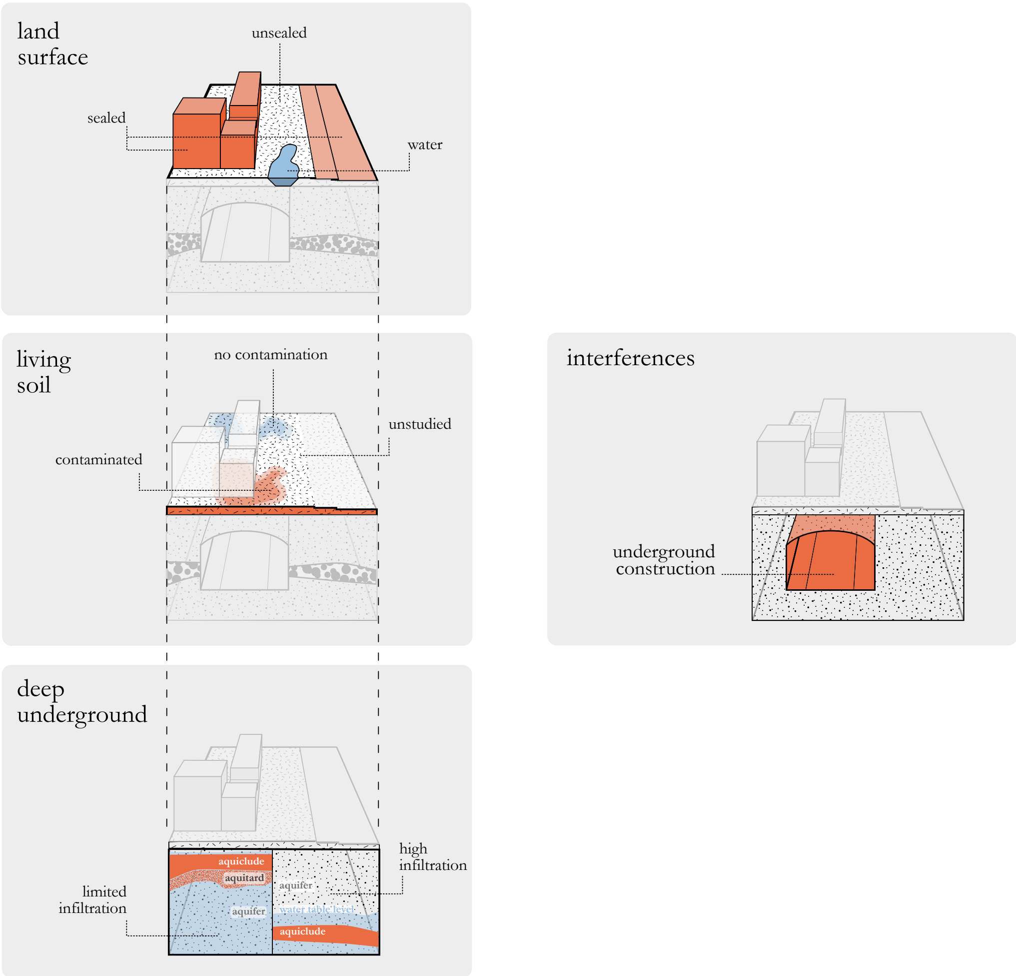
Through this interdisciplinary and three-dimensional perspective, soil is conceptualized not solely as a land surface but as a volume[14, 28], composed of layers of different thicknesses, where the concept of ‘living soil’ — a biologically active soil capable of sustaining life and fulfilling its ecosystem functions[29, 30] — is incorporated into a wider system. The upper soil horizons (O, A, E, and B), where soil host life is therefore seen in interaction with the geological structure and strata (horizons C and R)[31], as well as in interaction with the land surface, where urbanization and the urban environment occur. These horizon interactions will be described more thoroughly in subsequent sections. The proposed holistic view is essential for identifying and prioritizing areas where soil unsealing can enhance infiltration and thus improve the soil's function in water regulation, while minimizing potential complications and constraints.

27 Evans et al., 2021
28 Blanchart et al., 2018 Henry, 2023
29 Balfour, 1943
30 Barcelloni Corte & Boivin, 2022
31 IUSS Working Group WRB, 2022

METHODOLOGY

This work proposes a three-dimensional integration of principles from diverse disciplines by reading soil as composed by three main strata – (1) land surface; (2) living soil; (3) deep underground – as well as an additional layer of "interferences". It provides an overview of the different strata composing the soil system, commencing with the surface and progressing deeper [figure 1].

32 Fiji et al., 2013
33 European Commission, 2021
34 Directive 2023/416, 2023
35 European Commission, 2011



01 The proposed framework consists of three primary strata and one additional transversal stratum: land surface (top left); living soil (middle left); deep underground (bottom left), as well as an additional stratum of 'interferences' (right).

LAND SURFACE

The first –and visible- stratum is the land surface, the surface for an urban project, and an immaterial juridical space where rules accumulate (functions, density, protections, etc.).

These regulations are shaped by initiatives at global, European, and local levels. The United Nations designated 2015 as the "International Year of Soils" to raise awareness of the importance of sustainable soil management[32]. At the European level, the EU Soil Strategy for 2030 aims to set quantifiable and monitored national and local objectives to curb land take by 2030 across EU member states[33]. This strategy is complemented by the 2023 "Soil Monitoring Law", which seeks to monitor, protect, and restore soils[34]. These policies reaffirm the objective of achieving "no net land take" by 2050, a target previously outlined in the "Roadmap to a Resource Efficient Europe"[35].

European countries have also implemented initiatives at the national level to address soil consumption. In Belgium, efforts to limit soil consumption are encapsulated in initiatives such as “Stop Béton” in Wallonia and "Bouwshift" in Flanders[36]. In France, the 2021 Climate and Resilience Law established goals to halve the rate of soil artificialization by 2030 and achieve zero net artificialization (zéro artificialisation nette, ZAN) by 2050[37].

At the local level, the land surface is intricately shaped by regulations such as zoning plans, urbanism rules, and the designation of protected areas. These local regulations play a crucial role in determining the possibilities for land use and transformation. For instance, these regulations can specify areas where development is restricted in order to preserve natural landscapes or agricultural land, thereby protecting these areas against soil sealing. Urbanism rules may set limits on the extent of built or sealed surfaces, ensuring that new developments do not excessively contribute to land take.

