Mapping the desealing potential of soils by coupling Multi-Criteria Analysis, GIS and AI: Nantes Metropolis case study (France)

Fabien Prezeau[1,2], Mohamed Maanan[2], Meryem Tahri[3], Cécile Le Guern[1,4]

[1] IRSTV (FR CNR 2488), 1 rue de la Noé, 44300 Nantes, France
[2]LETG, Laboratoire – Environnement – Télédection – Géomatique, 44312 Nantes, France
[3] Faculty of Forestry and Wood Sciences, Czech University of Life Sciences – V Praze (CZU), Czech Republic
[4] BRGM, Bureau de recherches géologiques et minières, 44323 Nantes, France

Keywords: Desealing, soil, multicriteria analysis, GIS

ABSTRACT

Desealing soils presents lots of benefits but also some risks. To take them into account in desealing strategies, a methodology was developed to map the desealing potential of soils in urban area. It is based on the use of a multi-criteria analysis (MCA) combined with a geographic information system (GIS). A set of 26 criteria were selected and divided into 4 themes: characteristics of impervious surfaces, soil infiltrability, environmental constraints, advantages/benefits of desealing. The scoring and weighting system was developed during workshops with technical departments from the Nantes metropolitan area (France), which served as a case study. Most sealed soils show a medium potential for desealing. High potential for desealing occur particularly in residential areas. Further tests are in progress to include additional social and legal criteria, as well as managing uncertainties.

1. INTRODUCTION

Soil sealing refers to the process of covering a surface with an impermeable layer (Tobias et al., 2018). It is a consequence of urbanization driven by human activities. While soil sealing provides benefits that facilitate human activities, it also has significant negative impacts. These include disruptions to the water cycle (Roy and Shuster, 2009), increased flooding due to rainwater runoff, the creation of urban heat islands (Rhee et al., 2014), and limitations on the recharge of groundwater (Prézeau et al., 2024).

Desealing has been proposed as a potential solution to mitigate some of these negative impacts, which are further exacerbated by climate change. The benefits of desealing include reducing urban heat islands, promoting biodiversity through extended ecological continuity, and improving the water cycle. Desealing soil can be defined as an action aimed at "restoring part of the original soil profile by removing impermeable layers" (European Commission, 2012). However, desealing also presents certain risks, such as the remobilization of pollutants stored in the soil, floodings due to groundwater tables rise linked to increased recharge, or geotechnical instability.

In France, the 'Climate and resilience" law (2021) defined land artificialisation as "the long-term alteration of all or part of the ecological functions of a soil, in particular its biological, water and climatic functions, as well as its agronomic potential through its occupation or use". The law defines the objective of 'no net land take'. The territories must first reduce their artificialisation by 50% by the end of the decade and achieve the objective by 2050.

However, there are few maps available that detail the potential for desealing to support public policies. Notable examples of such projects include Berlin, Germany (Haag and Coeanradi, 2016), Grand Narbonne in France (Cerema, 2019), Renens in Switzerland (Poyat, 2022), and Parma in Italy (Ceci et al., 2023). The criteria chosen for desealing vary across approaches and range in number and complexity.

The objective of this paper is to present the methodology developed for mapping the desealing potential of soil in urban areas based on a multicriteria analysis (MCA) combined with geographic information system (GIS) and artificial intelligence (AI). It aims to comprehensively account for both the benefits and constraints of desealing, providing an effective approach for land management assessment. Furthermore, the methodology is designed to be replicable across the entire French territory.

2. METHOD

1.1 Study site

Nantes metropolis (523,4 km²) is composed of 24 municipalities located along the Loire river. The population reached 656,275 inhabitants in 2022.

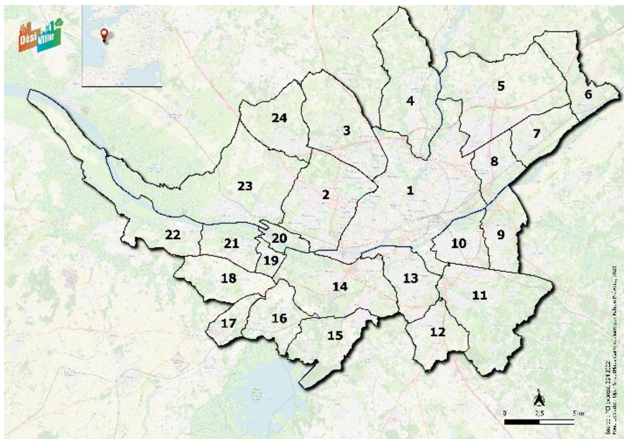

Figure 1 : Geographical area of Nantes metropolis ; (1) Nantes, (2) Saint-Herblain, (3) Orvault, (4) La Chapelle sur Erdre, (5) Carquefou, (6) Mauves sur Loire, (7) Thouaré sur Loire, (8) Saint Luce sur Loire, (9) Basse Goulaine, (10) Saint Sébastien sur Loire, (11) Vertou, (12) Les Sorinières, (13) Rezé, (14) Bouguenais, (15) Saint Aignan de Grandlieu, (16) Bouaye, (17) Saint Léger des Vignes, (18) Brains, (19) La Montagne, (20): Indre, (21) Saint Jean de Boiseau, (22) Le Pellerin, (23) Couëron, (24) Sautron

