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Mapping the intrinsic potential of water infiltration in urban subsurface: feedback from France

Mappatura del potenziale intrinseco di infiltrazione d'acqua nel sottosuolo urbano: feedback dalla Francia

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Riassunto

In un contesto di urbanizzazione crescente, con significativa impermeabilizzazione del suolo, and con l'aumento di eventi meteorici estremi, la gestione delle acque piovane nelle aree urbane sta diventando un tema di importanza primaria. Al fine di migliorare la gestione delle risorse idriche e di prevenire allagamenti di aree urbane, sempre più città stanno implementando, o già lo hanno fatto, sistemi di infiltrazione delle acque.

L'infiltrazione delle acque meteoriche non è possibile ovunque per ragioni naturali e/o antropiche. In questo quadro, il potenziale intrinseco di infiltrazione del sottosuolo è un parametro naturale chiave. Sono necessarie mappe per costruire strategie territoriali. In Francia sono disponibili molti studi ma non esiste un quadro metodologico nazionale per mappare questo parametro. Nel presente articolo, analizziamo diversi studi sviluppati in Francia per questa mappatura e compariamo i metodi con esempi raccolti da altre nazioni.

Molti degli studi francesi accoppiano un'analisi multi-criterio (MCA) ad un'analisi spaziale attraverso Sistemi Informativi Geografici (GIS). I criteri includono parametri geologici, idrogeologici e geomorfologici. Il metodo PHOEBUS sviluppato sulla metropoli di Rennes sembra essere il più rilevante e replicabile, per arrivare ad un quadro metodologico comune a scala nazionale. Esso considera 7 criteri, tra cui la permeabilità della roccia/suolo, la pendenza topografica e lo spessore della zona insatura.

Le mappe ricavate possono essere utilizzate direttamente o integrate con le mappe delle superfici impermeabilizzate, o incrociate con altri criteri associati all'ambiente urbano (ad esempio superfici impermeabili, inquinamenti del sottosuolo, isole di calore). Esse vanno a costituire uno strumento di supporto ai processi decisionali per la pianificazione urbana. In particolare, sono utili per migliorare la gestione delle acque piovane, ma anche per l'elaborazione di strategie di de-impermeabilizzazione o rinaturalizzazione. Infine sembra essenziale agire d'intesa con i portatori di interesse locali per identificare i loro bisogni e le specificità del territorio.

Abstract

In a context of increasing urbanization, with strong soil sealing, and with an increase in extreme weather events, the management of rainwater in urban areas is becoming a major issue. In order to improve water resource management and to prevent urban floods, more and more cities are considering or already implementing water infiltration systems.

Infiltration of water is not possible anywhere due to natural and/or anthropic reasons. In this frame, the intrinsic infiltration capacity of the subsurface is one key natural parameter. Global maps are needed to build territorial strategies. In France, a lot of studies are available but a national methodological framework for mapping this index does not exist. In this paper, we analyse various studies carried out in France for such mapping and compare the methods with examples in other countries.

Most of the French studies combine a Multi-Criteria Analysis (MCA) and a Geographic Information System (GIS) spatial analysis. The criteria include geological, hydrogeological and geomorphological parameters. The PHOEBUS method developed on Rennes Metropolis seems the most relevant and replicable one to provide a common framework at French scale. It takes into account 7 criteria, including rock/soil permeability, topographic slope and thickness of the unsaturated zone.

The obtained maps may be used as such, modified by integrating sealed surfaces or crossed with other criteria linked to the urban environment (e.g. sealed surfaces, soil pollution, heat islands). They provide a decision support tool for urban planning. In particular, they are useful to improve rainwater management, but also in the elaboration of desealing or renaturation strategies. It seems essential to act in concertation with local stakeholders to identify their needs and the specificities of the territory.

Introduction

In a context of climate change and urban population growth, cities need to adapt. Many cities are concerned by the scarcity and degradation of the water resources but also by the evolution of the rain regime. In particular, extreme events become more frequent. Heavier raining events exacerbate flooding due to rainwater flow that pipes are unable to manage. Infiltration of rainwater is a solution to regulate the water flow and limit floods. In this frame, one of the major challenges for land managers in urban areas is to propose optimal territorial strategies allowing together optimising water resource management and limiting risks linked to heavier rainwater events (e.g. floods).

In this context, for several years, there is an evolution of rainwater management in cities (Fletcher et al., 2015). The "all pipes" management system primarily focused on sanitary aspects (health protection) and flood mitigation. It occurred together with the sealing of urban soils, which facilitated travels by avoiding muddy roads and reduced dust in the air (Prézeau et al, 2024). Awareness has arisen on the disadvantages of too much soil sealing and "all pipes" systems. Indeed, it increased floods due to rainwater runoff and heat islands, and reduced biodiversity. Infiltrating rainwater in urban soils appears as a solution to limit the effects of climate change, by recovering the full water cycle. The concept of "permeable city" (Grand Lyon, 2017), at all scales, from the plot to the major water cycle, is more and more widespread. Several French urban planning documents force to infiltrate rainwater in soils in case of new building or redevelopment (e.g. Nantes Metropolis PLUi, 2019). Various, nevertheless close, concepts were developed worldwide like "Sustainable Drainage System" in United Kingdom, "Best Management Practice", and "Low Impact Development" (LID) in the United States and New Zealand or "Water Sensitive City" in Australia (Fletcher et al., 2015; Chui et al., 2016; Mao et al., 2017). China developed the concept of Sponge city, based on facilities such as waterways, sunken rain garden or green spaces to control stormwater runoff by accumulation, infiltration, natural purification, slow release and possible reuse (Wang et al., 2022). 30 Chinese pilot cities are experimenting this concept (Chikhi et al., 2023).

