Stormwater management in the city

20 years of research in action

Othu
Observatoire de terrain en hydrologie urbaine

Coordinator and knowledge broker

graie
PÔLE EAU & TERRITOIRES

Collective work of OTHU under the direction of Laëtitia Bacot, Sylvie Barraud and Gislain Lipeme Kouyi

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In order to ensure the widest possible diffusion, this publication is available in English and French on the Graie and Othu websites.

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Foreword

Laurent Roy,
Director General of the Rhône Méditerranée Corse Water Agency

The optimal control of stormwater has become a major challenge for health and environment, particularly due to the high level of soil artificialisation. In France, between 20,000 and 30,000 hectares are built on each year, which increases runoff onto impermeable surfaces where it becomes polluted. The combined sewerage systems are saturated by this water, which leads to untreated pollution being discharged into the natural environment.

Solutions exist and have been proven: the disconnection of rainwater from piped networks and the restoration of soils so that water can infiltrate where it falls. The rainwater is thus reintegrated into the water cycle on the spot, which has the effect of relieving the pressure on sewage systems but also helping groundwater recharge. In addition, this integrated water management makes it possible to re-vegetate cities thanks to nature-based infiltration solutions (vegetated infiltration ditches/ bioswales, rain gardens, etc.) and to combat urban heat islands.

This policy, supported by the Water Agency, has made it possible to reduce the volume of untreated wastewater discharged into the natural environment from 62 million m3 in 2018 to 35 million m3 in 2020. This is due to the commitment of an increasing number of local authorities who are tackling this issue. They have a key role to play in this fundamental change as they are responding to environmental and health issues, but also because they are meeting society's expectations for cities that provide more room for nature and adapt to the effects of climate change. Roads, car parks, schoolyards, etc. are all spaces that need to be re-permeabilised and reinvented by making them multi-use spaces that promote biodiversity and well-being.

This transition towards a permeable city could not have taken place without sustained research and observation. For 20 years, OTHU, financed by the Water Agency among others, has produced studies in this field in the Lyon Metropolitan area. For example, OTHU has demonstrated that in rainwater infiltration structures, most contaminants are retained in the first few centimetres of soil. This expertise is a strength that enables developers to build the city of tomorrow, while minimising the impact on the environment.

The Rhone-Mediterranean-Corsica Water Agency is delighted with the publication of this guide summarising the main findings of OTHU's research work, which will be very useful to those involved in land-use planning and sanitation in order to manage stormwater better. I hope you enjoy reading it.

We would like to pay tribute to Laurent Roy, who supported the writing of this book and wrote one of the editorials in his capacity as Director of the RMC Water Agency.
His human qualities combined with a strong commitment made him a major player in the preservation and sound management of water in the region. His death has deeply saddened us all, researchers and operational staff alike.

Foreword

Anne Grosperrin,
Vice-president of the Metropolis of Lyon,
Representative for the water cycle

For two decades, the Metropolis of Lyon has supported and contributed to the research and the observations of OTHU in respect to improving stormwater management in the city.

This responds to a relevant challenge because it involves **making our cities permeable.** In short, this proposal represents a profound change, a shift in the way we plan our environment, build the city, and relate to our natural resources.

Considering cities as permeable means breaking ties with the largely prevalent hygienist approach, which is purely hydraulic and based on flow management, and instead get closer to the natural water cycle and allow rainwater to infiltrate where it falls.

We must disrupt our traditional approaches to urban planning because what is at stake is the availability of water resources, the quality of the living environment, health, the protection of aquatic environments and, globally, the adaptation to climate change.

Cities are now undergoing major changes to improve the performance of sewage systems, reduce environmental pollution, promote groundwater recharge, combat runoff and flooding, increase tree cover and plant vegetation to favour Islands of Freshness (the inverse of urban heat islands), and develop biodiversity in cities.

This is the goal we have set for the Metropolis of Lyon through a global metropolitan strategy called «Permeable Cities». Backed by the technical skills of the metropolitan water and sanitation departments; as well as drawing on the experiences of OTHU; other local authorities, and public establishments of the State, this ambition today implies a change of scale and culture.

What makes this so difficult, is that our policies relating to water, a finite resource, must now guide the other public policies (concerning urban planning, roads, vegetation, public buildings, etc.). For this to happen, the elected officials must apply this to public policies in a transversal manner and other services must integrate rainwater management into their projects from the very beginning.

Local authorities have a responsibility to bridge the gap between the innovations necessary for adaptation to climate change and an ambitious ecological transition at the local level. This book, which is the result of twenty years of research by OTHU, is a valuable tool to help them meet this challenge.

Introduction

The management of water in urban areas and its discharge into the environment (rivers, soil, groundwater) is and continues to be one of the major concerns of urbanised (cities, peri-urban areas).

Simultaneously, over the previous decades, rainwater is increasingly perceived as an asset and creates added value as a resource for the city (use as an amenity, reuse for different purposes, urban temperature regulation, biodiversity elements...).

Water management is therefore ambiguously situated between threat and opportunity, which is complex, but stimulating, for water and urban practitioners.

In this context, more than 20 years ago, the urban water stakeholders in Lyon (researchers and operational staff) got together to combine their efforts to further understand and to take action. The Water Department (and originally with the Urban Ecology Department) of the Lyon Metropolitan Council and the Rhône Méditerranée Corse Water Agency decided, together with a consortium of Lyon researchers from different disciplines, to co-construct and coordinate a Field Observatory of Urban Hydrology (Observatoire de Terrain en Hydrologie Urbain, OTHU) aimed at responding to the major concerns of our time related to water management in cities and, in particular, to water management on its catchment.

An unusual and courageous approach for researchers and operational staff

Researchers - whose specific scientific disciplines sometimes confine them and distance them from each other - were reunited to tackle complex subjects co-constructed with operational staff. These subjects require cross-disciplinary work and working at the interfaces between disciplines, which in turn necessitate that practitioners jointly observe systems and phenomena in both real situations and over the long term.

For the operational staff, the challenge was also a courageous one: that of bringing «contextual realism» to the research, but also that of confronting the research results, which could call their practices into question. Despite this, the Metropolitan Council and the Water Agency, via the Agglomeration contract, chose to adopt what a researcher in French field observatories called «precautionary innovation» as opposed to «radical» innovation involving uncontrolled risk-taking (Soyer *et al*, 2013)[1].

An indispensable glue: the GRAIE

Finally, one may wonder what glue had made it possible to bring together this atypical federation of researchers from such diverse disciplines and operational people with sometimes divergent concerns. This major binding agent was undoubtedly the GRAIE association (research group, technical training and information on water), whose role, since 1985, has been to mobilise and bring together actors in water management, aquatic environments and urban development. It has played and continues to play a fundamental role in the coordination of monitoring and the promotion of results. These results will be widely used in the association working groups, technical meetings and national or international conferences that it organises.

[1] Soyer M. Deroubaix J.-F., De Gouvello B., Hubert G. (2013). *Does innovation in metropolises depend on their ability to build specific relationships with their scientific environment? Forms, scales of networks and innovation trajectories in stormwater management in France,* 8th International conference NOVATECH, 23-27 june 2013, Lyon, 10 p.

But let's talk a little about what this observatory is all about, whose twenty years of research are reported here in this book.

OTHU: an inspiring model

In addition to these actions, OTHU serves as a model and in 2001 merged with the ZABR (Zone Atelier Bassin du Rhône) and is one of the supports for the EUR H2O'Lyon, which, from 2017, structures university training in the field of water and hydrosystems. It is also used to support the city strategies (e.g. permeable city, environmental monitoring, self-monitoring methodology, rainfall network, etc.).

But why OTHU specifically? And what does it cover?

Understanding the phenomena related to water management in urban or peri-urban areas is confronted by significant complexity linked to the spatial scales and the variety of the «objects» studied (catchment areas, traditional structures such as combined or separate sewer networks with or without overflows, alternative systems such as nature-based infrastructures). It also comes up against the variability and complexity of the natural and anthropic events involved, which require the consideration of hydrodynamic (types of fluid flow), physico-chemical (mobilisation and transfer of pollutants) and biological phenomena (impacts of discharges on the environment, plant species), the temporal dynamics of which are very different and closely interdependent. Ultimately, the phenomena depend on human activities in the urban environment and therefore on the practices of managers of technical systems and users. In the end, the global and integrated understanding of all these phenomena is often limited by the very mono-disciplinary organisation of research in France and the very fragmented nature of the management services.

Better knowledge and control of water management in cities and natural environments in dry and wet weather requires the acquisition of observation data on hydrosystems. The current practice in this field, since the 1960s, has consisted in carrying out measurement campaigns over time, sometimes numerous but rarely concerted. Although these field experiments have made it possible to improve knowledge (particularly in terms of runoff pollution), they have not made it possible to understand the dynamics, mechanisms or long-term evolution.

It was to break from these previous approaches that OTHU was established in 1999, with the ambition of creating a network of observations : **intensive** (to be sure of correctly observing phenomena when they occur and have good spatial and temporal coverage of phenomena whose variability is significant), **reliable** or at least with controlled uncertainties, **perennial** (to intercept rare events, integrate the evolution of technical systems over the long term and measure the impact of global changes (climate, urban development, etc.) on these systems) and **holistic** in order to tackle problems at the global level) and **interdisciplinary** in order to address issues at the interface of sciences as different as engineering, ecology, urban planning and sociology.

Introduction *(continued)*

The sites

The main observation sites used for the research presented in this book were chosen to cover, as far as possible, a wide range of configurations in terms of catchment area (physical characteristics and type of urban development), stormwater management systems (separe networks, combined sewer systems, management system at source) and aquatic environment (groundwater and small rivers).

Below is a map of the OTHU sites, and the table shows their main characteristics. Today, these sites are complemented by:

– a **rainfall and meteorological network** distributed over the greater Lyon territory;

– **so called "satellite" sites (4)** which are less heavily instrumented and monitored over shorter periods. They aim at confirming or invalidating trends observed on the main sites, or aim to further increase the diversity of situations;

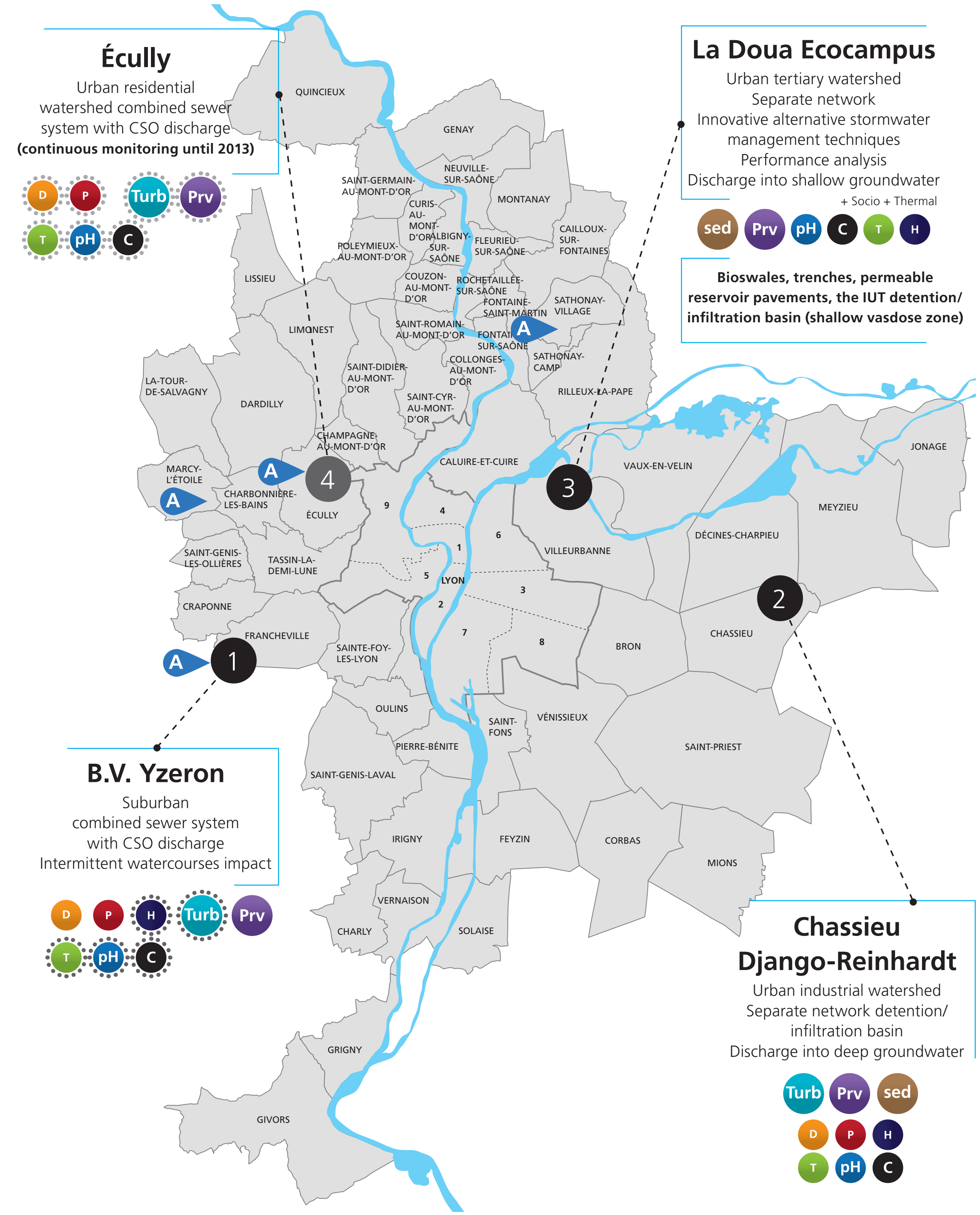
– **by "workshop" sites (13)** which have been monitored in the past or mobilized as part of research programs, and may be reactivated from time to time for research purposes or in connection with specific monitoring issues;

– **by laboratory facilities**under controlled conditions directly linked to observations made in the field.

Key of OTHU experimental sites

- D – Flow metering
- P – Rainfall
- T – Water temperature
- pH – Ph
- C – Electrical conductivity
- H – Water depth
- Turb – Turbidity
- sed – Sediment sampling
- Prv – Water sampler
- Measures adopted in 2013
- Measures adopted in 2017

Figure 1: **OTHU EXPERIMENTAL SITES**



\+ 13 *satellite sites* *(13 basins)*

\+ *3 remobilizable* *workshop sites* *for research projects DSM Sathonay, planted filter at Marcy l'Étoile, Grézieu la Varenne, Écully (A)*

Introduction *(continued)*

Table1: Summary of OTHU experimental sites

Information	BV Yzeron	Chassieu Django-Reinhardt	Écully	Ecocampus la Doua IUT
Type of catchment area (CA)	Suburban (130 km²)	Dense urban (industrial activity).	Medium-dense urban. Catchment area: 245 ha, sloping, area with Residential areas.	Medium dense urban 100 hectares, university activities.
Sewage system	Combined network	Separate network where the outlet is a detention basin followed by an infiltration basin	Mainly a combined network.	Intended for the study of water and pollutant flows, biodiversity produced by a drainage basin equipped with innovative alternative stormwater management techniques (bioswales, reservoir pavements, trenches, detention/ infiltration basin).
Environments affected by the associated discharges	Intermittent watercourses including the Chaudanne and Mercier streams.	Discharge into deep groundwater (unsaturated zone of around 13 m).	Numerous discharges via storm overflow into the Trouillat stream.	Discharge into shallow groundwater (unsaturated zone less than 1m for the infiltration basin).
Objectives	Characterisation of water and pollutant flows	Quantity and quality of water flows and pollutants loads produced on this drainage basin and assessment of their impact on the groundwater.	Quantity and quality of water flows and pollutants loads produced by this drainage basin.	Quantity and quality of water flows and pollutant loads produced on this drainage basin and assessment of their impact on the groundwater. Performance analysis of these techniques on The hydraulic, environmental and thermal aspects of source devices. Perception of at source stormwater mnagement by practitioners and users.
Operating status	Continuous rainfall monitoring (9 stations)/flow (9 stations) distributed over nested sub-basins. Quality monitoring via portable samplers (+ one fixed in porta-cabin that can be re-located).	2 equipped porta-cabin + groundwater piezometers.	1 equipped porta-cabin (de-equipped in 2013).	Since 2017: instrumentation of bioswales, trenches and porous pavements using 3 equipped measurement chambers. Since 2001: infiltration basin is equipped with piezometers for groundwater monitoring, instrumentation completed in 2021.

Sites shut down: The "Lyon centre" site located in a dense urban area (housing and commercial activities) on the Doua campus was initially equipped with a porta-cabin for monitoring discharges into the combined sewer system with monitoring of discharges via a storm overflow into the Rhône. For reasons of excessive maintenance, this site was shut down in 2008.

Workshop sites:

– the Écully site, which was monitored in detail until 2013 and was completely shut down in 2019 (de-equipped).

– the Grézieu la Varenne site within the Yzeron BV (2.5 km², 3 porta-cabins equipped on the Chaudanne stream to monitor the impact of the discharges of a storm overflow on an intermittent peri-urban watercourse: one upstream, one downstream the combined sewer overflow (CSO) and one at the outlet of the CSO, finely monitored until 2018. The site is being progressively de-equipped, with only the central porta-cabin (storm overflow discharge) remaining available for use if necessary.

– the DSM site (flow monitoring and control system) at Sathonay Camp, a canal designed to guarantee reliable measurements and monitoring of discharged pollutant flows.

– the filter planted with macrophytes in Marcy l'Étoile, which was designed to treat the discharge from a storm overflow and which served as a research tool.

Satellite sites (13 detention and/or infiltration basins) Bois Carré (Saint-Bonnet de Mure), Carreau (Décines), Centre Routier (Chassieu), Charbonnier (Vénissieux), Chemin de Feyzin (Mions), Chemin de Raquin (Chassieu), Grandes terres (Saint-Bonnet de Mure), Granges Blanches (Corbas), Leader (Saint-Priest), Léopha (Corbas), Minerve (Saint-Priest), Pithioud mi-plaine (Saint-Priest), Pivolles (Décines), Revoisson (Genas), Triangle de Bron (Bron) and ZAC du Chêne (Chassieu).

A book about more than 20 years of observation

Now that you have been informed of what a formidable knowledge tool this is, all that remains is for you to browse through the various articles classified under eight main headings. Each section begins with a general overview of the chapter.

These articles bring together the main scientific and technical advances and can be read in-part or out of order. They are stand-alone sources of information and have been produced jointly by researchers and operational staff under the watchful eye, and sometimes also the pen, of the GRAIE so that these articles can be, as far as possible, suitable for 'lay' reading.

Enjoy your reading!

Strategy 1

Stormwater management is constantly evolving to best meet the challenges of our century but also to satisfy the expectations of the ever-changing city and its inhabitants.

Question 1 reviews these developments and describes the goal to be reached: integrated management. The answer is not only technical, but also organisational and political. At the heart of this change, the local authority is the central link (driver or inhibitor). The initial feedback (question 2) shows that rethinking the internal organisation of these services can greatly assist change. Question 3 proposes to explain why support tools are also necessary and how they are developed. From a technological point of view, there are now many Alternative Solutions to networks: these facilities are often above ground, and in direct contact with the city and its users. They occupy shared spaces (parks, car parks, etc.). Question 4 deals with a fundamental aspect of these facilities: their integration into the urban landscape and especially their links with users. These facilities fulfil both social and technical functions.

Their appropriation by the public is a guarantee of their success: as shown in question 5, the facilities must serve the users or residents, but it is also a question of preventing these same people from damaging them. The last question deals with the maintenance of these structures: this is a recent concern because the systems is still fairly new, but OTHU has already been involved in the subject for several years.

1.1 Why and how to manage stormwater today?

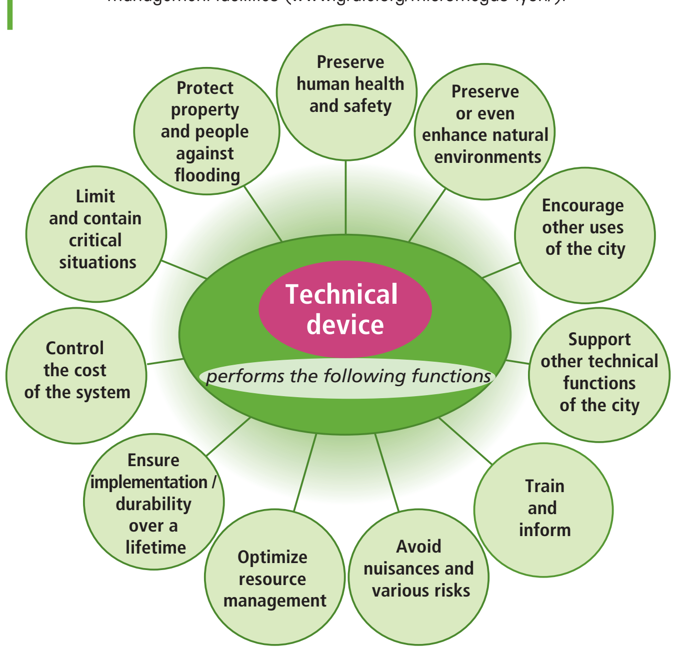
Frédéric Cherqui, INSA Lyon / University Lyon 1 – Elodie Brelot, Graie – Sylvie Barraud, INSA Lyon

The management of stormwater using an «all-pipe» approach is a headlong rush: concentrating water flows to evacuate them as quickly as possible results in generating risks downstream (flooding and pollution) and this simultaneously deprives us of water resources for the city (living vegetation and soil, islands of freshness, biodiversity). This management of water as close to the source as possible calls for a totally different conception of development and urban planning. Rather than techniques and integrated water management, it is about designing "water-responsible" regions: water-friendly development, which means that public services and interventions in the territory must be fundamentally transversal and multidisciplinary.

Pipes are not always enough to manage rainwater

At the end of the 20th century, many cities have started to realise the limits of the strategy initiated a century earlier of de-permeabilising the surface and using an "all-pipe" approach.

Figure 1: Set of service functions (performance to be ensured) of stormwater management facilities (www.graie.org/micromegas-lyon/).



In particular, the vast size of the works needed to cope with urban extensions or their saturation (overflows), the cost of these infrastructures (installation and renewal), changes in the hydrological regime of downstream waterways, or pollution of the natural environment. Cities have therefore turned to solutions aimed at managing rainwater at source (as close as possible to where it falls). These solutions, historically called, "alternative" in France (alternative to a piped network) stormwater management systems had the main hydrological function: to attenuate and/or delay peak flows generated by runoff on paved surfaces, to reduce the volumes transferred downstream (case of infiltration).

However, in the city, a space, even one used for stormwater management, is rarely dedicated to one function alone; it can be used for: roads, car parks, paths, parks, sports fields, etc. The city has a limited amount of land. The idea arose that it should not be wise to use part of this urban space only when it rains! These facilities have therefore been designed to be multi-functional from the outset. These functions can also evolve according to the manager's wishes or due to the way the public uses them.

Towards integrated management

Thus, the facilities must provide very different functions, and the hydraulic function is not necessarily the main one (as it does not rain most of the time). Figure 1 from the MicroMegas project provides a holistic view of these functions. We can identify "traditional" functions directly linked to water management, for example "protecting property and people against flooding", "preserving the health and safety of people»", "avoiding various nuisances and risks" or "preserving or even promoting natural environments". Other functions derive directly from the fact that these structures occupy urban space and are in contact with urban audiences, such as "promoting other uses of the city", "support other technical functions of the city" or "educate and inform" (e.g. by installing educational panels on stormwater and its course).

One dimension of integration is therefore the sharing of urban space for the cohabitation of water with other uses in the city. Another dimension of integration is to no longer consider each water management system independently. The historical view of distinguishing between wastewater, stormwater, drinking water and amenity water (fountains) makes less and less sense today: some cities, such as Singapore, produce clean water from wastewater (Lazarova *et al.*, 2013), while others reclaim rainwater for uses historically fulfilled by potable water (watering, washing, toilets). Rainwater is also often the main component of blue infrastructure, supporting biodiversity, but also in supporting the well-being and creating added value for the village.

The last level of integration concerns the practitioners, and it becomes essential to build a common vision (planners, design offices, local authorities, hydrologists, biologists, users, etc.) of the expectations and the ways to put this into action. This multifunctionality is experienced by some as a complexity that hinders the adoption of these solutions, but it above all a richness that brings multiple benefits for life and the city.

Different concepts for a common idea

This approach to stormwater management has different names in different countries and at different times. In North America, the concept of low impact development emerged in the 1980s. Around the same time, people started talking about sustainable urban water management or water sensitive urban design in Australia. More recently, Chinese President Xi coined the concept of the "sponge city". Although these concepts do not have exactly the same ambitions, the image of the sponge city illustrates well the objective of making the city permeable, so that it limits surface runoff in order to reduce flooding and the consequences downstream, and with a view to its reuse. The International Water Association (IWA) has recently launched an initiative with broader ambitions: the principles for water responsible cities (water-wise cities).

As shown in Figure 2, this is about planning and designing resilient cities. The aim of these principles is to encourage collaboration, supported by a common vision, so that local governments, urban professionals and individuals are actively engaged in identifying and implementing solutions for the management of all waters in the city, considering three new concepts: limited natural resources, urban densification seen as both an opportunity for economic development and a threat to quality of life, and the need to consider the uncertainty of the future in urban planning.

The answer to the question of stormwater management today is not only technical, it is also organisational and political. OTHU has been involved in this paradigm shift for more than twenty years by assisting local authorities in all aspects of urban stormwater management. The data acquired in the framework of long-term observations have made it possible, for example, to propose decision support methods based on the multi-criteria evaluation of the performance of structures and to make them operational via technical guides ("*L'infiltration en questions*"[1] for example). The articles in this book are all responses that OTHU proposes to accompany these processes.

Figure 2: Illustration of the 4 main principles for responsible water territories (IWA, 2016).

In Brief...

The image of water in the city has changed, as have its uses. Although the construction of any system has made it possible to manage stormwater drainage to limit the risk of flooding, it has also contributed to concealing this infrastructure and to making stormwater a nuisance or a risk. While the majority of wastewater and drinking water will continue to be piped, alternatives to piping have been developed for stormwater over the past several decades. These alternatives are no longer marginal and make it possible to design and manage a much more elaborate system, which go beyond the historical sewage/stormwater/drinking water divide.

TO GO FURTHER

- [1] **Barraud S., De Becdelièvre L.** (coord.), **Bedell J.-P., Delolme C., Perrodin Y., Winiarski T., Bacot L., Brelot E., Soares I., Desjardin-Blanc V., Lipeme Kouyi G., Malard F., Mermillod-Blondin F., Gibert J., Herbreteau B., Clozel B., Gaboriau H., Seron A., Come J.-M., Kaskassian S., Verjat J.-L., Bertrand-Krajewski J.-L., Cherqui F.,** (2009). *L'infiltration en questions : recommandations pour la faisabilité, la conception et la gestion des ouvrages d'infiltration des eaux pluviales en milieu urbain* - Guide published in the framework of the ECOPLUIES project – ANR PRECODD - lc.cx/ecopluies (in french)
- **GRAIE – Web page on the "Water-Responsible" principles**. *Highlighting the commitment of local authorities to "Water-Responsible" territories* - lc.cx/eauresponsables (in french)
- **IWA** (2016). *The IWA Principles for Water Wise Cities* - booklet, 6 p. Accessible: lc.cx/iwa2016

1.2

What roles do local authorities play in the development of at source stormwater management?