1.2 Multicriteria analysis Method

Combined with spatial analysis (GIS), multi-criteria analysis makes it possible to select and relate many criteria to guide a choice or a decision to solve a problem (EUROPA, 2015). It thus makes it possible, for example, to construct and/or compare development scenarios considering multiple issues in heterogeneous systems (Fisher and Nijkamp, 1993; Hickey and Jankowski, 1997, Papajorgii et al, 2012, EUROPA, 2015). The implementation of a multicriteria analysis involves several steps: choosing criteria, building the scoring and weighting system, and then aggregating (Malczewski and Rinner, 2015, Tahri et al., 2017; Haidara et al., 2019).

Multi-criteria methods are various and some are complex to implement. Malczewski and Rinner (2015) listed the multicriteria analysis methods coupled with a GIS mostly used in the scientific literature (Figure 2).

Combination rules		# of articles*	%
MADA	Weighted summation/Boolean overlay	143	39.3
	Ideal/reference point (TOPSIS, MOLA)	35	9.6
	Analytical Hierarchy Process (AHP)	34	9.4
	Outranking methods (ELECTRE, PROMETHEE)	17	4.7
	Other	30	8.3
	Total (GIS-MADA)	*259*	*71.3*
MODA	Multi-objectives programming algorithms (linear-integer programming)	57	15.7
	Heuristic search/evolutionary/genetic algorithms	29	8.0
	Goal programming/reference point algorithms	9	2.5
	Other	9	2.5
	Total (GIS-MODA)	*104*	*28.7*
	Total	363	100.0

Note: *some articles presented more than one combination rule.

Figure 2 : Survey of multi-criteria analyses applied to GIS in the literature (Malczewski, 2006)

Among all these multi-criteria analysis methods, the weighted sum was chosen to analyse the potential of desealing. Easy to implement, it is one of the most widely used in GIS (Malczewski and Rinner, 2015). The scoring system is based on a standardisation of the data so as to allow their comparison. Weights are often assigned empirically. The formula (1) summarises the weighted sum of the various criteria.

$$Score\ (A_j) = \sum_{i=1}^{n} W_i V_{ij} \, for e\ i\ \in [1, n] \quad (1)$$

where Aj = Alternative
n = number of criteria
W = weight value of criteria
V = value of criteria

Choice of criteria

The criteria were first selected based on existing projects (Table 4) and on the issues of desealing. Numerous projects have already been undertaken to reduce soil sealing. The areas targeted for desealing are typically selected based on opportunities arising from redevelopment projects or specific goals (e.g., school grounds), in alignment with political decisions or even citizen initiatives (Prézeau et al., 2024).

The first set of criteria selected based on the state of the art was adjusted according to data availability, which conducted to re-move some criteria (Figure 3). The selection was supplemented by discussions with the technical departments of Nantes Metropolis. 10 workshops were held to discuss the different criteria, as well as the rating and weighting system.

Name or localization of project	Criteria selected
Permeable city in Lyon (France) (Agence de l'Eau Rhône Méditerranée Corse, 2017)	Proximity to a hydrographic network
	Proximity to a sensible area
	Area of the project
	Priority area for servicing
	Geotechnical hazard
	Soil quality
	Highest water level of the water table
	Water infiltration capacity
Strasbourg, France (Antea Group, 2013)	DEM
	presence of cavities
	Permeability of surface formations
	Depth of the water table
	Historical HVOC pollution
	Database of former industrial sites and service activities
	Informing the administration of suspected or proven pollution
	Former landfills
	Site diagnosed with untreated pollution
	Water supply catchments and protection perimeters
	Agricultural catchments
	Domestic catchments
	Industrial catchments
	Zoning to restrict the use of water table
	Urban project areas
	Areas of chronic network congestion
Berlin, Germany (Haag and Coeanradi, 2016)	Land data
	Sealing soil
	Biodiversity
	Technical effort
	Feasibility over time
Parma, Italy (Ceci et al., 2023)	Land cover
	Permeability
	Area type (roads, parking lots, green spaces)
	Flood risk
	Urban heat island

Table 1 : Criteria taken into account in some examples of desealing projects

https://doi.org/10.5194/isprs-archives-XLVIII-4-W17-2025-271-2026 | © Author(s) 2026. CC BY 4.0 License.