Moreover, rainwater is no longer just seen as a risk, it is now considered as a resource that can contribute to the resilience of territories (Ashley et al., 2013). In this frame, desealing is a way to adapt to global change. It allows preventing urban floods by reducing surface runoff, improving groundwater recharge, bringing biodiversity to the city when nature based solutions are implemented or fighting against urban heat islands (Prézeau et al., 2024). Nevertheless, it may also present disadvantages. The following questions arise thus: What are benefits and risks of water infiltration? Where is it more relevant to infiltrate? This question is key to build appropriate territorial water infiltration strategies.

Many solutions exist to infiltrate rainwater in soils: ponds, raingarden, paved areas, etc. Infiltration is however not relevant anywhere in the urban environment due to natural and/or anthropic reasons. In this frame, maps are useful decision aid tools. A spatial knowledge of the factors favorable or unfavorable to water infiltration are necessary. Among the natural factors are the intrinsic capacity of the unsaturated zone to infiltrate water, as well as environmental constraints like the presence of soluble rocks or the risk of groundwater table rise, etc (Prézeau et al., 2024). Soil pollution or constraints linked to the urban fabric (like sealed surfaces and some large underground infrastructure) belong to anthropic factors,

In this paper, we focus on the determination of the intrinsic capacity of rainwater infiltration of the unsaturated zone in the urban zone (from soil to groundwater table), which is a key criteria and becomes a real need for cities or wider territories (Fletcher et al., 2015). The aim of this paper is to question the methodologies used to produce such maps. Our analysis is based on a non-exhaustive French feedback of mapping the intrinsic potential of water infiltration in urban soils and unsaturated zone and on a comparison to some international studies.

The why and how of mapping intrinsic water infiltration capacity of urban soils

In France, rainwater management is a responsibility of communities of municipalities through urban rainwater management, water and sanitation as well as land use planning. We observe an increasing number of studies producing maps of the intrinsic potential of water infiltration in the urban subsurface. It appears as a major issue in urban planning, for different uses: rainwater management, desealing strategies, groundwater recharge, reuse.

Fletcher et al. (2015) shows that terminology describing the principles of urban drainage has become increasingly diverse which can generate confusion or misunderstanding. Indeed different terminologies are used in French studies:

- infiltration capacity,
- aptitude (of soils) for infiltration,
- infiltrability,
- potential for infiltration,
- infiltration possibilities,
- potential for infiltrability,
- infiltration potentiality.

A detailed definition of these terms is rarely given but it appears that they all designate the same phenomenon: the ability of the subsurface (approximately < 10 m deep, depending on the thickness of the unsaturated zone) to allow infiltration of rainwater without causing disorders on the facilities, the environment and the uses of concerned territories, respecting some constraints. We choose to use mainly the term "subsurface intrinsic potential of water infiltration" throughout this paper. The term infiltration capacity is also used synonymously.

CEREMA (French centre for studies on risks, environment, mobility and urban planning) published a guide of stormwater zoning which describes the need to map the natural soil infiltration capacities (CEREMA, 2020). One of the most suitable method to develop this infiltration capacity map combines a Multi-Criteria Analysis (MCA) and a spatial analysis. MCA is based on the principle of classification and weighting of different parameters. The spatial analysis combines the interpreted parameters thanks to a Geographic Information System (GIS).

The MUSE project led by CEREMA in collaboration with other organizations (INRAE: French research institute for agriculture, food and the environment, IRSTV: French research centre on urban science and technologies, BRGM: French geological survey, Aix-Marseille University, CEREGE: French research and teaching centre environmental geosciences, Chamber of Agriculture of Indre), aims to take into account the multifunctionality of soils in urban planning documents. The term multifunctionality is used to define all the ecological functions that a soil can perform (biomass production, regulation of the water cycle, carbon storage, reservoir of soil biodiversity…). The MUSE project offers a method partially based on a MCA (Branchu et al., 2021) to map the capacity of soils to infiltrate water. French soil typology distinguishes Soil Mapping Units (SMU) – portions of the soil cover which presents common characteristics in terms of landscape and soil distribution and which represents spatial extension of one or more soil types – and sub-units called Soil Typological Units (STU). Each SMU is characterized by a grouping of one or several STU, in order to be able to make a cartographic representation at 1:250,000 scale. In the MUSE project, scores are assigned to the criteria used to describe the STU (soil thickness, texture, organic matter content…). A SMU can contain one or several STU presenting different agronomic potential modalities, there is therefore a need to aggregate the information to represent a single modality per SMU. One of the particularities of the MUSE method lies in the fact that for each SMU, the percentages of STU presenting the same score are summed, and the score whose percentage is the largest in the SMU is retained as the value for the SMU.

Other methods are based on:

– modeling rainwater management scenarios (Bonneau et al., 2022) ;
– accumulation of informations (Belbeze, 2022), a method close to MCA;
– remote sensing based on SPOT satellite imagery (Dornier et al., 2001, Desprats & Dutartre, 1994).

