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# Soil-water adaptive management process: The case of on-site wastewater treatment systems in peri-urban areas in France



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## ABSTRACT

This paper proposes a contribution to tackle urban sanitation issues giving some hindsight on a place-based science-practice collaborative project. Insights from a French public service in charge of On-site Wastewater Treatment Systems (OWTS) highlighted the need to deepen the understanding of soil infiltration assessments and to clarify their relation to some misunderstandings between actors. The initial aim was to explore how a knowledge based approach can offer an original perspective to historical “septic tanks” and overcome technical and organizational difficulties. In this work we consider OWTS as hybrid infrastructures necessary to collect, transport, treat and dispose of domestic wastewater on the plot where it is generated. We suppose that OWTS adaptive management (sludge not included) offer many opportunities regarding water circulation (ecological function), infrastructure diversity (redundancy), and soil-based decision making (spatial planning). The main objective of this paper is to document the French sociotechnical configuration through the interplay between soil and water actors, OWTS technics and local institutions. The originality is to look at OWTS through the lens systemic perspective of Nature-Based Solutions (NBS). We first contextualize OWTS implementation and planning by presenting technical design studies (water-soil interactions, indicators assessment) and the diversity and capacity of actors. Second, we build on the application of a soil-based methodology in a peri-urban district to provide a place-based outlook on the influence of soil infiltration rates variability in day-to-day management. While the current consideration given to soil infiltration rate in OWTS design studies created a situation of conflicts and contestations between actors, a sociotechnical transition is taking place with new regulations and innovative energy-driven device. Moreover, collective infrastructure for domestic wastewater is currently challenged by densification constraints in metropolitan areas (urban sprawl regulation). As a consequence, resolving binding measures for indicators assessment would support OWTS integration into mainstream urban development. Careful investigation of soil hydraulic functions is thus a steppingstone in the search for an adaptive strategy both at the plot and the neighborhood scales. Not only OWTS are opportunities to support the adaptive management process in the water sector, but OWTS have also the potential to improve soil-based decision-making in urban areas. Finally, valuating OWTS as useful NBS for wastewater management in urban areas supports the evaluation of soil capacities to deliver ecosystem services and contributes to justify land-use changes on a functional knowledge basis.

## 1. Introduction

While urban infrastructure are at the core of sustainability efforts (Elmqvist et al., 2019), last decades developments have created some organizational difficulties in “peri-urban areas” (Allen, 2003), a notion that groups heterogeneous realities. A common feature of these in-between or transition spaces, intermingling agricultural and residential uses (Wandl and Magoni, 2017), is their under consideration in spatial planning although their potential for ecosystem services provi-

sion (Clergeau, 2014; Wandl et al., 2017). Considering ecological constraints and reaching collaborative outcomes is one of the greatest challenge faced by fast-growing cities (Bai et al., 2018), 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 study the overall approach implicitly acknowledges the transformative functions of any transdisciplinary process (Daudin et al., 2021), thus recognizing the importance of context for the realization of ecosystem services in cities (Andersson et al., 2021).

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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 (Molle, 2009). Wastewater systems have evolved during the last decades (Lofrano and Brown, 2010) towards technological infrastructure to improve treatment performances, reduce human health risks and consider environmental impacts (Burkhard et al., 2000; Tchobanoglous et al., 2014). 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 (Leigh and Lee, 2019). For example, drivers of infrastructure development (future amount and composition of wastewater, effluent requirements) may change much more rapidly than their physical life expectancy (Neumann et al., 2015). Hence, the large capital investments required for sewerage network implementation and long investment cycles hinder transition (O’Brien et al., 2014). 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 (Maurer, 2009).