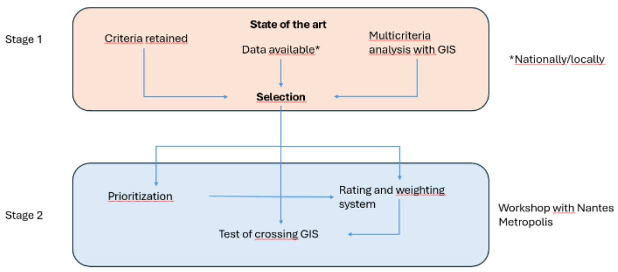

Figure 3 : Diagram showing the steps used to build the methodology to map the desealing potential of soil (Prézeau et al., 2024)

RESULTS

Criteria

A total of 26 criteria was selected and classified under four themes: 1/ characteristics of the sealed surfaces, 2/ soil intrinsic infiltrability, 3/ environmental constraints, 4/ advantages and benefits of desealing (Tab. 2). Cross-referencing the first three themes enables to assess the intrinsic feasibility of desealing. Combining feasibility with the benefits of desealing provides information on the potential for desealing (Prézeau et al., 2024).

Depending on the criteria, 2 to 5 classes are considered, with rates ranging between 1 and 5 (1 being unfavourable for desealing and 5 highly favourable). The weighting ranges from 0.5 to 2. The example of land use is detailed in Table 4. Primary production areas (agricultural areas) are not considered interesting for desealing because they are outside of cities and show few soils to be desealed. On the contrary, in primary and production areas, large surfaces of sealed soils occur such as parking lots which appear very relevant for desealing.

Land cover	Rate
Primary production	1
Other use	2
Logistics and storage services; Public utility networks; transport networks	3
Residential use	4
Primary, tertiary production	5

Table 2 : Example of rating system for the criteria land cover based on the French OCS GE 2016 (IGN) model.

Two criteria are considered as exclusion criteria: the presence of soluble rock and slope above 10%. Indeed, when water infiltrates into areas containing soluble rock (eg. gypse or anhydrite), the latter will dissolve and cause geotechnical instability, which can be at-risk in-built environment. Steep slope causes rainwater runoff on the surface preventing its infiltration.

Some criteria are considered predominant, such as soil pollution hazard, flood hazard due to rising groundwater tables, urban heat islands, and flood hazard due to rainwater runoff. A weight of two is given to these criteria, which is twice the weight (of 1) given to most other criteria.

Mapping approach

Two mapping approaches were proposed based on the availability of identified GIS datasets (Table 1). The first one uses freely accessible national data, which allows replicating the methodology across the whole French territory. The second one incorporates local data to refine some datasets (Prézeau et al., 2024).

Many datasets are mobilized to map the various criteria considered. As mentioned above in the criteria description, a distinction is made between the feasibility and the potential for soil desealing. Feasibility considers three themes: characteristics, constraints, and infiltrability, while the potential for desealing includes the advantages and benefits in the analysis (Prézeau et al., 2024).

The sealing data

The GIS layer of impervious surfaces represents the basis of the spatial analysis. In France, two databases are available: CORINE Land Cover – Imperviousness from the European Copernicus program and the OCS GE layer from IGN. The latter was selected because it allows a precise analysis of land cover and provides a typology of land use. To better differentiate between built-up and unbuilt areas, this layer was refined with a building layer from BD TOPO IGN (Figure 4).

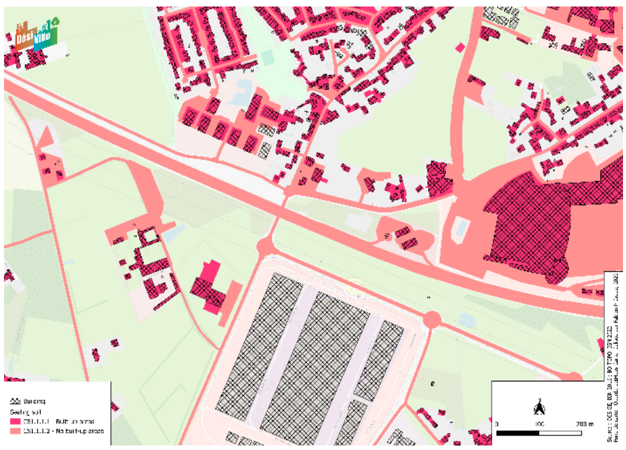

Figure 4 : Crossing the IGN OCS GE layer (2016,) and the buildings from the IGN BD TOPO (2022) database (Prézeau et al., 2024)

		Themes	**Nb classes**	**Criteria**	**Generic scale**	**Specific scale**	**Weigh**	**Nb classes**
Potential of desealing	**Feasibility of desealing**	Characteristics of sealed surfaces	5	Land ownership	1/5 000	Id	1	2
				Size depending on whether it is dense or not			1	5
				Built / unbuilt			1	2
				Land cover			1	5
		Soil infiltration	5	Slope	1/50 000	Id	Exclusion	
				BRGM[1] method (Lucassou et al., 2024)				5
		Environmental constraints: natural and anthropogenic risks and resources to be protected	5	Soluble rocks	1/50 000	Id	Exclusion	
				Soil pollution hazard	1/25 000		2	4
				Water table rise hazard	1/100 000		2	2
				Geological hazard	1/50 000		1	4
				Drinking water catchment areas	1/25 000		1	2
		Advantages and benefits of desealing	5	Urban heat islands	1/10 000	Id	2	5
				Flood runoff hazard	1/50 000	1/500	2	3
				Soil multifunctionality	1/25 000	Id	1	5
				Biodiversity	1/10 000	Id	1	2
				Amenity	1/10 000	Id	1	2
				Flood – river overflow	1/10 000	Id	0.5	2