Categorizing land surfaces based on their sealing status—whether sealed, such as surfaces supporting buildings or surfaces covered by impervious materials such as roads, sidewalks, parking lots, or public spaces, or unsealed—is essential for assessing the impact and effectiveness of these regulations on the soil system. While regulations themselves do not cause sealing, they establish the parameters within which sealing and unsealing occur. Changes in land surface regulations directly affect the possibilities for soil sealing, thereby influencing the overall soil system.

LIVING SOIL

The second stratum is the one of living soil. In pedology, soil is seen as an interface between the geosphere, atmosphere, and biosphere[38, 39], shaped by the interactions between these elements[40, 41]. Consequently, soil emerges as a dynamic stratum undergoing continuous transformation, intricately responsive to the influences of living organisms, atmospheric conditions, and the underlying mineral structure. Soil is composed of various layers, known as horizons, which are fundamental to its classification. These horizons include the organic layer (O), the topsoil (A), the eluviation layer (E), the subsoil (B), and the parent material (C and R) [figure 2]. The World Reference Base for Soil Resources (WRB) utilizes these horizons as a primary framework for soil classification, and is the international reference for soil classification[31]. While the WRB provides a standardized system, it is important to note that local variations in soil classification also exist.

In urban contexts, soils are particularly heterogeneous[42] due to the numerous transformations over time, often artificial, consisting predominantly of backfill materials[43]. This heterogeneity greatly increases the difficulty in categorizing and mapping urban soils, leading generally to blank areas where cities are located[44, 45]. This lack of data is also exacerbated by the historical emphasis on agricultural objectives in soil-mapping efforts, which has led to the omission of urban soils[46]. The transformations of urban soils, along with the different human activities that took place on these soils, also often result in contamination, which is mapped to varying degrees in certain cities[47, 48], albeit as a different kind of soil map.

36 Labo XX+I, 2021
37 LOI n° 2021-1104 du 22 août 2021 portant lutte contre le dérèglement climatique et renforcement de la résilience face à ses effets, 2021
38 Peleman et al., 2022, p. 9
39 Vialle, 2021
40 Darwin, 1881
41 Protasoni, 2022, p. 23
42 Pouyat et al., 2010
43 Barles, 1993, p. 49
44 Gis Sols, 2011
45 Marechal & Tavernier, 1971
46 Sojka & Upchurch, 1999
47 Bruxelles Environnement, 2025
48 Dupont, 2025

Soil assessment presents challenges due to the diverse functions that soils perform, which require site-specific evaluation. Soil functions refer to the various roles and services that soil provides, including vegetal production, climate regulation, carbon storage, water management, and biodiversity preservation[16, 17, 49, 50]. These functions often conflict and are influenced by societal and historical biases, such as the predominant importance given to agricultural productivity until the 1990s[46], and the rise of environmental and health functions from the 1990s to the 2010s. In the last decades, soil assessment has incorporated broader indicators, such as ecosystem services or functions, and resilience[51]. An emerging area of interest lies in the recognition of the ecological value of urban and postindustrial soils. These soils, previously regarded as heavily degraded, have now been rediscovered as a support for unique biodiversity and ecosystem functions[52]. Overall, Gallagher's paradigm shift challenges traditional perceptions of soil degradation and underscores the potential of such soils to positively contribute to urban and ecological systems.

As this study focuses on unsealing and the functions of soil related to the water cycle, given the impacts of soil contamination on these aspects, the question of contamination still needs to be addressed. Furthermore, the European Thematic Strategy for Soil Protection[53] identifies soil contamination as a significant threat. Due to the lack of comprehensive soil data in urban areas, soil contamination data also becomes one of the most reliable sources of information available for assessing soil conditions. Therefore, the presented framework does not intend to fine-tune the assessment of living soil but integrates considerations of soil contamination. Contamination assessments often determine the necessity of remediation processes and may restrict potential soil uses, such as vegetable gardens or agricultural activities, thereby impacting the previously discussed land surface strata.

Urban projects are heavily impacted by soil contamination, both economically and environmentally, through remediation efforts[22]. Consequently, an indicator assessing the probability and severity of soil contamination is crucial for soil-sensitive urbanism. The proposed classification, not intended as a framework for soil remediation, acknowledges the variety of contaminants and their distinct effects, necessitating site-specific studies and remediation processes. The living soil stratum is categorized into three classes based on the potential influence of contamination on urban transformation projects: (1) No contamination, including studied or already remediated soils, where pollution levels do not exceed legal thresholds. These soils are deemed safe for urban transformation or unsealing projects without further action. (2) Unstudied soils, referring to soils that have not been evaluated for contamination. Suspicions of contamination may arise from historical activities such as former gas stations or sites previously used for chemical storage. To assess the risks of contamination, an initial site observation can identify potential contamination sources, and a soil evaluation can confirm or refute the presence of contaminants. (3) Contaminated soils, including studied soils, where contamination levels exceed legal thresholds. A risk study is necessary to evaluate the impact of contamination and identify a potential remediation strategy.

49 Mantziaras, 2016
50 Tosi & Munarin, 2022
51 Bünemann et al., 2018
52 Gallagher et al., 2018
53 European Commission, 2006

DEEP UNDERGROUND

The third proposed stratum is the deep underground. It lies beneath the relatively thin living soil stratum, mainly composed of parent materials, called horizons C, when it is still slightly impacted by pedogenesis, and R when its structure is a fully mineral bedrock. The parent material is primarily studied by geologists. It is classified based on the age of the different strata (chronostratigraphy) [figure 2] or according to their composition (lithologic classification)[54, 55].

The composition and structure of these geological strata significantly influence water infiltration dynamics, which in turn affect groundwater recharge and flood risk[16]. For instance, the presence of clays tends to limit water infiltration, whereas sands favors it[19].

Therefore, hydrogeologists further classify geological strata based on their permeability [figure 2] as follows: (1) aquifers, highly permeable strata that allow water circulation and serve as potential water reservoirs; (2) aquitards, strata with limited permeability; and (3) aquicludes, impermeable strata that block water circulation and act as barriers to water infiltration[56]. Additionally, hydrogeological characteristics are determined by geological vertical features. For instance, whereas an unconfined groundwater system can be recharged by rainwater, confined aquifers are isolated from direct rainwater recharge due to surrounding impermeable layers[57].