In 2016, CEREMA identified almost thirty French territories having soil suitability maps for rainwater infiltration (Vallin et al., 2016). These may be cities or urban territories like Lyon Metropolis (Vallin et al., 2016), Strasbourg (Petter, 2013; Urban, 2011), Nantes Metropolis (Conil & Plat, 2015) or Bordeaux Metropolis (Pierlot et al., 2016), watersheds such as Hérault watershed (Dornier et al., 2001) or even departments like Hauts-de-Seine (Pierlot et al., 2011) in the Ile-de-France Region. These maps were developed with varied methodologies, adapted to specificities and needs of the territories (e.g. variable territorial context and size of territory, more or less highly urbanized areas, sectors subject to significant flooding risks, issues regarding water resources), with different aims (e.g. support rainwater management policy, aid to decision-making, capitalize on knowledge, for internal or external use). Since 2016, several other French cities have adopted such maps: Rennes Metropolis (Pinson et al., 2019), Libourne and Angoulême (Bouvard, 2021) and Toulouse (Belbeze, 2022). Most of these studies result in a map of potential of water infiltration based on MCA (Fig.1).

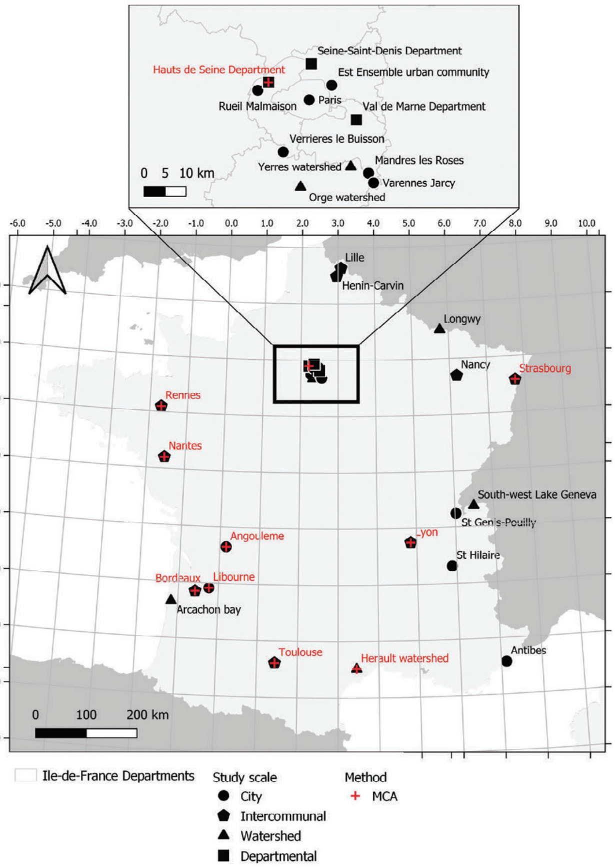

Fig. 1 - Location of the main intrinsic potential of water infiltration maps listed in France and focus on MCA method (when described) - modified from Vallin et al., 2016.

Fig. 1 - Ubicazione delle principali carte di potenziale intrinseco di infiltrazione elaborate in Francia ed indicazione di quelle elaborate con metodo multicriterio (MCA) - modificato da Vallin et al., 2016.

There are different scales of implementation of these studies but most of the maps of intrinsic potential of water infiltration consulted have a restitution scale close to 1/50,000 and are carried out at large urban area or department of reduced extent. They provide a global vision of the infiltration capacity of subsurface (soil or unsaturated zone) in an area, but cannot replace the permeability measurements requested before construction.

In these different studies, different criteria are taken into account in the MCA to build the infiltrability map but some of them, including geological, hydrogeological and geomorphological criteria, are common to almost all studies (Table 1): soil and/or rock permeability (ability of the environment to allow water to pass through), thickness of unsaturated zone (USZ - which gives an indication of the depth of the groundwater table), topographic slopes, lithology (nature of rocks), soils characteristics, etc. Some additional

Tab. 1 - Criteria used for the multi-criteria analysis of soil and/or subsurface intrinsic potential of water infiltration (IDPR : Surficial water Network Development and Persistence Index).

Tab. 1 - Criteri utilizzati per l'analisi multicriterio del potenziale intrinseco di infiltrazione del sottosuolo (IDPR: indice di sviluppo e persistenza delle reti di acque superficiali).

Study area	Soil/rock permeability	Unsaturated zone thickness	Topographic slopes	Rocks/soil characteristics	IDPR	Impermeable bedrock hanging wall
Hérault watershed				X (translated to infiltration class)		
Libourne	X					
Angoulême	X					
Strasbourg urban community (2013)	X	X (highest 100-year waters)				
Strasbourg urban community (2011)	X	X				
Rennes Metropolis	X	X	X	(X soil)	X	
Lyon Metropolis	X	X	X	(X soil)		
Bordeaux Metropolis (2016)			X	X		
Bordeaux Metropolis (2024)	X	X	X	X (storage coefficient by lithology)	X	X
Hauts-de-Seine Department	X		X			
Nantes Metropolis		X	X	X	X	
CEREMA Guide "stormwater zoning"		X		X		
Toulouse	X	?	X		X	
MUSE	X (pedotransfer function)			X (texture)		X

data, such as natural and regulatory constraints or linked to urban activities are considered to lower MCA score in some areas where infiltration needs to be avoided (Table 2): polluted soils, drinking water protection areas, presence of cavities or instabilities, swelling and shrinkage hazard of clayed soil, cemeteries, etc.

