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Kevin Daudin, Christiane Weber, Olivier Fouché, Laure Maton

► To cite this version:

Kevin Daudin, Christiane Weber, Olivier Fouché, Laure Maton. Soil-water adaptive management process: the case of On-site Wastewater Treatment Systems in peri-urban areas in France. *Environmental Challenges*, 2021. hal-03413567v1

HAL Id: hal-03413567

<https://hal.science/hal-03413567v1>

Submitted on 3 Nov 2021 (v1), last revised 13 Apr 2022 (v2)

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Environmental Challenges

Soil-water adaptive management process: the case of On-site Wastewater Treatment Systems in peri-urban areas in France --Manuscript Draft--

Manuscript Number:	
Full Title:	Soil-water adaptive management process: the case of On-site Wastewater Treatment Systems in peri-urban areas in France
Article Type:	Full Length Article
Keywords:	domestic wastewater; nature-based solutions; on-site sanitation; sociotechnical system; soil infiltration rate; urban planning
Corresponding Author:	Kevin Daudin Montpellier University: Universite de Montpellier FRANCE
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Montpellier University: Universite de Montpellier
Corresponding Author's Secondary Institution:	
First Author:	Kevin Daudin
First Author Secondary Information:	
Order of Authors:	Kevin Daudin
	Christiane Weber
	Olivier Fouché
	Laure Maton
Order of Authors Secondary Information:	
Abstract:	<p>Today the scientific growing interest on soils capacities to deliver ecosystems services is at the crossroads with the promotion of Nature-Based Solutions (NBS) for water management and with the necessity to justify land-use changes on the basis on a functional analysis. On-site Wastewater Treatment Systems (OWTS) are opportunities to support the adaptive management process in the water sector, but also to develop a soil-based decision-making in urban areas. In this paper we consider OWTS as hybrid infrastructures necessary to collect, transport, treat and dispose of domestic wastewater on the plot where it is generated. We draw from the results obtained during an applicative science-practice collaborative work on the Montpellier case study (France), with the combination of technical and organizational difficulties. We propose a sociotechnical functional perspective to systematically explore how on-site sanitation may contribute to adaptive management processes both at the plot and the neighborhood scales. We draw from insights from territorial actors for the contextualization of OWTS implementation and planning, and from the application of a soil-based methodology in a peri-urban district for a place-based outlook on soil infiltration rates. We show that conflicts in-between urban and water managers were triggered by urban sprawl regulation and driven by unresolved binding measures for indicators assessment. Soil infiltration rate are not appropriately considered in OWTS design studies, a situation that created an increase of contestations with many direct impacts on the local sociotechnical system. Finally, we discuss on the consideration of passive OWTS as NBS that would give the opportunity to implement a soil-water adaptive management process and to favor original urban initiatives.</p>
Suggested Reviewers:	Lea Fuenfschilling Centre for Innovation, Research and Competence in the Learning Economy lea.fuenfschilling@circle.lu.se Sociotechnical system, sustainability of transition

	Anne Blanchart Laboratoire sols et environnement anne.blanchart@univ-lorraine.fr
	Catherine Boutin INRAE Catherine.boutin@inrae.fr
	Dan Childers Arizona State University dan.childers@asu.edu
	Robert Siegrist Colorado School of Mines siegrist@mines.edu
Opposed Reviewers:	
Additional Information:	
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Dear Editors,

We are submitting our manuscript entitled “Soil-water adaptive management process: the case of on-site wastewater treatment systems in peri-urban areas in France.” written by Kevin Daudin, Christiane Weber, Olivier Fouché and Laure Maton for consideration for publication in *Environmental Challenges* as an Original Article. This work was originated from a 6-month internship within the inter-municipality of Montpellier (France), in direct contact with the daily problems of the public service in charge of On-site Wastewater Treatment Systems (OWTS) management. It is originated from the numerous misunderstandings between actors and the willingness to test an alternative methodology for soil infiltration assessments. The trainee’s position at the interface between scientists and managers made it possible to point at many opportunities for improving collaboration through a knowledge-based approach. The manuscript is the result of a sociotechnical approach applied on what results to be a good example of integrative scientific object: OWTS.

Considering OWTS as a Nature-Based Solution offers an original perspective to historical “septic tanks”. Through the description of OWTS specificities (role of actors and soil indicators) and the analysis of a case study, the paper explores institutional barriers and proposes pathways for more integrative practices. The overall objective is to reconsider OWTS as useful solutions for wastewater management in urban areas. This valuation would surely result in increasing efficiencies in wastewater transport but also in supporting citizen awareness of waste production and in giving space to other environmental services. This paper intends to balance current trend towards the use of technological solution with the many opportunities provided by passive systems (beyond which a careful investigation of soil hydraulic functions).

We used an interdisciplinary approach (water management, soil hydraulics, geography and engineering sciences) to build this work. To our knowledge, OWTS systems have never been looked at through the lens of NBS. We hope that you agree that it is relevant to the journal’s mission and will be a valuable contribution. Please let us know if you have any questions about the manuscript.

Yours truly

Kevin Daudin

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Title: Soil-water adaptive management process: the case of On-site Wastewater Treatment Systems in peri-urban areas in France.

Authors' names and affiliations:

- Kevin Daudin: TETIS, Univ. Montpellier, AgroParisTech, CIRAD, CNRS, INRAE, Montpellier, France
- Christiane Weber: TETIS, Univ. Montpellier, AgroParisTech, CIRAD, CNRS, INRAE, Montpellier, France
- Olivier Fouché: Le Cnam, IRD, Institute of Ecology and Environmental Sciences (iEES-Paris), CNRS, Sorbonne Université, Paris, France.
- Laure Maton: Department of Water and Sanitation, Montpellier inter-municipality (3M), Montpellier, France.

Corresponding author: Kevin Daudin, kevindaudin@hotmail.fr

Maison de la Télédétection, 500, rue Jean-François Breton, 34 093 MONTPELLIER Cedex 5

Acknowledgements: The authors are grateful to the department of Water and Sanitation of 3M, in particular to the “3M-ANC” project team Sylvie Heinemann-Luna, Yvon Danvert, Vincent Chiron, Nicolas Philippe, Louis Moulis and Behzad Nasri. Special thanks to VC and NP for their engagement in their day-to-day mission, without which this work would not have been initiated. We are also very grateful to all the actors who accepted informal discussion and open debate (owners, consultants, installers and local authorities).

Funding sources: The initial work was supported by the inter-municipality of Montpellier Méditerranée Métropole (3M) during a collaborative project with the Conservatoire National des Arts et Métiers (CNAM). Montpellier inter-municipality provided financial support for the conduct of the research, in the collection and analysis of the data. The funding source (from April to October 2018) had no involvement in the decision to submit the article for publication.

Declarations of interest: None

Credit author statement: Kevin Daudin: Conceptualization; Methodology; Investigation; Writing – Original Draft; Visualization. Christiane Weber: Conceptualization; Methodology; Writing – Review & Editing. Olivier Fouché: Investigation; Writing – Review & Editing; Project Administration. Laure Maton: Investigation; Project Administration.