Nina Cossais, University of Tours CITERES/University of Lyon EVS – Anne Honegger, ENS Lyon

Despite their many benefits, at source stormwater management techniques are still in the minority compared to the traditional network. local authorities and their bureaucracy are often considered obstacles to their development... however, the reality is more nuanced.

Despite its recognised advantages, source control is struggling to become widespread

From the second half of the 20th century onwards, increasing urbanisation has led to a high level of depermeabilisation of the region, which generates ever greater runoff. To remedy this situation, stormwater management specialists are calling for a paradigm shift. This change goes beyond the field of sanitation and is of particular interest to urban planning stakeholders. The new water management tends to get as close as possible to its natural cycle, by using water on the surface rather than buried in pipes. Specialists encourage the adoption of a global approach in order to better integrate technical, social, economic and environmental issues linked to water.

Photo 1: Collective visit to Oullins as part of the internal Ville Perméable project, Metropolis of Lyon (source N. Cossais, 5 june 2016).

"The approach to the problem must be widened by strengthening the links with urban development on one front, and with the management of natural aquatic environments on the other" (Certu, 2003). This new approach is brought to life by the implementation of specific technical solutions: Sustainable Drainage Systems (SuDS) and, in particular, source control of rainwater as close as possible to its point of impact.

These systems have hydrological qualities that are recognised in technical and scientific circles. When vegetated, they can contribute to more sustainable urban development. However, despite numerous successful experiments over the past fifty years, source control is struggling to become widespread and to occupy a dominant position in relation to the traditional network.

A survey in immersion within the Metropolis of Lyon

As with any innovation, one of the major obstacles to their development is the inertia stemming from the bureaucratic or technocratic attitudes of the organisations in charge of implementing and maintaining the assets.

(Patouillard *et al.*, 2013). Our immersion survey in the services of the Lyon metropolis, between 2015 and 2018, allows us to validate this statement. Based on the study with this pioneering local authority, we show that the organisation of local authorities does indeed limit the widespread use of source control, but nevertheless offers sufficient flexibility to encourage experimentation.

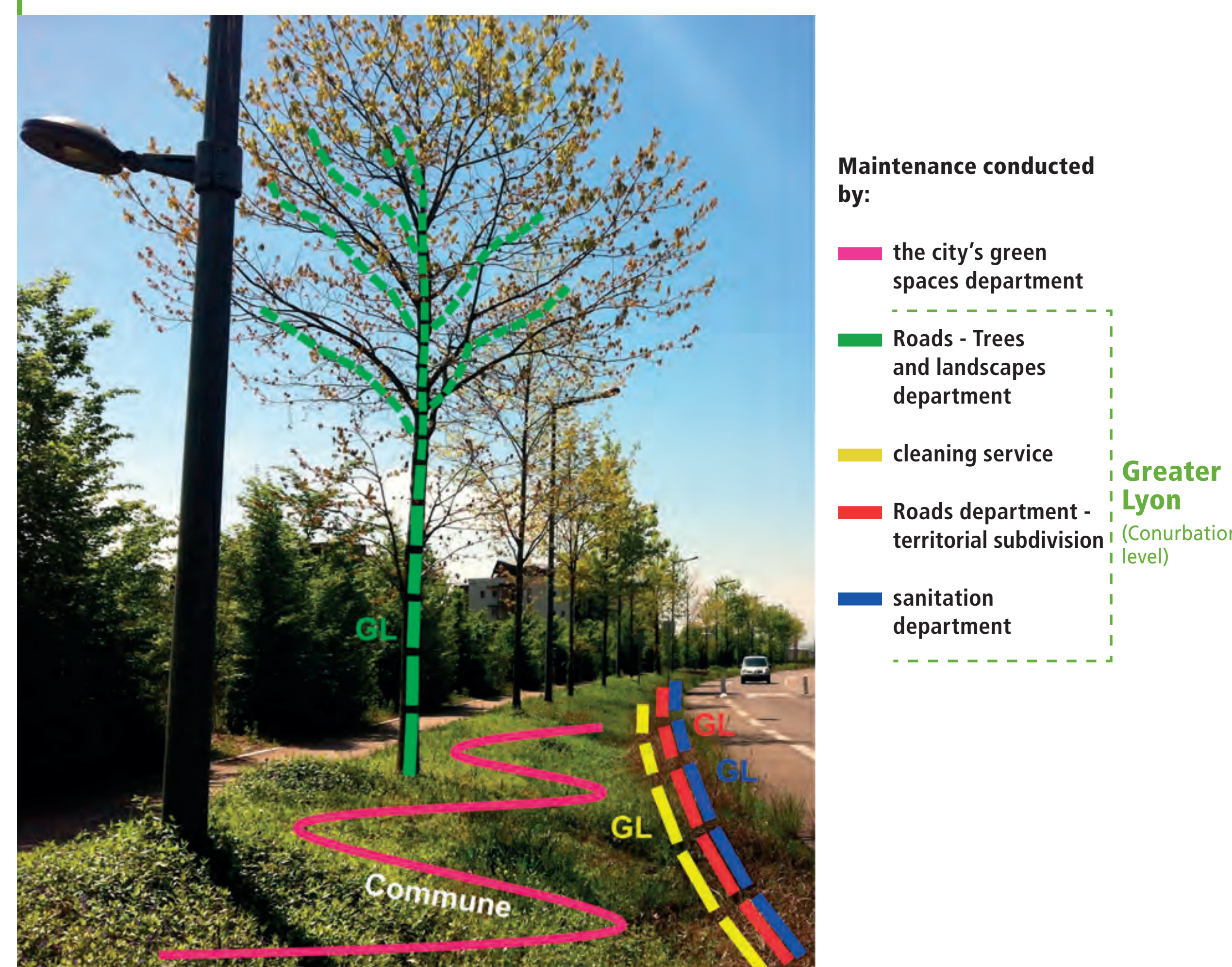
The socio-anthropological approach implemented is based on four complementary modes of investigation: a long immersion study within the design office of the water department (between 2015 and 2018), participation in the internal project *Ville Perméable*[1] (Cossais *et al.*, 2016), one-month periods of participant observation with the four main departments involved in the management of the works, as well as a campaign of semi-structured interviews with the designers involved in the development projects piloted by the Lyon metropolis.

To assess the applicability of our results, we also conducted a secondary survey of other communities: Strasbourg, Montreal and Melbourne. We also participated in working groups and scientific and technical conferences on urban stormwater management [2].

[1] The guide resulting from the project is available on the website www.grandlyon.com

[2] GRAIE Stormwater and Development Working Group, Working and Exchange Group, National Federation's Stormwater Management Department (FNCCR).

Figure 1: Technical services involved in the maintenance of a roadside, rue Hélène-Boucher in Bron (Cossais, 2019, p. 121).



1.2

Source control challenges the traditional organisation and competences of local government departments

The testimony of the project leaders confirms the role played by the Lyon metropolis among the pioneering local authorities in stormwater management. SuDS have been implemented since the 1990s. However, the systematic study of the use of source control in development projects is still very recent (around 2015) and the feedback is weak, not standardised and not very widely shared outside the design office of the water department. The distribution of design, construction and maintenance tasks between departments remains unclear. In a context of reorganisation of the metropolitan services, the development of source control disrupts the inter-service processes and questions the skills of the agents. Moreover, stormwater management is generally not a priority issue in development projects. Nevertheless, individual journeys and informal relationships largely encourages experimentation with these techniques.

On the whole, the departments responsible for the maintenance of public spaces are facing budgetary restrictions, which makes managers sceptical about new methods. The ban on agrochemical products further increases tensions and can lead to the rejection of techniques that encourage the proliferation of plants, such as permeable pavements. In addition, the distribution of responsibilities, budgets and maintenance tasks is perceived as complex. For example, vegetated ditches may require the intervention of four different departments (Figure 1). Finally, the management of the assets of the SuDS raises many questions, concerning both the conditions for carrying out and monitoring an inventory of the structures and the nature of the maintenance tasks to be programmed and their frequency.

The road, cleaning and green space workers who intervene directly in the field have little knowledge of SuDS. They are generally unaware of the hydraulic role of the assets located on the territory for which they are responsible, they have no opinion on alternative stormwater management.

The sewage workers, on the other hand, have a mixed view of SuDS. Below ground sewer inspections are becoming increasingly rare and the time workers spend underground is no longer sufficient to reach the 800 hours deemed necessary by the Caisse Retirement of Local Government Officials to benefit from "unhealthy status" (which involves early retirement and reduced hours). While many sewage workers point to the time spent on stormwater management works as a reason for this, the participant observation reveals other reasons. Firstly, mechanisation is reducing the amount of physical work in favour of monitoring tasks, which require less time on the sewer. Secondly, it is sometimes difficult to put together the three-person teams needed for below ground sewer inspections.

Apart from the important issues related to their status and the related social benefits, some sewage workers see the recent evolution of their activities, in connection with the constant increase in the assets linked to source control calls into question their traditional skills and they fear the disappearance of their profession. It is their professional identity that is at stake here. Conversely, some see interesting prospects for development in the management of stormwater at the source (Cossais *et al.*, 2018).

Local Authorities are a barrier on the widespread use of source control techniques

In terms of design, project managers emphasise the lack of feedback available to them. Stormwater management does not appear to be a driving force in development projects, which are mainly motivated by issues of attractiveness, mobility, safety and improvement of the living environment. The procedures for the validation of preliminary projects, as well as the criteria for the choice of works, do not allow the multiple benefits associated with SuDS to be taken into account. Nevertheless, the personal trajectory of certain project managers, who are aware of the issue of water management, and/or their links with practitioners involved in the development of source control, lead them to favour the use of this solution from time to time.

Even if the metropolis of Lyon is an exception due to the large number of employees (about 9,000), the varied projects it carries out, and its involvement in alternative stormwater management since the 1990s, many local authorities are facing comparable difficulties in the development of source control. The cases of Strasbourg and Montreal confirm the tensions concerning the distribution of tasks and budgets between departments. The case of Melbourne, on the other hand, alerts us to the risks concerning the durability of the works, linked to the difficulties of maintenance and upkeep also observed in this region.

The organisation of local authorities is thus, in part, an obstacle to the generalisation of source control. The Metropolis of Lyon was structured around major infrastructure projects, such as main roads or the sewer network. These projects required the intervention of dedicated services, made up of specialised practitioners. The new paradigm of water management requires a global approach. Source control systems are characteristic of this new paradigm. Their implementation and maintenance involve a large number of technical services that test their cooperation and coordination.

The existence of an interpersonal network conducive to innovation makes experimentation possible within communities

Beyond the obstacles described above, our analysis also highlights the crucial role played by local authorities in experimenting with new techniques. In their operations, there is a space that is particularly conducive to the experimentation of new technical devices. This flexibility allows practitioners working in a network to adopt innovation strategies. This network is mainly based on interpersonal relationships based on shared value systems. The internal mobility of agents within the metropolis favours the growth and solidity of the network. The interdepartmental processes still need to be perfected in order to improve the flow of information and to move from the experimentation of source control to its generalisation.

In Brief...

Saturated sewage systems cause flooding and discharge of pollutants. After forty years of experimentation, a few local authorities are committing themselves to 2010s towards the generalisation of Source Control. The analysis of the development projects piloted, designed and maintained by the Lyon metropolis shows that the organisation of the local authorities limits the generalization of source control, but it does provide room for experimentation. Local Authorities play a driving role, thanks to the network of source control supporters, and an inhibiting role, linked to the persistence of silo effects limiting the capacity and willingness of services to collaborate.

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1.3

What are the methodological tools to support the paradigm shift?

Frédéric Cherqui, INSA Lyon/Université of Lyon 1 – Laëtitia Bacot, Graie – Sylvie Barraud, INSA Lyon

The main challenge today is to move from managing a sanitation system to developing an integrated urban water management. To support this transition, operational actors need methodological tools to guide and inform their choices.

The origins of the urban climate

Why do we often talk about a paradigm shift in stormwater management? A paradigm is a representation of our reality, a model or a way of understanding it. It is therefore also a vision of how stormwater management should be done (objectives and solutions). Without going back over the history of water management in cities, it can be noted that at the beginning of the last century, stormwater was seen mainly as a nuisance, a risk.

The first concern is to evacuate it as quickly as possible from the city, here the river often plays the role a sewer without any real consideration of the impact on the natural environment.

Today, rainwater is also (and perhaps especially in some areas) an important resource that should be developed. The interested reader may wish to consult Mahaut (2009). The city must no longer be watertight, but must instead allow water to infiltrate and tend to have a minimum impact on the natural water cycle. At source stormwater management is a major solution to this paradigm shift. These solutions are themselves a far cry from the solutions of the last century. The networks are indeed very technical works, manufactured and maintained by engineers and technicians. The so-called "alternative structures to the network" are often more vegetated, co-constructed, multidisciplinary and dependent on natural processes (see for example photo 1).

Within OTHU, several research projects have aimed to provide methodological answers to help communities achieve this progressive paradigm shift.

The principle of methodological tools for decision support

Decision support covers all the methods or processes that enable a decision-maker (person, group of people or organisation) to reach the best possible decision. The operational tool is developed to help the decision-maker (who ultimately makes the choice), but it never makes the decision on its own. It is difficult to talk about the "best decision" because it is usually a compromise and therefore sacrificing one element for the greater good. Therefore, the term 'most adapted decision' is more appropriate to the context, or 'informed decision'.

These methodological tools are based on scientific methods such as :

- Multi-criteria analysis methods or performance evaluation systems (formulation and evaluation of indicators, construction of summary criteria);
- functional analysis tools (in particular the NF X 50 family of standards) which make it possible to characterise a system through the functions it must fulfil. These functions are often poorly known or poorly defined, yet they are a necessary prerequisite for assessing the system's performance;
- quality management tools (in particular the ISO 9001 family of standards) and, more specifically, risk identification or failure cause identification methods. These methods also make it possible to evaluate the performance of a system (in terms of risks or impacts), but also to seek out the factors limiting performance;
- Statistical tools, especially for the collection and analysis of case study data, as well as for the interpretation of these data.

OTHU has produced a large number of methodological tools related to stormwater management. These guides and data sheets cover a wide range of topics, from recommendations for the design and management of facilities to methods for assessing the service provided by the water management system.

The result of collaboration between operational staff and researchers

The approach when developing these decision support tools differs from how it is done in ecological engineering (Rey *et al.*, 2014).

The first step is to translate the engineer's questions into research questions in order to define the particular research subjects and topics to be developed. The next step is to develop specific methodologies and experimental protocols to answer these questions. This work usually relies heavily on the use and development of multidisciplinary knowledge and lay knowledge. The methodologies and protocols are then translated into operational tools and tested in the field.

A major difficulty is that it is often impossible to validate the method developed by validating the results obtained. Validation then frequently relies on the explicitness of the methodical approach to the construction of the methodology. Thus the problem of constructing a method for the professional world evolves from "determining the right way to act (substantive rationality) to finding a way to determine a way to act (procedural rationality)" (Simon, 1991).

In other words, it is often very difficult to validate a method by validating the results it produces; the only possibility of validation is then to validate (or justify) the steps in the construction of this method.

Therefore, helping stakeholders to choose the most effective strategies to improve the service levels of their urban water management system is mainly a matter of constructing an assessment: a space for discussion between different 'expert' knowledge around criteria and information that answer their questions, in order to rationalise decisions and allow stakeholders to make an informed choice.

Photo 1: "Rain garden" type of stormwater management, Meyzieu. Vegetation plays several important roles: aesthetic, biodiversity support, it also protects the landscaping (which could otherwise be trampled) and contributes to maintaining soil permeability (source F. Cherqui, 2015).

In Brief...

The desired evolution of a compartmentalised water management system (rainwater/wastewater/drinking water) towards a "holistic" system makes its management more complex. This can only be done with the help of tools and decision support methods that take this new complexity into account. We propose here a discussion on decision support tools and their construction.

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1.4

What is the link(s) between users and stormwater management facilities?

Frédéric Cherqui, INSA Lyon/University of Lyon 1 – Jean-Yves Toussaint, INSA Lyon

Whether they are researchers, planners, landscapers or local authorities; the promoters of alternative rainwater management techniques emphasise the need to integrate these systems as well as possible into urban developments. It is thus fundamental to define the uses produced or induced by these developments from their design.

Uses and functions of facilities: what are we talking about?

When considering what can be expected from stormwater management facilities, it becomes important to distinguish between uses and functions. In simpler terms, this means considering two points of view: that of the manufacturer who designs a product to meet specific functions and that of the customer (or user) who will use the product (uses). Let's take the simple example of a pen, its function is to write and one of its uses is to take notes.

Functions are the means by which a system can be made suitable for activities, to enable the system to function. For stormwater management, this means mainly storage, infiltration, evaporation, filtration, etc. A distinction can be made between service and technical functions. The service function, according to the NF EN 1325-1 and NF X 50-151 standards, corresponds to the action expected of a product to meet a given user's need. The technical function, according to these same standards, is the internal action of the product (between its components), chosen by the designer and producer within the framework of a solution, to ensure one or more services. For example, a service function of a detention basin is to protect against flooding and the associated technical function is water retention.

Together, these functions are to the rules of use that govern individual and collective behaviour (rules for generating practices). The application of these then regulate interactions between individuals and groups of individuals, by regulating access to manufactured objects and technical devices and their mobilisation in individual and collective social activities. These rules are generally implicit and not always codified in law (habits, habitus, routines, etc.). In this sense, uses make it possible to discount the behaviour of others: it is because these rules exist that I discount the behaviour of others, that I can coordinate my behaviour with that of others (typically walking in the street, crowds in the street).

A simple rule of use for a pedestrian path is, for example, to walk on the right in France and on the left in Australia: this is known to all and does not need to be put on a sign.

Traditionally the design of a stormwater management facility is carried out by one or more experts, using various modelling tools and based on the expected functions of the system to be designed. Unlike pipes, "modern" stormwater management facilities are often above ground and interact directly with urban audiences. These facilities must therefore adapt to the social norms of urban use to ensure their integration into the city.

Multi-functional stormwater management facilities

From a water management perspective, the objectives are to retain water, infiltrate it where possible, and retain pollution. When considering the development itself, the functions are much more numerous: Figure 1 lists a large number of them (the term performance is considered here as a synonym for function).

The desired functions will thus lead to the creation of very different types of facilities. It could be a detention-infiltration basin, a porous pavement, a bioswale, etc. Figure 2 shows examples of the diversity of possible designs.

Uses that depend on the number of visitors and the type of development

A specific study (Ah-leung *et al.*, 2013) of a development in the Metropolis of Lyon (the Kaplan park including a rainwater detention/infiltration device, Figure 3) showed the many different uses occurred in this development. Three investigative methods were used: documentary research on the "traces" of the project (administrative documents, deliberations, municipal newsletters, etc.), interviews with the practitioners involved in the construction of the park, and in situ observations of practices.

About 60 different behaviours were observed during the summer and spring of 2012: running, walking the dog, climbing on the gabions, reading, smoking, watching children, jumping in the water, playing, playing football, picnicking, working, chatting, recreational drug use, etc. These behaviours mobilise technical devices constituting the layout ("moat"1 , gabions2 , swings, benches, trees, fences, plants, etc.). They also mobilise other objects and technical devices such as books, computers, picnic boxes, balloons or bicycles. These behaviours involve adults (parents, workers, elderly), children and teenagers. The constitution of these people around the park would depend on its development and the presence of offices, housing and a school in the vicinity. Among these people; parents, workers and children are in the majority.

Figure 1: Set of service functions or performances that can be provided by stormwater management facilities (Cherqui *et al.*, 2013).

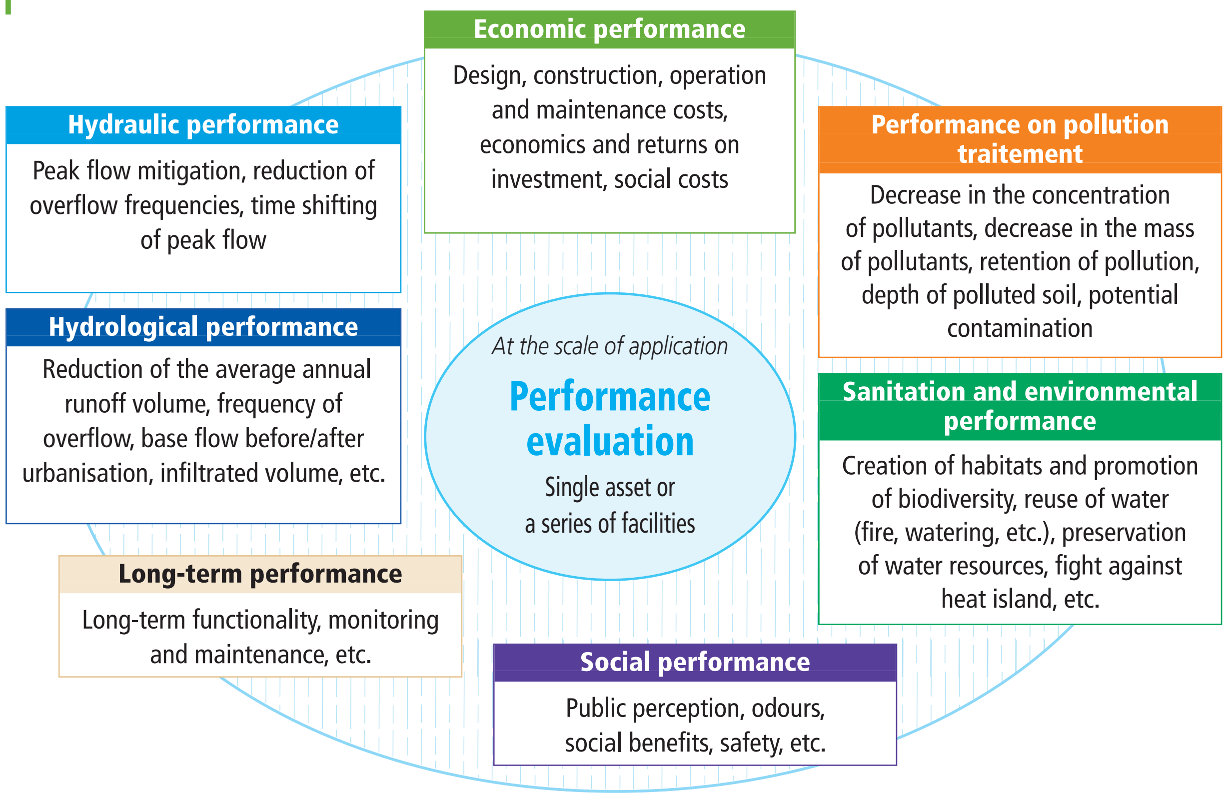

Figure 2: Examples of stormwater management systems: swales, simple infiltration basin, porous and permeable car park, infiltration basin designed as a football playgroundl (source: F. Cherqui).

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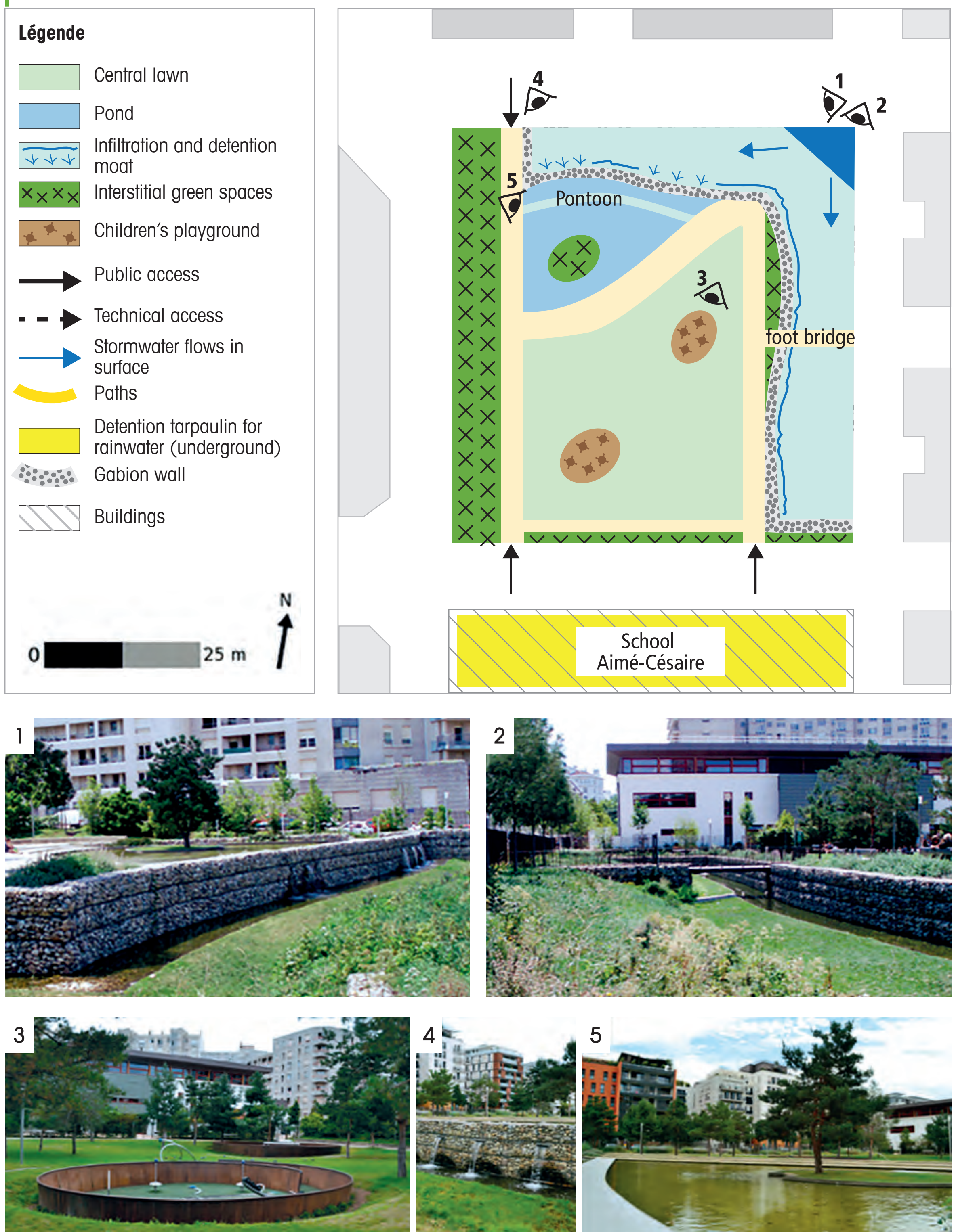
The analysis of the practices observed in the park suggests that it is perceived as a public square or garden, or even as a playground or sports ground. The behaviours observed refer to the usual practices in these places; these practices are typical of those commonly accepted in parks and gardens. In this respect, stormwater management systems do need to be distinguished from other technical systems forming the development in terms of urban practices and audiences: the sanitation function and the management of stormwater is invisible or undisguised in terms of its daily use.

[1] A moat normally filled with water and surrounding an element of the urban landscape (in reference to the defenses of fortified castles).
[2] A metal cage filled with stones and initially used as a retaining wall before becoming an element that had its moment of architectural glory.

Figure 3: General diagram and photos of Kaplan Park (Ah-leung *et al.,* 2013).



The use of facilities will depend directly on the facility itself and its environment. The urban functions fulfilled by the facility partly condition its uses: a park or garden type facility will have the uses usually observed in a park or garden, a car park type facility will also have corresponding uses. The urban environment and accessibility also play a very important role, since the uses also depend on the public using the facility (age, profession, reason for using the facility, etc.). In conclusion, it is not enough to consider only the hydraulic function of the structure when designing it. It is essential to define the uses produced or induced by urban morphology and urban types (the different developments that give shape to urbanised areas) from the design stage.