Today, adaptive water resource management is recognized as a key-stone for human societies to sustain their ability to live in an increasing uncertain world (Falkenmark, 2020). All water cycle flows and stocks are important and everyone is a stakeholder in maintaining all of the interconnected parts of the water cycle (Gleeson et al., 2020). Many recent studies contribute to the research stream on Nature-Based Solutions (NBS) for urban water management (Oral et al., 2020). More specifically, works concerning sanitation services show that water infrastructure design can both take advantage of natural ecological processes and benefit to human activities (Wang et al., 2018; Cross et al., 2021; Willcock et al., 2021). It generally relies on the observation that small and medium-sized infrastructures that depend on temporary storage at the soil surface or underground, soil infiltration and interaction with vegetation facilitates resource recovery (rainwater harvesting and recycling) and reduces vulnerability to droughts and floods. Transition from fully centralized to decentralized solutions lead 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 (Elmqvist et al., 2019).

Integrating “decentralized” sanitation into mainstream urban development is a steppingstone for a positive trajectory to sustainability. In this work, we put emphasis on a specific alternative technic still undervalued but able to address urban challenges: On-site Wastewater Treatment Systems (OWTS). We suppose that OWTS may contribute to reconnect both people to water related processes (operation and maintenance activities directly handled by inhabitants) and hydrological systems to land-use activities (spatial distribution of domestic water discharges). Indeed, OWTS take part in water recycling at the landscape scale and indirectly favor water reuse for any downstream human activities. Hence, the novelty of this work is to posit that OWTS are hybrid NBS, just like constructed treatment wetlands (Capodaglio et al., 2021). 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 (Yates, 2011). Sole option for rural landscapes (Massoud et al., 2009), OWTS provide site specific solutions for urban environments as well. Indeed, OWTS are becoming economically attractive (Roefs et al., 2017; Jung et al., 2018) and financially consistent (Wang, 2014), which result in a growing interest as a viable and necessary alternative to treatment plants (Libralato et al., 2012; Bernal et al., 2021). Still, understanding of the receiving environment for treated wastewater is crucial to limit concurrent impacts on human health and the environment (Richards et al., 2016; Risch et al., 2021).

While some studies warn about the potential impacts of dysfunctional OWTS on groundwater quality (Robertson, 2021) and implications for marine coastal ecosystems (Wada et al., 2021), we consider

OWTS as an opportunity to consider soil-water interactions since treatment and evacuation performances depend on soil capacities to regulate water quantity (infiltration) and quality (depuration). Still, soil-based on-site sanitation present many challenges for a better consideration in urban development, notably it has to be properly designed and correctly located (Iribarnegaray et al., 2021). Hence OWTS actors encounter difficulties in soil function characterization both at plot and neighborhood scales for design and planning respectively, all the more so in an urban environment where soils are highly variable. Some difficulties also appear when considering the social elaboration of technical indicators in the evaluation of a given situation (Haase et al., 2014; Bouleau and Deuffic, 2016; Carré et al., 2017). With regard to urban indicators, a trend is emerging to provide a territorial dimension alongside with existing monitoring frameworks, which entails geolocated information (Lenormand et al., 2015) and contextualized interpretation of urban dynamics (Gómez-Álvarez et al., 2018).