Abstract

Today the scientific growing interest on soils capacities to deliver ecosystems services is at the crossroads with the promotion of Nature-Based Solutions (NBS) for water management and with the necessity to justify land-use changes on the basis on a functional analysis. On-site Wastewater Treatment Systems (OWTS) are opportunities to support the adaptive management process in the water sector, but also to develop a soil-based decision-making in urban areas. In this paper we consider OWTS as hybrid infrastructures necessary to collect, transport, treat and dispose of domestic wastewater on the plot where it is generated. We draw from the results obtained during an applicative science-practice collaborative work on the Montpellier case study (France), with the combination of technical and organizational difficulties. We propose a sociotechnical functional perspective to systematically explore how on-site sanitation may contribute to adaptive management processes both at the plot and the neighborhood scales. We draw from insights from territorial actors for the contextualization of OWTS implementation and planning, and from the application of a soil-based methodology in a peri-urban district for a place-based outlook on soil infiltration rates. We show that conflicts in-between urban and water managers were triggered by urban sprawl regulation and driven by unresolved binding measures for indicators assessment. Soil infiltration rate are not appropriately considered in OWTS design studies, a situation that created an increase of contestations with many direct impacts on the local sociotechnical system. Finally, we discuss on the consideration of passive OWTS as NBS that would give the opportunity to implement a soil-water adaptive management process and to favor original urban initiatives.

Key-words: domestic wastewater; nature-based solutions; on-site sanitation; sociotechnical system; soil infiltration rate; urban planning;

1. Introduction

Adaptive water resource management is a keystone for human societies to sustain their ability to live in an increasing uncertain world [1]. All water cycle flows and stocks are important and everyone is a stakeholder in maintaining all of the interconnected parts of the water cycle [2]. Water and sanitation public services have been developed for 150 years based on conventional Western approach: hydraulic engineering drives centralized infrastructure implementation in urban areas. Engineering design and cost-benefit analyses are the dominant concepts for infrastructure development in the water sector [3]. The co-evolution of institutional rules with technologies during the lasts decades was mainly achieved within a “global sociotechnical regime” [4] favoring large-scale infrastructures, large economic groups and control in public-private partnerships. The concept of sociotechnical system intends to capture the set of interacting rules, actors and technologies forming a dynamic structure that is more or less organized and interacting with the external environment [5]. Shifts from one regime to another have been the focus of many theoretical works, all acknowledge the need to contextualize a technology within the underlying sociopolitical and economic template [6]. Transition, as an underway process that unfolds at several scales and involves a wide variety of actors [7], can be analyzed through the evolution of the interactions between societies and their technical environment.

While urban infrastructure are at the core of sustainability efforts [8], last decades developments have created some organizational difficulties in “peri-urban areas” [9], a notion that groups heterogeneous realities. A common feature of these in-between or transition spaces, intermingling agricultural and residential uses [10], is their under consideration in spatial planning although their potential for ecosystem services provision [11,12]. Considering ecological constraints and reaching collaborative outcomes is one of the greatest challenge faced by fast-growing cities [13], especially in the Global South. Still, within both the developed and developing world urban policy and planning need to adapt to specific local contexts and create knowledge for place-based solutions. In this paper we will focus on developed nations of Europe, and more specifically on the case of discontinuous spaces located on the outskirts of metropolises. More precisely, we will examine mix-used built area located in the crown of large cities in France, which current densification is problematic for infrastructure development like water sewage network. In this regard, we intend to contribute to the analysis of conflicts and contestations in multi-actor processes, which is expected to allow for urban systemic changes [6].

Wastewater systems have evolved during the lasts decades [14] towards technological infrastructure to improve treatment performances, reduce human health risks and consider environmental impacts [15,16]. Many attempts to improve physical and economic efficiencies have been proposed in the literature, but technical and economic rationality is difficult to challenge considering strong path dependencies related to infrastructure technology [17]. For example, drivers of infrastructure development (future amount and composition of wastewater, effluent requirements) may change much more rapidly than their physical life expectancy [18]. Hence, the large capital

investments required for sewerage network implementation and long investment cycles hinder transition [19]. Moreover, centralized systems are more vulnerable to climate events and show functional limitations in fast growing urban areas: over or under capacities due to system sizing are very costly [20].

Two disconnections took place: between people and water related processes since flows in pipes are not visible, and between hydrological systems and land-use activities because of the centralization of water withdrawals and discharges. In the recent years many works put emphasis on alternative technics to address urban challenges and pressures, and contribute to sustainable urban water management [17]. Small and medium-sized infrastructures that rely on temporary storage at the soil surface or underground, soil infiltration and interaction with vegetation may indeed facilitate resource recovery (rainwater harvesting and recycling). System design can indeed benefit from natural ecological processes [21]. Transition from fully centralized to decentralized solutions lead thus to advanced conditions of resilience, working independently or combined with conventional infrastructure, as they both contribute to a greater path diversity, redundancy and more efficient resource usage [8].

On-site Wastewater Treatment Systems (OWTS) are small and autonomous plot-based units that operate close to the actual demand and treat wastewater as close as possible to its source of generation [22]. Sole option for rural landscapes [23], OWTS provide site specific solutions for urban environments as well. Indeed, OWTS are becoming economically attractive [24,25] and financially consistent [26], which result in a growing interest as a viable and necessary alternative to treatment plants [27,28]. Moreover, OWTS compels to consider soil-water interactions since understanding of the receiving environment for treated wastewater is crucial to limit concurrent impacts on human health and the environment [29,30]. Treatment and evacuation performances depend on soil capacities to regulate water quantity (infiltration) and quality (depuration). Still, highly variable properties in urban areas makes it important to improve soil function characterization both at plot and neighborhood scales for device design and sewage planning respectively. There is thus a great need for common evaluation measure of soil functions, based on verifiable data. Indicators from which one may evaluate a situation [31] are decision-support tools that condense complexity and convey information [32]. Indicators are also socially constructed [33]. With regard to urban indicators, a trend is emerging to provide a territorial dimension alongside with existing monitoring frameworks, which entails geolocated information [34] and contextualized interpretation of urban dynamics [35].

In this paper, we propose a contribution to tackle urban sanitation issues giving some hindsight on a place-based collaborative project. Our position is that integrating “decentralized” sanitation into mainstream urban development is a steppingstone for a positive trajectory to sustainability. We consider on-site sanitation as a soil-based hybrid infrastructure for wastewater management. We draw from the Urban Ecological Infrastructure framework [36] to unravel difficulties related to soil infiltration rate assessment and to institutionalized formal and informal rules. Besides willingness to bridge urban scientists and practitioners, this inclusive concept provides an integrative perspective to systematically address the relationships between 1) local technical frame of reference and 2) the complex balance between water processes and soil structures. We propose to test the two following hypothesis: (i) economic or regulatory forcing have more influences on OWTS local practices than environmental data and expertise on soil characterization, and (ii) OWTS can source innovative solutions by considering soils as ecological interfaces in urban planning.