In Brief...

The system used to manage rainwater must no longer be considered as a structure but as a development. It is no longer a question of creating technical objects with a mainly hydraulic function, but rather of thinking about water management in the organisation of the city and its development.

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1.5

How do the public use alternative stormwater management systems?

Sébastien Ah-leung, INSA Lyon

By participating in the reintegration of the As a «natural» solution in the city, alternative rainwater management techniques fulfil both social and technical functions. However, the installation of these systems in public spaces can, in certain cases, pose problems of appropriation by the public and lead to degradation of the works.

Why observe the relationship between Sustainable Drainage Systems and the public?

In France, over the last forty years, so-called "alternative" techniques have been developed to manage rainwater in the network. These techniques contribute to the aspirations shared by the elected representatives, managers and the general public on the reintegration of "nature" in the city.

They propose water management at the plot level through a set of hybrid devices, both in their appearance (half-natural, half-artificial) and in the functions that can be attributed to them. Indeed, Sustainable Drainage Systems (SuDS) can have various technical characteristics and forms (bioswales, ponds, planted filters, etc.) but also combine technical functions (purifying rainwater) and social functions (participating in the well-being of the city) (Figure 1).

However, the installation of SuDS in public space by manufacturers seems to cause many problems due to appropriation by the public. Under the all-encompassing term «manufacturers», a myriad of roles are hidden, ranging from the designer of the object (engineer, researcher, etc.) to the manager of the object (community, technician, company, etc.). These manufacturers build and enable life in the city through the objects and/or devices they deem necessary (whatever the reasons and justifications). The "public", on the other hand, refers to all the people likely to be confronted with the devices in the public space.

These problems arising from appropriation can lead to malfunctions and are due to using SuDS for unintended purposes. For example, in the case of a stormwater detention pond, the attraction of water combined with hot weather can lead to the public entering and swimming in the pond. In doing so, the public can damage the structure, particularly by tearing the geotextile covering the bottom of the pond. This damage can lead to malfunction of the structure and possible contamination of the water table. It is therefore important to understand the reactions and behaviour of the public with regard to these facilities. The objective is to adapt the specifications of these structures to improve their reception and their integration into the public space, but also to limit incompatible uses.

Figure 1: SuDS include a wide range of structures: ponds, reed filters, ditches, etc. built in different ways in different environments (source S. Ah-leung).

What do these observations tell us?

The observation of the behaviour resulting from the relationship between the public and SuDS has revealed a number of Elements relating to the activities, audiences, and installation of SuDS in urban areas

Multiple uses of Sustainable Drainage Systems by the public

Stormwater management systems appear to elicit multiple behaviours; the intensity and diversity of which differ between the systems studied (Table 1). These behaviours can be associated with several activities (sports, recreation, etc.) and vary according to many variables: minor (seasons, weather conditions, location, etc.) and major, such as the type of public or the composition and type of device. For example, detention and/or infiltration basins seem to result in more behaviour than other types of SuDS. The boundaries between these categories are not strict and some differentiations can be questioned: for example, when a group of children play with a ball, is this behaviour a sport or a play activity? Thus, this classification is partly subjective and the classification of an activity in a category is therefore left to the discretion of the observer according to the action situations observed in the field.

Stormwater management systems represent for the public places they can use to socialise, play and relax. However, the

Table 1: Main behaviours observed on SuDS.

Types of activities	Subtypes	Main behaviours observed
Leisure	Sociability	Meeting up, talking
	Sports	Running, badminton, snorkelling, motorcycling, canoeing, horse riding, rollerblading, skateboarding, cycling, volleyball, scootering; playing bowls, football, golf, rugby, tennis; swimming, fishing, diving
	"Playful"	Fetch the ball from the bins, play with stones dig holes, slide down the slopes, climb, throw objects, play with a bungee cord, play with a ball, play with pieces of iron, play with the grating, play with the vegetation or infrastructure, walk on the gabions, observe the outlets, collect algae, hide
	By nature	Sunbathing, contemplating the landscape, throwing rocks, playing with wild animals, feeding wild or stray animals, observing animals, picnicking, taking photos, collecting rocks, lying in the grass, dipping feet in water, making fire
	Other 'leisure' activities	Listening to music, smoking, lying on benches, sitting on infrastructure elements, tagging
Domestic	Child-related	Walk the children on the gabions, supervise the children
	Animal-related	Burying pets, playing with or walking your pet
	Related to housework	Beating car mats, hanging out laundry
Professional		Work, revise, write, read, read the signs
Travel-related		Quad biking, scootering, cycling, parking, walking, crossing
Related to physiological needs		Resting, eating and drinking
Illegal or inappropriate		Damaging vegetation, damaging fences, setting off fireworks, removing stones, jumping on infrastructure elements, throwing branches or stones, drinking alcoholic beverages, breaking infrastructure elements, swimming dogs in pools, making fires for cooking, having sexual intercourse, throwing away rubbish, buying/selling cigarettes or hashish, driving through green spaces in a motor vehicle, urinating

1.5

How are these practices and uses observed?

The survey is based on direct observation in situ at all times of the day. It was carried out over 18 months at 12 different sites and four types of Sustainable Drainage System (SuDS). This method allowed us to collect behaviours with a minimal change. In addition, the observation was coupled with systematic photo-taking to evidence the observed behaviours (Figure 2). OTHU's help in selecting the sites to be investigated was invaluable, thanks in particular to a database and the knowledge of researchers and practitioners of the various sites in the Lyon metropolitan area. Feedback from current or previous local or national studies helped to adopt the appropriate methodology.

social activity present is not specific to this type of facility: similar activities can be observed in other spaces that do not have them.

The characteristics of the public influence the observed behaviour

The Public does not constitute a smooth homogeneous entity, they are characterised through different criteria that play a role in the fluctuations observed within the social activity. This diversity is qualified through three criteria: age, gender and configuration.

First of all, we can see that some of the behaviours can be observed across all audiences. Indeed, behaviours such as walking one's pet or eating out are not attributed to a particular type of public. Similarly, the fact of being male or female has only a minor influence on the number and type of behaviours (except for children, where the differences are quite clear between boys and girls). On the other hand, when we consider the distribution of behaviours by age, differences appear in terms of diversity but also in terms of nature. Children show more and more varied behaviours than the other age categories. Finally, the study of configurations (carrying out activities alone, in pairs or in groups) shows that when individuals are on their own, their behaviour is more numerous and diverse. Each of these characteristics seems to shape the social activity related to nature objects and partly explains the differences that can exist between two technical devices with the same facilities.

Differentiating between "uses" and "practices"

Some practices are recurrent and can be observed on all SuDS (feeding wild animals, throwing stones in the water, pulling up plants, etc.) while others seem to be more occasional (setting off fireworks, swimming one's dog, having intercourse, etc.) or contextual (e.g. littering in connection with a cultural event). It is mainly these practices that have the potential to cause physical damage to technical devices, damage their reputation and alter how well they function; thus, generating a demand for intervention by manufacturers. However, not all practices necessarily result in negative external factors for their manufacturers.

Observed at different intensities on most of the SuDS, the practices were recorded more among male children and adolescents than among other audiences. Although there are no direct correlations between a specific technical device and the existence of these practices, we can nevertheless observe that certain types of SuDS result in more activities than others. For example, reed filters or detention or infiltration basins lead to a lot of playful or natural behaviour (pulling up plants, bathing in the basins, etc.).

Factors favouring the emergence of penalising practices

Practices are neither associated with a type of SuDS, nor are they systematically associated with a type of audience or a type of setting. They derive mainly from the way in which each individual envisages the use of the devices present in his or her environment through the attainment of objectives which are specific to him or her. For example: using the SuDS as a waste disposal area because

"It's still closer and easier than going to the waste centre, you don't have to queue" or using the SuDS as a playground because "Jumping the fences [of the asset] is a bit of a challenge! It's to see what we've got in us" (photo 1).

However, the observations did highlight a few factors that could explain the greater presence of the practices on certain sites.

SuDS are composed of a large number of technical elements. Some of these elements generate very little practice, while others generate a lot. This is the case, for example, with fences, wooden elements, signs and ditches. The presence of these different elements on a site systematically generates practices that can potentially cause management problems on sites that have them. In addition to the composition of the SuDS, its appearance also plays an important role: poorly maintained or features that appear poorly maintained tend to generate certain practices, such as littering, more than others.

Photo 1: Example of a practice where individuals break into a SuDS installation. The aim here is to take up a challenge: to enter an enclosed space and retrieve an object as proof of the challenge, in this case a handful of reeds (Sébastien Ah-leung, 2013).

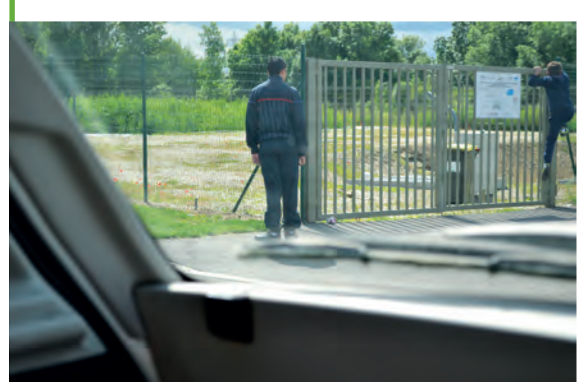

Figure 2: Direct observation as the main methodology (Sébastien Ah-leung, 2014).

Informing the public and raising awareness can limit these practices

In addition to the technical aspects that support the practices, the way in which the SuDS installation project is conducted also plays a role. Overall, projects that have integrated the public throughout the design process of SuDS report a limited number of practices. This is because the public feel part of the project and can discuss with the manufacturers and understand the value of integrating SuDS into their environment. Similarly, SuDS projects that include explanatory panels, information campaigns and/or visits generally generate fewer practices.

In Brief...

By integrating Sustainable Drainage Systems (SuDS) into the public space, they seem to attract multiple behaviours. These can be of different types (sporting, recreational, professional, etc.) and vary according to the characteristics of the audience (gender, age, etc.). Not all behaviours have the same impact on SuDS. Some of them can damage technical devices and lead to malfunctions. These disruptive behaviours can in some cases be favoured by technical (fencing around the SuDS) or organisational (frequency of maintenance) factors. They can be limited by implementing active public participation upstream of the project and effective communication in the field.

TO GO FURTHER

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1.6

The thorny issue of maintenance of Sustainable Drainage Systems: myth or reality?

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Frédéric Cherqui, INSA Lyon/University of Lyon 1

Some of the first alternative stormwater management facilities are now over thirty years old. Beyond the problems of cleaning and regular maintenance of these structures, there is now the question of their ageing and long-term management.

The need to implement asset management of stormwater management facilities

The issue of maintenance of stormwater management facilities seems to have become increasingly important in recent years. Due to the fact that local authorities already have old assets, the question is worrying. For some, it would even be an obstacle to the adoption of Sustainable Drainage Systems (SuDS).

Déjà vu, the older generation will say. Not long ago, much was written about the design and sizing of these structures. It was also a major obstacle to their adoption. Today, the design is much better mastered and there are even online tools[1] to facilitate the pre-sizing of structures.

The problem of maintenance arises in the longer or shorter term. In the short term, the various players are wondering about the nature, frequency, and distribution of maintenance tasks. In the long term, the maintenance of facilities requires the implementation of a new organisation. It is true that the management of rainwater management facilities is only just beginning for many communities. The main principles are well known: take an inventory and know your assets; measure the performance of the system, investigate the works, evaluate their state of health and their potential impacts; plan for the future and therefore determine priorities; rehabilitate the works, control the quality during and at the completion of works; improve the knowledge-base. All these elements are linked to past or present OTHU work. Future work and feedback will progressively fill in the current gaps.

How to get started?

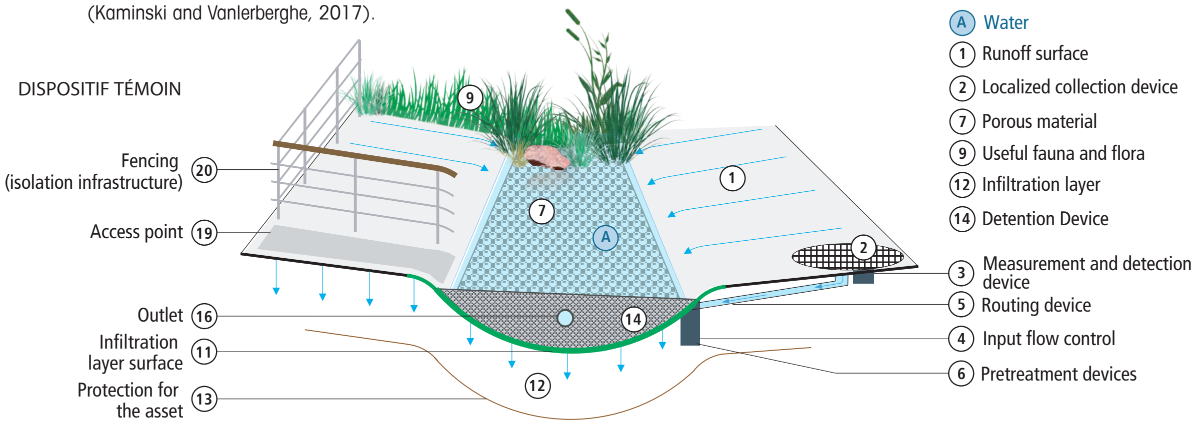
The inventory stage (inventory, detailed description, constituent elements, etc.) is particularly important here. The stormwater management structures have been and still are very poorly inventoried by the communities, even if some have started this work. The inventory is often carried out by entering the structures on a specific layer of the community's Geographic Information System (GIS). This potentially allows the evolution of the performance of the works to be monitored and interventions to be better coordinated, while storing operating data. Indeed, as various trades are likely to be involved in the construction of the SuDS (civil engineering, roads, green spaces), their integration into the GIS is often incomplete or insufficiently shared between the services. This sometimes leads to their degradation for the installation of equipment, such as lighting masts or tramway cables.

The description of each structure should include at least: plans of the structure; list of components; design assumptions. Figure 1 shows the variety of components that can be found in a development.

For each structure, it is also necessary to set up a logbook specifying the regular maintenance operations, the services in charge of these operations and their periodicity. This logbook will also specify the checks to be carried out and the actions to be taken or the services to be contacted in the event of a malfunction being observed. Linking this information with the GIS will allow for better monitoring over time.

[1] Such as www.parapluie-hydro.com, https://ewater.org.au/products/music or www.pcswmm.com

Figure 1: Hypothetical stormwater management facility, containing all the components that would be observed (Kaminski and Vanlerberghe, 2017).



The division of maintenance tasks

Within the Lyon metropolitan area, the question of the upkeep and maintenance of structures, as well as better consideration of these aspects from the design stage of the development, were the subject of the internal Ville Perméable project (2015-2017). A thesis in urban planning and development was carried out within this framework and has been completed (Cossais, 2021). It analyses the organisational factors linked to the development of SuDS and with a particular focus on maintenance. Participatory observation with maintenance teams allows for a better understanding of the issues facing the services concerned and their compatibility or otherwise with stormwater management.

The nature, distribution and frequency of maintenance tasks were observed in the Lyon metropolitan area. They are subject to different configurations: there is no systematic rule. The tasks have been categorised according to their historical department. For example, C1 (surface cleaning, grids and gutters) and C2 (waste collection) are traditionally assigned to the road workers in the cleaning department. The different possible configurations for the distribution of tasks by type of work are presented in Table 1.

The analysis of these configurations reveals, first of all, that certain tasks appear to be "unusual" for certain services (they do not fall within their historical specialities): mowing for the cleaning service, waste collection in fenced basins by the sewage workers, cleaning of porous pavements by t he road services, etc. Secondly, there are significant differences in the number of services involved, depending on the type of work considered. Secondly, there are significant differences in the number of services involved, depending on the type of structure considered. Infiltration basins closed to the public, which are fenced off, only involve sewage workers. On the other hand, bioswales may involve four different departments. Finally, informal interviews conducted in the field show that unusual tasks are very often subcontracted to a company, postponed or insufficiently carried out (Cossais, 2019).

Why does it seem so complicated?

The main difficulty here is to adapt the principles of asset management to a continuum of techniques (of very variable form and composition) that is more often "natural" (soil,

Table 1: Possible configurations for the allocation of stormwater management maintenance tasks in the Metropolis of Lyon in 2016 (Cossais, 2019).

		Cleaning	Sanitation	Green spaces	Roads
Infiltration wells		C1 Surface cleaning of grids and drains (if required)	E1 Maintenance of hydraulic structures (if required) + E2 Cleaning or unclogging (if necessary)	–	–
Drainage trench				–	–
Noue	grassy	C1 C2 Waste collection (according to dirt and expectations) J1 Mowing (1 to 4 times/year)		–	E2
	landscaped	C1 C2		C2 / J1 J2 All plants (approx. 1-2 times/year) J3 Weeding (if necessary) J4 Watering	
Underground pool		C1	E1	–	–
Open pond	closed	–	E1 / E2 / C2 / J2 D1 Weeding (if necessary) E3 Self-monitoring	–	–
	accessible to the public	C1 C2	E1 / E2 / E3	C1 / C2 J1 / J2 / J3 / J4	–
Porous coating		C2 / J3 V2 Coating maintenance	–	–	V1 Coating repair V2 / E2

1.6

vegetation, water) than constructed (concrete, steel, etc.), as illustrated in photo 1.

The second difficulty is to adapt maintenance to the functions performed by the structure, which can be very diverse: hydraulic, hydrological, sanitary, environmental, social (see Question 1.1: *Why and how to manage stormwater today?*). For example, if the structure supports recreational activities, frequent mowing will be desirable; if, on the other hand, the objective is to encourage biodiversity, the minimum intervention will be prescribed.

Thus, it is necessary to be able to adapt the investigations and the performance levels. Depending on the placement of each structure (at the entrance to the city, in an industrial zone, near a school, etc.), the expected level of performance may be different. For example, a bioswale (vegetated ditch) at the entrance to a town has a showcase role and its vegetation must be regularly inspected and maintained (unlike a bioswale or ditch at the bottom of an industrial zone), or a structure near an area vulnerable to overflow (near a crèche for example) will not be monitored in the same way as an area that is not very vulnerable (such as a car park).

The third difficulty is the teams responsible for the maintenance of these facilities. These teams must be specifically trained to understand the operation of these structures (and thus identify malfunctioning situations). Depending on the type of development concerned, the teams mobilised may also be different (Table 1). It is therefore essential to define the responsibilities and actions of each person.

Several avenues of research to improve the management of structures

The maintenance of stormwater management structures is a very recent emerging issue, and many avenues of research are open, directly related to the difficulties raised above. Part of this research can be based on the experience of the asset management of other structures such as sewerage networks or dykes.

A first line of work concerns the precise definition of the performances expected from these structures and the formulation of indicators to measure these performances. This work was initiated by the Ecopluie research programme and the thesis of Priscilla Moura (2008). It has continued within the MicroMegas research programme. The second track concerns the development of structure inspection sheets in order to provide the person in charge of monitoring the structures with elements that make it possible to assess the functioning of the structure. This work is part of the MicroMegas project (mentioned above) and the European Mind4Stormwater project.

The next step is to envisage systematic and automated monitoring solutions for the structures, which would provide alerts in the event of malfunction. This continuing work is part of the observatory (OTHU).

Photo 1: Example of a rainwater management structure: rain gardens, Meyzieu (source N. Cossais).

Contrasting feedback

The example of Melbourne, Australia, where an audit of built works was carried out in 2017, prompts us to remain vigilant. The audit, carried out as part of the Living Rivers programme and funded by Melbourne Water, covered 95 structures: 57 rain gardens, 25 tree pits and 13 wetlands.

The study concluded that 75% of biofiltration systems or tree pits were not functioning properly. Worse, 25% of these systems are malfunctioning and are likely to have a negative impact on water management. The primary cause of malfunction is water supply, firstly due to design problems, secondly due to maintenance faults, and thirdly due to construction problems. However, if this example prompts us to be cautious, the Australian and French cases cannot be easily compared. Firstly, Australian sanitation is largely based on a separate system. The objectives of alternative stormwater management structures are therefore primarily qualitative, with relatively fragile structures. Secondly, the organisation of communities is very different.

In the case of the Lyon area, it should be noted that despite the poor maintenance (or lack of maintenance) of many structures over several decades, initial observations, particularly in the context of the Ville Perméable project, suggest that these structures are quite resilient. Moreover, most maintenance operations are relatively simple and do not require advanced expertise. They can therefore generally be carried out by the services usually responsible for managing public space, subject to satisfactory coordination.

In the case of the development of the Porte des Alpes site in Saint-Priest[2], systematic monitoring was planned from the creation of the works. Global balances on three lakes that serve as water detention basins for rainwater, on the biodiversity that they host, have been established in this spirit every five years. This monitoring covers plant and fish species and the physical and chemical quality of the water and sediments. They are the responsibility of the Lyon metropolitan authority, and the results are shared between the design and operating teams, as well as with the partner associations. This monitoring enables the site management practices to evolve continuously to maintain the biological diversity and balance of this new ecosystem and to preserve the hydraulic functioning of the structures. The ecological development of the lakes is described as remarkable by all the associations for the protection of fauna and flora (Sibeud and Mazereel, 2007).

[2] See lc.cx/portedesalpes, sheet produced by the Graie's Observatory of exemplary operations for stormwater management: www.graie.org/portail/animationregionale/techniques-alternatives

In Brief...

There is a growing concern about the long-term management of Sustainable Drainage Systems (SuDS). It is explained both by the ageing of the structures and by the complexity of their management, linked to the diversity of the structures, their status and the actors involved. This issue is growing rapidly and there are now tools and strategies to be implemented for the efficient management of these structures. Several cities are currently embarking on this process.

TO GO FURTHER

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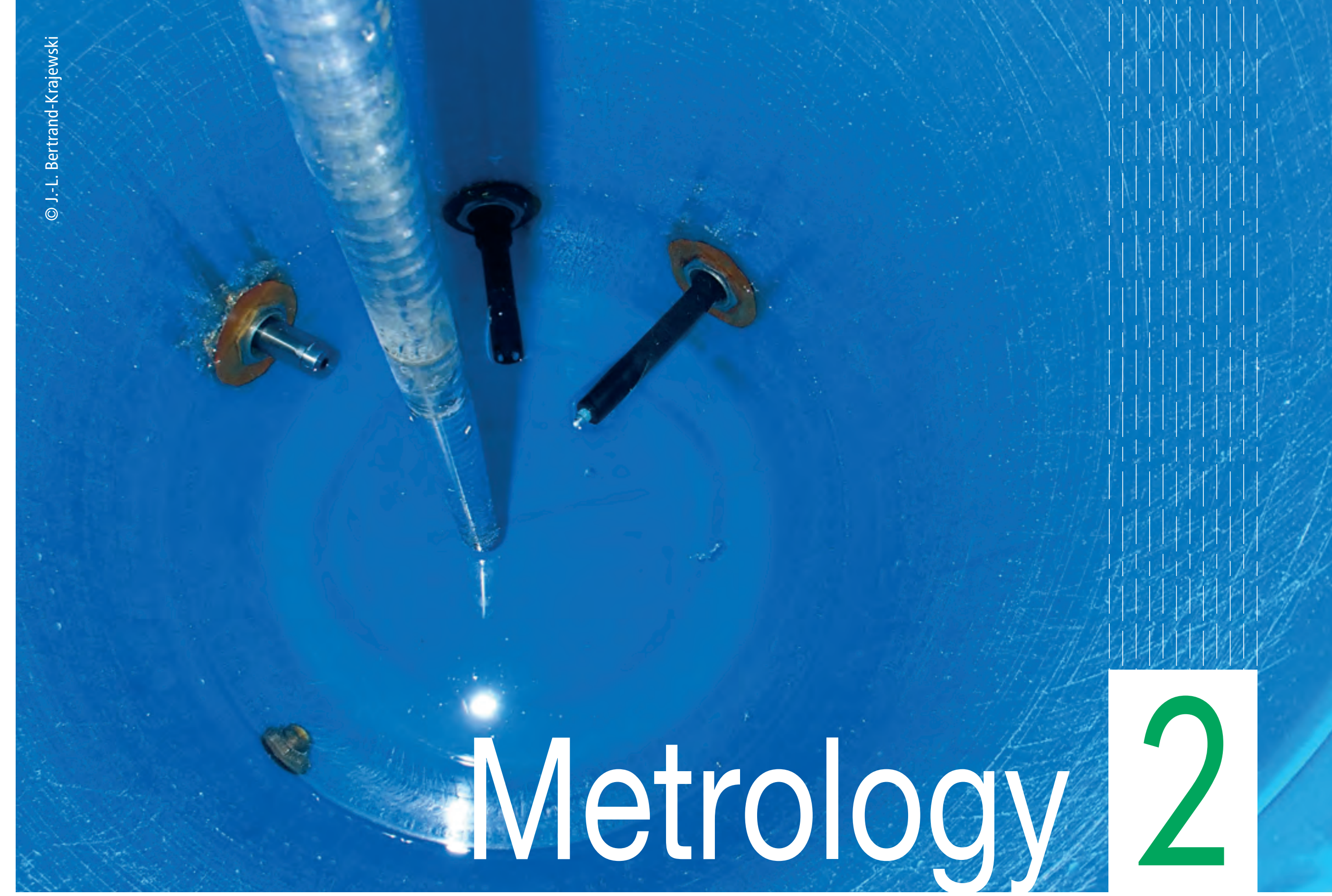
- **Chocat B., Insa de Lyon and the Graie working group « Eaux pluviales et aménagement »** (2014 updated in 2020). *Nature objects: What place(s) in the city? Conditions of appropriation of stormwater management systems in the Lyon metropolis.* Note sur les techniques alternatives, Graie, 58 p. - lc.cx/graietechniquesalternatives (in french)



Metrology 2

OTHU is an observatory. Observing requires specific metrological devices to measure the quantities of interest to the observer, with defined requirements for data quality and availability. In urban hydrology, the spatial scales of observation range from a few tens of m² for stormwater sour ce control facilities to a few km 2 for urban separate or combined catchments. The time scales range from one minute to measure the intensity of rainfall to several years to reliably assess the efficiency of urban rainfall discharge management and treatment facilities.

The work of OTHU has led to progress in many aspects of metrology, some of which are presented in this chapter. Firstly, it is a question of adapting the metrological devices to the relevant time and space scales for each measurement site, as well as to the ranges of the quantities to be measured. They must then be regularly upgraded thanks to the knowledge and experience acquired, both in the sewers network and at the combined sewer overflows (CSO), and for the source control facilities. As observations have shown the extreme variability of urban discharges in wet weather, it is necessary to consider measurements over long periods to obtain representative results. Continuous measurement by sensors provides a better understanding of the dynamics of the phenomena than analyses of samples, which nevertheless remain indispensable for many pollutants. As physico-chemical quantities only give a partial view of the impacts of UWWD (Urban Wet Weather Discharges) on aquatic environments, in situ biological monitoring is an essential complement. Finally, rigorous metrological practices must be adopted to ensure the quality and availability of data, from the calibration of sensors to the estimation of uncertainties.

2.1

Why, what and how to measure in order to better understand the functioning of a catchment?