In this paper, we propose a contribution to tackle urban sanitation issues giving some hindsight on a place-based collaborative project, which focus on discontinuous spaces located on the outskirts of a European metropolises. In a context of growing concern about urban sprawl in the crown of large French Mediterranean cities (Robert et al., 2019), we will examine mix-used built area which current densification is problematic for infrastructure development like water sewage network. We build on insights from a French public service in charge of OWTS, obtained during the course of a 2-year project (2017–2019) between OWTS experts and water managers from the Montpellier inter-municipality. The initial aim was to explore how a knowledge based approach can offer an original perspective to historical “septic tanks” and overcome technical and organizational difficulties. The need to build a common understanding of soil infiltration assessments and to clarify their relation to some misunderstandings between actors led us to propose a retrospective systemic perspective. For this purpose, we use the concept of sociotechnical transition (Geels, 2004), which puts emphasis on the set of interacting rules, actors and technologies forming a dynamic structure that is more or less organized and interacting with the external environment. Hence, transition, as an underway process that unfolds at several scales and involves a wide variety of actors (Bourg et al., 2015), can be analyzed through the evolution of the interactions between societies and their technical environment. Shedding light on the interconnection between technical and organizational factors and its impacts on OWTS implementation and long-term functioning, we intend 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 main objective of this paper is to document the French sociotechnical configuration through the interplay between soil and water actors, OWTS technics and local institutions. First, on-site sanitation systems are briefly described and a case study of peri-urban management issues is presented. Second, we propose an adaptation of the Urban Ecological Infrastructure (UEI) concept (Childers et al., 2019) on OWTS to highlight the relationships between (1) local technical frame of reference and (2) the complex balance between water processes and soil structures. While the UEI concept provides an integrative perspective to bridge urban scientists and practitioners, it also gives a framework to systematically address difficulties related to soil infiltration rate assessment and to institutionalized formal and informal rules. An original scientific flowchart for the coupled evaluation of the social and physical dimensions of a hybrid NBS is then proposed and applied to OWTS: building on the combination of two French contextual analyses, about technical indicators and multi-actor governance respectively, we analyze the results obtained from the science-practice collaborative project (Daudin, 2018). The place-based social-ecological-technological outlook of OWTS on a practical peri-urban case (Montpellier, France) finally provides an illustrative example of an attempt, by environmental managers, to improve soil infiltration rate characterization and to

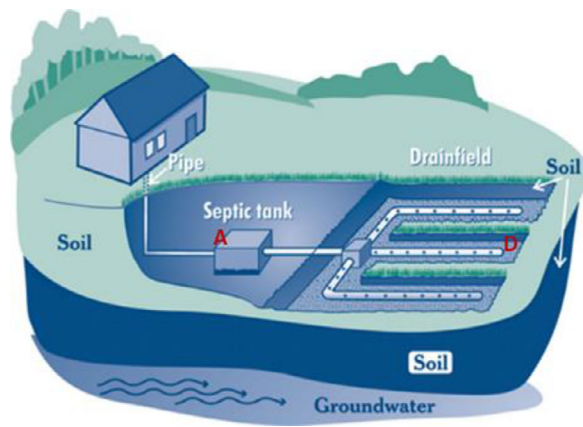


Fig. 1. Schematic representation of a septic system (adapted from EPA (2005)) and illustrative photos before filling operation (© KD, A: septic tank, B: sand filter, C: media filter, D: drain field).

collaborate with urban planners. Finally, we identify opportunities for an adaptive management and for the assessment of soil hydraulic functions. In this regard, we show that capitalization and collaboration may help resolve conflicts and contestations in multi-actor processes. While some clues are identified for OWTS and soil hydraulic functions, there are still important gaps to provide decision-support tools that condense the complexity of soil characteristics and convey information on their various functions.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. On-site wastewater treatment systems (OWTS)

While latrine fosses exist for many centuries, the very first design of a wastewater primary treatment probably dates back to 1860s (Lofrano and Brown, 2010). Improvements were proposed in the following decades, leading to the proposal of “septic tanks” in the beginning of 19th century. 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 (filtration trenches, landfill filter), also called leach field or percolation area (Wang et al., 2021) that provides both secondary treatment of the septic tank effluent and dispersion to the subsoil. Available information in academic paper present septic systems as the most prevailing technics in Ireland (Dubber and Gill, 2014). OWTS account for approximately 20% of US households (Schneider et al., 2017), the same as in France (Fouché, 2014). 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 (Dubois and Boutin, 2018). 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 (Boutin and Olivier, 2017).