The objective of this work is to shed light on technical and organizational factors that are interconnected and ultimately affect OWTS implementation and long-term functioning. We propose an integrative evaluation of the social and environmental challenges in OWTS and emphasize on the importance of adaptive management processes. First, on-site sanitation systems are briefly described and a case study of peri-urban management issues is presented. Next the combination of two French contextual analyses, about technical indicators and multi-actor governance respectively, supports a place-based social-ecological outlook of OWTS on a practical peri-urban case (Montpellier, France). Hence, the main results from a science-practice collaborative project are presented [38], which was an illustrative example of an attempt to improve soil infiltration rate characterization and to collaborate with urban planners. Finally, we draw from Montpellier’s insights to identify opportunities for an adaptive management and for the assessment of soil hydraulic functions.

2. Materials and methods

2.1. Materials

2.1.1 On-site Wastewater Treatment Systems (OWTS)

The first form of wastewater primary treatment through designed “fosses” date back to 1860s, at the origin of the various evolution of septic tanks [14]. In 1970s appeared the necessity to implement a secondary treatment that

uses micro-organisms either in biofilms or activated sludge (attached or suspended growth). Today, gravity-driven OWTS include a septic tank and a subsurface infiltration system, also called leach field or percolation area [39]. Available information in academic paper present septic systems as the most prevailing technics in Ireland [40]. OWTS account for approximately 20% of US households [41], the same as in France [42]. Since 2009 and the evolution of European standards for small OWTS, activated systems (electricity-driven) hold great promise to meet environmental standards, reduce health risks and overcome site conditions limitations [43]. These systems consist in a single unit (or package plant) proceeding to biological treatment (activated sludge or media filters) and aeration (electromechanical control). Compared to conventional or passive systems, advanced OWTS generally consume more energy and require more maintenance and operation [44].



Figure 1: Schematic representation of a septic system (adapted from [45]) and illustrative photos before filling operation (© KD, A : septic tank, B : sand filter, C : media filter, D : drain field).

Many experimental studies are now available on performances of OWTS [39,41,43,46–48], environmental impacts of pollutant discharges [29,49], innovative designs [50] or reclamation and reuse technics [51–53]. Although water quality is controlled by various biophysical processes [39,54], efficient pathogen removal is difficult to forecast, and site conditions may favor negative impacts [55], steep slope or shallow groundwater for example.

The choice of an OWTS device depends on wastewater characterization (domestic wastewater, graywater, or industrial effluents), performance requirements and site conditions. Generally overlooked compared to treatment performances, plot conditions make the main physical concern.

2.1.2. Case study of peri-urban OWTS

While OWTS provide a great opportunity for public policies to consider soil functionality in urban planning and localization of new housing areas [37], many difficulties may arise in practice [56]. The case study has been drawn from insights from water managers in charge of following up OWTS devices in a fast growing French Mediterranean metropolitan area; we use results from the study by [38] of a peri-urban residential district near the city of Montpellier, France (Figure 2).

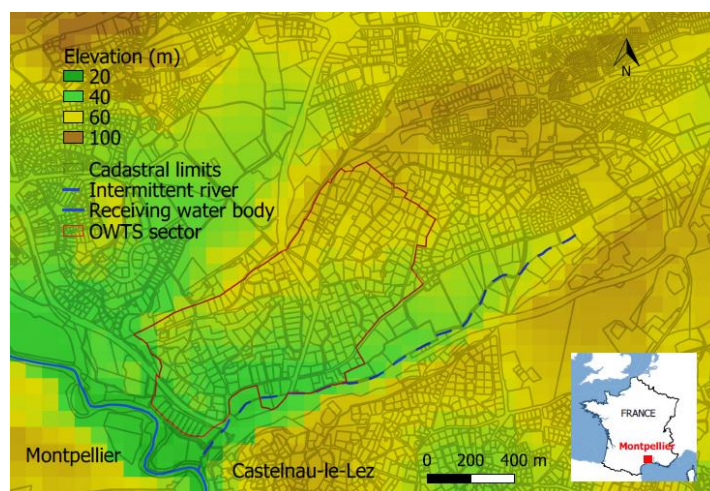


Figure 2: Case study of an OWTS peri-urban district. Source: Montpellier inter-municipality for sewage zoning and cadastral limits (2018), BD TOPO® for streams.

From 2014 local authorities are increasingly confronted to difficulties in managing OWTS. Before this date, around 350 OWTS were in operation (more than 2000 m² for each individual private plot), but plots are becoming smaller and activated OWTS are implemented instead of recommended sand filters, ponding issues are reported in the part of the restricted OWTS sector (between the intermittent river and slope variation of natural ground level). In this area, constraints on topography and housing density historically justified decentralized devices (expensive pumping station and sewer collection network). But national development plan to limit urban sprawl [57] led to the cancelation of minimum plot areas for building new housings, and divisions is directly operated by owners with large properties. For example, before 2014 a 2000 m² plot might only be divided once whereas today 8 individual plots may be created on the same area. The rise in device malfunctioning and the rapid spread of activated systems (often perceived as more space efficient) lead to a lock-in situation between OWTS authorities (device controllers and water managers) and urban planners. Densification thus stirs up organizational difficulties between water and land management. Finally, a specific hydrogeological context (alternating limestone and marl layers, slope and subsurface flow) produces highly variable environmental characteristics, which emphasizes difficulties in assessing soil functions. Hence, the interpretation of technical indicators (mainly infiltration rate) used to choose a specific design may favor misunderstandings between actors [56].

2.2. Methods

The concept of Nature-Based Solution [58] is a cluster for ecosystem-related approaches, which are largely based on integrative visions of social-ecological system (often mentioning the socio-political and the biophysical templates). More recently, the Urban Ecological Infrastructure (UEI) framework is expected to help bridge operational gaps towards more hybrid systems fully adopted by urban planners [36]. Drawing explicit relationships between ecological functions and built infrastructures is thought to facilitate the integration of ecosystems services into urban planning. In Figure 3 we propose an adaptation of the UEI framework to OWTS. We suppose that OWTS can be considered as hybrid infrastructures (note the terms “device” and “infrastructure” are used interchangeably to refer to OWTS) that use soil ecological functions to provide services for wastewater management in urban areas.

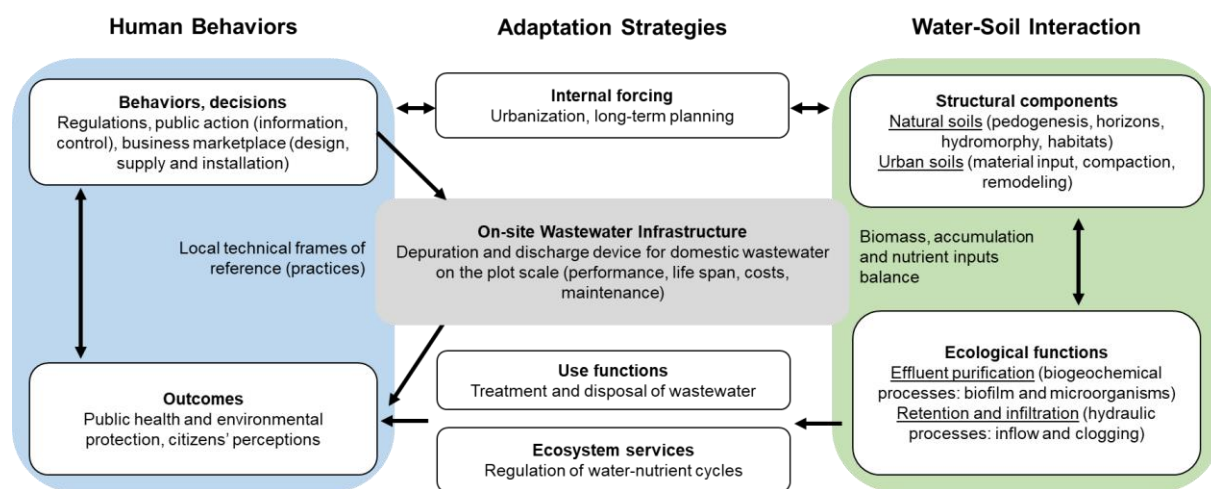


Figure 3: On-site Wastewater Treatment Systems, a sociotechnical functional perspective (adapted to OWTS from [36]).