Flora Branger, INRAE Lyon - Bernard Chocat, INSA Lyon

Urban and peri-urban catchment areas are particularly complex systems where natural (watercourses, groundwater, vegetation) and artificial (sewerage networks, structures) components of the water cycle are mixed. Knowing, understanding and modelling the flows of water and pollutants therefore requires the construction of a network of hydrological observations with adequate choices in terms of measured variables, as well as time and space resolutions.

The watershed, a fundamental concept in hydrology

Extremely complex hydrological phenomena

Observable hydrological phenomena, such as the flows of water and pollutants observed at a particular point following a rainfall event, are the result of a very large number of elementary phenomena that take place simultaneously and/or sequentially and interact with each other. A rainfall event is made up of a multitude of drops and, in theory, it should be possible to follow each of the water molecules that make up the drops individually to then understand how they interact with each other and with the other components of the environment to produce these flows.

The forces at play in quantitative hydrology, i.e. for water flows, are relatively few: they are mainly those due to gravity, interactions between water and the atmosphere (condensation and evapotranspiration), and interactions between water and air in soils. However, hydrologists are confronted with an irreducible difficulty: the extreme complexity of the physical environment where these forces apply. In practice, the surface and the increasingly deep layers of the soil cannot be described with sufficient precision to be able to explain the genesis of flows as a resultant of all the elementary forces applied to water molecules.

The catchment area is a relevant study scale for understanding and modelling

It is therefore necessary to consider this on a larger scale, conventionally that of an elementary catchment area (generally defined as a plot of a few hectares to a few square kilometres) with one or more outlets to which converge the flows being studied. At this scale, it is possible to apply holistic modelling (i.e. lumped modelling) of the phenomena, without necessarily trying to link this modelling explicitly to the elementary laws governing flows at the microscopic scale.

It is only when flows begin to concentrate in a sufficiently homogeneous way to be described simply (a river, a pipe, a water table, etc.) that a so-called physical-based model can be used effectively. The catchment area is therefore the scale at which we wish to know, understand and model water and pollutant flows.

Why observe watersheds in urban and peri-urban areas?

Catchment areas can vary greatly in size. In urban and peri-urban areas, we are generally interested in catchments ranging from a few dozen square metres to several dozen square kilometres. Often, depending on the needs of the research or study, they are nested within each other. The largest catchment area may be broken down into sub-catchments, which may in turn be broken down into sub-sub-catchments, and so on. In all cases, these are complex systems in which all the components of the water cycle interact, whether natural (groundwater, watercourses, vegetation) or artificial (sewerage systems, stormwater management facilities). The diversity of land use, ranging from dense urban to agricultural and forest areas in the case of peri-urban catchments, adds further complexity. It is at the level of the catchment area that the impacts on the environment, watercourse or water table are studied, both from a quantitative point of view (flooding, drying up of watercourses, lowering of the water table, erosion, incision, etc.) and from a qualitative point of view (pollutant concentrations and flows, ecological quality of the environment). It is also the scale at which stormwater management is carried out, whether the management works are centralised or scattered across the basin.

Good observation for good modelling

The notion of catchment area is always linked, more or less explicitly, to that of modelling, whether to better understand phenomena and/or to better manage the operation of a structure. Modelling allows to quantify the flows of the various hydrological compartments of the basin (rain, evapotranspiration, infiltration towards the water table, runoff, flow in the watercourse, etc.), which are useful for the design of structures and/or for carrying out prospective studies (climate change, evolution of land use, etc.). These models necessarily require to be built, calibrated and verified with observation data. This is why it is important to build hydrological observation networks on a spatial scale compatible with that on which we wish to build catchment representation models. OTHU's research has mainly focused on knowledge of the water flows produced by peri-urban basins and on the water and pollutant flows produced by more urbanised catchment areas.

What variables should be measured?

If we are only interested in water flows, the approach to adopt is to consider the hydrological balance of a catchment area: water inflows and outflows (Figure 1). The main inputs are rainfall and sometimes wastewater in the case of combined networks. The main outputs are evapotranspiration (which includes evaporation of water from surfaces and transpiration of plants), and the flow at the natural and artificial outlet(s) of the catchment: rivers, groundwater and sewerage systems.

Rainfall and flow rates are variables that can be measured with commonly used equipment (rain gauges, water level sensors, flow meters). Measuring evapotranspiration is more difficult and requires expensive instrumentation that is beyond the reach of local authorities or non-specialist laboratories. However, it is possible to obtain evapotranspiration data from specialised models available by the national French national meteorological service Météo-France.

The measurement of other hydrological variables is useful to get a more accurate idea of the distribution of flows within the catchment. For example, soil moisture can be measured with dedicated probes and/or the depth of the water table with piezometric probes. Unlike the previous variables, these are not directly useful for calculating water balance, as the value measured at a given point is not representative of the whole catchment area. Several measurement points may therefore be necessary.

Measuring pollutant flows is much more difficult. Different physical variables (conductivity, pH, turbidity, and water temperature) can be measured quite easily. Some other quantities (TSS, or even COD and nitrogen) can in some cases be deduced. However, in most cases, it is necessary to take water samples and analyse them to determine the concentration of the pollutants to be monitored. These samples, as well as their conservation and analysis, must be carried out under rigorous conditions if we are to be able to estimate the flows with an acceptable uncertainty.

In addition to these measurements of the catchment outflows, other local measurements are required. For example:

- to find the origin of the flows: composition of rainwater, contribution of dry deposition or different types of urban surfaces;
- or to know the efficiency of the management works: analysis of settled sediments or of the quality of the water under the infiltration works for example.

How to measure?

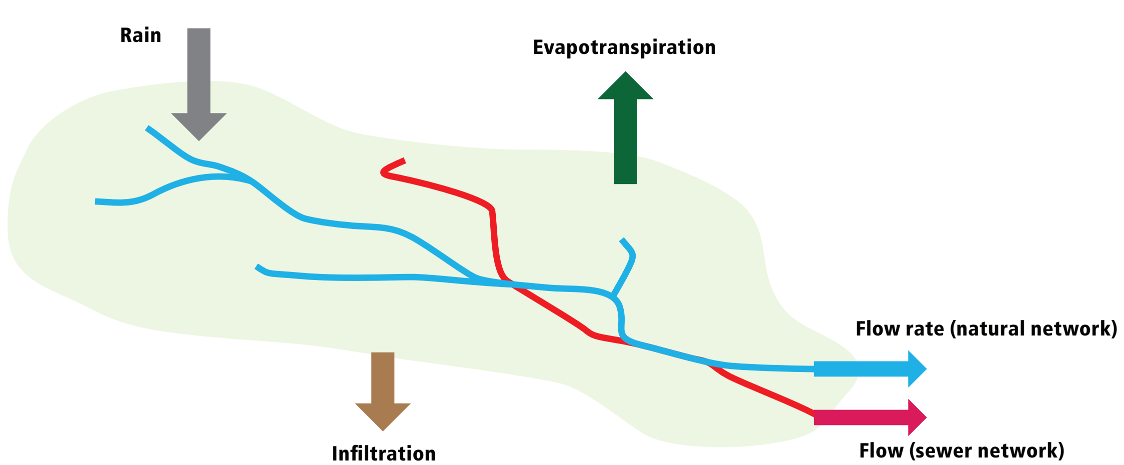
In time

If we want to monitor the functioning of a catchment area over time and carry out balances, it is important to carry out continuous monitoring, i.e. even in dry weather. It is therefore necessary to ensure the possibility and quality of measurements even when it is not raining. This leads to the installation of metrological devices for reliable measurement of dry weather flows, even when they are low (photo 1). Another important aspect is the time step for data acquisition, which must be adapted to the size and reactivity of the catchment. Urban catchments generally have very short response times, so it is necessary to be able to go down to the minute to measure rainfall and flows.

In space

The strategy for deploying measurements in space must factor in the size of the catchment. Beyond a few square kilometres, it usually requires several rain gauges to consider the spatial variability of rainfall, especially for convective events such as summer thunderstorms which can be very localised. From this point of view weather radars provide very interesting spatially distributed information, as a complement to ground-based rain gauges. At the flow level, the idea is also to estimate the distribution of flows within the catchment, by deploying measurements at the level of different sub-catchments. These sub-catchments can also be chosen to sample different land uses of interest (rural/urban, or residential/industrial). Underground sewage networks should also be included and instrumentation installed at the main outlets or network separation points where possible.

Figure 1: Summary diagram of the water cycle in an urban or peri-urban catchment area. (Source : F. Branger, INRAE)



2.1

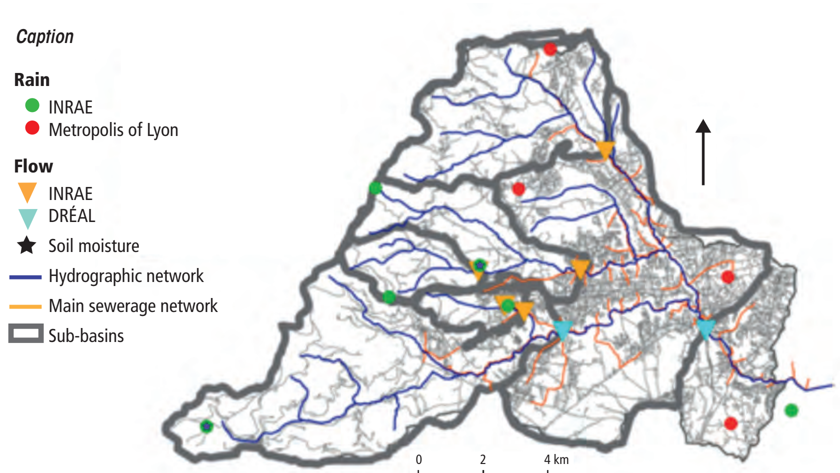
Photo 1: Ratier hydrometric station at Saint-Genis les Ollières on OTHU site of the Yzeron catchment area. The station is equipped with a concrete weir and a triangular weir for good quality measurement of low flows (source : Mickaël Lagouy, INRAE, 2011).

Catchment instrumentation monitored by OTHU

Yzeron peri-urbain catchment a better knowledge of water flows

20 years of observation by OTHU have enabled the development of a suitable measurement strategy for the Yzeron peri-urban catchment area peri-urban Yzeron (150 km²). Several small catchment areas, with contrasting land uses, were instrumented, such as the Mercier (forest and crops) and Chaudanne (crops and peri-urban) sub-catchment areas. The other stations were then positioned to measure the main tributaries of the Yzeron (Ratier, Charbonnières) and to nest the catchment areas within each other (figure 2). Six research rain gauges, supplemented by four rain gauges from the Lyon metropolitan area, offer a spatialized view of rainfall in the basin. This data is used to feed and evaluate distributed hydrological models, representing the spatial variability of land use, soils, and networks.

Figure 2: Instrumentation for monitoring water flows during 2020 at OTHU site in the Yzeron catchment. The shifts in the contours of the sub-basins are due to the areas drained by the sewerage network.



Urban catchments: better knowledge of pollutant flows

In the case of urban catchments, the work of OTHU has mainly provided much better knowledge of the flows of pollutants produced during wet weather: concentrations, event-driven or annual flows, origins, fate in the network and in the structures. In addition to the classic indicators (TSS, COD, BOD, hydrocarbons, nitrogen, etc.), significant progress has been made on many micropollutants (metals, PAHs, pesticides, etc.). The approaches implemented have made it possible to obtain average values and to evaluate uncertainties.

In Brief...

It is important to have a reliable measurement network to study the functioning of catchments. Continuous rainfall and flow measurements at suitable time steps are essential. Continuous measurement of physical quantities, such as turbidity, can reduce uncertainties in the flows of many pollutants. It is also necessary to take into account the spatial dimension, in particular by installing several rain gauges if necessary and by deploying a strategy of nested sub-basins for the measurement of water and pollutant flows.

Vocabulary point:
Measurement: A set of operations aimed at determining a value of a quantity.
Measurand: A particular quantity subject to measurement.

TO GO FURTHER

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2.2

Why is long-term monitoring of the quality of urban wet weather discharges necessary?

Jean-Luc Bertrand-Krajewski, INSA Lyon

In urban areas, discharges from separate stormwater systems and combined sewer overflows are a major source of contamination of surface water. Many sewer systems operators and natural environment managers carry out measurement campaigns to quantify and qualify these polluting discharges. However, contrary to well-established practices, the measurement of a few randomly selected rainfall events is not sufficient to characterise the pollutant loads in a reliable and representative manner and may even lead to biased conclusions.

The facts

Concentrations and loads of pollutants during rain events rainfall are highly variable and unpredictable

The quality of urban wet weather discharges (UWWD), i.e. the concentrations and loads of pollutants they carry, is characterised by its great variability, both from one rainfall event to another, and within rainfall events themselves. This distinguishes it from domestic wastewater, which in most cases has a notable pattern to flows and concentrations on a daily scale.

Indeed, from one rain event to another, the properties of the rain (duration, intensity, previous dry period, succession of antecedent events) vary randomly.

The transport of pollutants by raindrops and the washing of the atmosphere by falling raindrops are also highly variable factors. Similarly, the accumulation and availability of pollutants on the surfaces of the catchment area and in the collectors and sewerage systems at the time of the rainfall event are highly variable. As a result, the average event mean concentrations (EMC) of pollutants and the corresponding loads are largely unpredictable from one rainfall event to the next one and highly fluctuate.

Figure 1 illustrates the average EMCs measured in two OTHU catchments for two different pollutants (TSS and COD). In the Ecully combined catchment area, the EMC of TSS measured over 239 rainfall events varied from 13 to 1,433 mg/L, with a volume-weighted average of 168 mg/L. In the Chassieu separate catchment area, the EMC of COD measured over 263 events varying from 54 to 966 mg O_2/L, with a volume-weighted average of 118 mg O_2/L. In both cases, the distribution of the EMC values are very wide and follows a very approximate lognormal distribution. This high variability of EMCs is also seen for event-driven pollutant masses (Métadier and Bertrand-Krajewski, 2012).

There is no relationship between rainfall characteristics and average pollutant concentrations

Furthermore, there is no relationship between the characteristics of the rainfall events (e.g. rainfall or runoff volume) and the EMC values. In the case of the separate network in the Chassieu catchment area (Figure 2, left), runoff volumes of about 1,000 m³ have EMCs ranging from less than 20 to more than 1,400 mg/L depending on the rainfall event. Conversely, an EMC of about 150 mg/L was observed in runoff

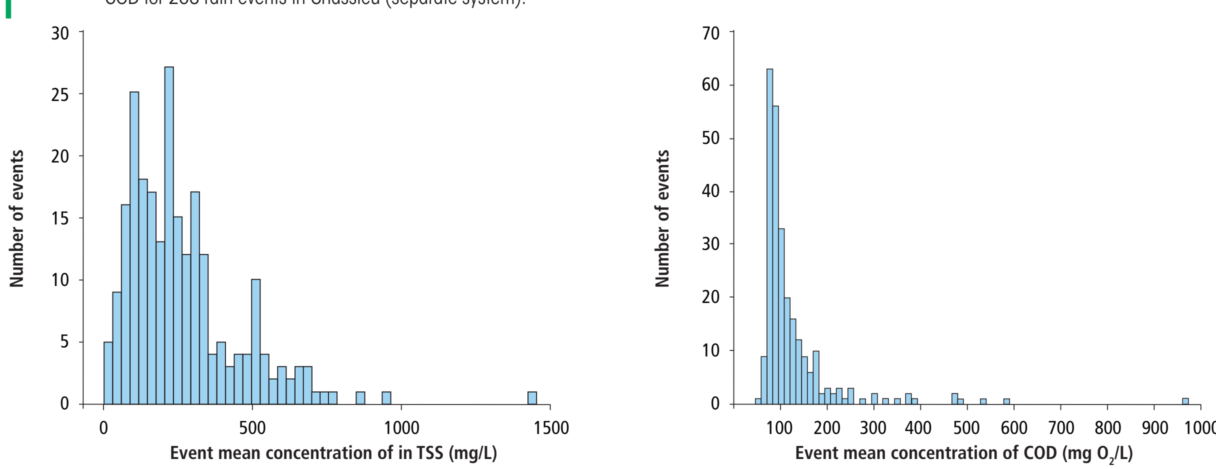


Figure 1: Distribution of event mean concentrations. On the left, EMCs of TSS for 239 wet weather events in Ecully (combined system); on the right, EMCs of COD for 263 rain events in Chassieu (separate system).

volumes ranging from a few thousands of m3 to more than 40,000 m³. There is no doubt that monitoring more events at this site would have led to even wider ranges of values.

The relationship between runoff volume and event mass is less dispersed (Figure 2, right): an event mass of 1,400 to 1,500 kg can, however, be transported in volumes ranging from 1,000 to 30,000 m³.

Conversely, runoff volumes of about 29,000 m³ can carry eventual TSS event masses of 1,500 to 4,200 kg. This lower dispersion and the overall tendency to observe higher masses when runoff volumes increase is largely due to the fact that mass is correlated to volume since it is equal to the sum of instantaneous concentrations multiplied by instantaneous volumes… Volumes and concentrations are independent quantities, but not volumes and masses.

Analyse of the data from both OTHU and other experimental sites also show that there is no link, for example, between the return period of rainfall events and the return period of EMCs or event masses.

Pollutant concentrations vary significantly during a rain event

During the rain events themselves, pollutant concentrations evolve in an extremely significant way, over time scales of a few minutes, often with one or more peaks, and very variable orders of magnitude. Figure 3 gives an example for the event on the 17th of May 2008 in at Chassieu. Turbidity, measured with a time step of 2 minutes, is proportional to the TSS concentration (as a first approximation) and varies from a few NTU (Nephelometric Turbidity Unit) to 300 NTU during the event. The variability of flows and concentrations

Figure 2: Event mean concentrations (left) and event masses (right) of TSS as a function of runoff volume (mm³) for 263 events in Chassieu.

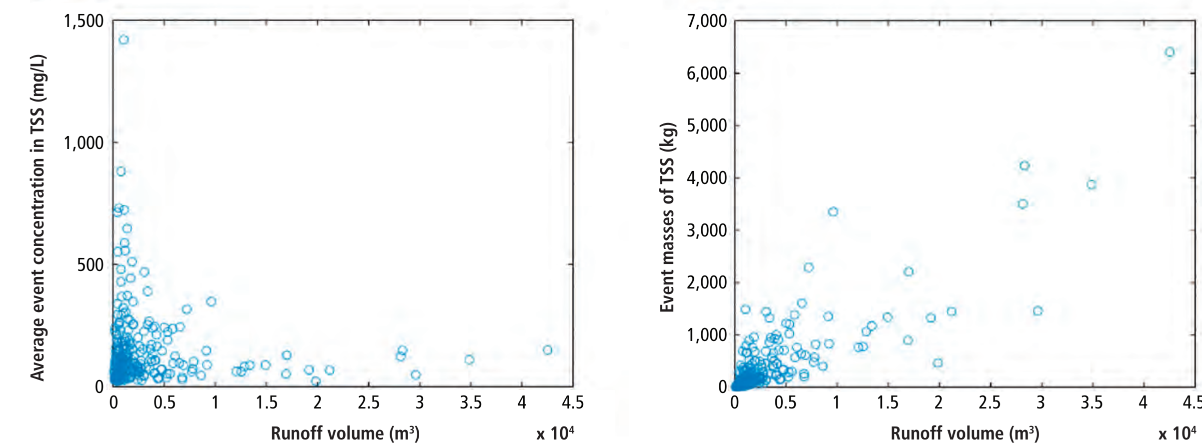
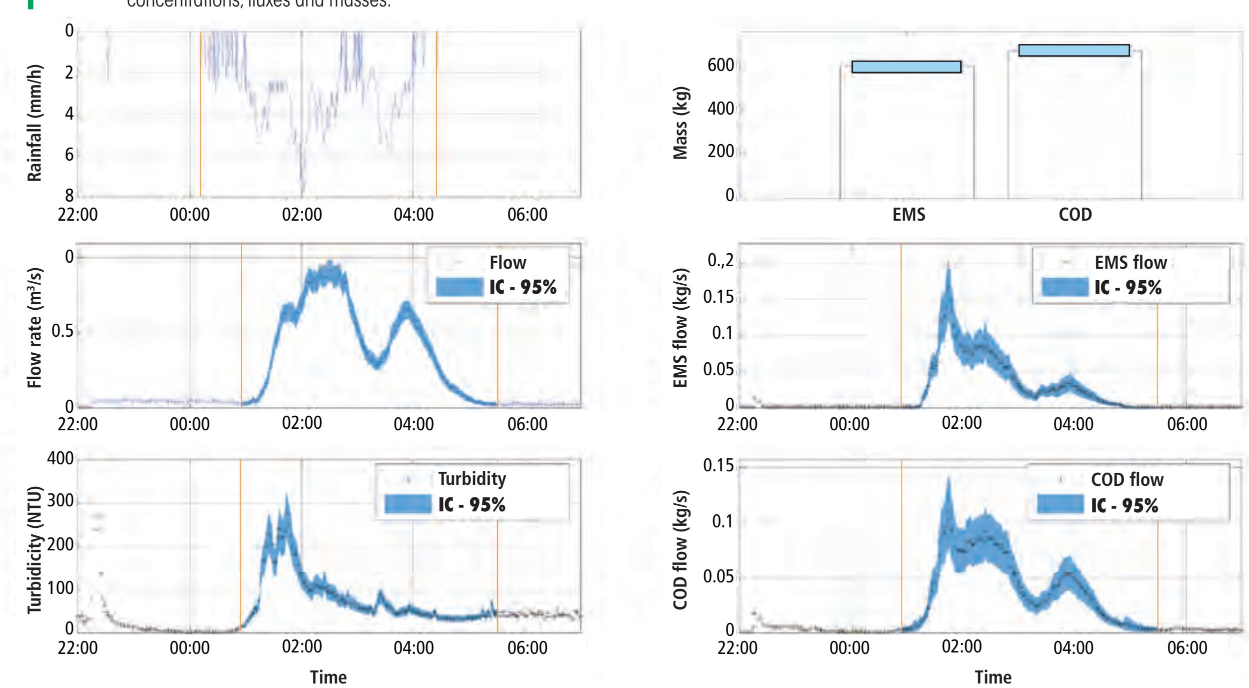


Figure 3: Evolution of rainfall intensity, flow rate, turbidity and mass fluxes of TSS and COD during the rain event of 17 May 2008 at Chassieu. On the left, from top to bottom: rainfall intensity, flow rate at the outlet and turbidity; on the right, from bottom to top: COD mass flux, TSS mass flux and event mass of TSS and COD. The blue bands represent the 95% uncertainty coverage intervals on the measured and calculated values of flows, concentrations, fluxes and masses.



during rainfall events can be represented synthetically by mass-volume curves (MV curves). The MV curves make it possible to quantify the first flush phenomenon: they show that this phenomenon is not the most frequent case by far (see Question 5.2: *Does it make sense to base an urban wet weather discharges control strategy on the first-flush principle?*).

Practical consequences for in metrology

A very high number of measurements is necessary

When a process or quantity is highly variable and random, a large number of measurements are required to correctly estimate its range of variation and a reliable order of magnitude of its mean value.

Let us take again the example of Chassieu and the average event mean concentrations in COD. The volume-weighted average COD concentration is 118 mg O_2/L, based on the values measured during 263 events. It is assumed for the following that this value is well known (although it could change if more events were measured). What would be the value of the average EMC if less than 263 events were measured? For example, if we measured only 5 events, chosen at random from among the 263 available ones? If ten million different draws of 5 events from the 263 ones are simulated, the calculated average mean EMC varies from 66 to 652 mg O_2/L depending on the draw. For draws of 50 events from the 263 ones, the calculated average EMC varies from 87 to 186 mg O_2/L.

These results are generalised in Figure 4, which shows the range in which the estimate of the average EMC varies with the number n of rainfall events measured. If, for example, we want to know the average EMC with a relative error of plus or minus 20% (i.e. between 94 and 142 mg O_2/L), Figure 4 shows that we would need to measure between 80 and 125 events out of 263. This is because the distribution is not symmetrical: for a given number n of measured rainfall events, the probability of overestimating the average EMC is higher than underestimating it.

Measuring pollutant loads over a small number of rainfall events, for example 3 to 5, will not provide reliable and usable information, given the enormous variability of urban wet weather discharges (in volume, concentration and mass released). It is therefore certainly taking the risk of believing (since we will have no other information, we will replace incomplete information with a belief) that all wet weather events will be similar to these three to five ones, which will have been obtained by chance, and for which we will have no guarantee of representativeness.

Focus on the number of rain events measured, rather than on a small measurement uncertainty

Other analyses show that it is much better to measure a large number of rainfall events with somewhat high metrological uncertainties than to measure only a few events with very low metrological uncertainties. Consider the case of a stormwater detention-settlement facility located downstream of a separate catchment, whose annual interception performance is to be evaluated (see details in Bertrand-Krajewski *et al.*, 2002). If the runoff volume during the rainfall event is less than the volume of the structure, the runoff volume is fully intercepted by the structure and subjected to settling. If the volume runoff is greater than the volume of the structure, the excess is discharged directly into the aquatic environment. It is considered that there are N = 80 rainfall events per year likely to generate significant runoff. Among these 80 events, we assume that we measures only a number n < N. We are interested in the interception efficiency, i.e. the ratio between the mass of pollutants entering the structure and the mass of pollutants discharged downstream of the catchment, on an annual scale for the 80 rainfall events. By combining the analysis of experimental data on different real catchments and numerical simulations, and taking into account on the one hand the metrological uncertainties (measurements of flows, concentrations, number of samples taken and coverage of sampled events) and on the other hand the uncertainties of representativeness of the sampled events, it is possible to estimate the uncertainty with which the annual interception efficiency of the structure is known as a function of the number n of sampled events. The results are shown in Figure 5. If only 5 events per year are measured, the annual interception efficiency of the structure will be known with an uncertainty of 115%. And if only 3 events are measured, the uncertainty reaches 180%... In other words, we really do not know how effective the structure is under these conditions. If we want to know its annual efficiency with an uncertainty of 30%, for example, we would have to measure 30 events per year out of 80.

This example shows how extremely uncertain conclusions can be drawn when only a few rainfall events are measured. The major source of uncertainty is the number n of rainfall events measured, which is greater when n decreases. Measurement uncertainties for flows and concentrations are less critical. This problem of under-representativeness of the diversity of rainfall events and their pollutant flows also exists for estimating the flows discharged or the impacts on the aquatic environment.