Many experimental studies are now available on performances of OWTS (Wang et al., 2021; Schneider et al., 2017; Dubois and Boutin, 2018; Nakajima et al., 1999; Roberts et al., 2014; Ross et al., 2020), environmental impacts of pollutant discharges (Richards et al., 2016; Fouché et al., 2019), innovative designs (Abbassi et al., 2018) or reclamation and reuse technics (Curneen and Gill, 2015; Opher and Friedler, 2016; de Anda et al., 2018). Although water quality is controlled by various biophysical processes (Wang et al., 2021; Nasri et al., 2015a), efficient pathogen removal is difficult to forecast, and site condi-

tions may favor negative impacts (Nasri and Fouché, 2019), 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 (Fig. 1).

#### 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 (Bispo et al., 2016), many difficulties may arise in practice (Fouché et al., 2017). 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 Daudin (2018) of a peri-urban residential district near the city of Montpellier, France (Fig. 2).

From 2014 local authorities are increasingly confronted to difficulties in managing OWTS. Before this date, around 350 OWTS were in operation (more than 2000 m<sup>2</sup> for each individual private plot), but plots are becoming smaller and activated OWTS (energetic system) 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 (ALUR, 2014) led to the cancellation of minimum plot areas for building new housings, and divisions is directly operated by owners with large properties. For example, before 2014 a 2000 m<sup>2</sup> 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 (Fouché et al., 2017).

### 2.2. Methods

To analyze the evolution of relationships between evolving sociotechnical framing and the evaluation of soil hydraulic functions, we



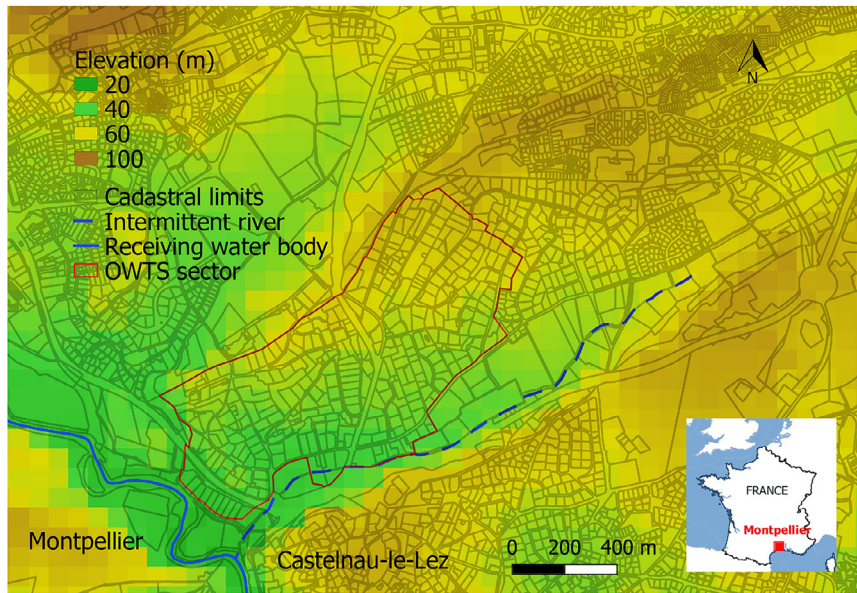


Fig. 2. Case study of an OWTS peri-urban district. Source: Montpellier inter-municipality for sewage zoning and cadastral limits (2018), BD TOPO® for streams.