We recognize that this figure is necessary limited, but it gives shape to the concept of resilience (e.g. the degree to which the system reduces the magnitude of failures while rendering services in its lifetime) by figuring complex sociotechnical dynamics. The framework thus provides a useful comprehensive support for disentangling interconnected factors that operate in OWTS management. Moreover, emphasizing on adaptation strategies help envision the role of soils in water management and reciprocally. Note the overall template is embedded in a given *territoire*, notion which refers to a French social-geography perspective [59] to map collective choice through the analysis of local multi-stakeholder's decision-making processes with an emphasis on social and technical infrastructures.

We propose to analyze the French sociotechnical system through the interplay between soil and water actors, OWTS technics and local institutions. First we contextualize technical design studies (water-soil interactions, indicators assessment) and the diversity and capacity of actors (policy and planning) respectively. The methodology relies on a literature review of French institutional and technical frames of reference (defined here

as the interactions between behaviors and perception that make up practices). We also benefited from insights from a public service in charge of OWTS management (working conditions, day-to-day problems, archived e-mail) and from open debate with local stakeholders' (field trips with public technicians and researchers, observation of site investigation for device design and participation to regulatory controls). Second, to analyze the adaptation strategies we build on the application of a soil-based methodology and on the compilation of available data at a territorial level [38] during the course of a 2 year transdisciplinary project (2017-2019) between OWTS experts and water managers from the Montpellier inter-municipality.

3. Results

3.1. Design studies and indicators assessment

Most OWTS involve a septic tank for pretreatment (liquefaction of pollutants and sedimentation process) that gravity flows to a soil absorption field (or sand filter) for secondary treatment and dispersal. Conventional OWTS thus rely on a natural or reconstituted soil profile, which intrinsically needs to support effluent purification, elements and particles retention and water transfer. Whatever the alternative for treatment, the disposal of treated wastewater into the receiving environment is unavoidable. This step consists in the distribution of the effluent for infiltration and percolation through the soil; gravity-flow is preferred but sometimes pressurized methods may be useful to overcome a variety of environmental limitations or to enable effective distribution of effluent across the area [60].

Soil-water interaction is thus inherent in any OWTS since (treated) wastewater is evacuated through soil infiltration and eventually ends in surface or underground hydrological systems. As there is a probability for contamination by microorganisms and risks to human health, understanding of soil hydraulic functioning is crucial. A few characteristics of the soil and the subsoil govern the overall OWTS long-term performances [61]. Although biodegradation processes are the basis of soil depurative function, action of soil microorganisms on organic pollutant strongly depends on the time of residence. Infiltration rate and rhythm are thus the most critical parameters for OWTS performances. Still hydraulic processes are very difficult to assess: after an initiation phase (around 100 to 200 days [62]), a dynamic balance is established with biogeochemical processes. Finally, conventional OWTS performances rely on the capacity of a complex biophysical reactor (e.g. the soils) to regulate water quantity and quality (water and bacteria dynamics), which is intrinsically variable in natural environments (soil moisture and air temperature influence).

Forecast of infiltration and biofilm formation without surface clogging being a challenge for many soils, institutional standards for design sizing rely on field knowledge and experience feedback. Initially driven by health and hygiene concerns, technical guidelines for long-term device performances are proposed in the early 1980s by national agencies from different countries (for an example see [63]). These reports stand as manuals for the design, construction, operation and maintenance of generic types of OWTS. As concerns arose about impacts of effluents quality on the environment, handbooks and manuals are progressively proposed for improving professionals' practices. The main objective of all these "codes of practice" [40] is to avoid problems of inadequate percolation that would result in ponding or breakout of partially treated wastewater. Whatever the national institutional setting, it seems that intensive site assessment procedure is the rule.

A site investigation consists in identifying implementation conditions and possibilities for wastewater disposal (owner's project, available space on the spot, localization). Then field investigations are carried out based on public environmental data available for the surroundings (geology, boreholes, water bodies ...) and on the location history (run-off water stagnation, flood-risk ...). The final step of this multi-criteria methodology involves the assessment and combination of plot indicators for the classification of the OWTS' suitability (conclusion on the advised device technology and sizing). Table 1 presents a set of indicators to be measured for design studies and ranges of acceptable conditions in French practices.

Table 1: Set of environmental indicators for OWTS suitability assessment.

Indicator	Technical measurement	Favorable conditions	Limitations
Soil infiltration rate	Soil survey and percolation test	30-500 mm/h	Rocks, variability and representativeness
Water table and Bedrock depth	Lithological data, soil excavation	> 1,5 m	Scalable information from public data, mechanical shovel to reach the appropriate depth
Field slope	Topographical survey	< 2 %	-

Note subsoil water flows are complex and many solutions have been proposed so far in an attempt to simplify their assessments. With regard to OWTS, “permeability” is the most often used indicator of soil infiltration rate and the piezometric surface at a given date may not be illustrative of water table maximum height. In practice, environmental indicators assessment’ depend on parameters such as soil moisture, in-situ measurement principle of infiltration rate, and hydrogeological conditions. The result of this plot approach finally depends on the experience of the engineering consultants (field knowledge, public data access, integration of drainage conditions prior to the measurements...). Moreover, plot investigations are expensive and time-consuming so that soil functional characteristics may not be appropriately characterized in OWTS design studies. The selection of an appropriate infrastructure can thus be challenging with regard to uncertainties in indicators assessment:

- the importance given to the soil infiltration rate contrasts with the intrinsic variability of the percolation test [54], and high heterogeneity of soil profiles in urban areas (bedrock depth, texture, structure and constitutive elements) produces variable hydraulic properties. Hence, simplifications introduced into technical guidelines, like threshold values for soil permeability, may be controversial in design studies with a wide range of infiltration rate measurements across the plot. As a consequence, soil permeability measurements are often subject to different interpretations and in-depth characterization of hydraulic conductivity (infiltration regime and clogging) would require specific expertise [42];
- hydrogeological characterization (piezometric surface, bedrock depth) without soil excavation is interpretative, but the latter remains very expensive and time-consuming compared to a classical auger hole. Nevertheless, surrounding boreholes lithological data can be precise enough.