This classification of geological structures based on their permeability allows for an evaluation of the underground capacity to infiltrate and store water. This is achieved by modelling the underground volume available for water infiltration and storage. The underground infiltration potential is primarily constrained by the first obstacle to water movement, which can be an impermeable geological stratum (aquiclude) or a water table, a stratum that is already waterlogged. A shallow impermeable geological stratum or a high water table significantly limits the underground ability to absorb and retain water. Conversely, a substantial depth of permeable underground, not saturated with water, can act as a natural reservoir for rainwater[19].
To assess these variations in infiltration potential, geological structures have been categorized into two distinct classes: (1) high infiltration, where the volume of unsaturated, permeable geological strata is large, allowing the storage of significant quantities of rainwater; and (2) limited infiltration, where the presence of shallow water table or aquiclude limits water infiltration.

INTERFERENCES: UNDERGROUND INFRASTRUCTURES

Urbanization comes with heavy constructions not only on land surfaces but also within the different strata of soils, and the use of urban underground space is increasing[58]. These underground infrastructures, such as transport networks, sewage systems, water supply, electricity, and communication cables, cross and interfere with each of the three layers observed.

Deep underground undergoes significant alterations due to the presence of these underground infrastructures, as these infrastructures limit rainwater infiltration and influence water table levels by disrupting groundwater flows[59, 60]. Additionally, these infrastructures often incorporate technical

54 Cohen et al., 2022
55 Devleeschouwer et al., 2017
56 Sethi & Di Molfetta, 2019
57 Peeters, 2010
58 Bobylev et al., 2022

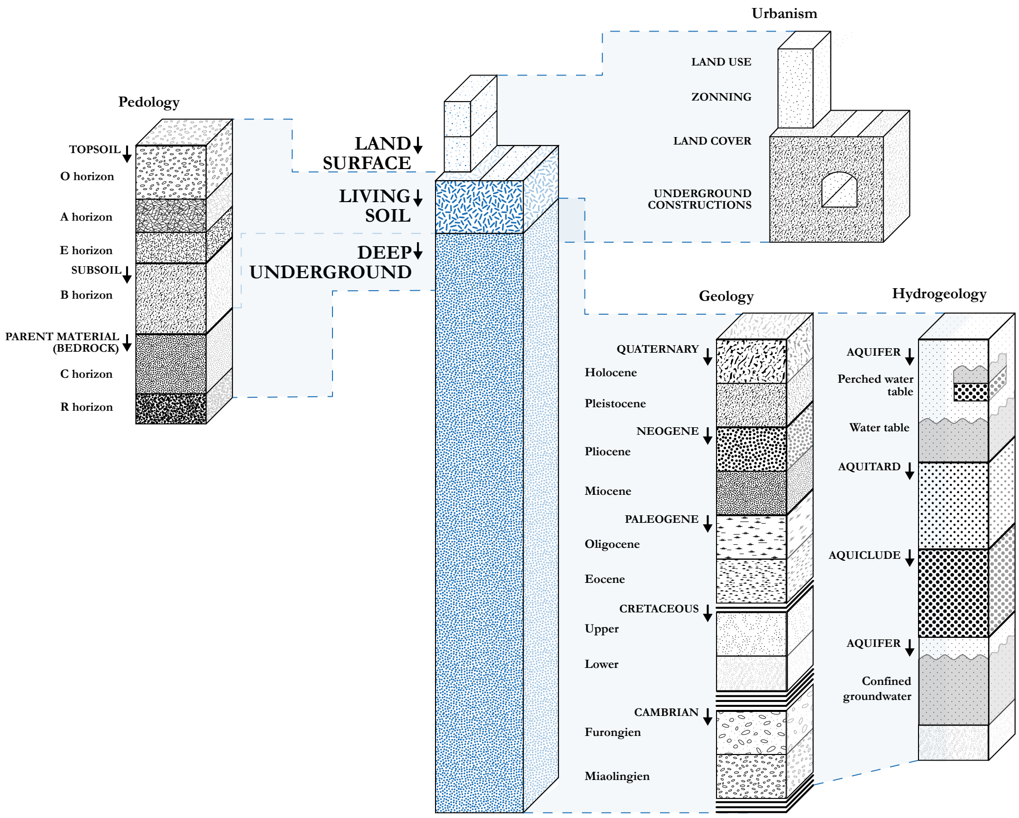
installations designed to mitigate groundwater pressure, such as drainage systems or waterproofing and ballasting techniques. These installations manage groundwater-related challenges and redirect water flows, significantly affecting the surrounding hydrogeological environment[61].

Moreover, underground infrastructures can affect both the temperature and quality of groundwater. They also tend to increase the risk of contaminant dispersion as a result of groundwater flow disruption by redirecting shallow groundwater, which is generally more prone to contamination, to deeper aquifers[59, 60]. Depending on the materials used in construction, there is also a risk of direct contamination[62] and, in the case of sewage systems, leaking is known to induce groundwater contamination[63, 64].

Underground infrastructures interfere with land surface – limiting reorganization possibilities - and living soil strata, as restricted rooting volumes and altered water systems reduce the soil's capacity to sustain certain vegetation[65]

Therefore, identifying and localizing these underground infrastructures within the proposed 3D soil matrix is crucial.

59 Attard et al., 2017
60 Kamath & Unnikrishnan, 2020
61 Attard et al., 2016
62 Chae et al., 2008
63 Eiswirth & Hötzl, 1997
64 Ly & Chui, 2012
65 Sieghardt et al., 2005, pp. 315–316



02 Composition of each strata, illustrating the elements and disciplinary terms used. Based on the classifications described in Bruxelles Environnement, 2020; Cohen et al., 2022; IUSS Working Group WRB, 2022; Peeters, 2010

EXPERIMENT

In this section, the framework and methodology discussed are applied to the case study of the Brussels Capital Region. The Belgian and European capital serves as a particularly compelling case study, as the city's industrial past have a significant impact on its soil dynamics. Furthermore, the pressure exerted on soil is exacerbated by the city's demographic growth[66], intensifying the demand for available soil.

The question of soil in the Brussels Capital Region is currently at the core of several policies and studies. The proposed new regional urbanism regulation[67] limits soil sealing by fixing the maximum proportion of built and sealed soil for new construction projects or major renovations. In line with the European strategy for 2030[32], Brussels' environmental agency (Bruxelles Environnement) proposes the "Good Soil" strategy[68] to protect and improve soil quality, including tools as the Atlas des sols bruxellois[69] and introducing a soil quality index (IQSB)[70]. Additionally, research projects such as Brusseau[71] and Brusseau bis explore water and flooding issues, with an emphasis on water infiltration and the role of soil in these processes. De Bondt[16] examines the hydrogeological structure to improve water management, while the Super Terram project[72] addresses urban soil management and governance in Brussels, and the ArchiSols project[73] centers on understanding soil through archive documents and past land use.