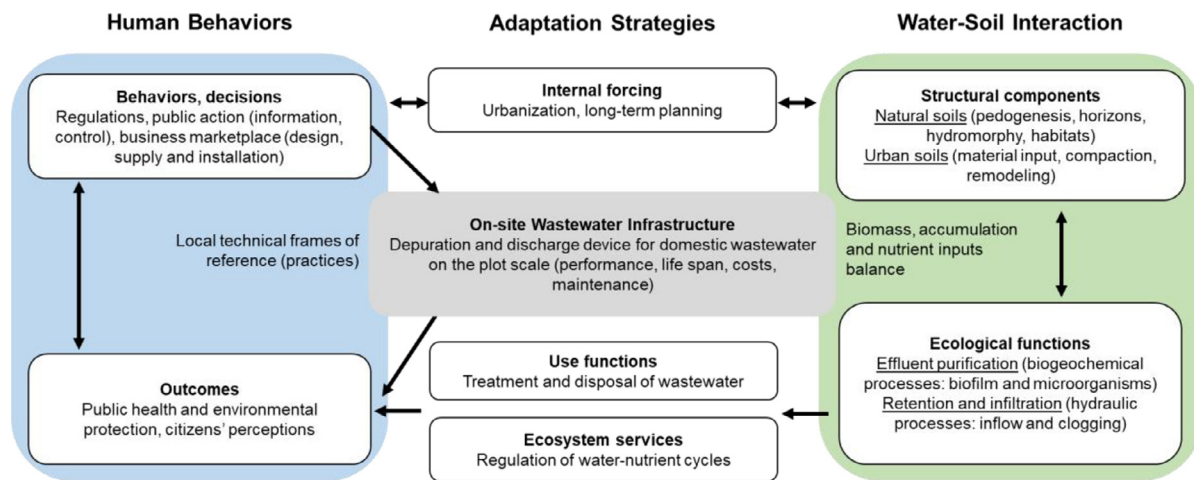


Fig. 3. On-site wastewater treatment systems, a sociotechnical functional perspective (adapted to OWTS from Childers et al. (2019)).

develop and test an original methodology for the analysis of on-site sanitation “social-ecological-technological systems” (Markolf et al., 2018). Through the use of two main concepts, we couple some views about “transition”, that unfolds at several scales and involves a wide variety of actors, and others concerning an integrative perspective to bridge urban scientists and practitioners. First, building on a sociotechnical system perspective (Geels, 2004), we propose to analyze the interplay between soil and water actors, OWTS technics and local institutions. Second, we draw from the framework of Urban Ecological Infrastructure (UEI), an extension of the Nature-Based Solution (Cohen-Shacham et al., 2016) concept, which is expected to facilitate the use ecosystem-related approaches in urban planning (Childers et al., 2019).

We propose to map this original perspective in a synthetic scheme: Fig. 3 is an attempt to adapt the UEI framework to OWTS. Drawing explicit relationships between ecological functions and built infrastructures is thought to help bridge operational gaps for the integration of socio-political and the biophysical dimensions. We consider OWTS 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. By implicitly figuring complex social and physical temporal dynamics (one configuration at each time step), this framework 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). Note the overall framing is embedded in a given territoire, notion which refers to a French social-geography perspective (Raffestin and Space, 2012) to map collective choice through the analysis of local multi-stakeholder’s decision-making processes with an emphasis on social and technical infrastructures.

Referred to as a sociotechnical functional perspective, this framework, necessary limited, supports the integrative analysis of interconnected transition in the social and physical dimensions of a hybrid NBS. More precisely, this perspective should provide a useful comprehensive support for disentangling interconnected factors that operate in OWTS management. Moreover, we suppose that emphasizing on adaptation strategies help envision the role of soils in water management and reciprocally.

To analyze the evolution of the interactions between soil infiltration rate assessment and design practices (ecological and technical environments) and institutionalized formal and informal rules (societies), we derive and test this framework through a 3-steps methodology. First and second, we contextualize technical design studies (water-soil interactions, indicators assessment) and the diversity and capacity of actors (policy and planning) respectively. These steps rely upon a literature re-

view approach 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). Third, to bind the social construction of a physical phenomenon (step 1) and the physical contextualization of a social phenomenon (step 2), we build on the application of a soil-based methodology tested during a development project (2017–2019) between OWTS experts and water managers from the Montpellier inter-municipality (Daudin, 2018). Through an overview on a case study, we analyze the adaptation strategies and identify some tracks about the compilation of available data at a territorial level.