3.2. Institutional arrangements: OWTS management

Public health risks of on-site sanitation systems combined with negative image of wastewater [64] may explain the historical lack of institutional attention to decentralized solutions [65]. However, specific legislations have been implemented in European countries to regulate OWTS. In France, we suggest the starting point for OWTS management to be the “second water act” in 1992, adopted in a context of decentralization and modernization of public services [66]. This legislation was applied through a decree published in 1996, which laid down technical requirements based on design standards [56]. Still, the regulation of OWTS discharges by local authorities are mandatory only 10 years after. In 2006, many public services are created across France to undertake inspections and visit households not connected to a sewer network. Before OWTS had generally received little attention from inhabitants, and some communication was necessary to support the public acceptance of a centralized management. Based on European requirements (Water Framework Directive, 2000), the French inspection plan relied on rehabilitating too old or dysfunctional devices and was supported by financial support through water agencies (state public institution in charge of implementing the river basin management plan and which provides significant contribution to actions of common interest). For example, more than 20,000 rehabilitation projects have been funded between 2013 and 2017 in the Rhône-Mediterranean watershed (average cost of 8,300 euros per infrastructure [67]). But the question of the upgrading level and whether grants are available is still pregnant for dwellers.

At the management level, public officers are specifically dedicated to the control of the device with regard to technical standards and national regulations and they are supposed to register all the systems in public databases (www.data.eaufrance.fr). Except for the control during operation, design and implementation inspections require public servants to check if the consultant and the installer respect methodological and technical guidelines. Note that for OWTS inter-municipality management is economically preferable for public services (sufficient number of devices), and that in France delegation agreement are rare (basic control mission do not require extensive technical skills or large-scale pooling of resources).

Local authorities largely rely on private stakeholders since the decision-making process (e.g. selection of an appropriate technical device) depends on designers, the realization on suppliers and installers, and the use on the house owner or tenant (inhabitant of the house). Hence, each private actor contribute differently to OWTS management (Table 2). Note that a municipal regulation addressed to professional (mostly consultant and installer) may impose specific approaches and/or technical measures, and that regional authorities may ban any superficial disposal of treated wastewater. The resulting diversity in regulation’ local declination is a structuring difficulty for practitioners whose perimeter of action never match with only one inter-municipality. Indeed, a given design study or realization may be judged compliant with standards by a local authority but not by another [68]. Nevertheless, recent national and regional communications intend to harmonize management practices by proposing factsheets to support control operation, guidelines to describe the various OWTS devices and regional briefing days to support local regulation implementation.

Table 2: Set of stakeholders involved in the decision making process, a French perspective.

	Mission	Level of capacity	Effectiveness of action
House owner	Project manager, financial investment, operation and maintenance	Implementation limitations, fees to local authorities	Best affordable and sustainable infrastructure
Engineering consultant	Design study, infrastructure recommendation	Field knowledge, soil expertise	Best practices (professional guidelines)
Supplier	Non-passive systems developers (plant packages)	Accreditation, installation guidelines	Business marketplace
Installer	Infrastructure implementation	Excavation works	Best practices (professional guidelines)
Local authorities	Management controls (design, implementation, operation), owners' information	Local regulations, soil databases (sewage zoning, design studies)	Public service, health and environmental issues
Regional and national	Regulations	Ministerial and departmental decrees, factsheets	Harmonization of practices

In the early 2010s, while the national strategy intends to harmonize local management by making actions prioritization depending on costs and benefices for human and environmental health, many OWTS devices do not comply with technical prescriptions. But the numerous non-conformities have more to do with the status of controls (inspections found many older legacy systems to be inadequate) rather than with an overall performance. In 2009 and 2012, driven by European standardization and innovation, specific French regulations open up the market for advanced technologies [56]. Unlike gravity-fed systems, package plants depend on an authorization procedure based on off-site experiments of treatment performances [44]. In 2018, around 60% of new devices implemented are activated systems (data from the French professional union representing all OWTS professionals, www.ifaa.fr). Hence, besides greater frequency of operation and maintenance, non-passive OWTS are more and more implemented in France.

3.3. Overview of the Montpellier case study: a science-practice collaborative project

To support OWTS management, soils suitability maps (soil investigations at the district scale and recommendation of OWTS device) is available and corresponds to a rare example of soils consideration as ecological interfaces in urban planning [37]. Still, mapping of soils characteristics (infiltration rate for example) is extremely demanding with regard to field investigation. Suitability maps thus generally only delimit areas where some device should be restricted. For example, in the main problematic OWTS sector in the Montpellier inter-municipality (presented in section 2.1), sand filters are recommended. Mainly implemented before 2014, we note the significant presence of activated device on the few data available in OWTS database in 2018. Figure 4 also illustrates the poor consideration given to suitability maps in urban planning. Hence, this practical case highlights potential tensions and conflicts as it shows that OWTS can slow urbanization dynamics and become an obstacle to the added economic value generated by housing densification.

For the Montpellier inter-municipality service, the increase in management difficulties (water practitioners technically handle consequences of urban choices and soil infiltration rates are controversial) triggered the start of a collaboration with OWTS experts. In search for objective data and to complement regulatory packages, a science and practice project “3M-ANC” (2017-2019) used an innovative approach to classify soil abilities for domestic wastewater treatment and evacuation (challenge the soil infiltration rate assessment limitations, Table 1) [42]. The initial methodology was built on the assumption that measurement of soil properties in laboratory could supplement *in-situ* percolation tests for the characterization of biophysical processes [69]. First, the compilation of *in-situ* percolation test measurements (available in public authorities' databases, mainly from design studies by private consultants) present a high variability at the neighborhood scale (Figure 4). To address surfaced contestations, six soil samples were excavated at various depth all around the district [38].

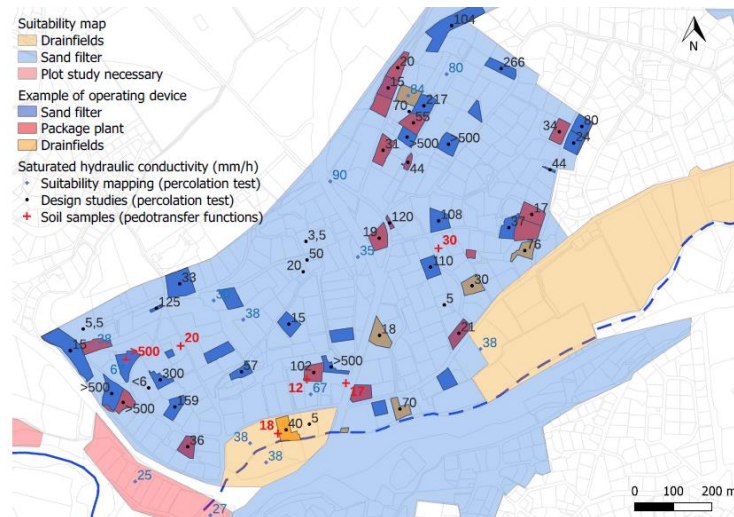


Figure 4: Application of a soil-based methodology to the Montpellier case study. Source: Montpellier inter-municipality for suitability map, device in operation and measured permeability (black and blue numbers in millimeter per hour correspond to data from suitability mapping and design studies respectively).