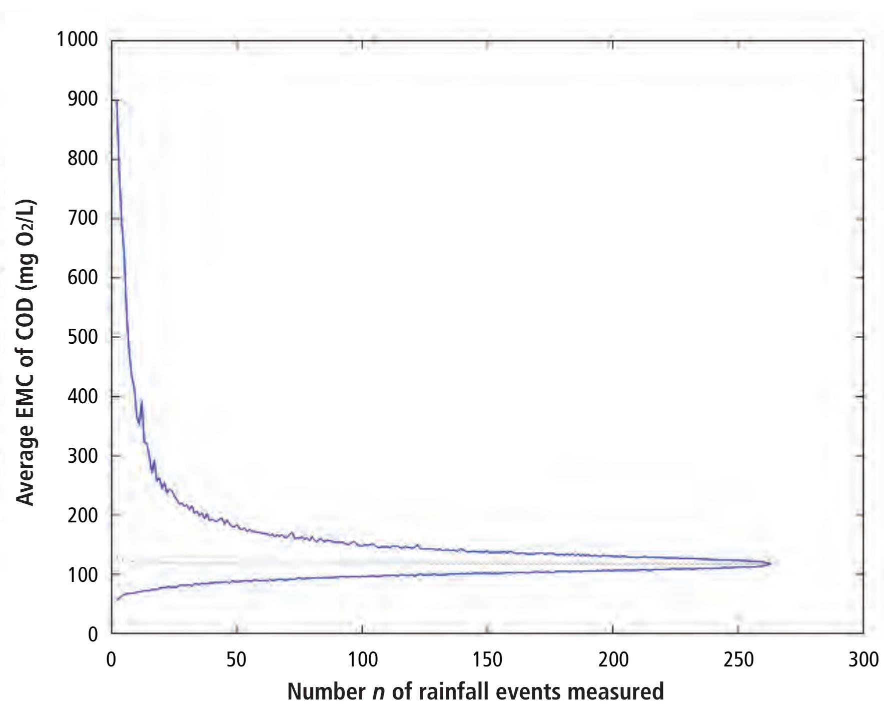


Fig. 4: Range of variation of the average EMC of COD estimated as a function of the number n of measured events among 263 available ones, for the Chassieu separative catchment area. In blue: the minimum and maximum envelope curves; in grey: the average

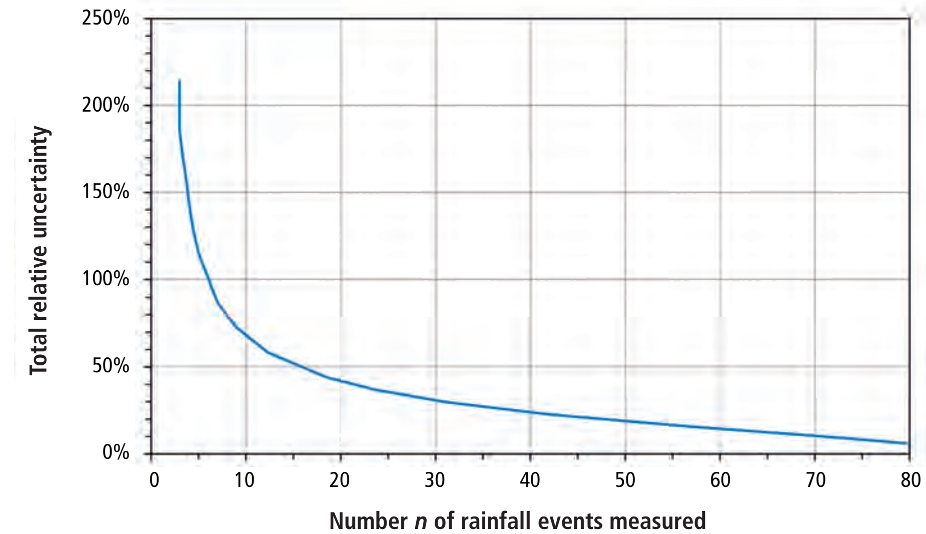


Figure 5: Total relative uncertainty on the annual interception efficiency of a stormwater detention-settling facility as a function of the number n of rain events measured among t N = 80 events on average per year.

In Brief...

One should not rely on chance to obtain reliable and representative data on the flows of water and pollutants from urban wet weather discharges given their great variability. This is nevertheless what happens when the measurement campaigns only include only a few rain events, from which conclusions are then drawn that may prove to be unfounded or biased.
The precautionary phrase indicating that «a few representative rainfall events will be selected» does not change this reality.
It is therefore necessary to plan campaigns covering a few dozen events to characterise a site properly, which requires medium-term planning of technical and financial resources. Whether this is obtained either by means of conventional sampling or, much better still, continuous measurement using online sensors which are providing richer information, the major issue is the total number of rainfall events measured.

TO GO FURTHER

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2.3

How have OTHU monitoring stations advanced metrological practices?

Nicolas Walcker, INSA Lyon – Laëtitia Bacot, GRAIE – Jean-Luc Bertrand-Krajewski, INSA Lyon

Reducing urban wet weather rainfall discharges (UWWD) and their environmental and health impacts requires a good knowledge of them. This knowledge, both quantitative (rainfall, flows, volumes) and qualitative (concentrations and loads of pollutants), is obtained us suitable metrological devices that allow long-term measurement campaigns.
Based on its 20 years of experience in the implementation and management of field monitoring stations, OTHU shares some lessons and recommendations for efficient instrumentation and successful monitoring of UWWDs.

The UWWD monitoring process

The definition of objectives is a prerequisite

Prior to any instrumentation project, it is important to set clear objectives in terms of the data and knowledge to be acquired, and the scope of the data to be collected.

Prior knowledge of the selected site and of the hydraulic conditions at the measurement point is also essential (identification of inlets/outlets, overflows, backwater effect, deposits etc.). Feedback from the various stakeholders (professionals and users) and studies already carried out in the area (master plan, modelling, previous campaigns, etc.) are effective means of meeting this preliminary need.

Quantitative and qualitative monitoring are complementary

The second step is to position the measurement points at appropriate locations in the catchment according to the defined objectives set (see Question 2.1: *Why, what and how to measure in order to better understand the functioning of a catchment?*) To do this, it is usually necessary to start the instrumentation with quantitative flow monitoring of the flows. The estimation of flows is often carried out using water level and/or flow velocity sensors (other measurement techniques are possible). The collected data produced provides information on the functioning of the system by delivering providing valuable information on flows and volumes. Coupled with rainfall measurements, they provide an understanding of the wet weather response of the catchment upstream of the measurement point.
Qualitative monitoring of the discharges effluents is a complementary means of understanding the system and enables estimating the pollutant flows transported by the UWWDs and their impact on the aquatic environment to be estimated. Numerous physical and chemical parameters can be measured continuously in WWTPs: temperature, electrical conductivity, pH, turbidity/TSS, DO, etc. The choice of parameters to be measured depends on the defined objectives set, regulatory obligations and the available financial resources available. The use of automatic samplers is necessary to collect samples requiring laboratory analys is of pollutants (metals, micropollutants, etc.) whose concentrations cannot be estimated using continuous online sensors.

A look back at 20 years of experience with OTHU monitoring stations

The need to consider the whole measurement chain

Over the past 20 years, the diversity variety of sites, stakeholders and research topics has given OTHU a significant experience in site instrumentation and UWWD measurement, which now allows the production of many results based on long time series of data sets.

For any instrumentation project, it is essential to carry out an in-depth complete preliminary reflection on the entire measurement chain: from the selection choice of sensors to data processing, including the management of the metrological equipment. Neglecting this approach often leads to a waste of time and money and to the collection of poor or unusable data. Naturally, this requires competent and qualified metrology personnel.

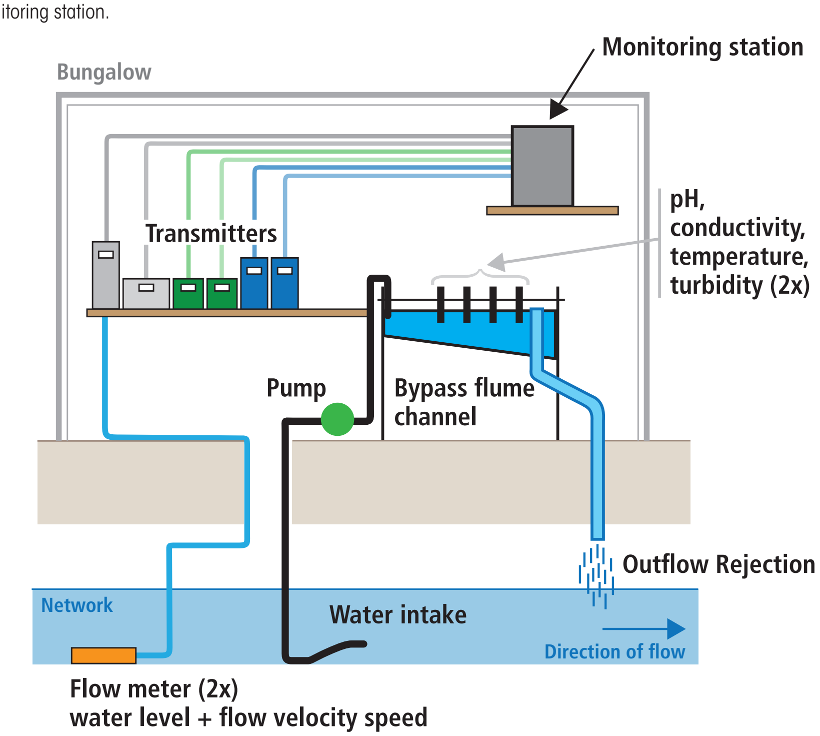
The selection choice of sensors and their location

For quantitative monitoring, these years of experience have shown the effectiveness of sensors without contact with water the effluent (ultrasonic or radar types). These proven and robust solutions offer the advantage of reduced maintenance, simplified control and a long service life. The cost of level sensors, reduced by the development of technologies and competition between manufacturers, encourages the use of these solutions. This does not apply to non-contact velocity sensors, whose cost is still dissuasive and leads to the use of immersed sensors or depth-discharge relationships. The use of flow velocity speed sensors is not systematically necessary but depends on the hydraulic conditions observed at each measurement point.

A continuous improvement approach

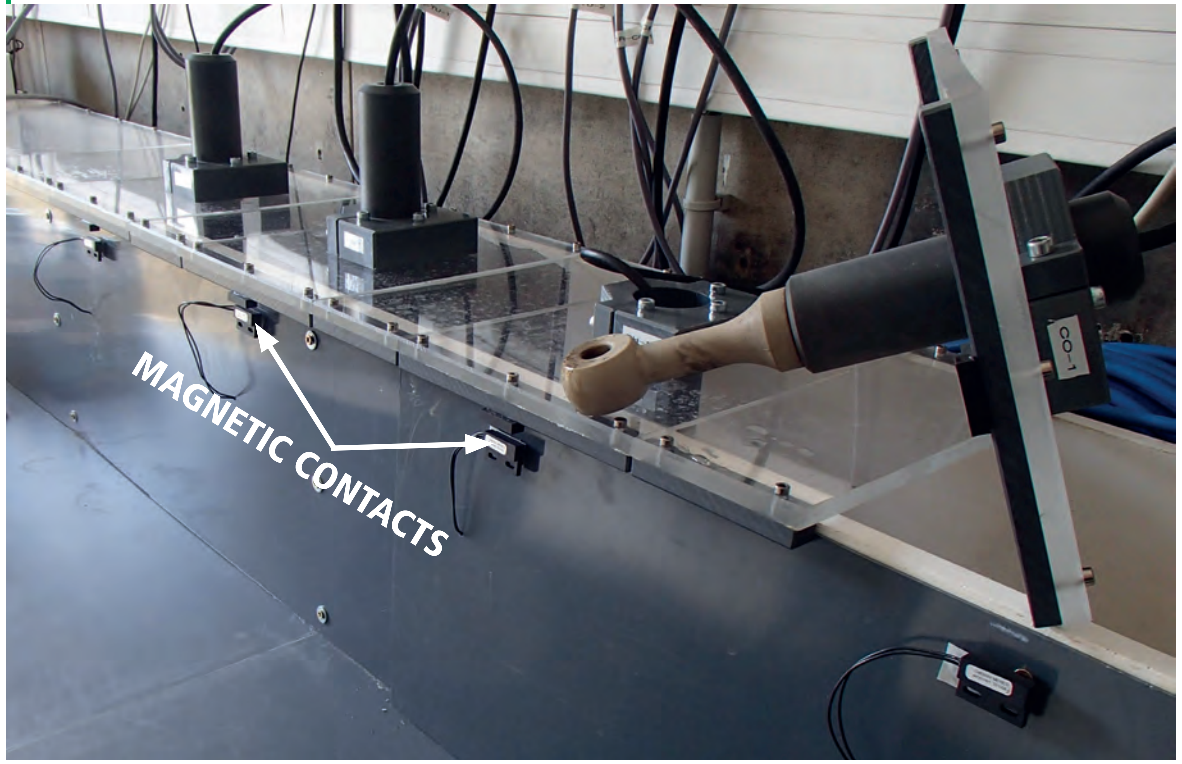
After several years of daily operation of the monitoring stations, many improvements, both material and methodological, have been made by OTHU teams:

Figure 1: An OTHU monitoring station.



- **Bypass channel:** a custom moulded channel with an ovoid cross-section and nozzles for automatic cleaning with drinking water reduces sediment settling in the system to optimise the representativeness of the measured sample.
- **Sensor covers (figure 2):** Transparent covers with a quick-release sensor attachment system ensure that the equipment is correctly positioned. These covers improve the reproducibility of measurements by reducing the differences in practice by of the various people working on the stations. They include magnetic contacts to automatically identify the opening and closing of the covers during sensor maintenance operations.
- **Computer and screen capture cards:** the use of a computer with screen capture cards considerably increases the possibilities compared to conventional data loggers (increased storage capacity, local and cloud storage, real-time data pre-processing, data size and formats, software, webcam, additional hardware, etc.).
- **HMI and the internet:** setting up an HMI (Human Machine Interface) on a connected computer connected to the internet makes it much easier to operate the station. The station can be controlled from anywhere and at any time (pump, cleaning nozzles, channel emptying, lighting, triggering of samplers, etc.).
- **Real-time data pre-processing:** the use of programming software for data collection and station control offers many possibilities. Outliers and/or non-representative data (e.g. sensor maintenance, by-pass flume cleaning, tank cleaning,

Figure 2: Covers for sensors and magnetic contacts.



pumping fault, etc.) can be detected and removed before averaging the remaining data. For example, the non-outlier data sampled at a high frequency, such as every second, can be averaged every two minutes to mitigate random errors.

- **Control of the samplers:** as the flow calculation (by flow depth and velocity measurements, depth /flow velocity equations or other various models) is instantly carried out within the program controlling the station, it becomes possible to trigger the samplers and to take samples according to the hydraulic conditions observed in real time (sampling proportional to time, volume or flow).

Qualified staff and a critical view of the data collected

Despite the effectiveness of all these tools and the innovations made, OTHU's years of experience confirm the need for regular and rigorous maintenance of monitoring stations by qualified personnel. From the choice of equipment to its operation, through its installation and maintenance, the skills of the users remain indispensable in order to ensure a continuous and relevant instrumentation.

Lastly, the specific and difficult monitoring conditions in urban hydrology require a permanent critical evaluation of the collected data. Methods and tools have been developed in OTHU to facilitate this data management, including sensor calibration data, uncertainty assessment and data validation, which have been integrated into the Evohé software (see Question 2.8: *How to can we produce quality data that can be used sustainably?*).

Towards a city connected to its stormwater disconnection

The emergence of the «Smart City» concept has generated new approaches and new tools in recent years. The development of the IoT (Internet of Things) and the emergence of new technologies (low-cost sensors) are leading to increasingly connected and autonomous solutions (from the energy autonomy of the sensors to the hosting of the data and their collection).
In the future, the availability of these technologies and reducing their costs should encourage the instrumentation of many facilities to better meet the needs of a global approach to drainage based on reliable and representative measured data.

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2.4

Continuous measurement and sampling: why do we need to go beyond the regulations?

Jean-Luc Bertrand-Krajewski, INSA Lyon

Continuous measurement of pollutant loads by flows by in situ sensors is still not widely practised by local authorities, engineering offices and private managers. However, limiting oneself to the analysis of a few samples collected for a few random rain events can only give a partial and biased version of the pollutant loads of flows of urban wet weather discharges during wet weather...

The film buff and the hydrologist: three short, parallel stories

FIRST STORY

Dominique, a budding film buff visiting her uncle (or grandfather, cousin, neighbour, I can't remember), wants to discover crime films. Her uncle (or grandfather, etc.) suggests that she goes to the local cinema: "*There's always one of the cinema screens showing them at some point, you'll come across something interesting*". And he adds: "*Take the envelope on the cabinet by the door, there should be a few euros left to pay for a screening*".

On the way, Dominique notices that the envelope contains only a few coins. At the cinema, the cashier, who is a bit strange, offers him, in exchange for his few coins, an original experiment: watch the film with a special mask. This special mask allows him to see a clip of a few seconds in the centre of the screen up to 24 times. She can set it up in two ways: either she sees a short clip every 5 minutes, or she sees a clip every time the film's musical theme is heard on the soundtrack. Dominique agrees to try the experiment. As she does not know the soundtrack of the film she is going to see, she chooses the option of a short sequence every 5 minutes and enters the room.

When she comes out two and a half hours later, she is very puzzled. The film was longer than expected, she knew nothing about the last half hour or how the story ended. Furthermore, sequence 8 didn't work and sequence 12 was blurry. She did see who she thought was the murderer, she thought she saw at least one victim, but she is not at all sure that she understood the motive for the crime. Secondary characters appeared or disappeared from one sequence to the next without her knowing their roles in the case. She heard the music, from the credits and throughout the film, which allowed her to recognise different moods, moments of tension and calmer moments. But it doesn't really help her to untangle the threads of the script. In the end, although she saw parts of the film as expected, she didn't understand much of the story. She wonders if all crime films are like this one (at least from what she vaguely understands) and goes back home very disappointed.

Sometime later, she hears that he was lucky, as many other novice filmgoers often only saw a small number of sequences during the experimental screening. What a frustration!

Dominique, a young urban hydrologist employed by the city (or an engineering office, a private operator, a public utility, I don't remember), wants to know the pollutant loads of flows in urban wet weather discharges during wet weather. Her director suggested that she set up a measurement campaign in a nearby catchment area: "*It always rains at one time or another, at some point, you will find a representative rain event*". And he adds: "*There is a residual budget available in your department to measure at least one rain event*".

As she prepares for her measurement campaign, Dominique notices that the remaining budget balance is rather meagre. On site, a strange operator tells her that with this amount she can do an original experiment: collect samples with a sampler and this sampler will allow her to collect up to 24 instantaneous samples at the watershed outlet. She can set it up in one of two possible ways: either she takes a sample every 5 minutes, or she takes a sample every time 200 m^3 has flowed. Dominique agrees to try the experiment. As she does not know the discharge flows that will occur, she chooses the option of one sample every 5 minutes and starts her campaign.

When the rain event ends after two and a half hours, she is very confused. The duration of the event was longer than expected, she has no samples for the last half hour and will not be able to calculate the total mass of pollutant discharged. In addition, the pump did not work for sample 8 and sample 12 does not have even half the volume needed for the analyses. She did see that there were pollutant discharges, probably at least one urban wet weather discharge (UWWD), but she is not at all sure that she understood how these flows were generated. Pollutants are present in some samples and not in others, without knowing whether this is linked to sporadic resuspension. She has the hydrological data, the histogram that generates the runoff and the complete discharge flow record at the outlet, which allowed her to identify different phases in the event, with peaks and breaks. But this does not really help her to estimate concentrations over time. Finally, although she gets samples of the event as expected, she did not understand much about the processes involved. She wonders if all rain events are like this one (or at least what she vaguely understands about them) and returns to the office very disappointed.

Sometime later, she hears that she was lucky, as many other novice hydrologists often only get a few samples per rain event. What a frustration!

Photo 1: Image of the film *The Third Man*, by Carol Reed (1948), scene in the sewers of Vienna in Austria. .

SECOND STORY

Despite this first disappointing experience, Dominique decided to persevere. But no more special masks, she wants to see his next crime detective film continuously! Having obtained from her uncle, not without difficulty, the money necessary to watch a new film in a more elegant cinema, she leaves enthusiastically.

And then it's a revelation! Continuous sound and image, at 24 frames per second, from the beginning to the end. At last, she can follow everything, understand everything, be sure of the culprit, the victims (there were two in this film), she has a clear idea of the motive. There are still a few unverified hypotheses built up during the screening, but they only concern minor aspects of the story.

Dominique now wants to see other crime films by the same director, she knows she has made dozens of them. Indeed, the cinema magazines reviews speak of him as a prolific filmmaker with an abundant imagination, capable of reinventing everything and surprising the viewer with each film, even starting from a few apparently quite similar elements. She looks forward to seeing his entire filmography.

Despite this first disappointing experience, Dominique decided to persevere. But no more samplers, she wants to measure the pollutant flows of the next rainfall event continuously! Having obtained from her director, not without difficulty, the necessary budget to calibrate and install water quality sensors in a new catchment area, she left enthusiastically. And then it was a revelation! The discharge flows and the pollutant flows, continuously at half-minute intervals, for the entire duration of the event. At last, she can monitor and analyse everything, correctly quantify the pollutant loads discharges and the overflows (there were two during this event), and she has a fairly accurate idea of the processes involved. She has estimated her measurement uncertainties: they are sometimes a little high, but they do not call her conclusions into question. Dominique now wants to measure the pollutant flows of other rainfall events in her catchment area, and she knows that there will be is no lack of rainfall. The literature indicates that the pollutant loads flows discharged vary enormously from one event to another, in a way that is very difficult to predict, although the basic processes involved are always the same. She is motivated to increase her database.

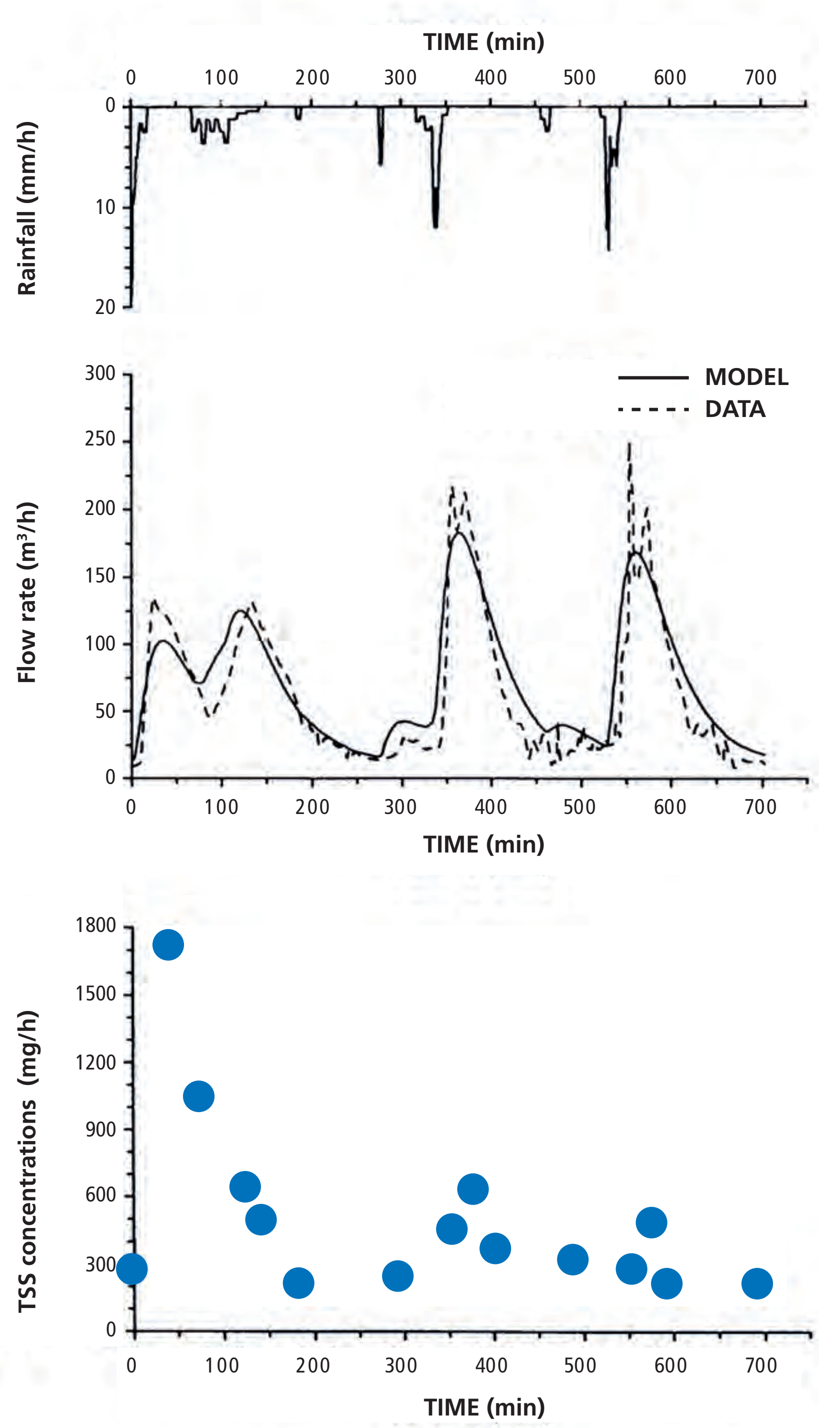
THIRD STORY

Sometime later, Dominique thinks that there must be many other talented directors she doesn't know of yet. Her local cinema is no longer enough for her, she wants to see more. She dreams that she is going to the brand new International Crime Detective Film Festival, in rooms with 360-degree screens, 3D films, dynamic seats, diffusion of smells related to the story. And then, surprise! She attends the world premiere of a fully restored and re-released version of the film.

Sometime later, Dominique realises that there are pollutants she has not yet measured. Her residential urban catchment area is no longer sufficient, she wants to measure discharges at other sites as well.

She is dreaming of a new international database on urban wet weather discharges, including on hundreds of catchment areas with various characteristics, with continuous data for all the emerging pollutants of interest, in different both dissolved. and particulate

Figure 1: Monitoring of a rainfall event by sampling: rainfall intensity and flow rate re-calculated at a 1-minute time step, TSS concentrations (blue dots) determined from15 samples collected in proportionally to the volume flowed (samples taken with at a 50 mm³ volume step interval) by an automatic sampler, Entzheim (Bas-Rhin, France), event on 3rd May 1987 (source: adapted from Bertrand-Krajewski, 1992).



She sees in high definition, in colour, on a 360-degree screen, and in its original language: a film that she had already seen a long time ago in black and white on a narrow 4/3 screen. She finally sees all the action, the cut scenes, the missing dialogues, the whole plot explained and sequenced perfectly. The original language version reveals explanations that the poorly translated French version had made confusing. What imagination in the script, full of twists and turns and peripheral action, as she recalled a terribly simplified story that her brain had once worked out with the limited elements she then had at her disposal.

And a new idea spring to her mind: after all the films of the many directors she has seen in hundreds of cinemas, she feels ready to write the ultimate and perfect screenplay of all existing and future crime films, the one that would represent them all in their infinite diversity.

phases, and even in the gaseous phase, to fully complete the mass balances. She imagines herself measuring old events again under these conditions: no more insufficient samples collected only at the catchment outlet, replaced by dozens of high-performance, low-cost sensors spatially distributed across the sub-catchments and the sewer systems, providing continuous data transmitted and validated in real time. Finally, she understands all the processes involved and their interactions, the role of overflows on mass balances that have remained incomplete until now, the contributions of e ach sub-catchment and of resuspension in the sewer structures. All of the contributions become quantifiable and interpretable. The systematic calibration of the sensors makes the data reliable. She manages to grasp all the complexity of the phenomena, and even their random aspects, while she it remembers the simplistic and unverifiable hypotheses and interpretations that she had previously built up from the few samples collected.