### 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 (Patel et al., 2008).

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 (Siegrist, 2014). Although biodegradation processes are the basis of soil depurative function, action of soil microorganisms on organic pollutant strongly depends on the time of residence. Septic tank effluent 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 (Laak et al., 1974)), 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 (Schmidt and Boyle, 1980)). 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" (Dubber and Gill, 2014) 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, avail-

**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%	–

able 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.

Note subsoil water flows are complex and many solutions have been proposed so far in an attempt to simplify their assessments. Moreover, soil infiltration rates are measured with the use of clear water, which may not be representative of septic tank effluents (clogging capacity). 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 (Nasri et al., 2015a), 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 (Fouché, 2014);
- 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 (Barbier, 2009) may explain the historical lack of institutional attention to decentralized solutions (Brown and Farrelly, 2009). However, specific legislations have been implemented in European countries to regulate OWTS. In France, we suggest the start-

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

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

ing point for OWTS management to be the “second water act” in 1992, adopted in a context of decentralization and modernization of public services (Colon et al., 2018). This legislation was applied through a decree published in 1996, which laid down technical requirements based on design standards (Fouché et al., 2017). 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 8300 euros per infrastructure (Prébay, 2018)). 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](http://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 (Matzinger, 2020). 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.

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 (Fouché et al., 2017). Unlike gravity-fed systems, package plants depend on an authorization procedure based on off-site experiments of treatment performances (Boutin and Olivier, 2017). These systems represent around 60% of new devices implemented in France in 2018 (data from the French professional union representing all OWTS professionals, [www.ifaa.fr](http://www.ifaa.fr)). Hence, beside 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 (Bispo et al., 2016). 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. Fig. 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) (Fouché, 2014). 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 (Nasri et al., 2015b). First, the compilation of *in-situ* percolation test measurements (available in public authorities' databases,