The intrinsic potential of water infiltration does not take into account the constraints linked to the urban environment. When the map is delivered as such, map users are alerted to the importance of taking into account these additional criteria. The combination between map of the intrinsic potential, which is a basic property, and additional data linked to the urban environment often only occur in a second step

Many maps involve "expert say". To avoid this as much as possible, field investigations are recommended in order to acquire additional data, in particular:

– piezometric campaign (groundwater table level measurement) to precisely map the thickness of the unsaturated zone (sometimes difficult to implement in an urban environment due to urbanization);
– permeability test of soils (double ring infiltrometer or constant load permeability test);
– pumping test (aquifer permeability, which includes the unsaturated zone);
– plot pedological description (~1/10,000) over a depth of 0-1 m or even 0-2 m.

Focus on the PHOEBUS method on Rennes Metropole

Among these studies, the PHOEBUS method (Depth of hydrogeological entities and assessment of constraints to infiltration of urban rainwater in the territory of Rennes Metropolis) carried out for Rennes Metropolis by BRGM (Pinson et al., 2019) seems the most relevant one, for the following reasons:

– the method used is based on a MCA which explicitly takes into account the three criteria most often used: soil/rock permeability, thickness of the unsaturated zone and topographic slopes;
– soil characteristics are taken into account implicitly since the IDPR (Surficial Water Network Development and Persistence Index, Mardhel et al., 2021) values are averaged within functional units which are defined on the basis of the contours of the geological, hydrological and soil units;
– the methodology, reproducible within other territories of comparable scale, is precisely and exhaustively described in a study report available online (Pinson et al., 2019).

In order to map the intrinsic potential of rainwater infiltration, the PHOEBUS method is based on a multi-criteria analysis of the following seven criteria (Fig. 2):

– thickness of the unsaturated zone, calculated by the difference between a Digital Elevation Model (DEM) and the water table altitude grid at 25 m intervals (from a piezometric campaign in high water);

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Tab. 2 - Additional data downgrading multicriteria analysis (MCA) score of soil and/or subsurface potential of water infiltration.

Tab. 2 - Dati integrativi per abbassare il punteggio del potenziale intrinseco di infiltrazione ottenuto dall'analisi multicriterio.

Study area	Polluted soils zoning	Water protection perimeters	Cavities, instabilities	Presence of clay	Hydro-morphism	Environmental constraints	Endorheic zones	Land use	Embank-ments	Low points	Risk of groundwater table rise	Presence of wetland
Hérault watershed								X (Type of crops)				
Libourne						X						
Angoulême						X						
Strasbourg urban community (2013)						X						
Strasbourg urban community (2011)									X	X		
Rennes Metropolis				X	X		X					
Lyon Metropolis		X										
Bordeaux Metropolis (2016)	X	X	X								X	
Bordeaux Metropolis (2024)	X	X				X						
Hauts-de-Seine Department	X	X	X	X								
Nantes Metropolis		X	(X)	X	X							X
CEREMA Guide "stormwater zoning"			X									
Toulouse	X						X					
MUSE					X							

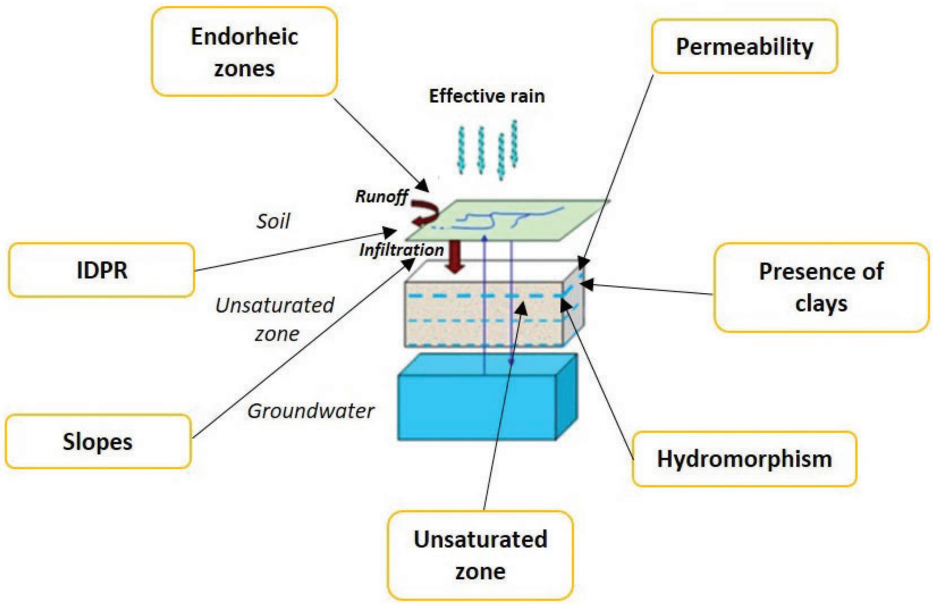

Fig. 2 - Influence of criteria of the MCA on the compartments influencing soil and rock infiltration capacity (unsaturated zone – modified, according to Pinson et al., 2019).