Table 3 : Set of criteria with rating and weighting system (Prézeau et al., 2024)

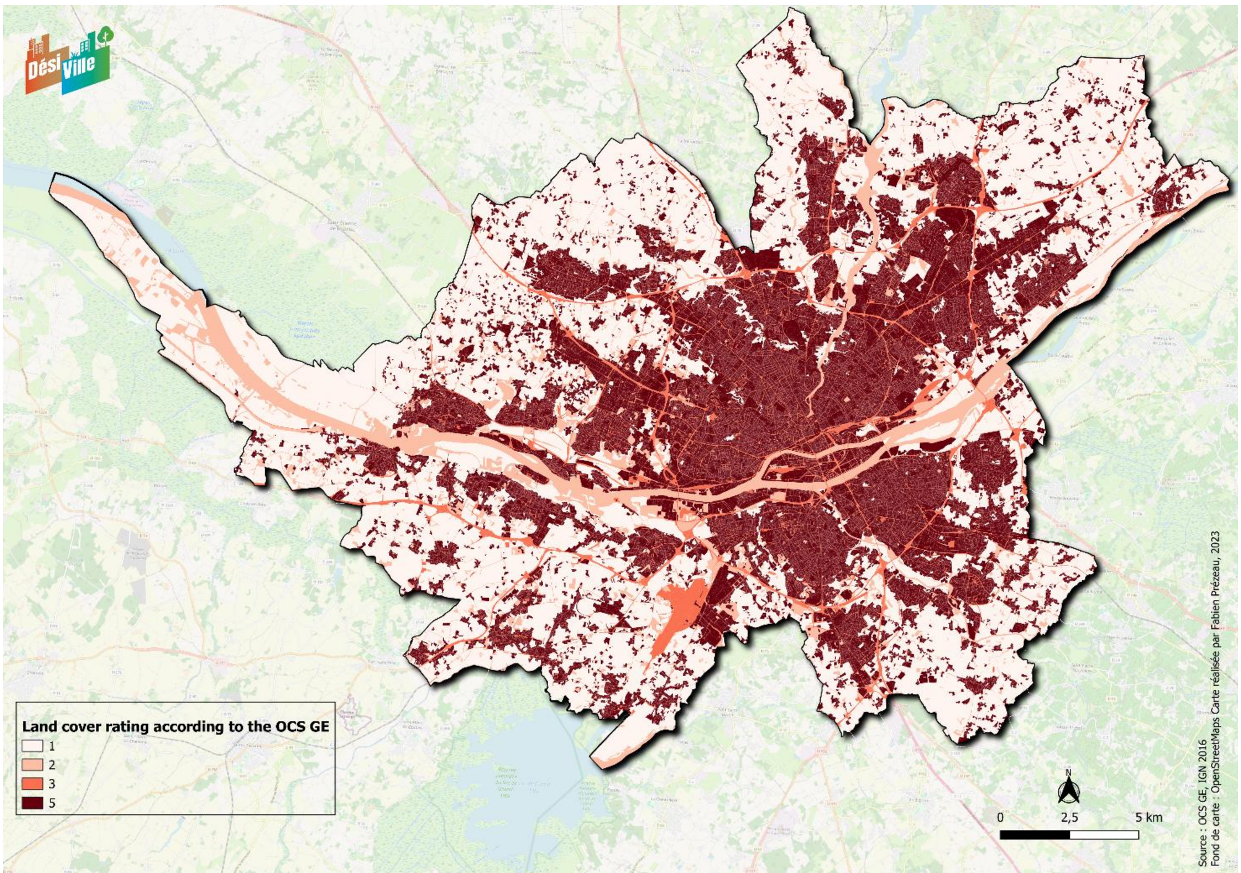

Figure 5 : Potential of soil desealing according to land cover analysis using the developed rating system for the French land cover model OCS GE 2016 from IGN (Prézeau et al., 2024)