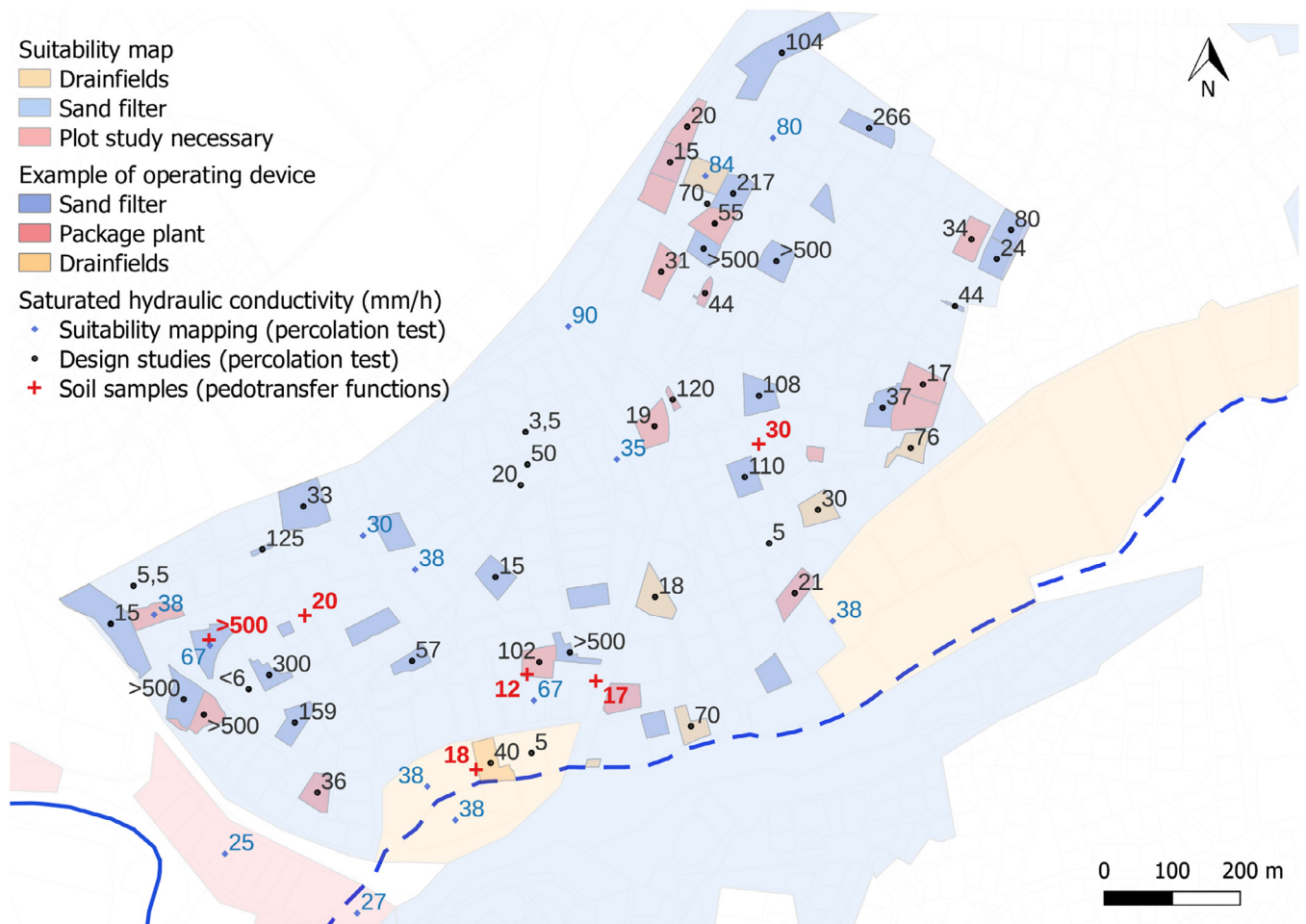


Fig. 4. Application of a soil-based methodology to the Montpellier case study. Source: Montpellier inter-municipality for suitability map, device in operation and measured permeability (black and blue numbers in millimeter per hour correspond to data from suitability mapping and design studies, respectively).

**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

mainly from design studies by private consultants) present a high variability at the neighborhood scale (Fig. 4). To address surfaced contestations, six soil samples were excavated at various depth all around the district (Daudin, 2018).

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 Nasri et al. (2015b)). The comparison between these outputs with *in-situ* infiltration rates is difficult due to various factors (Daudin, 2018):

- 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 (Patil and Singh, 2016);
- Diversity of measurements methods for saturated hydraulic conductivity and poor repeatability in space and time (Nasri, 2013);

- 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 (Daudin, 2018) of soil available information at the Montpellier inter-municipality spatial scale (439 km<sup>2</sup>). 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.

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, the soil-based new insights on the studied district did not help OWTS managers in their day-to-day problems. Indeed, the methodology (use of pedotransfer functions to replace *in-situ* measurements) was not robust enough to properly take into account complex environmental context with the occurrence of subsurface flows in alternating limestone and marl layers. 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 technics to spatialized data and used as managing tools are not neutral (Crampton and Krygier, 2001). 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' 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 (Melot and Hamilton, 2016), 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 depuration functions. Hence, formal and informal institutional arrangements (Hassenforder and Barone, 2019) 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. Indeed, given the many sources of uncertainties, favorable infiltration rates at the limit of the referenced range (e.g. 30 mm/h in France according to recent changes in national rules) may not be considered high enough for the implementation of a passive system;
- 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 (Dubois and Boutin, 2018) 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 (Fouché et al., 2017) 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 technics, 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 (Burch et al., 2018), 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 (Kabisch et al., 2016). Hence, it is of great importance to produce a comprehensive understanding of the system' functions and drivers which, combined with transdisciplinary collaborations (Daudin et al., 2021), have the potential to unlock sustainable management pathways (Burch et al., 2018; McPhearson et al., 2016; Grove et al., 2016).