Fig. 2 - Influenza dei criteri della MCA sui compartimenti (suolo, zona insatura, acque sotterranee) che influenzano la capacità di infiltrazione (zona non satura – modificato da Pinson et al., 2019).

- relative soil/rock permeability of pedo-geological units based on rock lithology, soil texture and drainage capacity. Soil texture and drainage capacity are known only on the zones covered by soil maps. In the urban environment, extrapolation was generally possible;
- susceptibility index for the presence of clays, using knowledge from swelling clay maps;
- IDPR: Surficial water Network Development and Persistence Index;
- soil hydromorphism (saturation of soil pores with water over a more or less long period of the year);
- topographic slopes;
- endorheic zones.

These natural criteria were hierarchized according to homogeneous contours (functional units based on hydro-pedo-geological units), making it possible to divide the entire study area into coherent polygons in terms of hydrological and pedological functioning. In this frame, although Rennes metropolis may be mostly classified as a hard-rock groundwater city (La Vigna, 2024), groundwater circulation occurs in the shallow subsurface mainly in more weathered sectors of rock mass, leading to a more or less continuous shallow aquifer.

The IDPR (Surficial water Network Development and Persistence Index), created by BRGM, is a qualitatively approach that describes permeability as areas of infiltration and runoff (Mardhel et al., 2021). It considers the disparity measurements between the theoretical hydrographic network produced by the raw automatic analysis of a digital model and the field reality represented by natural river network. The IDPR is a very integrative criterion, which also takes into account permeability, soil characteristics or presence of clays.

For each parameter, the data of which comes from national or local mapping or specific field investigations, a score varying from 0 to 10 is assigned (Table 3). It reflects the potential of rainwater infiltration: thus a score equal to 0 corresponds to “no infiltration possible” and a score of 10 to “favorable infiltration”. Between these two extremes and depending on the classes of each parameter, one or two intermediate notes can be created, to provide nuance. Before the combinatorial

Tab. 3 - System of scores and weights of infiltrability criteria used in the PHOEBUS method to map the subsurface intrinsic potential of water infiltration (Pinson et al., 2019).

Tab. 3 - Sistema a punteggi e pesi dei criteri di potenziale intrinseco di infiltrazione utilizzati nel metodo PHOEBUS (Pinson et al., 2019).

Infiltrability criteria	Data type	Availability	Score variability	Weights
Unsaturated zone thickness	Grid	Local map or specific high water piezometric campaign	0 / 5 / 10	5
Soil/rock permeability	Polygon	Local point or map data	0 / 2 / 5 / 10	3
Susceptibility index for the presence of clays	Polygon	National map of swelling and shrinkage hazard of clayed soil	0 / 2 / 5 / 10	2
Surficial Water Network Development and Persistence Index (IDPR)	Grid at resolution of 25 m	National map (1/ 50,000)	0 / 2 / 5 / 10	2
Soil hydromorphism	Grid	Local map	0 / 2 / 5 / 10	5
Topographic slopes	Grid	Calculation from DEM	0 / 2 / 5 / 10	2
Endorheic zones	Polygon	Calculation from DEM	0 / 2 / 5 / 10	1

analysis of these criteria, a weight is assigned to each parameter, according to its importance for the evaluation of rainwater infiltration (Table 3).

The spatial combination of the different criteria results in the creation of an infiltration capacity indicator, with a maximum value of 200. In order to be easily usable, this indicator was transformed into four classes characterizing the possibility of infiltrating rainwater: not favorable, quite unfavorable, fairly favorable and favorable. This resulting map can be used at a scale of 1/25,000 (Fig. 3).

It is possible to adapt the criteria according to the data available at the scale of the study area. Moreover, after the spatialization of the criteria retained at the territorial level, the allocation of scores and weights of each criteria can be based on a phase of consultation of territorial stakeholders.

Examples of international studies/methods

Like in France, on an international scale, a growing number of cities acquire rainwater infiltration maps, without specific guidelines (Gerolin et al., 2016). A method to create maps indicating feasible locations for sustainable drainage devices is explained in Warwick et al. (2013), with examples in England. This method is also based on geographical information analysis using a GIS. It takes into account i) environmental factors including geology, soil, topography and groundwater level as well as ii) anthropogenic factors such as groundwater protection next to boreholes, potential sites of groundwater contamination risk, variable factors such as land cover or planning constraints.

In Roma (Italy), the proposed method is based on a MCA with two criteria: the permeability of outcropping lithologies and the water table depth, calculated as the difference between the DEM and the piezometric level (Lentini & Galve Arnedo, 2022). The method is similar to that defined by Warwick et al. (2013) for sustainable drainage at city scale, with the predominance of hydrogeological properties and water table depth. The aim of the study in Roma is to identify areas suitable for the application of Sustainable Drainage Systems and Managed Aquifer Recharge. Five classes have been identified for the permeability and six classes for the water