[1] BRGM : French Geological Survey

Table 4 : List of data used for the generic method

Criteria	Data	Scale	Format
Soil sealing	OCS GE (IGN)	1/5 000	V
Land Ownership	Parcellaire Express (IGN)	1/5 000	V
	Parcelles des personnes morales	1/5 000	CSV
Land cover	OCS GE (IGN)	1/5 0000	V
Continous and discontinuous construction	Corine land cover (Copernicus)	1/100 000	V
Built / no Built	OCS GE (IGN)	1/5 000	V
	BD Topo	1/5 000	V
Development and persistence index of water network	IDPR (BRGM)		R
Hydromorphy	RRP Géoportail	1/250 000	V
Geological units	BD Charm (BRGM)	1/50 000	V
Clays	Géorisques	1/50 000	V
Slopes	MNT 25m (IGN)		R
Endorheic zones	RRP Géoportail	1/250 000	V
Soluble rocks	BD Charm (BRGM)	1/50 000	V
Flood hazard due to rising groundwater table	Géorisques	1/100 000	V
Polluted site and soils	Basias (Infoterre)	1/25 000	V
	Sis (Géoriques)	1/5 000	V
	Ex-Basol (Géorisques)	1/5 000 to 1/25 000	V
Underground cavities / karst	Géorisques	1/25 000	V
Landslide/rock fall	Géorisques	1/25 000	V
Hazard due to shrinkage/swelling of clays	Géorisques	1/25 000	V
Drinking water catchment areas	AAC	1/50 000	V
Biodiversity	SRCE (INPN)	1/100 000	V
Amenities	BD Topo (IGN)	1/10 000	V
Flood hazard due to owerflowing watercourses	PPRNP (Geoportail de l'urbanisme)	1/5 000	V
Water table depth	Field campaigns		R
Fight against urban heat island	Geoclimate (Bernard et al., 2024)	1/10 000	V
Runoff flooding	ExZEco method from CEREMA	DSM	R
Multifonctionality of soil	MUSE method (Branchu et al., 2021)	1/250 000	V

GIS Crossing results

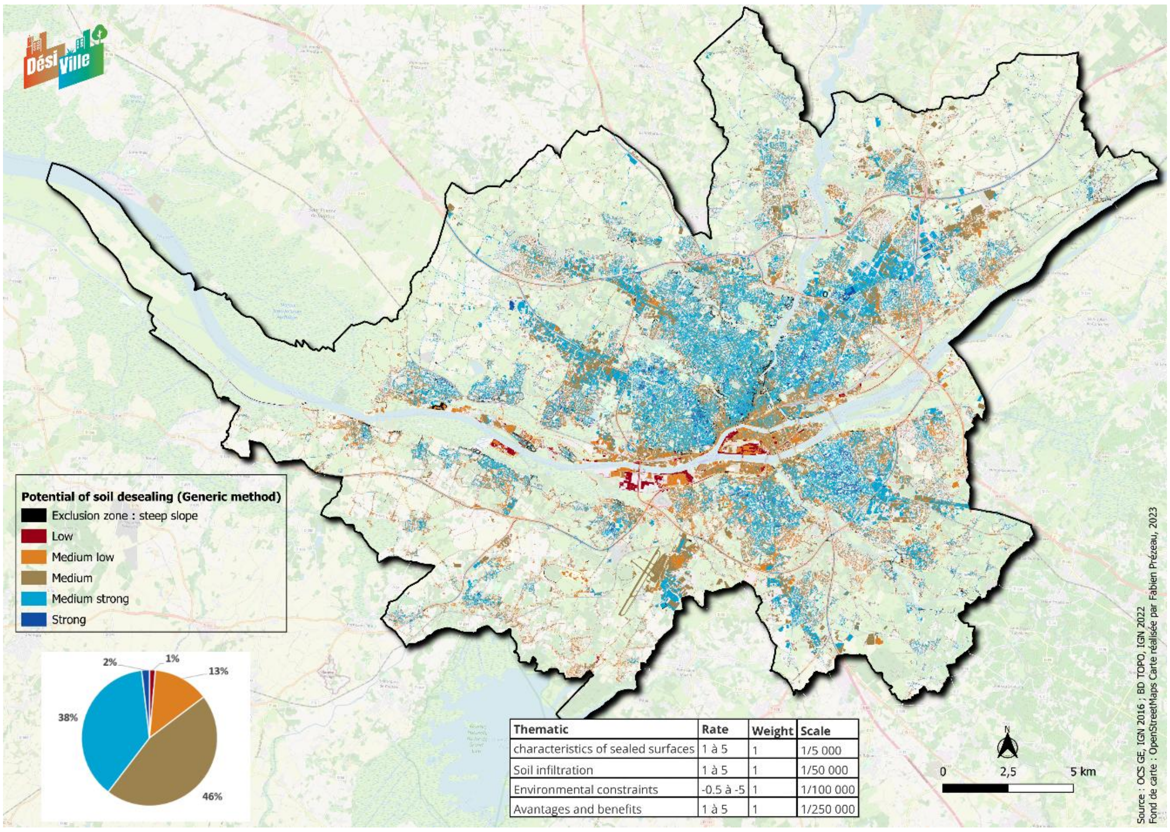

Figure 6 : Potential of desealing of soil (generic method) (Prézeau et al., 2024)