The physicochemical properties measured in private laboratory (soil texture and organic carbon content) have been used in empirical regressions to assess hydraulic properties (calculated hydraulic conductivity at saturation, averaged on six couplings of pedotransfer functions identified in [69]). The comparison between these outputs with *in-situ* infiltration rates is difficult due to various factors [38]:

- pedotransfer functions may have various statistical performances regarding the difference between soils on which they have been elaborated and the ones on which it is used [70];
- diversity of measurements methods for saturated hydraulic conductivity and poor repeatability in space and time [71];
- lack of confidence on *in situ* infiltration rates measured by private stakeholders.

Despite difficulties to conclude on soil-water interactions at the neighborhood scale, the Table 3 illustrates a compilation initiative [38] of soil available information at the Montpellier inter-municipality spatial scale (439 km²). Many punctual and spatialized data can be aggregated, but one need to be very careful during the analysis because of the diversity in map scales, quantity of punctual data and metrology used for physicochemical parameters estimation.

Table 3: Illustration of soil databases compilation concerning the spatial area covered by the inter-municipality of Montpellier

Map	Scale	Territorial recovery (%)	Number of soil unit	Polygon number	Number of soil profile	Type of measurements
Regional Reference	1/250 000	100	24	105	55	Laboratory analysis
Harmonization program	1/100 000	96,7	55	485	110	Laboratory analysis
Environmental association	1/10 000	49,4	21	2225	Visual interpretation	
OWTS suitability	1/10 000	6,8	11	374	982	<i>In-situ</i> measurement
Irrigation prospective	1/5 000 to 1/50 000	Maps not digitalized			411	Laboratory analysis

This heterogeneity is currently a big challenge for any kind of data management (harmonization issues), while it is a major source of money savings for soil digital mapping (expansive field investigations). For example, the long duration over which *in-situ* percolation test have been used for OWTS design studies make these data records precious for hydraulic conductivity characterization, but the establishment of a comparison basis for diverse sectorial databases is not simple (coupling of *in-situ* observations and development of local pedotransfer functions).

Finally, this new insight did not help in mapping OWTS feasibility for the district mainly because of the not sufficiently mature methodology and its incomplete application. Indeed, the variability of unsaturated zone thickness due to subsurface flows would have needed ground water table high resolution measurements. However, the compilation of soil data from various sources highlights a technical limitation on hydraulic conductivity assessment: threshold values in reference frames (Table 1) are not appropriated with regard to intrinsic uncertainty and variability. Moreover, one can be critical about mapping practices, since techniques to spatialized data and used as managing tools are not neutral [72]. Hence, we showed that there is a gap between the physical plot conditions and the decision level which may not be filled simply through digital mapping. Indeed, expertise appears as a prerequisite, but decision-makers' awareness of complex sociotechnical systems and understanding of uncertainties would benefit to adaptive strategies design and implementation.

To conclude on the 3M-ANC project, some perspectives have been identified for the problematic cases, like the definition of an allowable limit for plot divisions (owners become planners, but rules have to be set) based on hydrogeological data. Moreover, the project's realization triggered a change in Montpellier urban planners' perspective, with an informal commitment to properly study sewage zoning in future development projects. Still, political decisions may continue to favor the maintenance of existing local urban planning [73], which highlights the issue of building permits in zoning practices.

4. Discussion

4.1. "Montpellier", a typical OWTS case study

The Montpellier OWTS management' became critical when arrangements favored decision' disconnection from soil hydraulic and depurative functions. Hence, formal and informal institutional arrangements [74] may limit technical references and guidelines adaptation to the complexity of hydraulic and biogeochemical processes. While regulations exert coercive pressures within the French OWTS sector (urban sprawl limitation), labels or professional codes push to standardize technical solutions (increase in activated devices), which lead local authorities to be very attentive to design and realization compliance with technical references regardless the functionality of the solution (little risk-taking for fear of litigation). This trajectory of methodological shortcomings bypassed by business marketplace puts pressure on existing standards and indicators, which will be used differently depending on the actor' motivations and capacities. Indeed, from Montpellier local authorities' insights we can suppose that the legislative introduction of advanced OWTS prompted a change in actors' strategic positioning:

- first, given the complexity of the soil characterization, consultants may be prone to recommend activated systems in case of note only low but even an intermediate infiltration rate;
- second, the quality of implementation required for passive systems (mainly respecting the slope for gravity flows) is now balanced by plant package with installation guidelines (assembly instructions). In this regard, suppliers may deliver a certification to the installer, which calls into question local authorities implementation controls;
- third, a recent research study [43] statistically demonstrates that innovative systems have comparable in-situ performances as conventional devices, and poorer if maintenance and operation is not achieved regularly;
- finally, as a result of the legislative focus on theoretical treatment performances by innovative device, disposal capacities have been overlooked although they are deemed crucial for users [56] and for regional authorities. In order to limit the inadequacy with shrinking plot area, the new regulations also permit the reuse of treated wastewater through subsurface irrigation.

The 3M-ANC collaborative project contextualized and analyzed conflicts and contestation in the OWTS sector involving a network of actors. Conflicts in-between urban and water managers were triggered by urban sprawl regulation and driven by unresolved contestations for soil indicators assessment. The 2006-2018 OWTS management' pathway is characterized by successive attempts to discredit passive techniques, illustrated by contradictory injunctions between business and technical recommendations and at the origin of public authorities' difficulties. The increase of misunderstandings had many direct impacts on the sociotechnical system, beyond which the illegitimate making of the OWTS public service. Still, while the process of shifting development pathway is messy [6], the proposition of integrating public OWTS expertise in urban planning and sewage zoning can gain momentum over time, on the condition of engagement for collaborative works within city departments with restricted responsibilities [75]. Hence, it is of great importance to produce a comprehensive understanding of the system' functions and drivers which, combined with transdisciplinary collaborations [76], have the potential to unlock sustainable management pathways [6,77,78].

For the Montpellier water managers, the development of a Geographic Information System (GIS) tool compiling and comparing all data available on soil-water interactions would support discussions with urban planners and OWTS actors. Further, the other actors concerned with OWTS (owner, consultant, and installer) or more generally with subsoils works (excavation for housing construction or for public facilities) may participate in place-based diagnosis of soil-water interactions by sharing their situated knowledge (data, information and experience). We suppose that a GIS for OWTS management [42,79] could support such multi-actor initiatives, without forgiving that in many cases field investigations would remain necessary. Note that many OWTS multi-actor initiatives have already been proposed in France; each of these institutional emanation attempted to mediate collaboration. Still, their multitude somehow blurred the breeding ground and may explain the current difficulties to bring to light OWTS environmental issue and to carry out an action research project. Hence, operational gaps between public services and businesses, experts and citizens require the integration of knowledge to move beyond conflicts [80], which involve engagement capacities [81]. In this regard, collaborations among public and private actors may be facilitated by small enterprises with potential for implementing innovation [6], enabling “adaptive governance” [82].

4.2. Adaptive management process

The burgeoning local public interest in peri-urban OWTS, as illustrated by the Montpellier case study, may contribute to the implementation of more integrated approaches (in the sense of [83]) and participate to a “social-ecological turn” in urban water management. Place-based management strategies supported by a systemic approach accounting for social and ecological conditions in the target area is expected to give space and legitimate OWTS in the (French) water sector. Still, adoption of decentralization options results from strategic decisions made under a specific institutional arrangement as a response to changing conditions (e.g. in an adaptive management process).