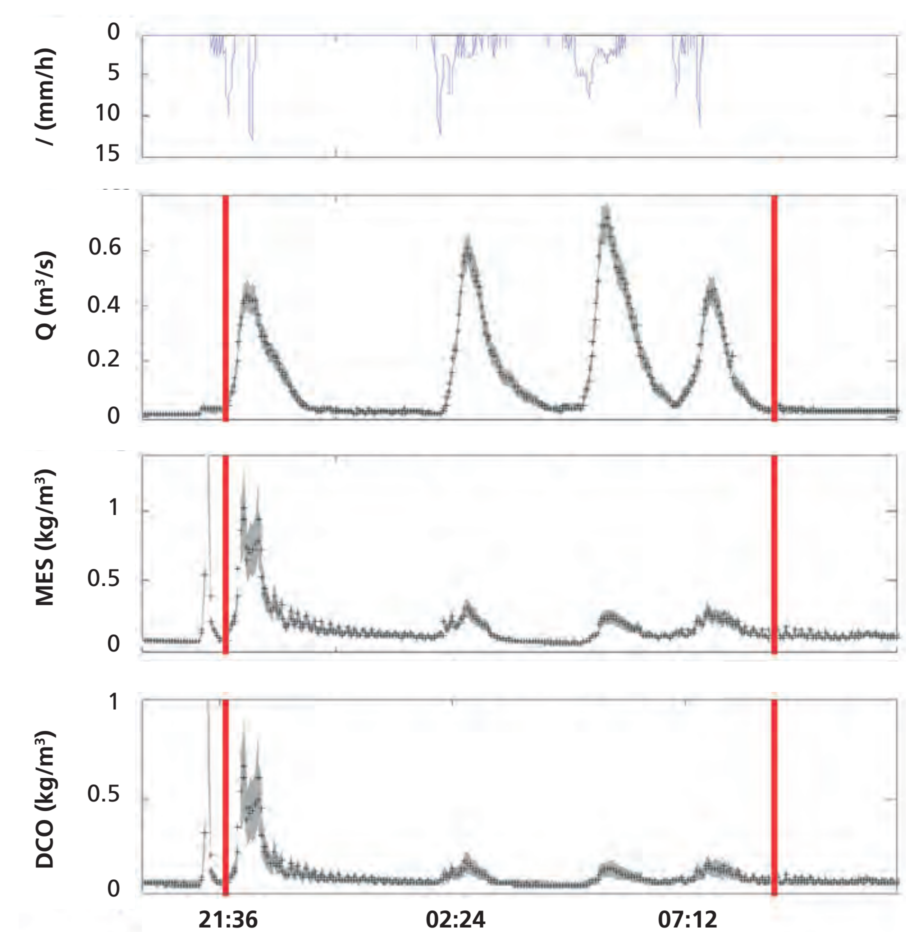
And a new idea springs sprang to her mind: with all the data and knowledge accumulated in her database, she feels felt ready to create the ultimate and perfect numerical digital model of all the urban wet wet weather discharges patterns of all the past and future rain events, one that would represent them all in their infinite diversity.

Back to reality

Figure 1 shows an example of monitoring TSS concentrations measured on samples taken at the outlet of a combined catchment during a rainfall event.

When a data point has a continuity gap, the human brain naturally wants to fill it in by linearly interpolating between two successive concentration values and accepting this

Figure 2: Example of monitoring a rainfall event by continuous measurement of rain intensity, flow and concentrations at a 2 minute time step, Chassieu (Rhône, France), event on 29 May 2008

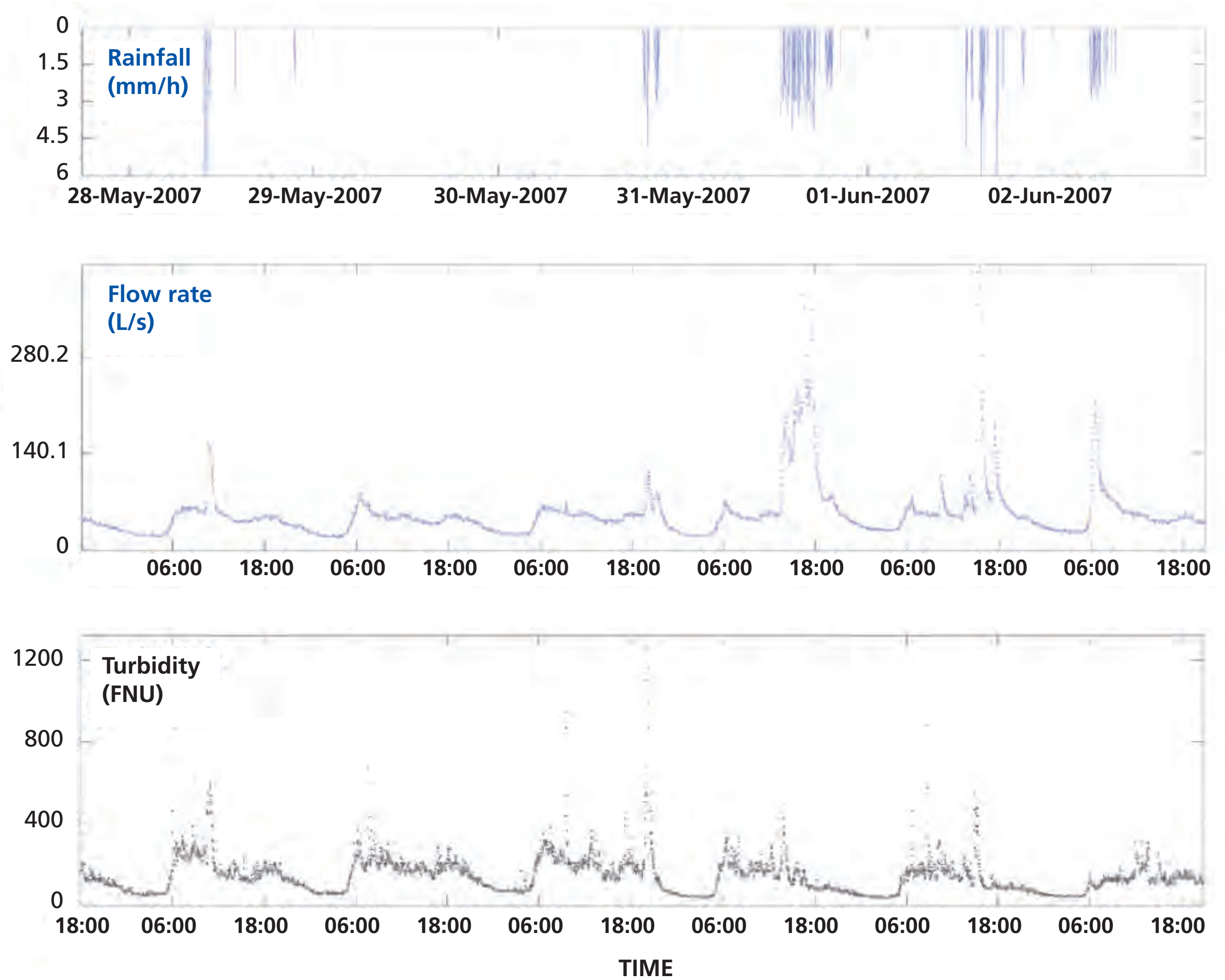


interpolation as fact. This is not the worst example, as there are many cases where the number of samples collected is well below 15. This type of information has long been the main source of knowledge on the pollutant loads flows of urban wet weather discharges.

For comparison, figure 2 shows an example of monitoring of TSS and COD concentrations estimated from turbidity measured continuously at the outlet of the Chassieu separative catchment. In this example, information is available every 2 minutes, which represents the real (and not imagined) dynamics of the processes, with a systematic estimation of the uncertainties. It is then possible to calculate mass balances or discharged flows in a much more reliable way (see Question 2.2: *Why is long-term metrological monitoring of the quality of urban wet weather discharges necessary?*). Continuous measurement overcomes the arbitrary temporal limits of splitting into distinct separate rainfall events and the technological constraints limits related to the extremely limited capacities of samplers. Time series of long-term data (see Figure 3) allow access to new information and knowledge, testing of models, better management of infrastructures, etc.

For combined catchment areas, continuous measurement makes it possible to estimate, from a database on dry weather flows, the contribution of wastewater to the total wet weather volume flowed and the pollutant loads flow discharged for each rainfall event (see Métadier and Bertrand-Krajewski, 2011). It also enables better management of the facilities and partly meets the regulatory obligation of self-monitoring. As shown by Lombard *et al.*, (2010), it is for example possible to estimate the concentrations of TSS, total and dissolved COD and dissolved sulphides at the inlet of an urban wastewater treatment plant by combining turbidity, UV-visible spectrometry and conductivity data measured continuously. Finally, continuous measurement allows daily mass balances to be established with lower uncertainties than with traditional conventional samples. This opens numerous perspectives prospects for its widespread use (Eggimann *et al.*, 2017).

Figure 3: Extract from a rainfall, discharge and turbidity time series, Écully (Rhône, France), 28 May-2 June 2007.



In Brief...

The continuous measurement of pollutant flows using in situ sensors provides much richer and more relevant information than that obtained by conventional sampling, whenever pollutant concentrations can be estimated using sensors (pH, conductivity, turbidity, UV-visible spectrometry, specific probes, etc.). The protocols and best practices to be implemented (regular calibrations, periodic checks, data validation, estimation of uncertainties) are known and have been available since for several years now. The practice of continuous measurement could develop much further, if existing habits and maintenance of outdated regulatory requirements (based almost exclusively on standardized sample analyses) were not powerful barriers to progress.

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- **Métadier M. & Bertrand-Krajewski J.-L.** (2011). *Assessing dry weather flow contribution in TSS and COD storm event loads in combined sewer systems.* Water Science and Technology, 63(12), 2983-2991. doi:10.2166/wst.2011.185. – lc.cx/metadier2011 (in french)
- And to reconcile cinephilia and urban hydrology, the film *The Third Man*, by Carol Reed, Grand Prix at the 1949 Cannes Film Festival, screenplay by Graham Green, original music by Anton Karas, with a police plot, spies, crimes, victims, an investigation, false leads, and several scenes with Orson Welles in the sewers of Vienna in Austria. Essential supplement: Timmermann B. & Baker F. (2002). *Der dritte Man* [The Third Man]. Wien (Austria) : Czernin Verlag, 288 pp. ISBN 978-3-7076-0143-9. (In German). lc.cx/troisiemehomme

2.5

How easy is measuring the performance of source control sustainable drainage systems?

Sylvie Barraud and Hélène Castebrunet, INSA Lyon

Reducing runoff and minimising the contamination of stormwater are arguments for promoting source control Sustainable Drainage Systems (SuDS).
Currently, the favoured method of managing pollutant flows is by limiting the volume of run-off, which in turn reduces the quantities of associated pollutant carried by the run-off water. Pollution is also reduced by the trapping of part of the pollutants in the structures. Only reliable and ambitious instrumentation can provide information on their real hydrological and treatment efficiency. However, instrumenting these structures is not easy and requires real expertise.

Issues around the effectiveness of source control techniques

SuDS for managing rainwater at the source (bioswales, trenches, porous and permeable pavements, green roofs, soakways, biofilters, raingardens etc.) are now widely used. Because of their claimed ability to reduce water flows and reduce contamination by limiting leaching, trapping or filtration/settling, they are also being adopted for their multifunctionality and their good integration into the urban environment. But are they really effective from a hydrological and treatment point of view? How can these systems be monitored?

Answering these questions requires asking several others:

- What performance is to be measured, given the multifunctionality of the structures (flood control, ability to limit pollutant discharges, good integration into the urban environment)? Which indicators should be defined and for which objectives? What are the quantities to be monitored?

Photo 1: A bioswale draining water from a car park in the Doua campus in Villeurbanne.

Photo 2: View of the three instrumented systems (from left to right: car park with bioswale, car park with gravelled trench, car park with reservoir pavement using permeable concrete) - Eco campus Villeurbanne..

- At what spatial and temporal scales are these performances assessed: local or catchment scale with SuDS? event-driven, annual or other temporal scale?

The question of the local performance of a structure or a local development element with regard to the attenuation of flows (flow rates and volumes) and pollutants on the scale of rainfall events (concentrations and loads) is addressed here.

The instrumentation of these structures faces several difficulties

Source control management solutions are based on the principles of detention/storage, infiltration (in the substrates forming the structures and/or in the underlying soil) or evapotranspiration. When instrumenting such structures, the difficulties are related to:

- the strong variability of water flows from one event to another: the volume is zero at the outlet for small rainfalls and significant for heavy ones.
- the diversity of water inlet devices (by surface runoff, pipe, etc.) or outlets (drain, infiltration into the ground, overflow, etc.).
- the need, when sampling water to quantify its level of contamination, to have a reference area for comparison with the values observed at the outlet. Indeed, as the inlet volumes of the source control devices are often small (the drained surfaces are small), any sampling of water at the inlet for analytical purposes distorts the measurements at the outlet. It is therefore necessary to find an artifice that allows this major bias to be avoided.
- the space needed to implement the metrological system on small and multi-functional sites.

The monitoring system set up under OTHU

Three infrastructures and a reference area

The Lyon tech La Doua campus in Villeurbanne is the OTHU site dedicated to the study of source control SuDS techniques. As part of the Campus master plan, it was decided to renovate public spaces with alternative and integrated stormwater management systems. OTHU has seized this opportunity to install equipment at the time of the SuDS, which facilitated the implementation of an adapted metrology for year-round monitoring. The objective was to measure the effectiveness of source control SuDS management systems in terms of limiting water and micropollutant discharges (metals, pesticides, flame retardants, PAHs and alkylphenols). The study is based on the in-situ monitoring of three car park runoff drainage systems (photo 2). Two are similar car parks of 290 m² and 270 m² with a "stabilised"[1] part and an asphalt part, whose water is evacuated respectively by a bioswale and a gravel trench (see table 1). The third system is a car park made from reservoir pavement draining an area of 90 m². This is comprised of a reservoir structure filled with gravels and permeable concrete on top. All the structures were sealed with an impermeable liner at the bottom for experimental purposes.

A reference area of 90 m² of traditional impermeable pavement adjacent to the reservoir pavement allows a comparison of water and pollutant flows between a conventional impermeable parking lot and a parking lot drained by SuDS.

The choice of performance indicators and associated metrics

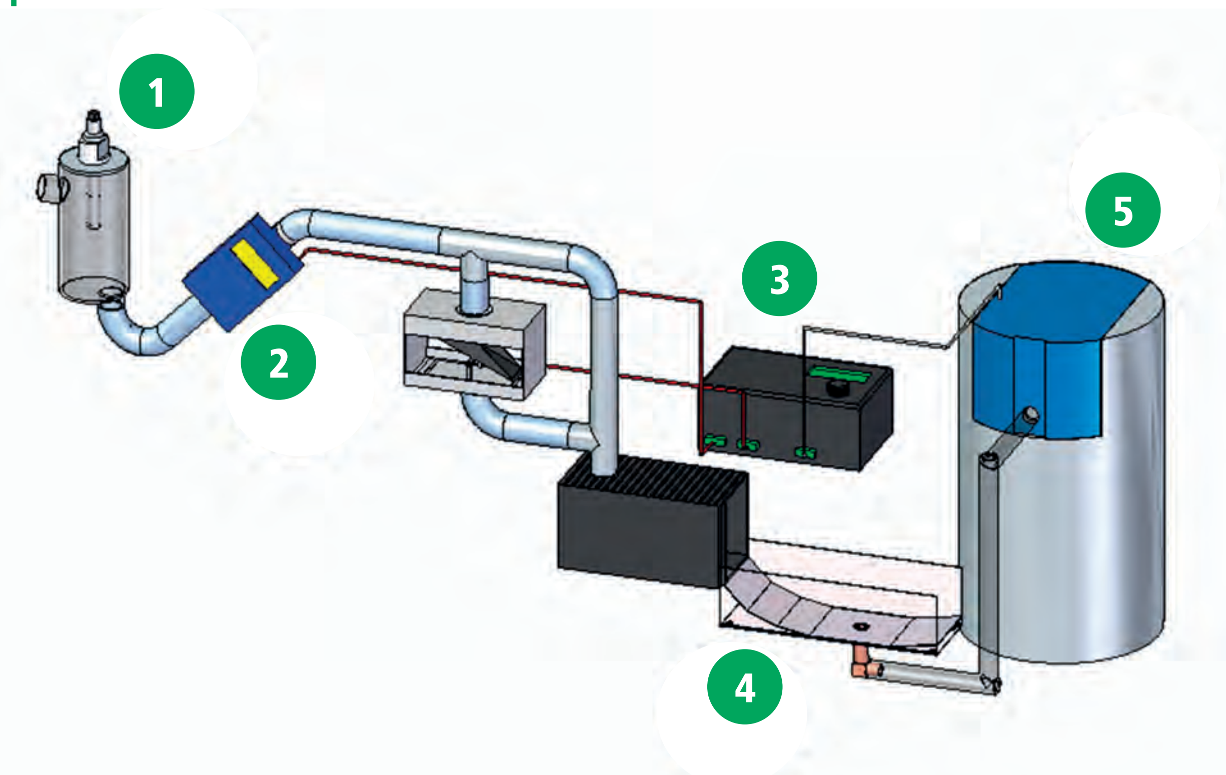
To evaluate the treatment and hydrological performance of the SuDS, several major indicators were chosen, which allow comparison of the output of the SuDS with the output of the reference zone. These indicators are the attenuation of peak flows and volumes, and the reduction of concentrations and total masses of pollutants for different rain-events. The statistical analysis of concentrations and masses allows an evaluation of the level of water contamination for different substances and an estimation of the observed performance.

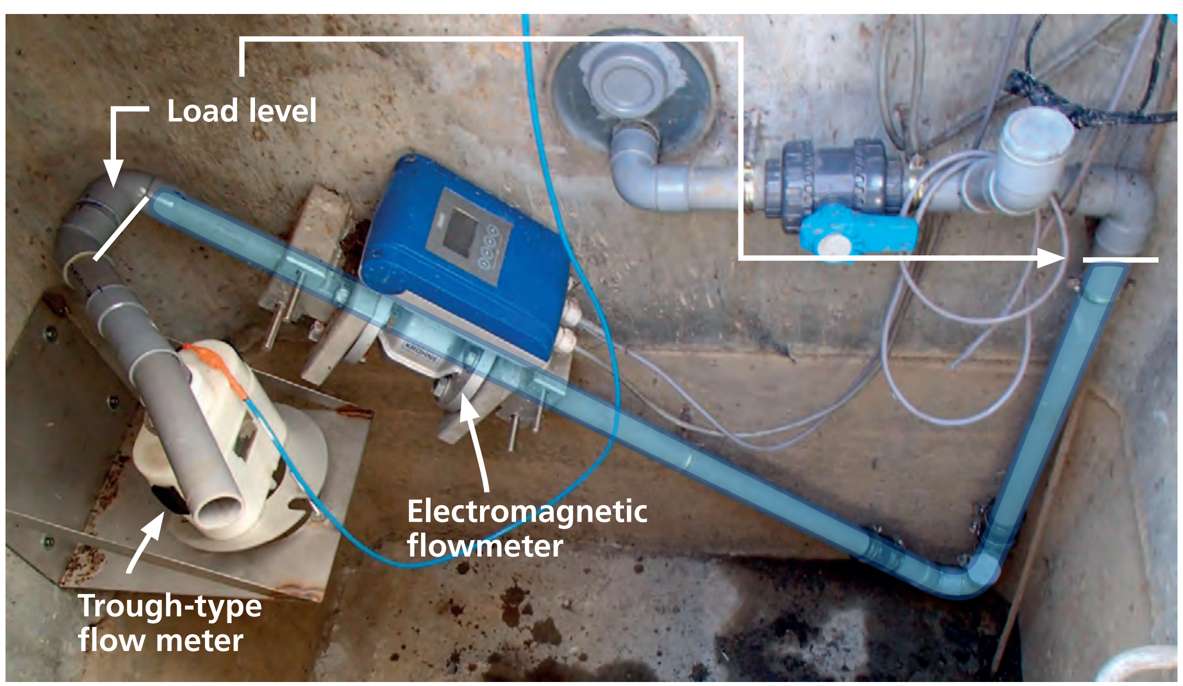
The masses are normalised to take into account the differences of the input surfaces (mass per active square metre was chosen). The indicators are determined for each rainfall event and allow the evaluation of the event performance.
To calculate these indicators, each structure is equipped with the following metrological device (Figure 1):

- ❶ an input area for placing sensors (e.g. conductivity, pH, temperature).
- ❷ double flow measurement: small flows (0 to 100 L/h) are measured by a tipping bucket flowmeter (20 g), larger flows (75 to 3,500 L/h) by an electromagnetic flowmeter. Over the overlap area, the flow rate is averaged.

[1] Stabilised soil is a mixture of gravel, sand, fines and binder, applied in one or more layers.

Figure 1: Schematic diagram for measuring water and micropollutant flows from stormwater source management systems. (Source: Garnier, 2020)





- ❸ a central acquisition unit which collects and archives data continuously every 2 minutes.
- ❹ a prototype stainless steel sampling channel, the shape of which has been studied to ensure the homogenisation of the volume of water at the time of sampling.

The subsamples are taken during the rainfall in proportion to the volume of rainfall and directed to a single bottle ❺ made of teflon-coated plastic. When the rain is low, the sample is taken directly into a teflon-coated canister. The effluents are then partitioned for analysis in amber glass or plastic bottles depending on the substances to be analysed.

Lessons learned from this monitoring: good practices and mistakes to avoid

The acquisition of good quality data is costly in terms of time and human resources. Firstly, it requires responsiveness. Staff must be operational as soon as the rain is announced and samples must be sent to the laboratories quickly, to be received and conditioned within 24 hours, to avoid degradation of the organic pollutants studied. And as the laboratories are not open 24 hours a day, many samples cannot be used: rain at weekends, public holidays, late arrival at the laboratory, etc.

Sampling requires reliable flow measurement control, i.e. sampling in proportion to the volume of water at the outlet of the structure. This makes it possible to obtain a sample that is representative of the water studied at the scale of the event. It is also necessary to rigorously delimit the rainfall events in time. One mistake not to be made is to start sampling before the water from the previous rainfall has finished passing through the structure.

Reliable results require an analysis of the uncertainties. OTHU work has shown that uncertainties in the measurement of pollutant flows arise more from the sampling phase than from the laboratory analysis phase. It is also necessary to select laboratories that guarantee detection and quantification limits compatible with the ranges observed in stormwater, in both dissolved and particulate phases.

Finally, sealing the devices is necessary to account for all discharges to the natural environment, although this is difficult to do for SuDs. But this is the price to pay for reliable and controllable results.

(Frustrated you don't see the results? Go to Question 8.5: *How effective are the sustainable drainage systems structures in regard to micropollutants?*).

Is it useful (and possible) for a community to instrument these structures to assess their performance with respect to pollutants?

The permanent diagnosis of systems, required by the decree of 21 July 2015, encourages local authorities to have a good knowledge of their stormwater management systems. There is a strong temptation to regularly and reliably instrument source control systems, even if this is not imposed by the regulations, in particular to assess their performance in terms of pollutant management. However, local authority departments often lack the material capacity and expertise to implement such a system. The studies on OTHU sites show that reliable instrumentation of SuDS requires significant material, human and technical resources that are difficult to mobilise on the scale of an entire conurbation. Collaborative scientific instrumentation between local authorities and researchers on targeted, diversified and representative sites, with common protocols and the sharing of metrological practices and results, is an appropriate approach for progressively improving knowledge of the performance of structures.

Things to remember

Operational staff, rather than embarking on instrumentation and monitoring of source control systems, data from research programmes and scientific studies are available to you, use them!

TO GO FURTHER

- **Garnier R.** (2020). *Alternative stormwater management systems: Contribution to the analysis of joint performance in quantitative hydrology and micropollutant trapping. Comparison of source-based systems and centralised systems.* Doctoral thesis of the INSA of Lyon. 318 p. - lc.cx/metadier2011 (in french)
- **Bacot L., Barraud S., Honegger A., Lagarrigue C.** (2020). *Operational synthesis of the MicroMegas research programme / Fate of micropollutants in source or centralised stormwater management facilities.* September 2020 – 18 p. - lc.cx/guidemicromegas (in french)

2.6 How to measure the discharge from a combined sewer overflow?

Gislain Lipeme Kouyi, INSA Lyon

Combined sewer overflows (CSOs) were not originally designed to simplify flow measurement. Their hydraulic operation is not mastered, which makes instrument installation difficult. In addition, regulations demand continuous measurement and recording of discharges from the main CSOs. This environmental regulation reflects the issue of these untreated water discharges represent. Although self-monitoring of these facilities should enable operators to better control polluting discharges into the environment, it can also be complex to implement.

Discharges from CSOs contribute to the degradation of aquatic environments

Combined sewer overflows (CSOs) are diversion structures installed in combined sewer networks. They protect downstream structures, and in particular the wastewater treatment plant (WWTP), against hydraulic overloads. Therefore, during wet weather periods, they can lead to the spill of untreated water into the aquatic environment. Discharges from CSOs contribute to the degradation of aquatic environments. By way of illustration, the Metropolis of Lyon has carried out an overall assessment of these discharges (Greater Lyon, 2017): in 2015, the overflow volumes represented nearly 7% of the total volume collected by the combined sewer networks. The pollutant load conveyed by this untreated 7% is equivalent to that carried by the 93% of treated water leaving the WWTP. In addition, the decree of 21 July 2015 on self-monitoring of the collection system requires continuous measurement of flows and estimation of the pollutant load at the main CSOs located downstream of a section intended to collect a gross organic pollution load in dry weather greater than or equal to 600 kg/d of BOD5 (biochemical oxygen demand in 5 days), when they discharge more than ten days a year on average over five years. This is why it is essential to quantify and qualify these discharges.

Les méthodes classiques de mesure des débits et volumes déversés

Figure 1 illustrates the main methods of measuring spill volumes and discharges, the relative advantages and weaknesses of which are described in Table 1.

Figure 1: Methods of measuring spill flow (source: adapted from A. Mate Marin, 2017)..

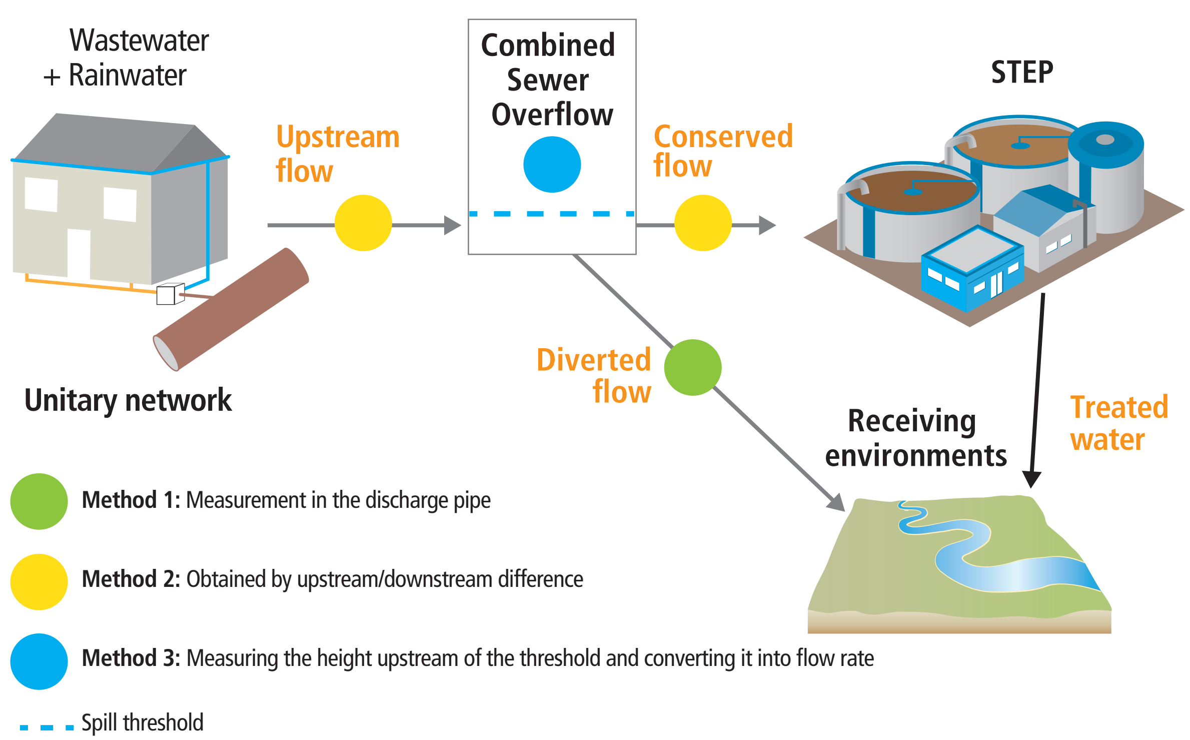


Table 1: Advantages and weaknesses of methods for measuring discharge and volume.