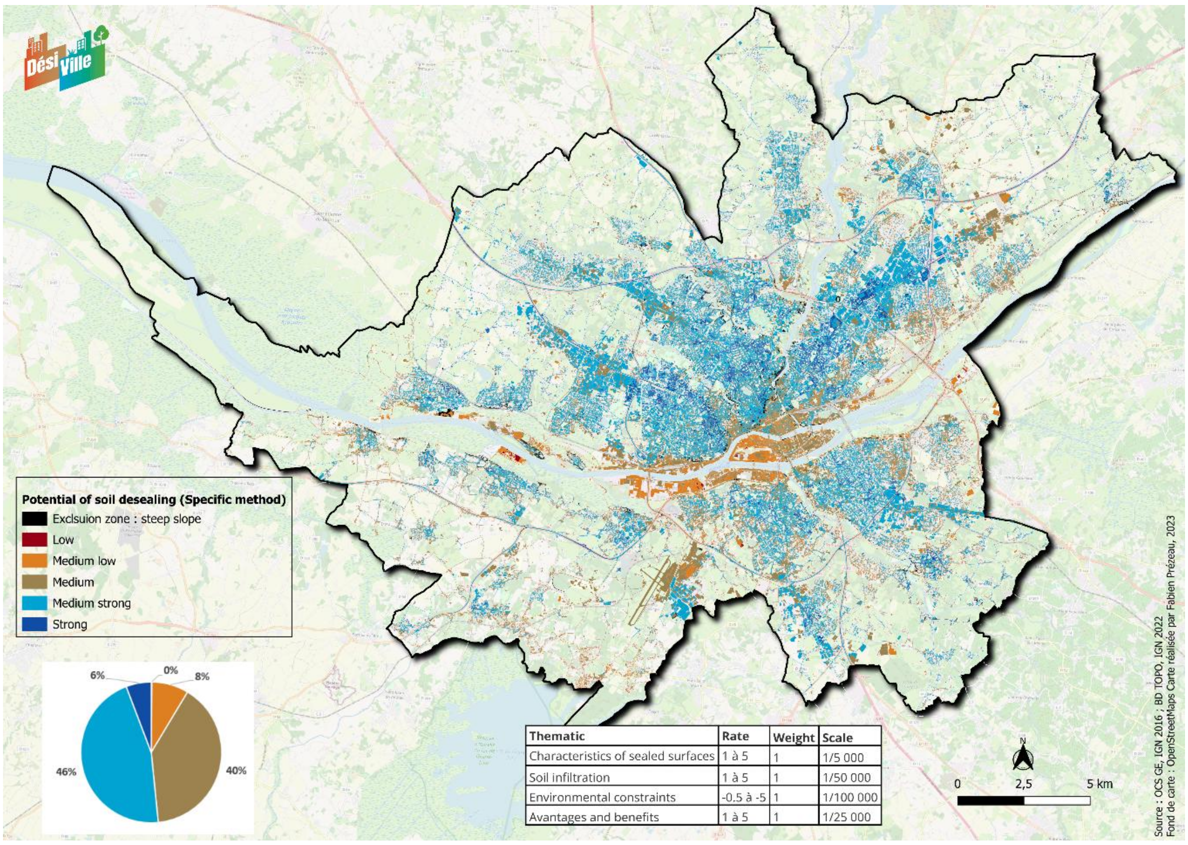

Figure 7 : Potential of desealing of soil (specific method) (Prézeau et al., 2024)

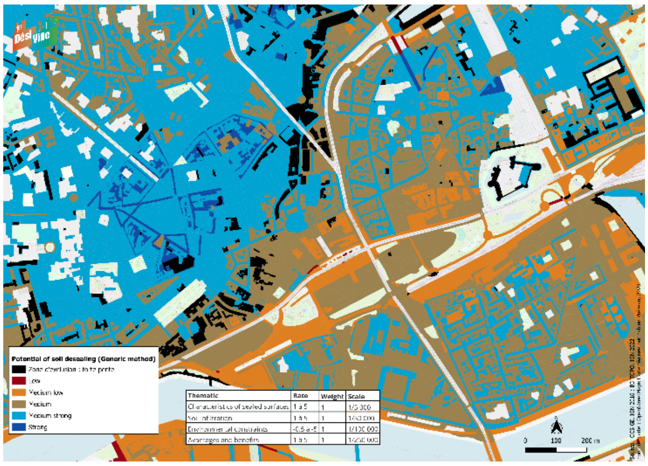

Figure 8 : Zoom on the desealing potential of soil in Nantes city center (generic method) (Prézeau et al., 2024)

Figure 9 : Zoom on the desealing potential of soil in Nantes city center (specific method) (Prézeau et al., 2024)

Figure 6 to Figure 9 present the desealing potential obtained with the generic and specific methods (Prézeau et al., 2024)

After combining the various criteria, sealing surfaces appear to be mainly distributed between the 'moderately strong' (37%) and 'medium' (45%) classes. The former are distributed mainly in residential areas and the latter across the entire territory of Nantes metropolis. Few surfaces present a 'strong' (1.84%) or 'weak' (1.39%) potential for sealing. The surfaces in the 'strong' classes are scattered across the territory; while the surfaces classified as 'weak' are located on the boards of the Loire. The latter were already evident in the feasibility maps.

With the specific method, the proportion of sealing soil classified as 'high' increases compared to the generic method (5% versus 1%). This significant difference is explained by the significant change the benefits thematic map between the generic and specific methods (Prezeau et al., 2024). On the one hand, the runoff flood hazard criterion is not taken into account in the generic method due to a lack of available data, whereas the local GIS layer considered in the specific method appears very accurate. On the other hand, the validity scale of the benefits thematic layer evolves significantly between the two methods (1/250 000 for the generic method against 1/25 000 for the specific method).