We suppose that considering OWTS as Nature-based Solutions would support the adaptive process. First, passive OWTS fulfil many of the NBS principles [58], which is a concept increasingly promoted across funding schemes and projects related to water management (infiltration trenches, constructed wetlands, raingardens). Indeed, OWTS are distributed approaches linking the performance of natural processes with engineering technics. Passive OWTS also conserve the use of the water cycle in the functioning of infrastructures. Not only areas equipped with passive OWTS improve urban resilience to floods (conservation of unsealed permeable areas to slow and store storm water), but at a watershed scale they may provide also a response for drought risk reduction (direct return of water in the landscape). Finally, while OWTS present many operational drawbacks for owners (space requirements and large capital investments, maintenance and operation), “soft” aspects of management may be useful (building ownership, changing attitudes). For example, the time spent for maintenance can be a lever for behavioral change (ecological gestures, awareness of regulation cycles), producing a fine understanding of operation which in return support long-term lasting [84].

Obviously, OWTS represent a complement to collective treatment plants and is not intended to replace it in urban areas. However, there is room for its valorization towards an increase in its relative importance. Indeed, the coexistence of various institutional rationalities [4] produces various levels of centralization-decentralization [27], which may be the clue for adaptive urban water management that combine the benefits of each perspective [85]. Identification of the optimal level of decentralization is a challenge regarding the wide range of parameters involved, but employment of on-site or cluster systems is gaining more attention in areas where funding for centralized facilities is lacking. Indeed group sewerage schemes or semi-decentralized systems feature space and economic advantages, operation and maintenance reduced costs, and environmental sustainability [26,40,86]. Custom and context sensitive solutions may for example be implemented in newborn districts in peri-urban areas, which would increase the overall efficiency and resilience of wastewater treatment systems [17] in a *territoire* through material and energy savings (less pipes and pumping costs) and spatial and functional diversity (multiple service paths, redundancy, buffer capacities).

4.3. Soil hydraulic functions

Many countries, including France, have a land use planning at a municipal scale. The respective authorities determine the legal uses. Generally considered as a support for infrastructure and housing, soils are still not well represented in the Ecosystem Services concepts [87]. We posit that OWTS as NBS could contribute to improve land-use changes on a knowledge basis. Hydraulic functions of soils (not only infiltration rate but all information that support soil-water interaction assessment, like piezometric surface or soil moisture) have many other potential applications in urban hydrology, for example flood prevention modelling could be refined by integrating

permeable areas. However, spatial distribution of soils horizons and their complex interactions in the landscape is a real technical barrier to the establishment of operational soil databases for decision-making.

Considering the necessary tradeoff between sophistication of composite indicators and availability of requisite data [35], OWTS might be a great opportunity for fine-tuning soil data and support the consideration of soils services in urban planning and water management. Aggregation of soil and water databases would need further investigation, for example using data sciences products (for example remote sensing of soil moisture at the plot scale [88]). Note that the underlying idea of gathering dispersed data between organizations (research, municipalities, consultants, ...) would need dedicated specifications in contracts (partnerships, market offers) and skills to operate capitalization (from raw data to transferable information). The latter could be strengthened by digital assessment (for example data mining [89], towards a fine-scale mapping of soil hydraulic functions in support of land-use planning.

5. Conclusions

In the one hand soils play a critical qualitative and quantitative role in the water cycle, but green water is still under considered in global assessments. In the other hand the water sector faces big challenges due to infrastructure ageing, urban sprawl and market-based logics. The combination of these problematic is well illustrated by peri-urban On-site Wastewater Treatment Systems (OWTS): many difficulties arise when one tries to develop a prototype of sustainable management accounting for social and environmental factors. Currently, given the leeway in the interpretation of a soil investigation and the variety of issues at stake, it is no doubt about potential inefficiencies regarding design, cost, energy, or performances. In this paper we proposed a place-based social-ecological outlook on the main challenges faced to improve multi-actor governance: a better assessment of soil infiltration rate would support adaptive management both at plot and neighborhood scales for device design and planning respectively. Hence, we showed that data and stakeholders feedback processes would support a better use of available resources and institutions.

Two main perspectives arise when considering passive OWTS as Nature-Based Solutions. First on-site sanitation can source an adaptive management process in the water sector and has transformative potential towards urban sanitation sustainability. Second, new data streams from OWTS sector and more globally from consultants and municipalities could improve the justification of land-use changes on a knowledge basis. For example, the characterization of water connectivity in the subsoils could be supported by the development of original proxies combining available water and soil data.

Finally, the Montpellier case study is depicted as an illustrative example of the search for an adaptive strategy for peri-urban areas in France. The OWTS sociotechnical transition (new regulations, centralized management and innovative device) is combined with densification constraints in metropolitan areas. Although strong differences with such transition spaces in low and middle income countries or regions (sanitation gap on the margins of formal urban settlements with important health impacts), we believe the global South could benefit from a systemic understanding on off-grid productive sanitation solution [90,91]. The tools and insights for OWTS adaptive management could indeed be used where the main development challenge remain (rapid transformation of cities, governance limitations, capacity barriers).