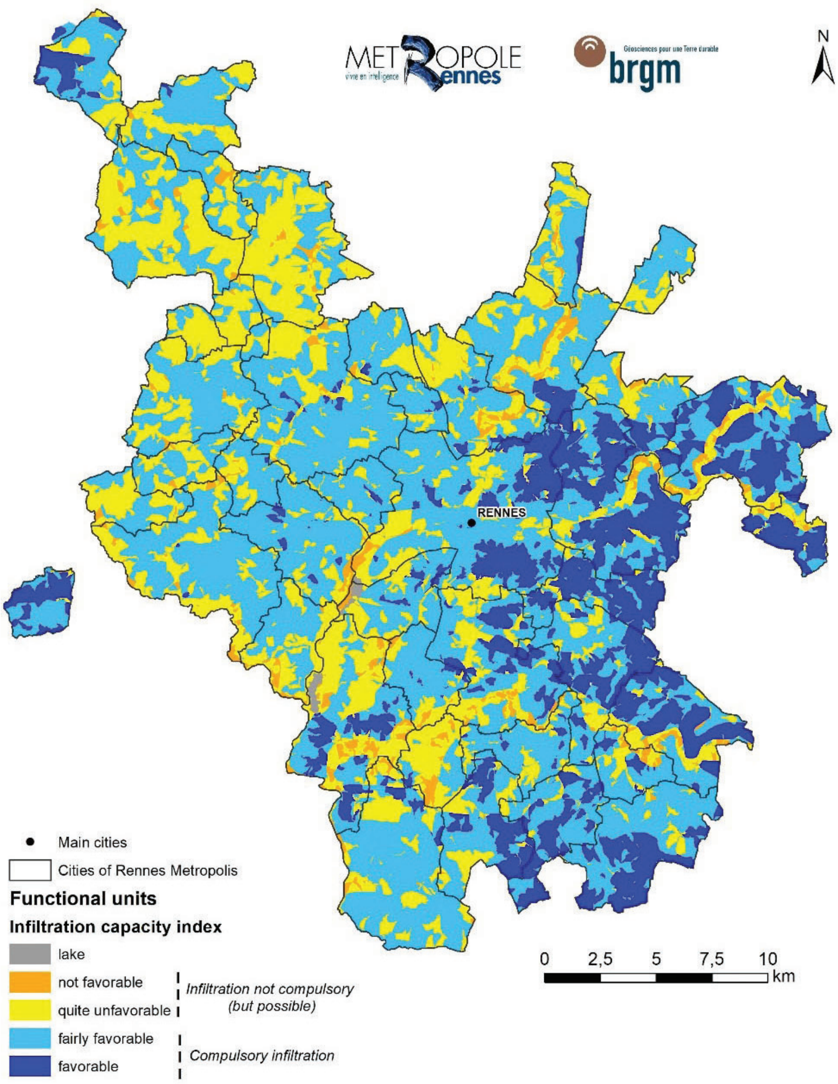

Fig. 3 - Infiltration capacity index to map the subsurface intrinsic potential of rainwater infiltration in the territory of Rennes Metropolis (Pinson et al., 2019).

Fig. 3 - Carta dell'indice di infiltrazione potenziale delle acque piovane nel sottosuolo sul territorio metropolitano di Rennes (Pinson et al., 2019).

table level. The same weight is given to the two parameters to reduce subjectivity.

In Renens (Switzerland), the desealing potential was also calculated with a MCA based on four criteria, quite similar to the criteria used in French studies: thickness of the unsaturated zone, rock permeability, depth of hard rock and slope (Poyat, 2021). The first two parameters were evaluated thanks to geological surveys. Polluted sites were also taken into account in this analysis because water infiltration is prohibited in these areas. Two legends are available for the desealing potential map: a simplified one with 5 classes, for a quick reading and a complete one, with 18 classes, for an in-depth understanding thanks to the distinction of all combinations of criteria.

On a larger scale, in Occidental Lebanon (5,000 km²), Shaban et al. (2006) produced a map of qualitative assessments of recharge potential. The factors which contribute to recharge potential (lineaments and drainage frequency density, lithologiy, kartstic domains and land use) were determined with remote sensing application and then integrated in a GIS (Shaban et al., 2006). Topographic and geologic maps (1/50,000 scale) were also taken into account and they carried out a field verification on several sites.

Kwicklis et al. (2005) provided an infiltration map for the Los Alamos area, New Mexico based on a combination of techniques: Richards equation (which describes water transfer in unsaturated soils), chloride mass-balance method and numerical modeling. In the areas the infiltration rate can not be calculated, it was extrapolated thanks to maps of environmental variables (topography, geology, land cover).

Discussion

The Phoebus method, developed for Rennes Metropolis, appears as one of the most complete method applicable in France: it is based on a MCA which takes into account the main three spatialized criteria generally used for this kind of maps (soil/rock permeability, thickness of the unsaturated zone and topographic slopes) as well as additional criteria (soil hydromorphism, presence of clays, Surficial Water Network Development and Persistence Index and endorheic zones). This method is transposable to other areas, provided that the necessary data is available. Indeed some data exists on a national scale (IDPR, DEM used to calculate topographic slopes) but others are local, such as points/map of soil/rock permeability, or require field investigations (groundwater level to calculate the thickness of the unsaturated zone), which can be time-consuming and expensive. An alternative is to use available and representative piezometric levels during period of high water, which is the most unfavourable condition for infiltrating rainwater (Barrière et al., 2024). However there are sometimes few piezometric measurements available in urban areas, it is therefore necessary to acquire additional field data in areas with little information.