The application of the methodology developed in this study to the case study of Brussels aims to deepen the understanding of the urban soil system within the Belgian capital. By employing this approach, this study offers a model to evaluate the potential effectiveness of soil unsealing projects on urban soil's water regulation function, as well as an assessment of the constraints imposed by soil pollution or underground infrastructures on unsealing.

As described in the previous section, this research initially dissects the soil system into three distinct layers: (1) land surface, (2) living soil, and (3) deep underground. In a subsequent section, the interactions among these layers are analyzed, enabling the reclassification of soil from a perspective of soil unsealing.

LAND SURFACE

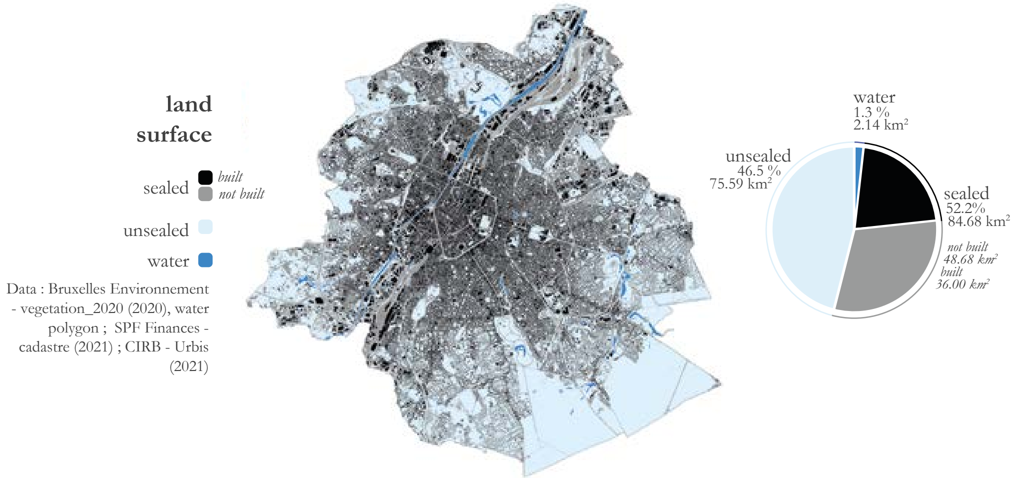
Categorizing land surfaces based on their sealing status—whether sealed (e.g., buildings, roads, sidewalks, or parking lots) or unsealed—is essential for evaluating the impact of urbanization on the soil system.

In this respect, the most detailed dataset available - a vegetation dataset[74] derived from high-resolution aerial infrared imagery - was utilized to construct the land surface dataset [figure 3]. The presence of vegetation does not automatically indicate unsealed soil, as the tree canopy often does not correspond to unsealed soil, and vegetated roofs could also skew the results[75]. Consequently, the vegetation layer was filtered in a GIS software (QGIS) to exclude buildings and roads, improving the level of detail and enabling a large-scale analysis, although some minor inaccuracies

66 Hermia, 2023
67 Project de Règlement Régional d'Urbanisme (RRU), 2022
68 Centre d'Ecologie Urbaine et al., n.d.
69 Bruxelles Environnement, 2024
70 Bruxelles Environnement, 2021b
71 Crespin, 2020
72 BRAL et al., n.d.
73 ArchiSols, n.d.
74 Bruxelles Environnement, 2022
75 Massy et al., 2011

might remain. A GIS operation further categorizes sealed soil into built and not built, using cadastral data[76] and geoprocessing tools. This analysis enables the calculation of sealed and unsealed surfaces and also facilitates the comparison of the current situation with regional regulations[77] and European objectives to limit land take[78].

76 Service Public Fédéral Finances, n.d.
77 Projet de Règlement Régional d'Urbanisme (RRU), n.d.
78 Bossard et al., 2023



03 Classification of land surfaces in the Brussels-Capital Region, based on (Bossard, 2023)

LIVING SOIL

Living soil encompasses a complex ecosystem that supports biodiversity, facilitates carbon cycling, and sustains plant life, extending far beyond mere contamination levels. However, due to the scarcity of comprehensive soil data in urban environments, contamination data often serves as a critical indicator for assessing soil health. As this study focuses on unsealing and the functions of soil related to the water cycle, it is essential to address soil contamination due to its significant impact on these aspects.

In the context of the Brussels-Capital Region, soil contamination is addressed through regulatory measures, with information regarding the presence, or potential presence, of contamination documented in the soil condition inventory [inventaire de l'état des sols][47]. This inventory, formatted as a vector GIS layer accessible by web service (WFS), reports data primarily through categorical classifications. Detailed contamination studies and results are uploaded by soil experts, although the specific details of contaminants are not publicly accessible. The database is continuously updated as new soil studies are conducted. However, Category 0 designations – indicating suspicion of contamination – remain fixed and are difficult to revise due to their legal implications and potential impact on land value.

This inventory – at the scale of the parcel – has a legal value in determining the process required in the event of a construction or transformation. It includes five distinct categories:

- Category 0 – suspicion of pollution due to past or present activities – regroups parcels requiring a soil evaluation, which is the starting point for the process that may lead to soil remediation if pollution is confirmed. This category may overlap with other categories, as ongoing activities might introduce new suspicions of contamination, regardless of prior soil investigations. The dataset also suggests the activity that may have caused the contamination. Category 0 parcels are determined by Bruxelles Environnement based on historical and current activities.