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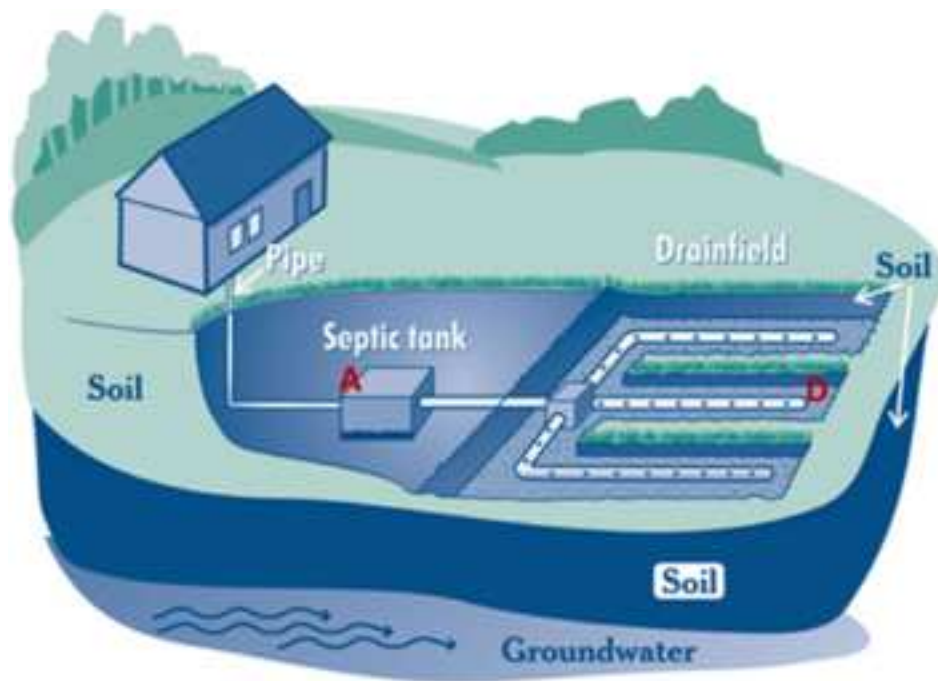
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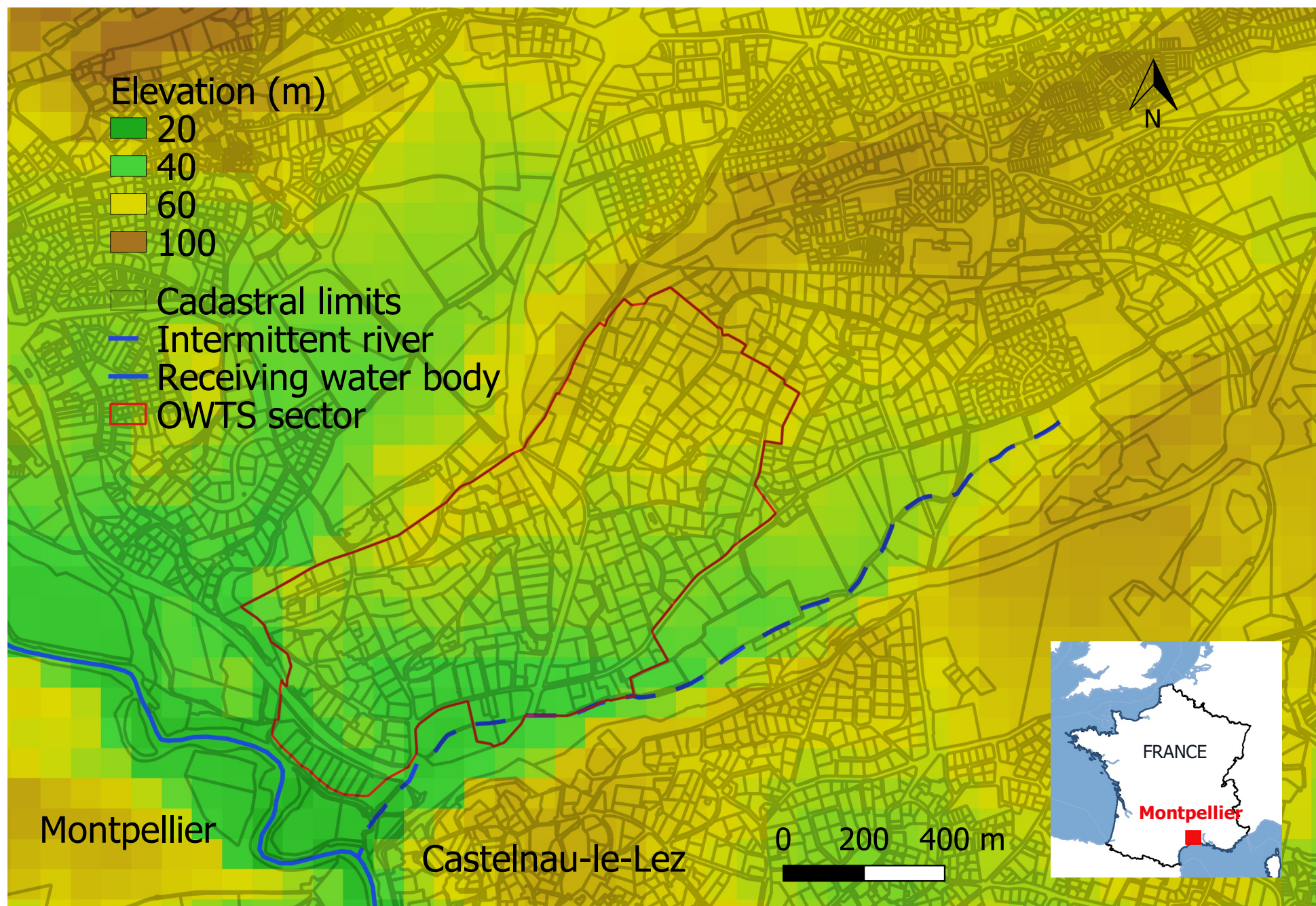
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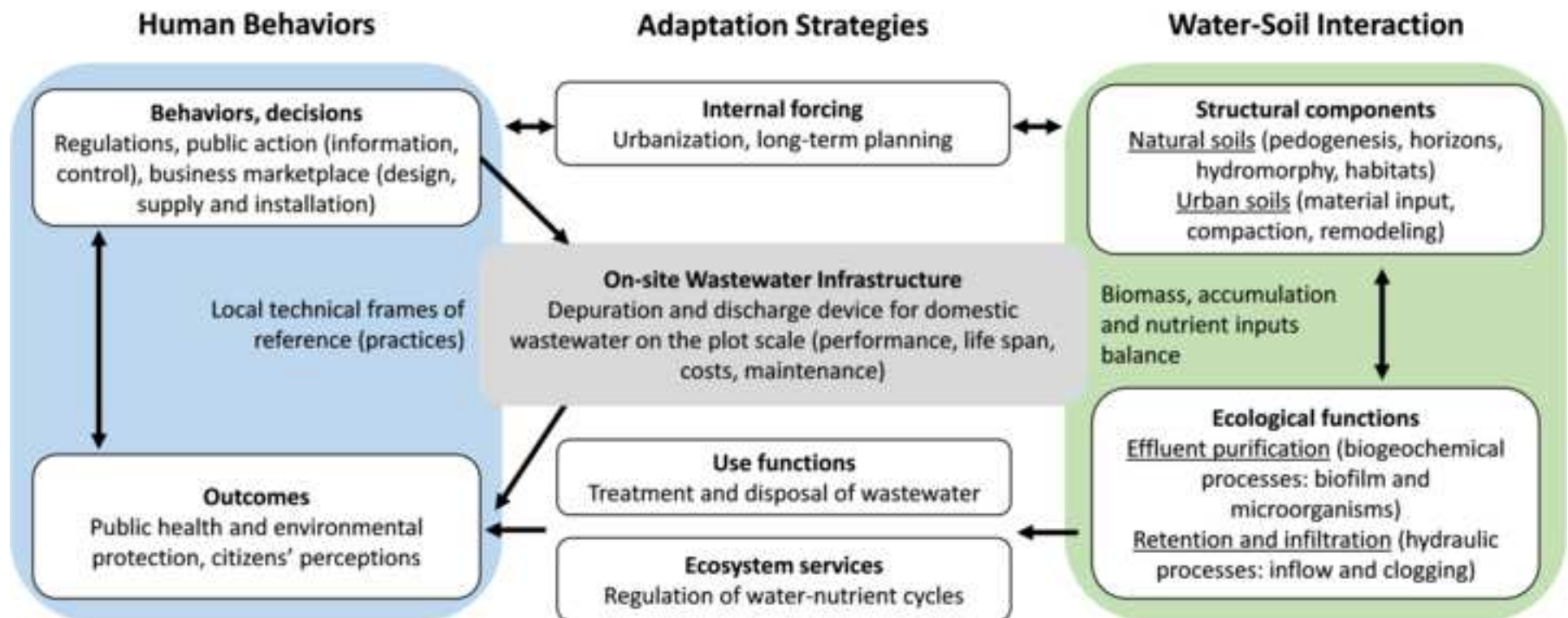
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