Concerning soil-water interaction processes, the application of a soil-based methodology on the case study was not conclusive for management uses. Indeed, pedotransfer functions have to be sufficiently robust to replace *in-situ* measurements, especially in complex environmental contexts. In comparison with a recent study on the mapping of OWTS aptitude (Clergeau, 2014), the place-based approach could not be based on the combination of simple environmental factors (vulnerability of the aquifer and soil texture) for two reasons: aquifer vulnerability is available at a large resolution, and soil texture greatly vary in the spatial dimension and may not be directly representative of soil infiltration capacities. Hence, 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 (Fouché, 2014; Dubber et al., 2014) 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 (Stepanova et al., 2020), which involve engagement capacities (Frantzeskaki and Rok, 2018). In this regard, collaborations among public and private actors may be facilitated by small enterprises with potential for implementing innovation (Burch et al., 2018), enabling "adaptive governance" (Folke et al., 2005).

### 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 Mollinga et al. (2006)) 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 fulfill many of the NBS principles (Cohen-Shacham et al., 2016), which is a concept increasingly promoted across funding schemes and projects related to water management (infiltration trenches, constructed wetlands, rain-gardens). 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 (Capodaglio et al., 2017).

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 (Fuenfschilling and Binz, 2018) produces various levels of centralization-decentralization (Libralato et al., 2012), which may be the clue for adaptive urban water management that combine the benefits of each perspective (Torre et al., 2021). 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 (Wang, 2014; Dubber and Gill, 2014; Bieker et al., 2010). 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 (Leigh and Lee, 2019) in a *territoire* through material and energy savings (less pipes and pumping costs) and spatial and functional diversity (multiple service paths, redundancy, buffer capacities). Still, no matter the OWTS system (active or passive) or the decentralization level, with regard to environmental performance the periodical removal of the sludge and its final disposal should be considered in an integrative management process. Overlooked in this paper, the entire life cycle of the wastewater treatment process is gaining more and more attention (Risch et al., 2021; Yoshida et al., 2013).

#### 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 (Blanchart et al., 2018). 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 modeling 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 (Gómez-Álvarez et al., 2018), 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 (El Hajj et al., 2017)). 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 (Boulil et al., 2014), towards a fine-scale mapping of soil hydraulic functions in support of land-use planning.

## 5. Conclusions

In this paper we proposed a social-ecological-technological framing of the main challenges faced to improve on-site sanitation public services in urban areas. On-site Wastewater Treatment Systems (OWTS) present great opportunities for sustainable urban water management, but many difficulties arise when one tries to solve management issues. 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. This is why we proposed a retrospective systemic perspective on a science-practice collaborative project in a context of urban sprawl in the crown of large French Mediterranean cities.

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 technological device) is combined with densification constraints in metropolitan areas. We developed and tested a systemic perspective to build a common understanding of soil hydraulic function assessments and to clarify their relation to some misunderstandings between actors. Balancing the respective influence of (1) economic or regulatory forcing and (2) environmental data and expertise on soil characterization, on OWTS local practices, we showed that OWTS can source innovative solutions by considering soils as ecological interfaces in urban planning. More precisely, a better assessment of soil infiltration rate would support adaptive soil-water management both at plot and neighborhood scales for device design and planning, respectively.

This paper contributes to various research streams, mainly concerning Nature-Based Solutions, sociotechnical system transitions and urban indicators from new data streams. The method may be duplicated to other mix-built ecological infrastructure and have potential implications for the justification of land-use changes on a knowledge basis. Finally, the new insights for OWTS adaptive management could be suitable for transition places in low and middle income countries or regions, where the main development challenge remain (rapid transformation of cities, governance limitations, capacity barriers). Still, off-grid productive sanitation solution would need to broaden the research scope to include sludge management and propose a life cycle assessment of on-site systems.

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None.

### CRedit authorship contribution 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.

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