	Benefits	Weaknesses
METHOD 1 Measurement in the discharge pipe	▶ Directly obtaining the discharge rate ▶ One measurement point	▶ Disturbances related to downstream influence due to intrusion of the natural environment ▶ Sensors mostly «dry», which can lead to drift and outlier data production ▶ Low accessibility and difficult maintenance
METHOD 2 Obtaining by upstream/downstream difference	▶ Simplicity (upstream/downstream difference)	▶ Doubling of measurement points ▶ Cost of maintenance and upkeep ▶ Increased uncertainty of spill rate
METHOD 3 Weir measurement and head/flow conversion	▶ Height/flow relationship ▶ Less maintenance	▶ Sensitivity to upstream and downstream flow conditions ▶ Invalid height/flow relationship if deposits are present

Delicate measurements due to complex hydraulic functioning

CSOs often have a complex hydraulic operation (see Question 8.1: *The storm overflow: an ally of sewerage systems, an adversary of the environment?*) The stormwater weir at the Ecully outlet was instrumented within the framework of OTHU (photo 1). It is a high-crested lateral spillway subject to regulatory self-monitoring. The spillway flow falls 6 m to reach the discharge pipe. Since 2002, flow meters have been installed upstream and in the discharge pipe.

Photo 1: Geometry of the Écully weir (source: Momplot, 2014).

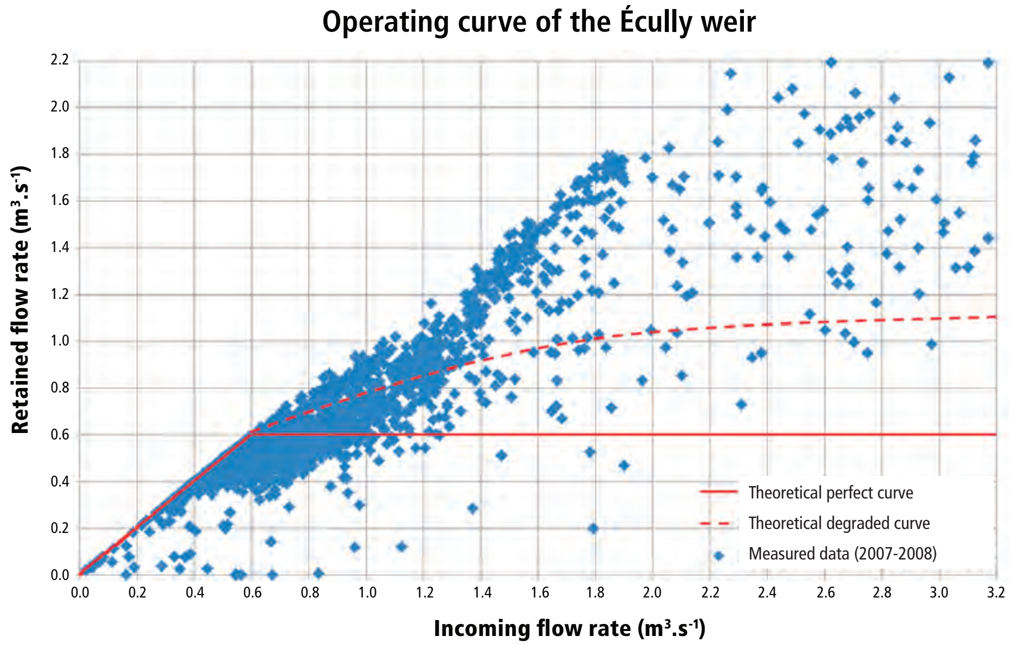


Figure 2: Operating curve of the Ecully weir: flow retained downstream as a function of upstream flow (source: Momplot, 2014).

Between 2002 and 2014, method 1 was used. However, two major problems affected the quality of the data over this period:

- *a :* the intrusion of the natural environment (Planches stream) into the discharge pipe for certain rain events;
- *b :* the air entrainment due to the 6 m drop creating bubbles that significantly disturb flow measurements.

Figure 2 shows the degree of dispersion of the spill data collected in 2007-2008.

Improving the measurement of the discharge rate

As a result, a relationship between the upstream flow and the discharge was proposed in 2014. This relationship was constructed from the results of the 3D modelling of the Ecully spillway. This new method is similar to method 3 (Figure 1). Indeed, it uses measured values of the flow in the upstream pipe and the spilled flows obtained by 3D modelling. However, this method is dependent on the upstream flow conditions, which are themselves a function of the weir geometry and upstream geometric or hydrological changes. Furthermore, an alternative solution was developed and patented in 2014 (Lipeme Kouyi et al., 2014). It is based on the installation of a discharge measurement channel at the discharge space (see positioning within the sewerage system in Figure 3). This original channel is called DSM-flux (device for monitoring and controlling discharged flows).

The DSM-flux is an alternative to existing methods and allows the measurement of flow rates and concentrations of pollutants discharged. A robust height-flow law, i.e. one that is valid whatever the inlet flow conditions, allows us to obtain flows with a relative uncertainty of less than 15%. The volumes discharged are known to within 1%. Figure 4 shows the schematic diagram of this device.

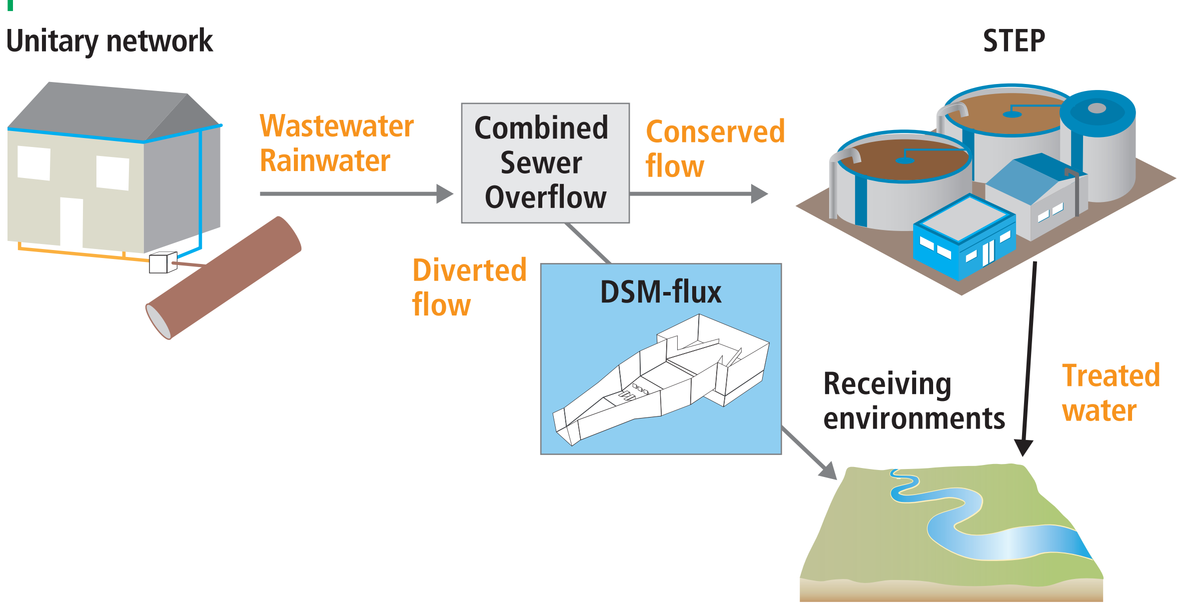


Figure 3: Illustration of the installation of a DSM-flux at the discharge area of a CSO. (Source: adapted from A. Mate Marin, 2017).

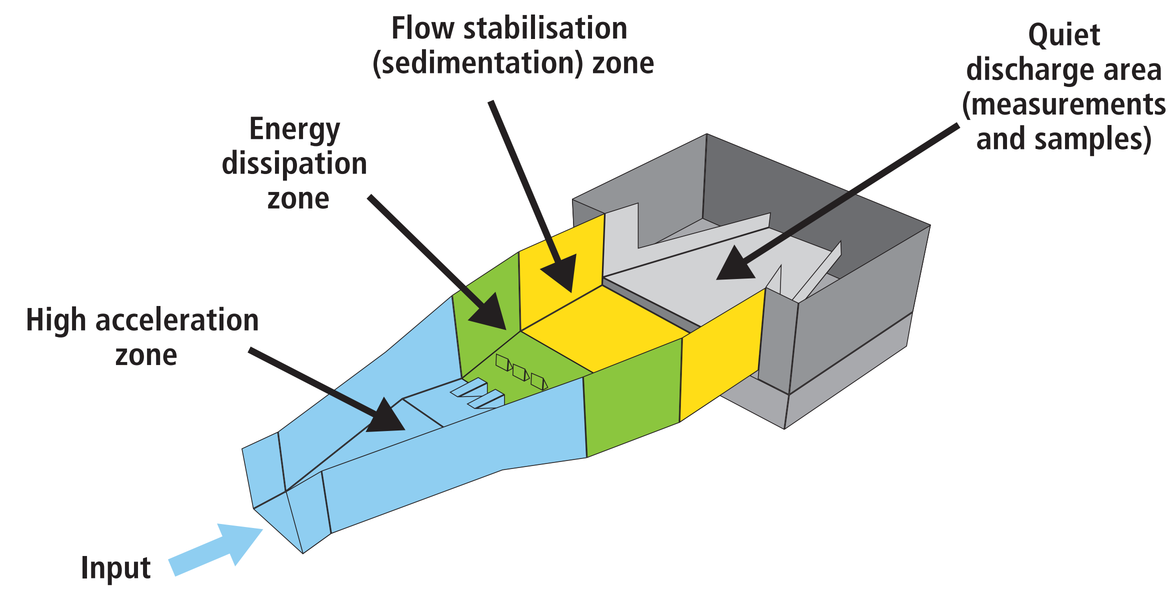


Figure 4: Schematic diagram of the DSM-flux.

In Brief...

Measuring the discharge from a combined sewer overflow (CSO) is not straightforward. If the hydrodynamic behaviour (especially the shape of the free surface) allows it and if there is no change in the upstream and/or downstream flow patterns, a height/flow or upstream/downstream flow relationship should be preferred. discharge (method 3). 3D modelling can improve the establishment of this relationship.
It is generally not possible to reliably measure the discharge rate simply in the discharge pipe, unless the geometry of the site allows for a specific suitable layout, such as DSM-flux.
Whatever the configuration of the weir, it is essential to carry out a preliminary analysis of the hydraulic operation of the CSO before any instrumentation!

TO GO FURTHER

- **Methodology sheet no. 6 :** Calculation of flow from water level, GRAIE – Groupe de travail Autosurveillance, 3 p. (2018) – lc.cx/FicheTechGraie-autoN6 – As well as all the productions of the GRAIE Autosurveillance working group – lc.cx/ProdGraieAutosur (in french)

2.7

Living organisms in the service of field metrology: which bioindicators are used to measure the impact of urban wet weather discharges on receiving environments?

Florian Mermillod-Blondin, Pierre Marmonier, CNRS and University Lyon 1 –
Claude Durrieu, Antoine Gosset, ENTPE

For several years, OTHU has been working on the development of in situ biological measurement tools, to put living organisms in the service of field metrology and the evaluation of the impact of urban wet weather discharges (UWWD) on aquatic environments.

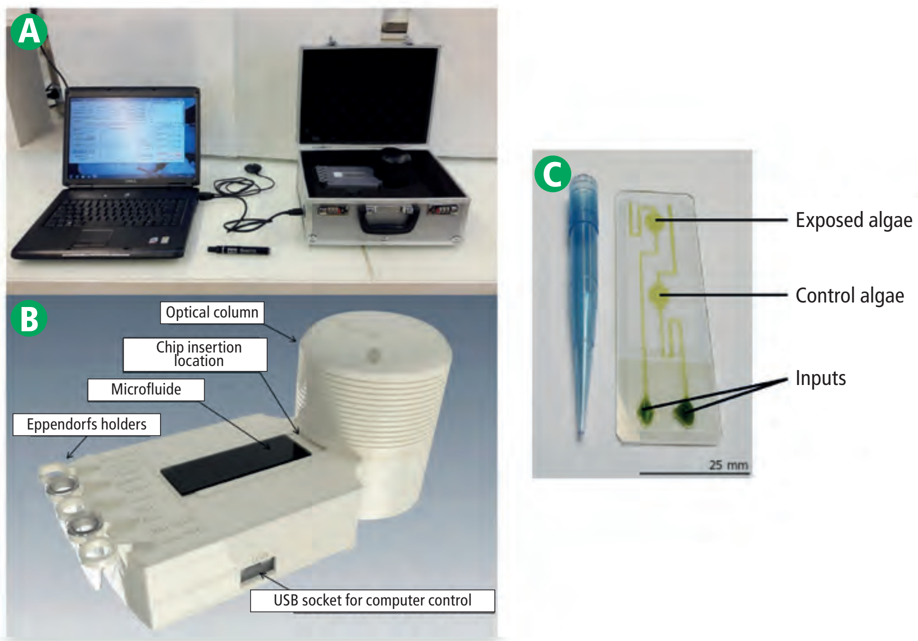
The limitations of classical approaches

The assessment of the quality of aquatic environments at the inlet and downstream of UWWD management systems is traditionally based on physico-chemical analyses to measure water flows, associated pollutants and the environmental performance of the structures. However, these analyses are insufficient: characterisation of the ecological status of the systems also requires the use of bioindicators that make it possible to assess the damage to ecosystems receiving UWWDs.

Within the framework of OTHU, various types of ecotoxicological bioassays, both standardised and non-standardised, were carried out on samples of storm water and CSO discharges. The objective is to measure the effects of UWWDs on living organisms, using representative organisms: unicellular green algae (*Chlorella vulgaris, Pseudokirchneriella subcapitata, Chlamydomonas reinhardtii)* and micro-crustaceans (*Brachionus calyciflorus, Daphnia magna, Ceriodaphnia dubia, Heterocypris incongruens*). These bioassays are laboratory tests that do not consider the dynamics of the systems studied. They are carried out under controlled conditions on samples taken at a given time. A "sensor" approach was developed to measure in-situ and continuously the response of aquatic organisms to the arrival of organic (e.g. pesticides), inorganic (e.g. nitrates) and metallic contaminants.

Moreover, in subterranean ecosystems (groundwater impacted by stormwater inflow), water quality assessment criteria are usually limited to physical and chemical variables without considering biological assessment tools. This is linked to the accessibility of the environment on the one hand which makes biological sampling difficult, and on the other hand to the Water Framework Directive which, unlike surface water, does not consider biological indicators in the assessment of groundwater quality. OTHU's work has sought to fill this gap by proposing tools using micro-organisms and invertebrates to assess the quality of aquifers impacted or not by the infiltration of stormwater runoff.

Figure 1: Overview photograph (**A**) and 3D representation of the developed microfluidic algal biosensor (**B**), and photograph of the microfluidic chip containing analysed microalgae (**C**). Modified from Gosset *et al.* (2018).



Several *in situ* measurement tools have been developed

Algal biosensors sensitive to metals and pesticides

A biosensor can be defined as a device associating a biological element with a measurement system allowing the in-situ analysis of the response of this element to the environmental variations to which it is subjected. The biological elements used here are unicellular algae. We therefore speak of algal biosensors.

The operating principle of such tools is based on the immobilisation of unicellular algae on supports that are themselves connected to transducers. These transducers allow the physiological state of the algae to be recorded by converting a biochemical phenomenon into an easily measurable physical signal. Various biological phenomena can be studied in this way, such as the emission of fluorescence by chlorophylls (green pigments in plants) or enzymatic activities (alkaline phosphatases and esterases being the most studied). The transducers used can be:

- fibre optics: for monitoring the fluorescence emitted by chlorophylls or the transformation of fluorescent products linked to the activity of enzymes;
- conductimetric elements (e.g. electrodes) to monitor changes in the conductivity of a medium generated by enzymatic reactions.

The sensitivity of these sensors is highly dependent on the method of immobilising the algae in contact with or in close proximity to the transducer. Different methods have been tested to date. They can be:

- physical: by direct trapping of algal cells on glass or quartz fibre membranes or by encapsulation in silica matrices.
- chemical: by cross-linking, a process of chemically joining several molecules by covalent bonding with the help of a cross-linking agent (e.g. glutaraldehyde) of algae with albumin, a natural protein found in egg white or blood, for example.

These different methods have enabled the design of innovative sensors for their detection specificity. To date, conductimetric sensors seem to be better suited to the detection of metals, whereas optical methods based on the fluorescence of chlorophylls appear to be more effective for the detection of plant protection products.

However, the immobilisation of the algae constitutes in all cases a more or less impermeable barrier to the molecules present in the medium studied. To overcome this difficulty, we have developed an optical biosensor that studies the disruption of chlorophyll fluorescence in algae. It is based on the use of microfluidic chips (figure 1 C), in which the algae are no longer immobilised, but freely circulating in micro-capillaries of about 100 microns in diameter. This makes it possible to maintain all the exchanges between the algae and the molecules present in the environments studied, in the same way as in the laboratory. These chips are inserted into an optical system including LEDs and photodetectors, connected to data acquisition software on a laptop computer (figure 1A).

Artificial substrates for sampling micro-organisms in groundwater

The originality of this approach is to use artificial substrates in the piezometers of OTHU sites (see Question 6.1 What is the impact of stormwater infiltration basins on groundwater? After an incubation period in the water table, the substrates are collected and analysed to estimate the biomass and activity of the micro-organisms developed on the substrates (microbial biofilms). These variables measured on the microbial biofilms aim to evaluate the quantity of organic matter available in the water table brought by the infiltration of rainwater. Indeed, the quantity of organic matter being a limiting element for micro-organisms in the water table, an enrichment of the water table by organic inputs from the surface can be reflected in the development of microbial biofilms.

Aquatic invertebrate burial in groundwater

The approach developed aims to incubate invertebrates in stainless steel mesh tubes and to measure their physiological state (or health status) after incubations of several weeks. This health state is a combination of their mortality rate and their level of energy reserves (glycogen and triglyceride). After testing several species, two different invertebrates were used: crustaceans living in surface water (*Gammarus pulex*) or in groundwater (*Niphargus rhenorhodanensis*, figure 2).

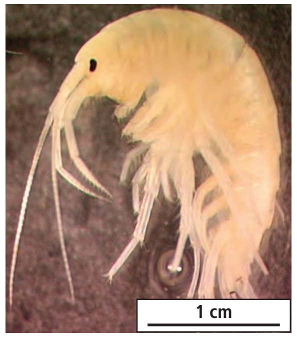
The main results

Microfluidics, a promising avenue for detecting micropollutants

With the development of the microfluidic station, it was

Figure 2: Photos of the caging systems and the invertebrates used.

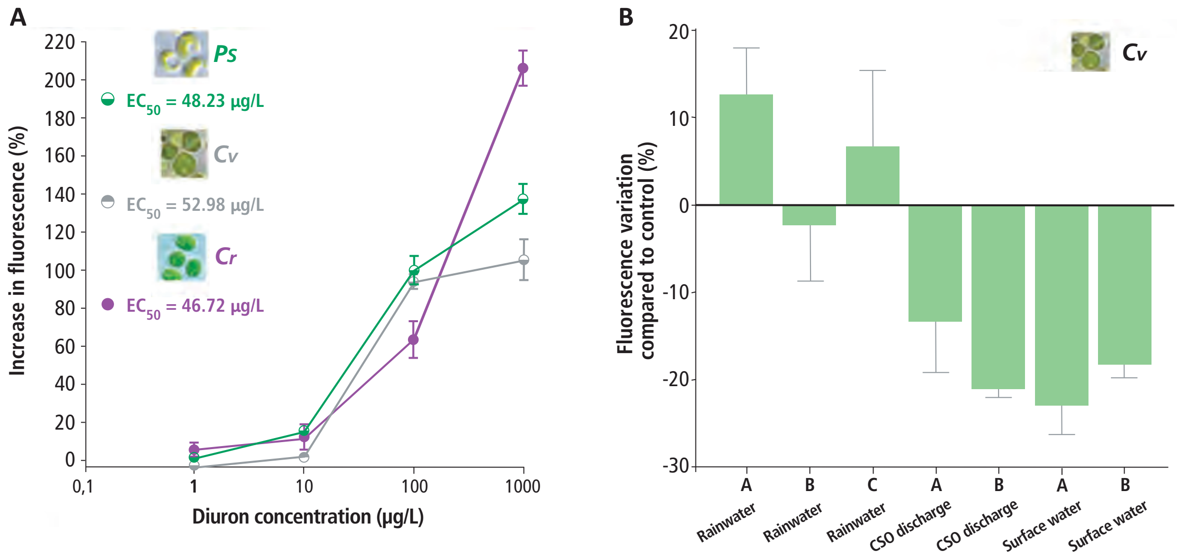
Cage for invertebrate incubation (© C. Maazouz).



A sentinel crustacean living in surface waters *Gammarus pulex* (© P. Marmonier).

A sentinel crustacean living in groundwater: *Niphargus rhenorhodanensis* (© A. Foulquier).

Figure 3: **A** : Rsor response to diuron for three microalgae species (Cv: *Chlorella vulgaris*; Ps: *Pseudokirchneriella subcapitata*; Cr: *Chlamydomonas reinhardtii*). EC50: concentration of substance (here diuron) generating an effect of 50% (here increase of the fluorescence of the algae) compared to the controls. **B**: Example of sensor response after exposure (5 minutes) of *Chlorella vulgaris* to different samples of storm water, storm water overflow and contaminated surface water. The measured quantities are the differences in chlorophyll fluorescence (positive or negative) of the exposed algae compared to control algae. Modified from Gosset et al (2018).



possible to meet all the constraints of field use. The validation of the sensor with a single pesticide (diuron, figure 3) showed the sensitivity of the device (response to low concentrations), after very short exposure times (5-20 minutes). The first results obtained on urban discharges during wet weather (figure 3B) are promising for the detection of ecotoxic micropollutants, especially those that act directly on the fluorescence level of algae (e.g. pesticides).

Biofilms are good indicators of the trophic status of groundwater

For two seasons (spring and autumn), the artificial substrates were incubated for two months in the upstream and downstream piezometers of three infiltration basins monitored by OTHU (IUT, Minerve and Grange Blanche). During incubation, the physico-chemical analysis of the nutrients in the groundwater was carried out on three occasions in each of the piezometers. The biofilms that grew on the artificial substrate beads were also analysed after two months of incubation in groundwater. These analyses, which consisted of measuring the growth and enzymatic activities of the biofilms, provided information on the availability of nutrients (mainly dissolved organic carbon and phosphates) and on the contamination of the groundwater by surface water downstream of the ponds. They revealed that biofilms were more developed and active downstream of the ponds compared to the control areas. Furthermore, the measured biomass and activity were positively correlated with dissolved organic carbon levels and, secondarily, with phosphate levels (figure 4). This method therefore provides an integrated assessment of the degree of groundwater disturbance over time.

The health of caged invertebrates is a good indicator of groundwater pollution

Invertebrates were caged and immersed in groundwater at the bottom of piezometers located upstream (control) and downstream (impacted) of four stormwater infiltration basins. The simple determination of the survival rate of these invertebrates after one week (for Gammarus living in surface water) or after one month (for Niphargus living in groundwater) is not very informative. Survival is generally good and seems to be controlled mainly by anoxia (oxygen deprivation). On the other hand, when survival is combined with the level of energy reserves, the health index of the sentinels obtained is lower downstream of the infiltration basins and significantly correlated with the quality of the groundwater (figure 5). This link between health status and groundwater quality is better when subterranean organisms are used because they are more resistant to environmental stresses and can therefore remain in the environment for longer.

Figure 4: Relationship between groundwater quality (dissolved organic carbon in **A** and phosphates in **B**) and biofilm biomass after two months of incubation (proteins in **A**, carbohydrates in **B**) at two times of the year (autumn in green, spring in white). Adapted from Mermillod-Blondin *et al* (2013).

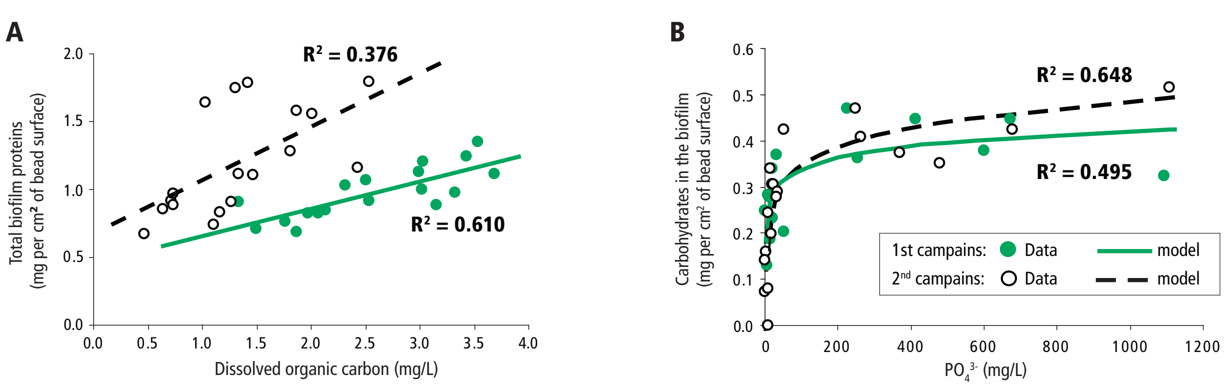
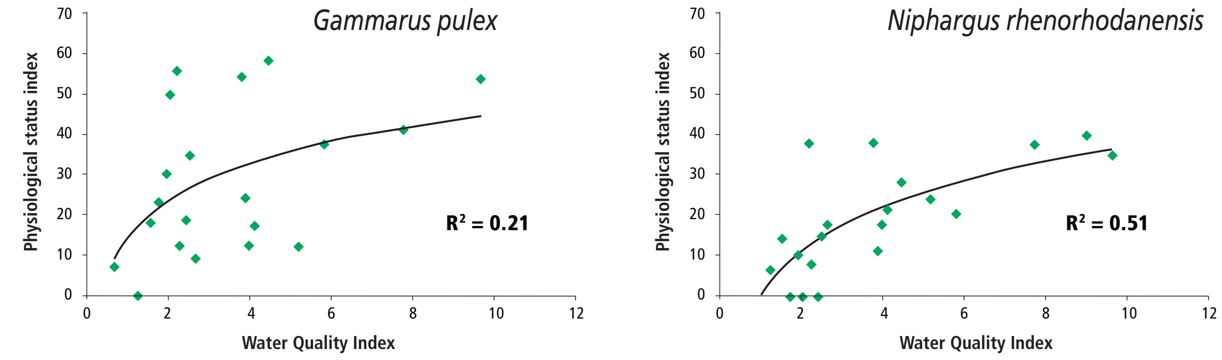


Figure 5: Relationship between the invertebrate health index (combining mortality and energy reserve levels) and the groundwater chemical quality index (combining oxygen and organic matter concentrations). The correlations for both species are significant (p-value = 0.019 for Gammarus and p-value = 0.0002 for Niphargus) although a strong dispersion is observed for intermediate water quality values.