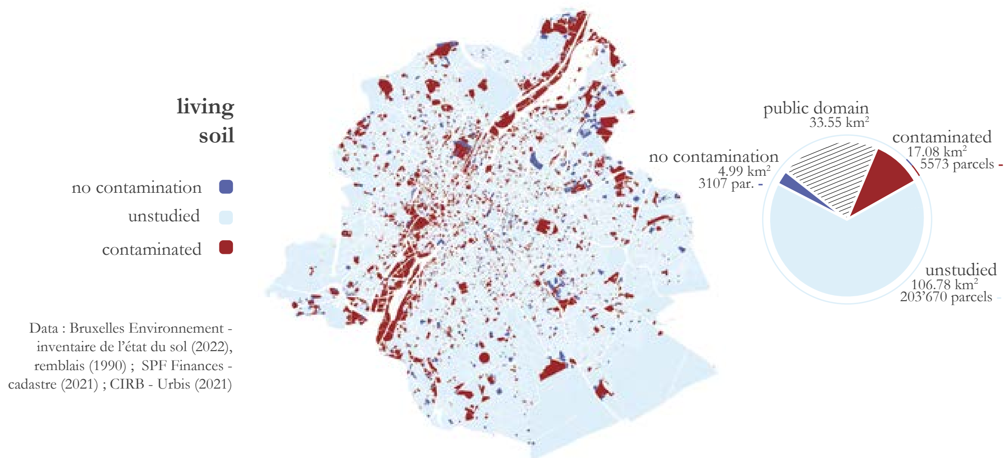
- Category 1 – legal contamination thresholds not exceeded – and
- Category 2 – pollution with no risk – includes studied soils that do not require any specific intervention.
- Category 3 – contamination with potential risks – regroups studied soils with limited possibilities of uses due to contamination. Establishing a vegetable garden may be forbidden, and rainwater infiltration projects limited[79].
- Category 4 – contamination presenting risks – regroups studied soils requiring risk assessment and interventions to mitigate these risks. Similar to category 3, uses and rainwater infiltration possibilities are subject to conditions.

79 Bruxelles Environnement, 2021a

80 Bruxelles Environnement, 2023

Parcels not included in the inventory remain unstudied. They only require observation of the site to identify potential contamination sources such as an oil tank or a stock of chemicals.

Based on these data, this study proposes reclassification according to soil contamination [figure 4]: (1) No contamination includes categories 1 and 2, where contamination is not detected or does not represent any risk ; (2) Unstudied includes category 0 and parcels out of the soil condition inventory ; (3) Contaminated includes categories 3 and 4, where a problematic contamination has been detected.



04 Classification of living soil in the Brussels-Capital Region

DEEP UNDERGROUND AND INTERFERENCES

The geological structure of the Brussels-Capital Region has been analyzed using the previously outlined hydrogeological categories - aquifer, aquitard, and aquiclude – along with an assessment of water table levels [figure 5].

This analysis utilized geological data from BruStrati3D datasets[80], which provide detailed models of the geological strata in Brussels and classify them into distinct hydrogeological units. Based on these units, this study identifies the shallower aquiclude or aquitard, marking a barrier to water movement and infiltration. The depth of this barrier to infiltration was computed using a GIS software (QGIS) in a raster file at a resolution of 1m2.

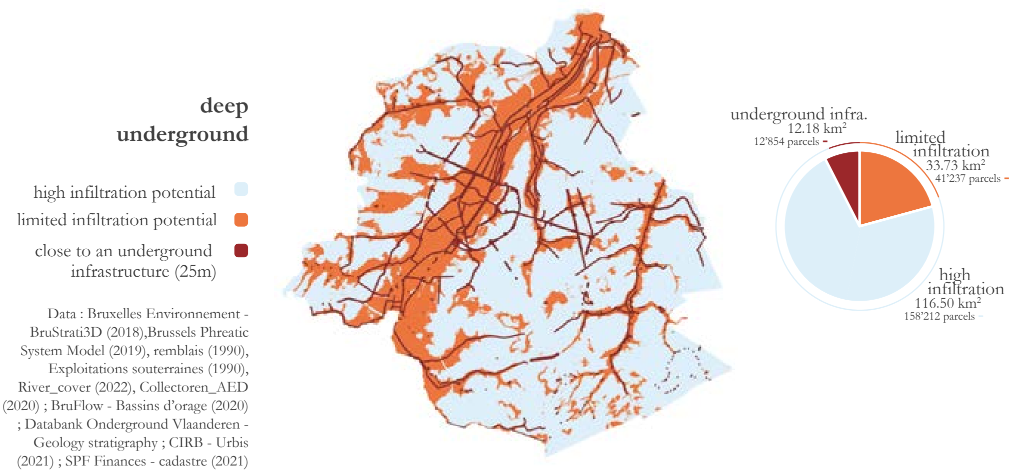
Since the water table also serves as a barrier to infiltration, the framework also incorporates data from the Brussel Phreatic System Model v.1.0[81]. This dataset offers a model of water table depth across the region.

81 Agniel, 2020

Calculating the shallower barrier to infiltration between both geological data and water table data enables the computation of the depth of the first barrier to infiltration. The framework includes topographical data to determine the depth (and the volume) available for water infiltration, thus enabling an assessment of the deep underground infiltration potential. A depth of less than 3 meters before the first barrier to infiltration is classified as having limited infiltration potential, whereas areas with a deeper barrier to infiltration are categorized as having high infiltration potential.

Given that underground infrastructures can significantly disrupt water infiltration and alter underground water flows, this framework includes data on major underground infrastructures, such as tunnels, metro tunnels and stations, main sewage collectors, and underground stormwater tanks, collected from various sources, as detailed in figure 5. A GIS operation generated a 25-meter buffer around these infrastructures to highlight areas close to them. The presence of underground infrastructure overrides the computation of the infiltration potential, as these constructions have a negative impact on water infiltration.

It is important to note that the type of data available inherently influences what can be mapped and analyzed. For instance, while a complete map of all underground constructions, including cellars and private underground parking, would be ideal, such detailed data are often unavailable. Therefore, the application of this framework to the case study of the Brussels-Capital Region is also guided by data availability.



05 Classification of deep underground and interferences in the Brussels-Capital Region, based on (Bossard, 2023)

RESULTS

The proposed and analyzed strata – land surface, living soil, and deep underground – are not independent. They exert influence and impact each other, which is exacerbated by interference arising from human constructions. Soil sealing and unsealing reveal these connections, as they disable or re-enable soil functions such as water infiltration, carbon cycling, and biodiversity, which collectively sustain the environment.