Moreover, the scale of restitution of potential infiltration maps may be limited by the availability of soils map: this map is available nationally (1/250,000) in France but, on the contrary to geological maps (available nationally at 1/50,000), it does not exist in urban areas. The scale of the geological maps and of the national grid of IDPR are not sufficient in urban areas. For this latter, a specific calculation with a high resolution DEM is recommended. For geological and soil maps, a 1/10 000 resolution would be relevant.

The Phoebus method explores the intrinsic infiltration capacity of the unsaturated zone. The map itself (Fig. 3) may be used in planning documents to help decision for rainwater management or managed groundwater recharge. It may help identifying zones where infiltration may be mandatory, and others not. Of course, additional knowledge on soils and the unsaturated zone must be taken into account before infiltrating. The risks of pollution, of flood due to groundwater table rise, of soluble rocks or geotechnical disorder must be checked as well. In this frame, the DésiVille project (Prézeau et al., 2024) developed a methodology to cross all this criteria to map the potential of soils for desealing, based on GIS layer available at French scale. Crossing the subsurface intrinsic infiltration capacity map with sealed areas (Figure 4), which are numerous in urban areas, allows assessing the current infiltration characteristics, which may be useful to map rainwater flow. The real infiltration capacity, as well as the other expected constraints, must be verified anyhow locally before implementing an infiltration solution

Among these different French and international studies, some common points can be highlighted: i) the production of a map of the infiltration potential mainly to promote the infiltration of rainwater, ii) the use of 3 natural criteria which are the topographic slope, the thickness of the unsaturated zone and the soil/rock permeability, iii) the integration of natural constraints but also iv) the combination of these different criteria by MCA.

No study takes into account underground infrastructure that may modify locally rainwater infiltration. For instance, buried networks, underground parking lots, metro lines modify water flow and rate. Some might conduct to preferential flow. The global detailed knowledge on underground infrastructure is however lacking (no GIS layer available). In practice, buried networks for instance are rather considered when coming to operational studies at very local scale.

However the criteria used for mapping potential rainwater infiltration in urban subsurface may vary depending on the scale of implementation and locally available data, which implies differences between studies, in the absence of a shared framework. Beyond the variability of the criteria, the weight assigned to each parameter varies from one study to another. This makes it possible to adapt the parameters to the local context but complicates the possibilities of comparing different studies.

New objectives appears recently for these maps such as managed aquifer recharge or multi-benefit approach: it is no longer just a matter of evacuating rainwater but of considering it as a resource. A recent study carried out in Bordeaux metropole (Barrière et al., 2024) is based on a different approach from the maps usually carried out to deal with the capacity for infiltration of a territory. It aims at establishing a cartographic decision-making tool for the deployment of innovative rainwater management systems on Bordeaux Metropolis. It takes into account the components relating to the groundwater storage and recovery of rainwater, as well as the direct benefit likely to be brought by the deployment of innovative rainwater management solutions (covering non-potable water needs). Therefore, the parameters to consider may differ. Moreover, this project was based on consultation and listening to the needs of land development stakeholders.

Soil water infiltration potential maps were also established to assess the desealing potential at territorial scale (Prézeau et al., 2024). In this frame, environmental constraints are taken into account such as the presence of soluble rocks, the risk of flooding due to groundwater table rise, the risk of soil pollution (linked to various human activities and to anthropogenic deposits) or geotechnical instabilities (linked to cavities, risk of landslides or swelling-shrinking clays). The criteria appears more numerous than those listed in Table 2. It is important to take into account such criteria for a holistic approach to ensure rainwater gets infiltrated at the best place, in order to optimize the associated benefits and limit the risks. For instance, infiltrating water through polluted soils may alter the groundwater quality, and the surface water when they drain the groundwater. Geotechnical risks are also major issues in the urban environment. Risks of flooding due to groundwater rise must be considered as well. This is even more relevant in low elevated estuarine and coastal zones, which are subject to sea level rise. The groundwater recharge due to infiltration cumulates indeed with rise due to hydraulic equilibrium with sea level (Bosserelle et al., 2022).

From a societal point of view, the consultation with local stakeholders seems to be an important step of these studies. This allows to verify the relevance of the criteria selected in relation to the needs of these end users, to guarantee their subsequent appropriation of the map, and on the other hand to take into account the issues and benefits linked to integrated rainwater management in all its complexity. The