DISCUSSION

The methodology is under test in other French territories to check its replicability. The test underway on part of La Réunion Island confirms its replicability, and the need of some adjustment according to the availability or format of some data. Further tests are expected on areas with more significant environmental constraints, such as the presence of soluble rocks.

Furthermore, it is interesting to note that the exclusion criterion of slopes is not necessarily contradictory to the possibility of desealing. In some configurations, it is technically possible to set up terraces on steep slopes to infiltrate water. Hard rock cliffs appear however more difficult to deal with. The term 'ability' instead of 'feasibility' might avoid understanding that desealing is technically impossible. Exclusion is used to alert on very complicated or at high-risk configurations.

Allowing the integration of data updates or new data in the GIS treatment is needed to improve the replicability of the method. For example, the land use model used (OCS GE from IGN) is updated regularly. The classification changes slightly between the 2016 version and the 2022 version. In particular, the residential areas are grouped with primary and tertiary production areas in the 2016 version and separated in the 2022 one. Residential areas are considered less attractive for desealing than primary and tertiary production zones. These latter show indeed large sealed surfaces such as parking lots that appear very relevant for desealing. In this frame, the rate for residential area is downgraded from 5 (very favourable) to 4 (favourable). The AI should help automating such updates.

Despite the construction of the rating system with the technical services of Nantes Metropolis, Maanan et al. (2018) show that broad consideration of local stakeholders is essential to obtain a result consistent with their expectations. The mobilization of local stakeholders also allows for questioning the choice, which complicates the analysis due to the integration of different or even opposing value judgments into the model. However, certain multi-criteria analysis methods can facilitate the management of this complexity (AHP, ELECTRE or Promethee). They would also make it possible to take into account potential legal divergences (Prévost et al., 2013). In addition to divergences in point of views, another important aspect to take into account in the development of desealing strategies is linked to uncertainties relating to the criteria and data considered (e.g. knowledge of soils, urban heat islands, etc.).

CONCLUSIONS

This methodology for mapping the potential for soil desealing is both highly satisfactory and innovative. It considers multiple aspects of desealing, addressing both constraints and benefits. Additionally, the integration of artificial intelligence is being explored to enhance data processing and sensitivity analyses. Moreover, it is replicable across the entire territory using national datasets. Compared to existing mapping methods, it offers a more comprehensive approach. Although easy to understand by stakeholders, the weighted sum AMC method coupled to GIS shows some limitations.

In this frame, further developments are in progress to test MCA methods allowing to take into account discrepancies (stakeholder opinions, legal framework) and to integrate uncertainties in the spatial analysis and representation. This combined technique of MCA, GIS, and AI is expected to allow for a more precise, data-driven understanding of optimal locations and methods for soil desealing in urban areas.

Acknowledgements

The authors thank the French Environmental Agency (ADEME) for the financial support of the DésiVille project (grant number: 21DAD0029), and the French Research Agency (ANR) for the financial support of the PerméPolis project (grant number: ANR-23-CE22-0015). They also thank all the colleagues from Nantes Métropolis, OTEIS, Cerema, AAU-CNRS and BRGM involved in the workshops.

REFERENCES

Agence de l'eau Rhône Méditerranée Corse, 2017. Projet ville perméable - Comment réussir la gestion des eaux pluviales dans nos aménagements ? Grand Lyon la métropole. 64 pages

Antea Group. 2013. Définition des potentialités d'infiltration des eaux pluviales sur le territoire de la Communauté Urbaine de Strasbourg (67) au regard des contraintes locales. Rapport final. A69568/A. 79 pages

Bernard, J., Bocher, E., Gousseff, M., Leconte, F., Le Saux Wiederhold, E., A generic algorithm to automatically classify urban fabric according to the local climate zone system: implementation in GeoClimate 0.0.1 and application to French cities, Geosci. Model Dev., 17, 2077–2116, https://doi.org/10.5194/gmd-17-2077-2024, 2024

BMUV, 2021. Bundesumweltministeriums. « Deutsche Nachhaltigkeitsstrategie ». Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz,

Branchu, P., Marseille, F., Béchet B., Bessière, J.-P., Boithias, L., Duvigneau, C., Genesco, P., Keller, C., Lambert, M.-L., Laroche, B., Le Guern, C., Lemot, A., Métois, R.., Néel, C., Sheriff, R., (2021). MUSE. Intégrer la multifonctionnalité dans les documents d'urbanisme. Rapport final, 155 pages et Rapport d'annexes, 194 pages

Ceci, M., De Noia, I., Tedeschi, G., Caselli, B., Zazzi, M., 2023. Soil de-sealing and participatory urban resilience actions: the "Green in Parma" case study. UPLanD - Journal of Urban Planning, Landscape & Environmental Design, 7(2), 5-18. https://doi.org/10.6093/2531-9906/10116

Cerema, 2019. Comment intégrer la désimperméabilisation des sols sur son territoire ? L'exemple du Grand Narbonne. https://www.cerema.fr/fr/actualites/comment-integrer-desimpermeabilisation-sols-son-territoire

EUROPA, 2015. Analyse multicritère. Capacity4dev. https://capacity4dev.europa.eu/groups/ evaluation_guidelines /info/analyse-multicritere_en.