REVEALING INTERACTION BETWEEN STRATA

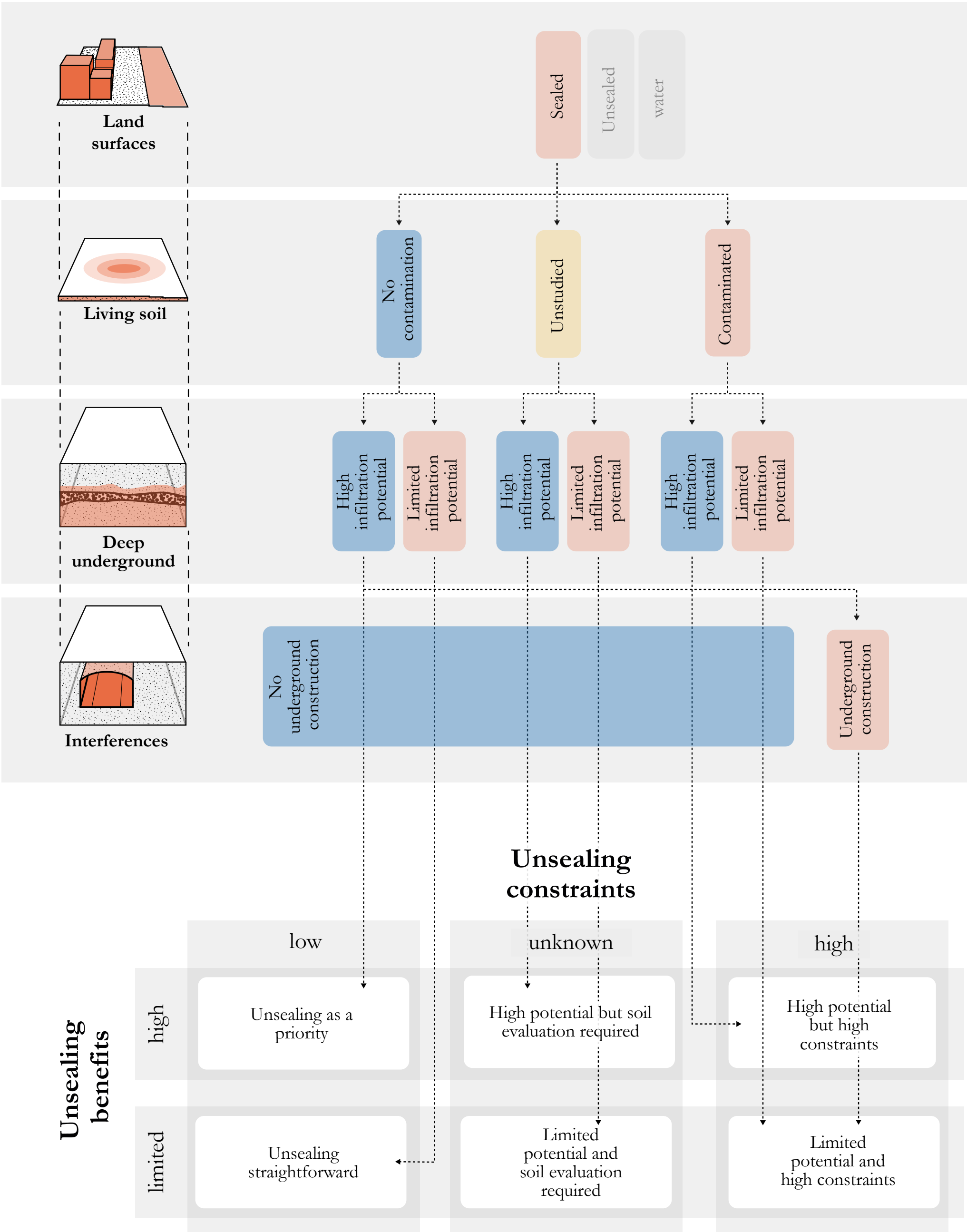
The success of soil unsealing (land surface strata) regarding water infiltration depends on the underlying deep underground and its hydrogeological structure, as a shallow water table or an impermeable geological stratum can significantly reduce infiltration[16]. Moreover, soil unsealing may require prior remediation to prevent exposure to pollutants and manage the risk of contaminant dispersion. As water is the primary vector of contaminant transport[82], a permeable soil exacerbates the spread of contaminants. Particularly in cities with a significant industrial legacy, such as Brussels, permeable soils enable widespread contamination, posing a substantial risk.

Permeable geological strata also facilitate the deeper dispersion of contaminants[21, 83, 84] and; in contrast, impermeable clay strata are used as a barrier to contaminants' movements[82].

To systematize the complex interactions between land surface, living soil, deep underground, and interferences from underground infrastructure, this work proposes a diagram [figure 6, top] presenting combinations of the previously discussed classification of these strata. Each combination results in an evaluation of the unsealing benefits and constraints, summarized in a two-entry table [figure 6, bottom].

Unsealing benefits are assessed according to the characteristics of the deep underground, including the (hydro)geological system and the presence of underground infrastructures. This model provides insights into the potential of water infiltration unlocked by soil unsealing. On the other hand, unsealing constraints are evaluated considering soil contamination and the presence of major underground infrastructures. This assessment provides information on the likelihood of encountering contamination and the necessary intervention in case of known contamination, as well as the challenges that could arise from the proximity of underground infrastructures.

82 Yong et al., 1992, pp. 131; 143; p. 203
83 Foster et al., 2013
84 Palmer & Lewis, 1998



06 Categorization of the different combinations of land surface, living soil, deep underground and interferences into a two-entry table.

SOIL CATEGORIZATION AS A TOOL FOR URBAN PLANNING

The diagram and the two-entry table [figure 6] identify typologies of urban areas for soil unsealing in the Brussels Capital Region. This research spatially mapped these typologies by integrating the previously described datasets: land surface, living soil, deep underground, and interferences. Each unique combination of datasets at the parcel level corresponded to one of the six typologies illustrated in the two-entry table [figure 6]. The resulting spatial distribution of these typologies is presented in [figure 7], with two typologies examined in greater detail, each supported by representative site examples.

The first typology results from the combination of soils with a high infiltration potential and low or moderate unsealing constraints [figure 7, top illustration and in blue on the map]. Unsealing this area could play a significant role in improving urban water cycle because its underground structure is highly permeable, free from major underground infrastructures and able to store large quantities of water. Furthermore, these highlighted areas are not contaminated, lowering the unsealing constraints and reducing the risk of negative consequences of unsealing, like contaminant dispersion. From a soil-sensitive urban transformation perspective, and more generally from an ecological planning perspective, soil unsealing should be prioritized in this area, given that it could drastically improve the soil ecosystem function of water cycle regulation.