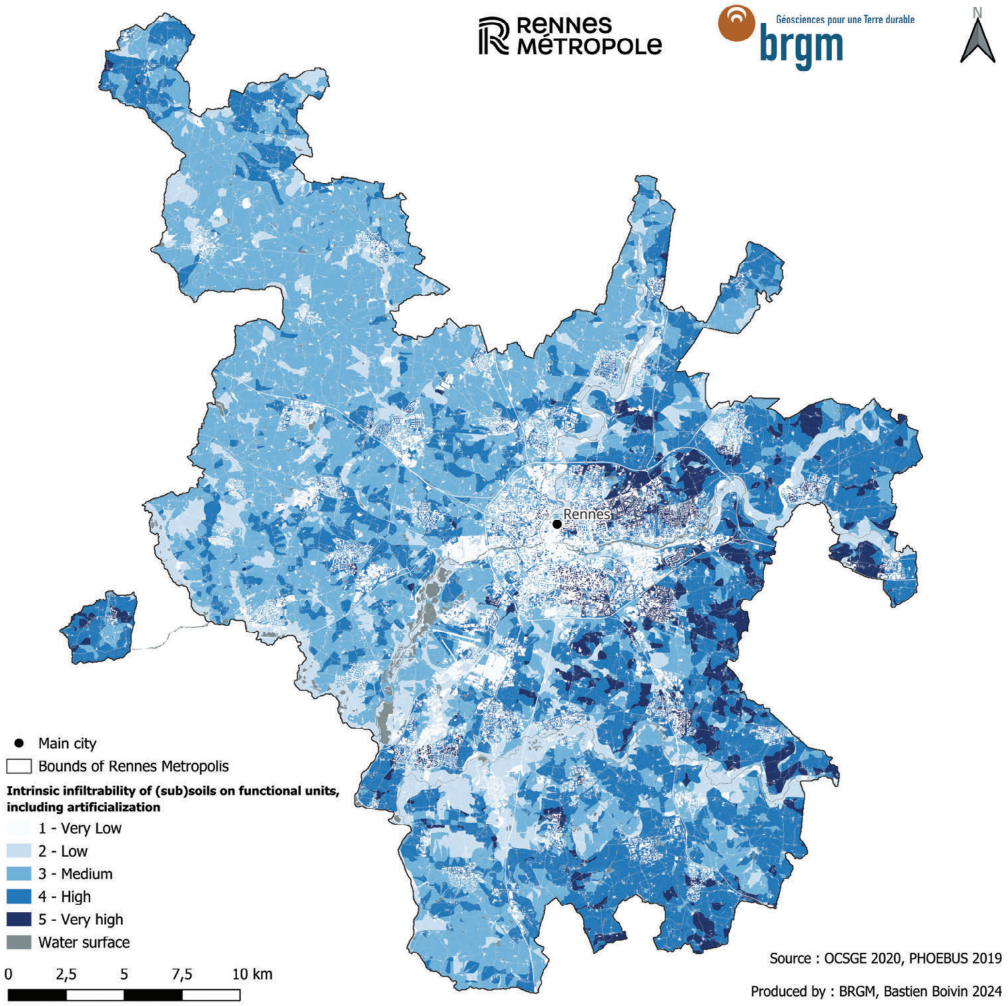

Fig. 4 - Rainwater infiltration capacity index map in the territory of Rennes Metropolis based on subsurface intrinsic infiltration potential crossed with sealed and compacted surfaces deduced from land use to reflect the current status of infiltration.

Fig. 4 - Carta dell'indice di infiltrazione potenziale delle acque piovane sul territorio metropolitano di Rennes ricavata dall'intersezione tra il potenziale intrinseco di infiltrazione e le superfici compattate dedotte dalla mappa di uso del suolo, per riflettere lo stato attuale dell'infiltrazione.

involvement of stakeholders at the start of territorial strategy construction phase facilitates the development and acceptance at global and local scale (Bierry and Lavorel, 2016).

Conclusions

The subsurface intrinsic potential of water infiltration is a key factor to develop relevant water infiltration territorial strategies. A common framework is however lacking in France to map this factor in the urban environment. Infiltrations maps are produced for various reasons and objectives (such as rainwater management, desealing strategies, groundwater recharge, reuse) and at different scale (cities, urban communities, departments or counties, watershed or larger areas). Most French maps of subsurface intrinsic infiltration potential are based on a MCA crossing various criteria, most of the time rocks and/or soils characteristics, thickness of the unsaturated zone, topographic slope and rock permeability). The scores and weigths assigned to each parameter can be discussed with local stakeholders. On an international scale, different methods are used to provide infiltration maps. They are based on several criteria, quite similar to those used in France, with algorithms that use various combinations of the parameters. The Phoebus method, developed for Rennes Metropolis, to map the intrinsic potential of rainwater infiltration appears the most relevant one for a common framework in France; it is based on a multi-criteria analysis of seven criteria, including rock/soil permeability, topographic slope and thickness of the unsaturated zone, with associated weights.

In order to increase the resolution of such maps, urban soil and geological maps with a better resolution (at least 1/10,000) are necessary. It is also important to consider other natural, environmental, urban and regulatory constraints, such as the presence of soluble rock or of soil pollution, to discriminate some areas where infiltration has to be avoided.

Abbreviations and acronyms

- BRGM: French Geological Survey
- CEREGE: French research and teaching centre on environmental geosciences
- CEREMA: French centre for studies on risks, environment, mobility and urban planning
- GIS: Geographical Information System
- INRAE: French research institute for agriculture, food and the environment
- IRSTV: French research federation on urban science and technologies
- IDPR: Surficial Water Network Development and Persistence Index
- MCA: Multicriteria analysis
- DEM: Digital Elevation Model

Additional information

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Competing interest

The authors declare no competing interests.

Author contributions

LUCASSOU Flora: Conceptualization; Writing - original draft, Review and editing.LE GUERN Cécile: Conceptualization; writing - original draft, review and editing.PINSON Stéphanie: Conceptualization; GIS mapping; writing - review.BARRIERE Jérôme: Conceptualization; GIS mapping; writing - review.CHRETIEN Pierre: Conceptualization; writing - original draft.

All authors have read and agreed to the final version of the manuscript.

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