European Commission, 2012. Lignes directrices concernant les meilleurs pratiques pour limiter, atténuer ou compenses l'imperméabilisation des sols. https://op.europa.eu/en/publication-detail/-publication/e9a42c93-0825-4fc0-8032-a5975c8df3c0/language-fr

Fisher, M., et Nijkamp, P., dir. 1993. Geographic Information Systems, Spatial Modelling and Policy Evaluation. New York, Spring Verlag

Haag, L., Coenradi, B., 2016. Versiegelungskartierung Berlin – Anwendung und Weiterentwicklung des hybriden Auswertungsverfahrens für das Jahr 2016 sowie Kartierung von Veränderungen. https://www.berlin.de/umweltatlas/en/soil/impervious-soil-coverage/2016/download/

Haidara, I., Tahri, M., Maanan, M., Hakdaoui, M., 2019. Efficiency of Fuzzy Analytic Hierarchy Process to detect soil erosion vulnerability. Geoderma, 354, Article 113853, 10.1016/j.geoderma.2019.07.011.

Hickey, R., Jankowski, P., 1997. GIS and Environmental Decision-making to Aid Smelter Reclamation Planning. Environment and Planning, 29 (1): 5-19.

Loi Climate and resilience, 2021. Chapitre III : Lutter contre l'artificialisation des sols en adaptant les règles d'urbanisme, Article 192 https://www.legifrance.gouv.fr/jorf/article_jo/JORFARTI000043957221

Lucassou, F., Chrétien, P., Pinson, S., Barrière, J., Le Guern, C., (2024). Mapping the intrinsic potential of water infiltration in urban subsurface: feedback from France. Acque Sotterranee - Italian Journal of Groundwater, 13(3), 67-77 https://doi.org/10.7343/as-2024-776

Maanan, M., Rueff, H., Adouk, N., Zourarah, B., et Rhinane, H., 2018. Assess the human and environmental vulnerability for coastal hazard by using a multi-criteria decision analysis. Human and Ecological Risk Ass.: An Int. J., 24, 1642-1658. DOI: 10.1080/10807039.2017 .1421452

Malczewski, J., 2006. GIS-based multicriteria decision analysis: a survey of the literature, International Journal of Geographical Information Science, 20:7, 703-726, DOI: 10.1080/13658810600661508

Malczewski, J., Rinner, C., 2015. Multicriteria Decision Analysis in Geographic Information Science. New-York : Springer

Papajorgji, P., Pinet, F., Batton-Hubert, M., Bonnevialle, M., Joliveau, T., Mazago, PO., Paran, F., (2012) Coupling Geographic Information System (GIS) and Multi-Criteria Analysis (MCA) for Modelling the Ecological Continuum in Participative Territorial Planning. 10.4018/978-1-4666-0333-2.ch010.

Poyat, Y., 2022, Personal communication.

Prévost, A., Molines, N., Bandet, J., 2013. Electre Tri, un outil d'aide à la décision pour l'urbanisme réglementaire : application au Plan Local d'Urbanisme (PLU) de Toulouse. 77th meeting of the European working group on multicriteria decision aiding, Rouen Avril 2013, 20p.

Prézeau, F., Clozel, B., Lucassou, F., Le Guern, C., avec la collaboration de Chrétien, P., Bruhat, C., Leduc, T., Musy, M., Rodler, A., Dufrasnes, E., Monnot, A. 2024. DésiVille : où et comment désimperméabiliser les sols ? Cartographie du potential de désimperméabilisation des sols à l'échelle territorial et locale. Guide méthodologique. https://librairie.ademe.fr/urbanisme-territoires-et-sols/7889-desiville-ou-et-comment-desimpermeabiliser-les-sols-urbains-.html

Rhee, J., Park, S., Lu, Z., 2014. Relationship between land cover patterns and surface temperature in urban areas, GIScience & Remote Sensing, 51 :5, 521-536, DOI: 10.1080/15481603.2014.964455

Roy, A. H., Shuster, W. D., 2009. The anthopogenic sealing soils in urban areas. Landscape and Urban Planning 90.1-10.10.1016/j.landurbplan.2008.10.011.

Tahri, M., Maanan, M., Maanan, M., Bouksim, H., & Hakdaoui, M. (2017). Using Fuzzy Analytic Hierarchy Process multi-criteria and automatic computation to analyse coastal vulnerability. Progress in Physical Geography: Earth and Environment, 41(3), 268–285. DOI: 10.1177/0309133317695158.

Tobias S., Conen F., Duss A., Wenzel LM., Buser C. and Alewell C. 2018. Soil sealing and unsealing: State of the art and examples. Land Degrad Dev. https://doi.org/10.1002/ldr.2919