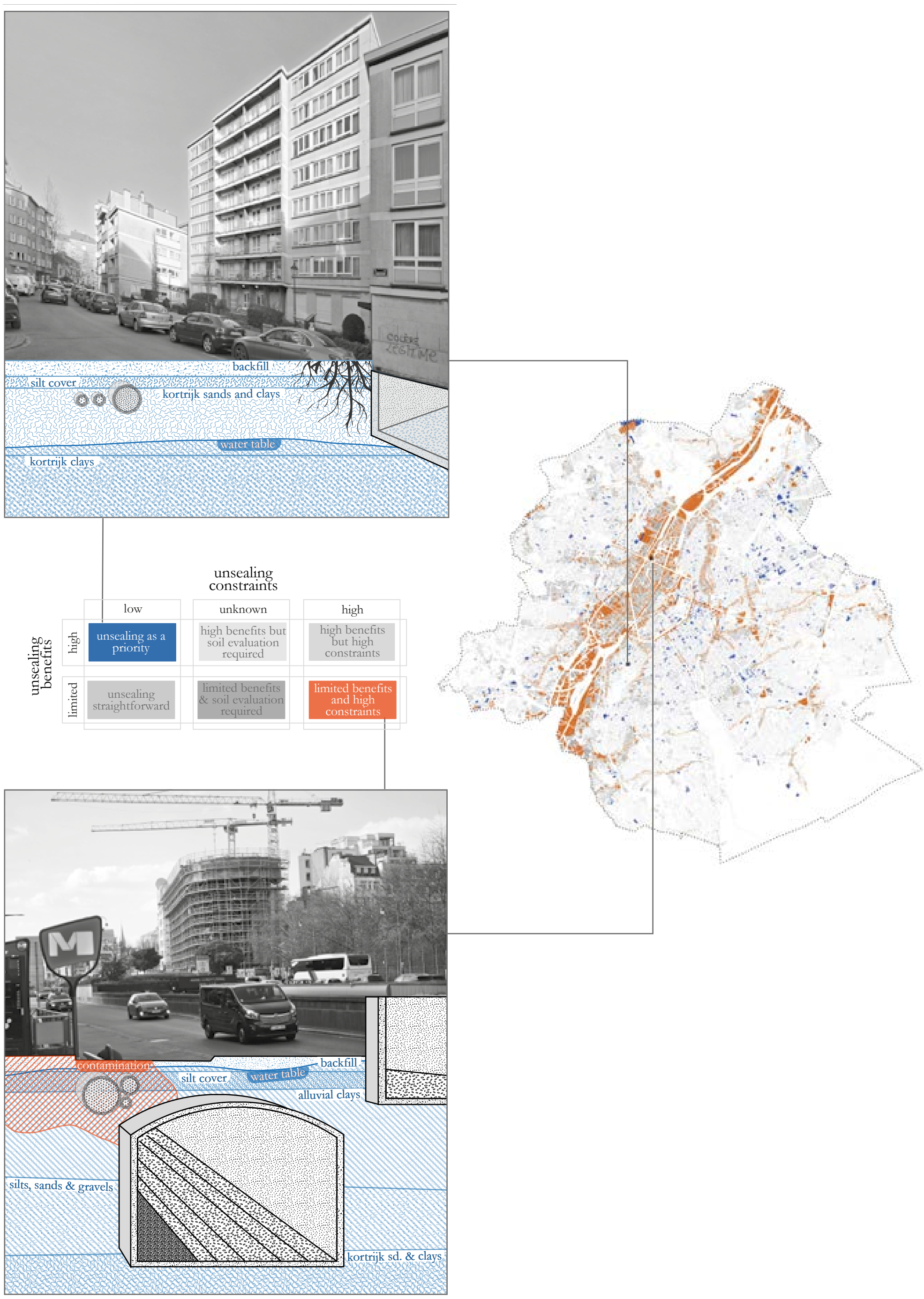
On the other hand, areas close to major underground infrastructures or locations where contamination risks are high present higher unsealing constraints. Therefore, soil remediation could be required, and an evaluation of the impact of an increased water infiltration on underground infrastructures could be necessary. In addition, the highlighted areas [figure 7, bottom illustration and in orange on the map] are composed of geological strata with low permeability and low water storage capacity, due to the shallow water table and/or a clay stratum (aquiclude), or are located near a main underground infrastructure compromising water infiltration. These high unsealing constraints and the low potential of infiltration in these areas make alternatives to soil unsealing more interesting. The preservation of existing constructions and activities could be prioritized in these areas, as well as the creation of green infrastructures that maintains the existing soil sealing. It is also interesting to note that these areas geographically occur in between river ridges or "valleys", where the less permeable clay strata together with the historical presence of industries, makes for subsequent higher risk of contamination.

While these constraints highlight the complexity of unsealing in high-risk areas, they must be balanced with broader findings from case studies; for example, Swiss research[85] has demonstrated that unsealing and soil restoration—when carefully implemented—can still deliver significant benefits for both ecosystems and communities.. However, the effectiveness of these practices can also be constrained by subsoil compaction and permeability issues, which may limit soil functionality. Additionally, maintaining continuity in unsealed areas is crucial for enhancing connectivity and optimizing the performance of ecosystem services, which are highly dependent on the specific soil conditions of each location[85]. Research on unsealing practices in France has further emphasized the importance of comprehensive soil characterization prior to unsealing, as well as monitoring. These measures are essential for achieving the desired ecological and hydrological outcomes[86].

Although the proposed model prioritizes unsealing in areas with high infiltration potential and low unsealing constraints to enhance water cycle regulation, it is also important to recognize broader soil ecosystem functions eased by soil unsealing, as outlined in the introduction of this paper. These functions can also significantly contribute to urban planning and design processes. This model deliberately distances itself from leveraging development as a revenue model for enabling remediation due to several considerations. Remediation efforts, while beneficial for long-term soil health, can be energy-intensive, leading to significant greenhouse

85 Tobias et al., 2018
86 Vieillard et al., 2024

gas emissions. In addition, they may cause immediate ecological disruptions and incur substantial costs. By focusing on healthier soils, the model ensures that unsealing efforts yield immediate ecological benefits, without the added complexity and potential risks associated with contaminated sites. This approach does not preclude future expansions of the model to include strategies for remediation and development in contaminated areas. However, it underscores the necessity for careful consideration of the trade-offs and additional evaluations required for such interventions.



07 Classification of the soil of Brussels Capitale Region based on interaction between strata. At the top, no contamination and high infiltration potential due to a deep water table and no shallow aquiclude (247 Chaussée de Forest, 1190 Forest). At the bottom, unsealing benefits are limited because of a shallow water table and a clay stratum that restricts infiltration, along with high constraints due to contamination and underground constructions (Bd d'Anvers 47, 1000 Bruxelles). On the right, the map highlights the parcels of both categories: in blue, those with high unsealing benefits and low constraints, and in orange, those with limited benefits and high constraints.

CONCLUSION

This study presents a comprehensive framework for assessing soil thickness within urban environments, emphasizing the importance of a three-dimensional and multidisciplinary approach to urban soil management. By dissecting the soil system into three distinct strata—land surface, living soil, and deep underground—and analyzing their interactions, this framework facilitates a soil-sensitive approach to urban planning and design. The proposed methodology not only highlights the critical role of soil in urban ecosystems but also underscores the necessity of considering underground and ground spaces as equally important in urban transformation processes.

The question of soil unsealing is complex and must be addressed on a case-specific basis. In some instances, the benefits of unsealing may be outweighed by significant constraints, such as the need for costly and high-emission remediation processes or minimal benefits for water infiltration and regulation. Therefore, policies must be tailored to specific sites, considering the unique characteristics and constraints of each location. Land surface regulations should be informed by the underlying strata and the requirements for minimum unsealing should be adjusted based on the potential benefits and constraints of soil unsealing. Areas where unsealing could play a crucial role in enhancing soil's water regulation function and where constraints are low should be prioritized.

While this framework was tested on the Brussels-Capital Region, its principles are applicable to other urban contexts. However, adaptation to local conditions and specific problems is essential for effective implementation. Interpreting the results of the analysis within the local context ensures that the framework is both relevant and actionable.

Further research is needed to deepen our understanding of urban soils, which remain largely unknown due to their heterogeneity and composition, primarily of backfill materials. Studying these soils in greater detail, including their formation and transformation, could refine this analysis and provide more precise insights. This deeper understanding would enable a transition from large-scale models to more site-specific analyses, addressing questions such as the presence of backfill, its depth, origins, and the historical activities that may have affected soil contamination and other characteristics.

Integrating soil considerations into urban planning is not only feasible but also essential for sustainable urban development. By adopting a nuanced, site-specific approach, urban planners and designers can optimize the ecological benefits of soil transformations while minimizing potential drawbacks, thereby fostering more resilient and sustainable urban environments.

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FIGURE REFERENCES

Figure 1: The proposed framework consists of three primary strata and one additional transversal stratum: land surface (top left); living soil (middle left); deep underground (bottom left), as well as an additional stratum of 'interferences' (right).

Figure 2: Composition of each strata, illustrating the elements and disciplinary terms used. Based on the classifications described in (Bruxelles Environnement, 2020a; Cohen et al., 2022; IUSS Working Group WRB, 2022; Peeters, 2010)

Figure 3: Classification of land surfaces in the Brussels-Capital Region, based on (Bossard, 2023)

Figure 4: Classification of living soil in the Brussels-Capital Region

Figure 5: Classification of deep underground and interferences in the Brussels-Capital Region, based on (Bossard, 2023)

Figure 6: Categorization of the different combinations of land surface, living soil, deep underground and interferences into a two-entry table.

Figure 7: Classification of the soil of Brussels Capitale Region based on interaction between strata. At the top, no contamination and high infiltration potential due to a deep-water table and no shallow aquiclude (247 Chaussée de Forest, 1190 Forest). At the bottom, unsealing benefits are limited because of a shallow water table and a clay stratum that restricts infiltration, along with high constraints due to contamination and underground constructions (Bd d'Anvers 40, 1000 Bruxelles). On the right, the map highlights the parcels of both categories: in blue, those with high unsealing benefits and low constraints, and in orange, those with limited benefits and high constraints.

JDU
Journal of Delta Urbanism

JDU is a project by Delta Urbanism Research Group
and DIMI Delft Deltas, Infrastructure and Mobility Initiative
Delft University of Technology

Graphic Layout
bruno, Venice (Italy)

Typefaces
Union, Radim Peško, 2006
JJannon, François Rappo, 2019

TU Delft OPEN Publishing

Publisher
TU Delft OPEN Publishing
https://www.tudelft.nl/library/openpublishing

Frequency: 1 volume per year

Publication Funding
TUDelft Delta, Infrastructure and Mobility Initiative

Contacts
For any further information:
delta-urbanism@tudelft.nl
https://journals.open.tudelft.nl/jdu/
www.deltaurbanism.org

N.6 | Depletion | Practice | 01
Winter / Spring 2026

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Keywords
Urban soil; Unsealing; Thick soil; Land surface; Living soil; Deep underground

Dates
Submitted: 10/06/2025
Reviewed: 03/09/2025
Accepted: 09/09/2025
Published: 22/12/2025

Citation
Bossard, A., & Cavalieri, C. (2025). Assessing urban soil unsealing constraints and potential for water regulation: a framework and case study of Brussels-Capital Region. *Journal of Delta Urbanism*, (6). 10.59490/jdu.6.2025.8216

Reviewed by
Teodora Todorcic Vekic, Chalmers University of Technology
Laura Thomas, Delft University of Technology
All published contributions are submitted to a Double Blind Peer Review process except for the sections Dialogues and Dictionary.

Funding Information
A significant portion of the research presented in this article was conducted within the '3Dcit-is' research project (Université Catholique de Louvain, 2021–2023), supported by Innoviris through its 'Joint R&D Projects' funding program. A minor part of the work also benefited from the ongoing 'Archisols' project (Université Libre de Bruxelles), funded by Innoviris under the 'Co-create' program.

Data Acess Statement
The geographic data used in this study are sourced from public, open-access repositories, with each data source cited alongside the corresponding map. While the raw data are freely available, the processed data generated during this study are available from the corresponding author upon reasonable request.

COI
There is no conflict of interest

Contributor Statement
Alexandre Bossard developed the methodology (under Chiara Cavalieri's supervision), conducted the investigation, gathered and processed the data, created the figures, and co-wrote the manuscript. Chiara Cavalieri provided supervision, secured funding for the research, guided the conceptual orientation of the study, and co-wrote the manuscript.

Use of AI
During the preparation of this manuscript, the authors used Le Chat (Mistral AI) as a writing assistant, primarily to correct English spelling, grammar, and improve clarity. All substantive content, analysis, and interpretations were conducted by the authors.

ISSN: 2666-7851
p-ISSN 2667-3487