Several ongoing and future developments

Concerning the biosensors, we plan to develop the microfluidic device into a «lab on chip» system that would make it possible to simultaneously study the response of several parameters on different algal species. This would make it possible to multiply the data to better target the contaminants to be detected.

The methodology based on the use of biofilms as indicators of the effects of stormwater infiltration on groundwater is very promising. Using molecular tools to determine the bacterial species present in biofilms, it is now possible to assess changes in bacterial communities linked to infiltration practices and to specifically look for the presence of pathogens (see Question 5.3: *What are the microbiological contaminants carried by urban wet weather discharges and how dangerous are they for humans?*).

For the encampments, it is planned to develop the methodology by using the isopod crustacean Asellus aquaticus, which has several advantages: easy access to biological material, use in numerous ecotoxicology experiments, genomic approaches already developed on this organism. With this species, it will be possible to go further into the effects measured on organisms via the expression of genes expressed as a function of the pollutants present.

In Brief...

The work carried out within the framework of OTHU has enabled the development of relevant bioindicators for assessing the quality of stormwater runoff and aquatic environments (surface water, groundwater). In addition to traditional chemical approaches (point sources), these integrative tools shed new light on the ecological status of dynamic systems impacted by urban wet weather discharges (UWWDs).

TO GO FURTHER

- **Gosset A., Durrieu C., Renaud L., Deman AL., Barbe P., Bayard R., Chateaux J.-F.** (2018). *Xurography-based microfluidic algal biosensor and dedicated portable measurement station for online monitoring of urban polluted samples* – Biosensors and Bioelectronics 117: 669-677. - 10.1016/j.bios.2018.07.005 – lc.cx/gosset2018 (in french)
- **Mermillod-Blondin F., Foulquier A., Maazouzi C., Navel S., Negrutiu Y., Vienney A., Simon L., Marmonier P.** (2013). *Ecological assessment of groundwater trophic status by using artificial substrates to monitor biofilm growth and activity.* Ecological Indicators 25: 230–238. - 10.1016/j.ecolind.2012.09.026 – lc.cx/mermillod2013 (in french)
- **Marmonier P., Maazouzi C., Foulquier A., Navel S., Francois C., Hervant F., Mermillod-Blondin F., Vienney A., Barraud S., Togola A., Piscart C.** (2013). *The use of crustaceans as sentinel organisms to evaluate groundwater ecological quality.* Ecological Engineering 57: 118-132. - 10.1016/j.ecoleng.2013.04.009 – lc.cx/marmonier2013 (in french)

2.8

How can we produce quality data that can be used sustainably?

Flora Branger, INRAE Lyon – **Nicolas Walcker**, INSA Lyon – **Laëtitia Bacot**, Graie

Producing quality data, managing it over time, and making it available is a real challenge for researchers and operational staff in water management. Meeting this challenge requires a rigorous data capitalisation process, from the establishment of measurements to the final sharing stage.

Scientific, operational and regulatory issues

The challenges of managing sewer networks and stormwater management installations, the regulatory obligations to self-monitor and the need, at both research and operational levels, to better understand the functioning of urban systems, lead to the acquisition of a large quantity of field data. A major challenge is to ensure that this data is of sufficient quality to answer questions and to ensure that the data is stored in a way that allows it to be used successfully and sustainably, in accordance with the FAIR principles: Findable Accessible Interoperable and Reusable (Wilkinson *et al.*, 2016). In addition, a European regulatory injunction (EU Directive 2019/1024 on open data) requires that all data produced by public activities (research, state services, local authorities) are freely accessible. The data capitalisation process must therefore take these issues into account from the outset.

The data capitalisation process

Data capitalisation is a progressive process in several stages that applies to the entire measurement chain. It therefore begins with the installation of sensors and samplers in the field and continues through to the qualification, storing and sharing of data (Figure 1).

Once the acquisition chain has been chosen and installed, this process is divided into the following steps.

STEP 1: Sensor maintenance, checks and calibrations
The first stage of field verification is the maintenance of sensors and signal conditioning elements. It includes the usual operations of periodical calibration, control of the good functioning, cleaning, and verification operations by carrying out spot-checking measurements This can be, for example, a visual check of the water level on a water level gauge, the collection of rainwater from a rain gauge to check the cumulative volume over a given period, or the measurement of conductivity or pH using standard solutions.

These control operations are crucial to ensure that the data acquired is reliable. It is therefore essential to keep a record of them, for example in the form of a sensor or measurement point life sheet, in paper or digital format.

STEP 2: Data validation and qualification
Data validation is the step that enables the transition from raw data (output from the acquisition chain) to validated data, i.e. data that can be used for analysis, modelling, reporting, or dissemination.

This step differs according to the nature of the data acquired and the operating protocols in place in the laboratory or department carrying out the validation. Most often, it consists of detecting and removing outliers, smoothing out micro-variations corresponding to measurement noise, if any, and correcting sensor drifts, using the spot-checking measurements and sensor calibration mentioned above. The calibration relationships are used to correct the data and estimate the uncertainties. Secondly, the values of one sensor are compared with those of other sensors in the vicinity, to verify that the recorded values are consistent with each other. For example, the variation of water level observed by a sensor can be compared with the signals of other sensors located upstream and/or downstream to check that they are consistent, and even with data from a rain gauge located nearby. Data critique and validation requires knowledge of the factors influencing the measured quantities as well as an understanding of possible correlations between different quantities. Validation can be manual or assisted by specialised software.

The final stage of validation is the qualification of the data, i.e. the attribution to each measured value of a code indicating its quality, and therefore the confidence that can be placed in it. This is the equivalent of a grade, which can take the form of a number (1 to 3 for example) or a letter (v for valid, d for doubtful, I for deficient: example in Figure 2 on the following page). Qualification guarantees users that the data has been produced within a controlled framework (validation process) implementing good metrological practices and communicates the producer's expertise as to the reliability of its data.

STEP 3: Data storage
Data storage is the archiving of data so that it can be used in a sustainable way. You can archiv data at various stages of validation. However, two stages should be prioritised: raw data and validated data. The interest of sarchiving validated (directly usable) data is obvious, but potential errors (human or material) during validation also justify rigorous archiving of raw data, which thus serves as a reference. Not only the measured values themselves are to be archived, but also the associated information that is essential for the exploitation of the data: for example, the geolocation of the measurement point, the measured variable, the unit, the time zone and the owner of the data. This is called metadata. All the information (data and metadata) must be stored electronically in open and durable formats, to ensure readability even after a few years. Similarly, the information should be structured to allow easy retrieval.

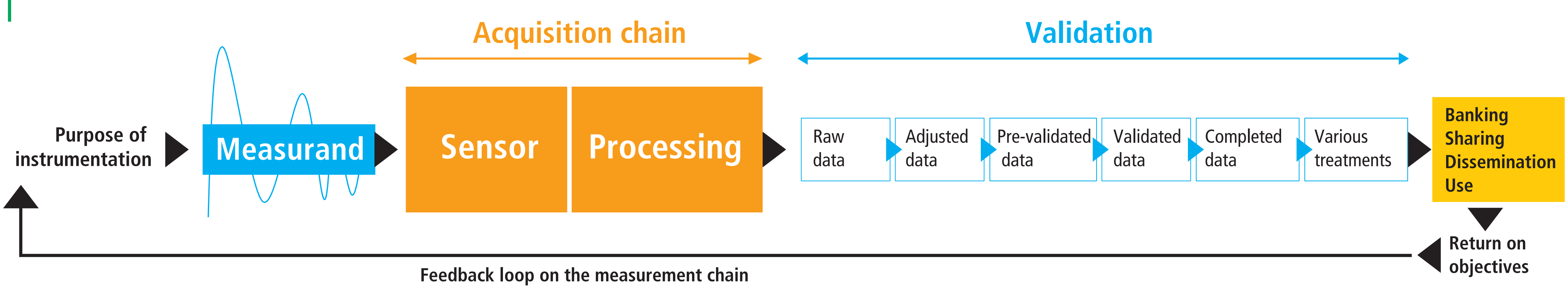
Estimating uncertainties: an essential complement to qualification

Uncertainty provides a quantitative value where the quality code is only qualitative. According to the International Bureau of Weights and Measures (GUM, 2008), measurement uncertainty "characterises the spread of values attributed to a measured quantity, based on the information used". It is generally expressed in statistical form (standard deviation, confidence interval) and takes into account all the factors that can influence the measurement: the properties of the sensor used (its resolution and accuracy, generally indicated by the manufacturer), but also the method used, the operator and the environmental conditions (temperature, nature of the flow, etc.).

Ideally, an uncertainty should be provided with each measured value. In practice, this is unfortunately rarely the case. While it is not always easy to calculate the uncertainty of each value exhaustively, software can help to estimate it.

If the data is stored in the form of files, for example, text or csv formats should be preferred to Excel workbooks, which are very popular, but whose proprietary format is closed and vulnerable to version changes. A rigorous architecture must also be put in place, with, for example, a classification by year and a nomenclature to be respected for file names. Finally, a backup system must ensure that the data is always available. However, the file solution has disadvantages as soon as the data sets become large, particularly for sharing the data and guaranteeing their integrity (maintaining a reference version against modifications and copies). The solution in this case is the use of relational databases, which organise information in a structured and efficient way in the form

Figure 1: Illustration of the data capitalisation process (GRAIE).



of tables (Horsburgh *et al.*, 2016), and allow querying, i.e. fast and efficient access to data regardless of the size of the dataset. Finally, database management software also has access rights management and backup capabilities, which help to ensure data integrity.

STEP 4: Sharing and using the data

The last step is to share the data, and more precisely to share it on the Internet. Several solutions are possible and complementary.

The first is to catalogue the data and make this catalogue available. This corresponds to the “F” “Findable” of the FAIR principles, i.e. making it known that these data exist. Several software packages now allow metadata catalogues to be compiled and made available online, such as Geo-network used by OTHU.

The second solution corresponds to the “A” “Accessible” of the FAIR principles: it is access on the Internet not only to the metadata, but also to the data itself. While home-made solutions such as shared folders or FTP (File Transfer Protocol) servers are still possible, the solutions offered by database management systems associated with web applications guarantee secure, traceable and efficient access to data. OTHU’s BDOH application offers a web interface that allows users to consult, view and download archived data.

The third solution consists of allowing the visualisation of data at a first level of interpretation. This can take the form of dashboards, graphical summaries, indicators that are calculated regularly and allow an assessment of the data acquired.

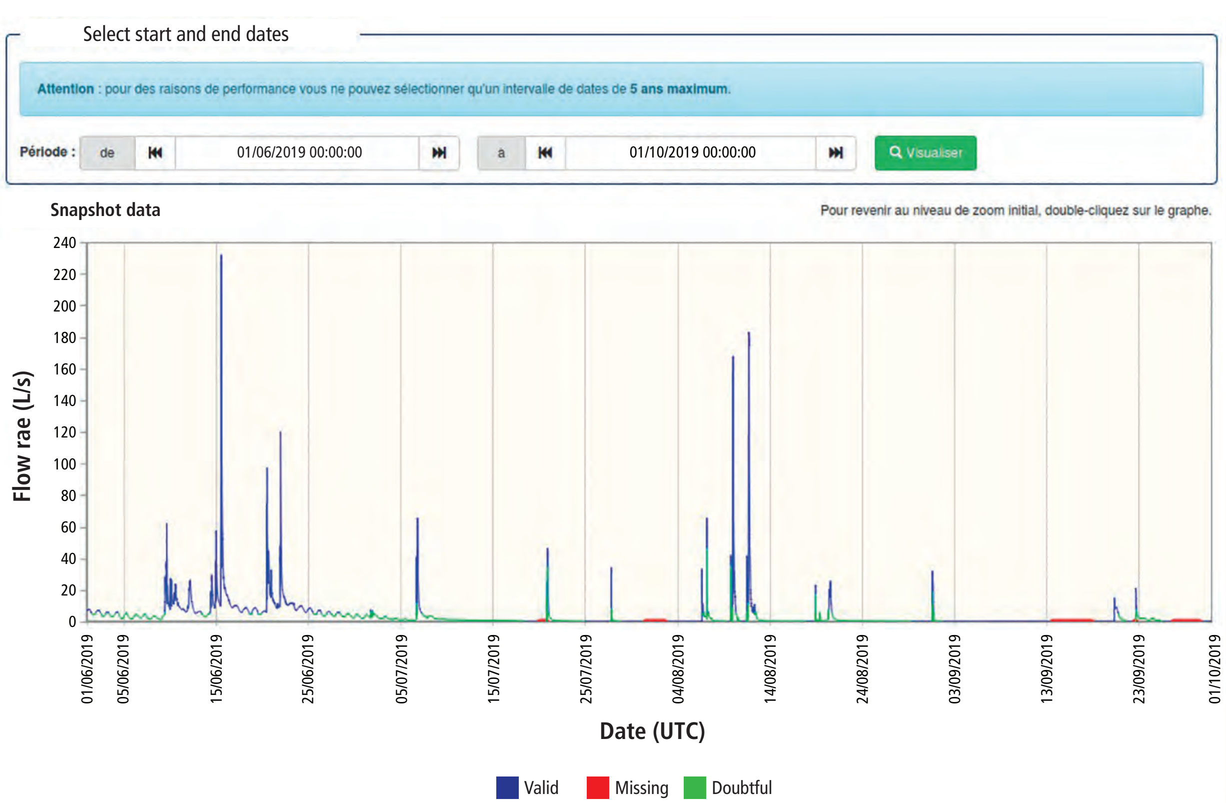
Here too, the functionalities of web applications coupled with database management systems make it possible to generate these monitoring and valuation indicators automatically.

OTHU has developed several protocols and software for data management

With 10 million data values produced annually, OTHU has developed real expertise in the acquisition of intensive, reliable, multidisciplinary and long-term data. Since its creation, OTHU has always focused on the data acquisition and qualification processes. A detailed methodology has been produced, allowing the development of several validation protocols applied by the research teams on the different experimental sites. OTHU has also developed several software packages that are an integral part of these protocols:

- Based on the results of research conducted within OTHU since 2000, EVOHE is a software developed by INSA. It allows the automatic processing and validation of long time series of urban hydrology data and offers numerous metrological functionalities in a single tool, from raw data acquisition to the validation of corrected data and their operational use.
- BaRatin (Bayesian Rating curve) is a method and software developed by INRAE since 2010 to provide an operational solution for the construction, calibration and estimation of uncertainties in rating curves. BaRatin and its graphical environment BaRatinAGE are available in French and English with a free individual license.

Figure 2: Graphical representation of the extract of a streamflow time series on BDOH (Mercier station at Bridge D610). The colours correspond to the quality code of each measured value (here: doubtful quality for the lowest flows and deficiency for the missing data).



- The BDOH database and application have been developed by INRAE since 2011 for the online storage, management and sharing of hydrological field data time series. BDOH includes functionalities for data search, graphical visualisation, export in different formats and time steps, as well as automatic calculations of derived data. A fine-grained role management allows to assign different viewing/downloading/editing rights to different users.

In Brief...

To produce good quality, usable and sustainable data, it is necessary to have:

- **a clear definition of the objectives of data acquisition and their intended uses;**
- **a detailed procedure for the entire capitalisation process: from field verifications (metrology) to archiving and sharing, including data validation, qualification and uncertainty estimation;**
- **adequate software and tools to help carry out this work, such as those offered by OTHU research teams;**
- **sufficient and competent human resources and coordination between the different data producers.**

TO GO FURTHER

- **OTHU metadata catalogue,** on Geonetwork: lc.cx/metadonneesothu
- **Data management software developed by OTHU teams:**
  – EVOHE software (INSA Lyon): c.cx/evohe
  – the BaRatin method and software (INRAE): lc.cx/baratininrae
  – the BDOH application (INRAE) and OTHU data of the Yzeron basin: c.cx/bdoh

Climate and rain 3

The climate, in all its components, is one of the determining factors in the functioning of urban water management systems. If rain is the central component, wind, temperature or sunshine are also to be considered: they modify the evapotranspiration capacity or change the evolution and transfer of pollutants.

In the context of climate change and the need to design and build stormwater management systems that must operate for decades, it is necessary to predict the evolution of these climatic parameters.

The basis of forecasting is observation. It is because of long series of data, obtained through a rigorous monitoring process and under varied climatic conditions, that we can build models that allow us to know, understand and simulate the evolution of the climate and its various components. The duration of observation is even more important as we are sometimes interested in phenomena that occur only very rarely (very heavy rainfall, for example).

The twenty years of observation by OTHU have made it possible to build up a climatic database of exceptional interest, both in terms of its duration and its density. This chapter provides an outlook.

3.1

What rainfall is of interest for urban stormwater management?

Bernard Chocat, INSA Lyon

Rain is at the origin of the hydrological cycle. In cities, it replenishes water resources and is also the cause of flood risks. It is the of rainfall, which mainly determines the design and operation of stormwater management facilities.
Knowledge of rainfall is therefore essential for effective urban water management. However, it faces several problems that can only be solved by dense and long-term observations.

Extremely diverse rainfall

The simple phrase "you have to know the rainfall" covers a complex reality in practice. Rainfall is extremely diverse. As a result, their consequences on the city and the functioning of the management systems are also numerous and diversified. The technical guide La ville et son assainissement (The city and its sanitation) distinguishes, for example, 4 levels of operation of the sanitation system, associated with increasingly heavy rain risks:

- Level 1 corresponds to **routine rainfall** (which occurs several dozen times a year), for which there should be no discharge of untreated water into the natural environment.
- Level 2 corresponds to **average rainfall** (which occurs a few times a year), for which discharges of untreated water from storm overflows but no hydraulic malfunctions.
- Level 3 corresponds to **heavy rainfall** (which occurs a few times per decade), for which the priority is to prevent overflow of the surface networks.
- Level 4 corresponds to **extreme rainfall** (which occurs a few times a century), for which the priority is to control the risk of overflows without hoping to prevent them.

Knowledge of rainfall faces several difficulties

The first difficulty associated with knowledge of rainfall for urban stormwater management is therefore that it is necessary to associate a frequency of occurrence (i.e. an average number of overflows).

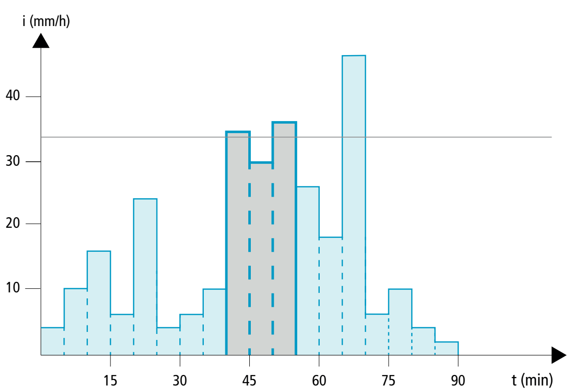
The second and more important difficulty is to choose the quantity to be used to characterise the importance of the rain. The simplest and most traditional way is to use the notion of maximum average intensity[1]. This is calculated as follows:

- for a given rainfall, different reference times must be chosen, for example 6, 15, 30 or 60 minutes;
- then identify, by going through the total duration of the rain, the periods of time when the rain was the most intense on each of the considered durations;
- and finally calculate the average intensity over these periods (Figure 1).

A reductive view of rain

However, this simple model is far from ideal.
The first problem is that it is a simplified view of rainfall that does not really take into account its possible effects on the stormwater management system. For example, a

Figure 1: Example of finding a maximum average intensity over 15 minutes.



rainfall event where the maximum average intensity is at the beginning of the event (when the network is empty) will not have the same consequences as if the peak intensity occurs at the end of the event (when the network is full).

The second problem is that it is a local vision (observed on a specific point of the territory). However, rain is a spatially distributed phenomenon and depending on whether the area of high intensity is very small or very large, it is easy to imagine that the volumes of runoff produced will be very different.

In the end, to effectively characterise the rain to better manage urban stormwater requires, deploying a set of measuring devices, distributed over the area of interest with a sufficient density and with regard to the spatial variability of the phenomenon studied, and, secondly, to have this in place and functioning for a long period of time in order to increase the probability of observing rare events.

[1] See Wikhydro article: lc.cx/curves

What have we learned from long-term observations?

In the Lyon metropolitan area, we are fortunate to have a dense network of rain gauges (more than 30 stations) which was installed in 1985, i.e. for 35 years (at the time of writing). The data produced by this network was integrated into OTHU at its creation. All the data has made it possible to achieve several major research and operational results:

- Establishment of a spatially distributed rainfall database that serves as an input to the CANOE software for simulating the operation of the Metropole's wastewater system.
- Construction of intensity-duration-frequency curves[2] using an original method of regionalisation: these curves make it possible to estimate the local rainfall risk up to return periods of the order of a century.
- Improved coupling between ground rainfall and radar data.
- Better knowledge of the trajectories of rainfall events in the agglomeration.
- Better knowledge of the performance of interpolation methods that allow the calculation of probable rainfall intensities between monitoring stations.

This progress has made it possible to improve the understanding of how the sewerage system functions during wet weather by combining modelling and metrology. They have also served as a basis for the development of tools for the design and sizing of stormwater management solutions at the plot level.

Why is it important to continue?

There are three issues that still need a lot of attention.

First of all, increasing our understanding of the waste and stormwater system processes is a continuous activity which requires us, every year, to question the acquired certainties by analysing the differences between measurements and modelling results. Improving the knowledge of rainfall inputs is therefore essential because the differences observed between measurements and modelling results are often the result of poor rainfall accounting.

The second problem is the change in rainfall risk. The climate is evolving rapidly, and this change will likely have consequences for rainfall. The structures being built today will still have to function reliably in 50 or 100 years' time. It is therefore extremely important to try to predict how the rainfall risk will differ over the coming decades. Even though knowledge of past developments is not necessarily a guarantee for predicting future developments with certainty, it is still useful information. Continuously measuring the rainfall observed in the agglomeration and analysing it regularly is therefore a tool to better understand the evolution of rainfall risk in the future. The update of the Montana coefficients[3] conducted in 2020 showed, for example, a significant increase in the rainfall hazard for long periods (over 12 hours).

[2] See Wikhydro article: lc.cx/averagemaximumintensity

The third problem concerns the forecasting of extreme events. Among the possible evolutions of the rainfall risk associated with climate change, there is the possible northward shift of the intense rainfall events that currently affect the south of France. If this risk is confirmed, the Lyon metropolis could have to deal with much more intense rainfall than has been considered during the design of the structures. One way of managing the consequences of such events is to anticipate sufficiently far in advance to allow warning and protection systems for the population to be set up. This requires coupling the local network of the Metropolis with devices capable of observing the evolution of rainfall at a longer distance (meteorological radars for example).

These last two aspects are examined in more detail in question 3.2: *Can the study of atmospheric circulations help us, at the city scale, to estimate rainfall and its evolution*?

How the addition of rain gauges increases the observation time

Regionalisation methods take advantage of the fact that measuring rainfall at several stations over a given period of time artificially increases the observation time.
Simply, if the stations measure completely independent events, doubling the number of observation stations is equivalent to doubling the observation time.
In reality, as the events measured on nearby stations are statistically dependent, the calculations are much more complicated, but the fact of having 30 stations over 35 years makes it possible to significantly increase the equivalent observation time.

[3] Montana's formula is used to numerically fit intensity-duration-frequency curves. It allows to calculate the average intensity i(d,T), (or the precipitated height h(d,T)) over a duration d, according to two coefficients: a(T) and b(T), depending on the considered return period T, inverse of the frequency. (See Wikhydro article: lc.cx/montana)

3.2

Can the study of atmospheric circulation help us, on a city scale, to estimate rainfall and its evolution?

Florent Renard, Lyon 3 University – **Hélène Castebrunet**, INSA Lyon

The study of large-scale atmospheric circulations provides a better understanding of the rainfall of a territory and its evolution. It can therefore prove invaluable in the context of climate change, in particular to anticipate the necessary adaptations in the urban stormwater management strategy.

The impact of global climate change on Lyon's rainfall

Although the global climate is constantly changing over paleoclimatic scales, it has undergone significant variations since the end of the 19th century. These variations can have repercussions on a local scale, particularly on the rainfall regime in Lyon. These rains do not all have the same characteristics in terms of water height, duration, or intensity. These differences can be explained by the type of atmospheric circulation1 that generates them. The characterisation of these large-scale circulations, which has been little studied until now in this territory, can provide a better understanding of rainfall phenomena and thus provide elements for adapting stormwater management structures to climate change.

Stable annual totals in the Lyon area

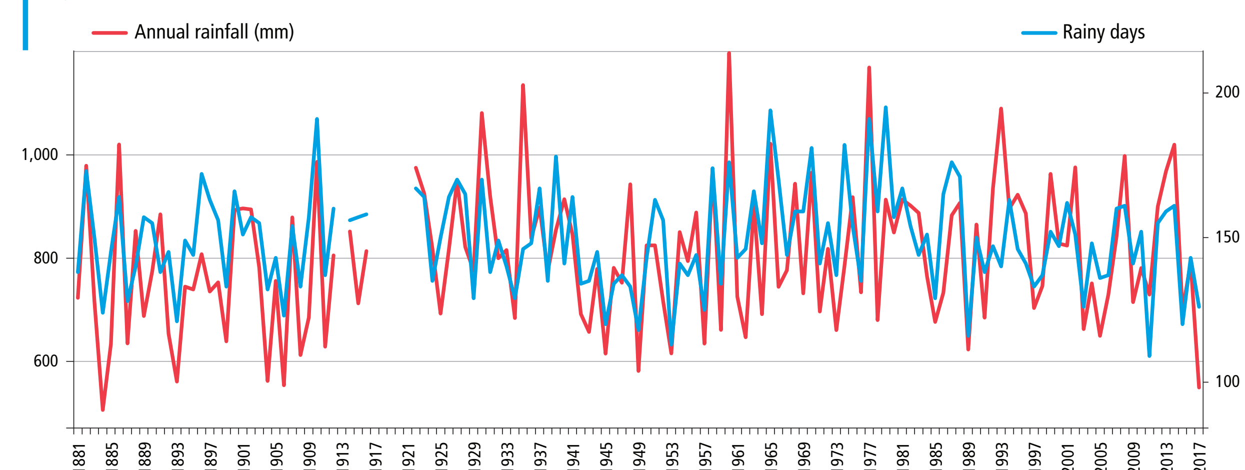
The Météo-France rain gauge at Lyon-Bron provides information on annual rainfall totals and the number of annual rainy days since the end of the 19th century (Table 1 and Fig. 1).
At first sight, no significant changes are visible. Statistical tests do not allow us to identify any change in the number of rainy days since 1881. Annual rainfall totals are slightly (but significantly) increasing, as are daily rainfall totals. However, this overall stability may mask profound changes in the types of rainfall encountered in Lyon as well as in the types of regional meteorological situation (pressure, wind, temperature) at their origin.

[1] Circulation types are defined as persistent, large-scale flow patterns that occur repeatedly over a given area. They organise the synoptic systems that condition the weather on a local scale over several days. These types of circulation can be catalogued according to different methods.

Table 1: Cumulative rainfall and annual rainy day parameters since 1881 at the Météo-France station in Lyon-Bron.

	Annual rainfall (mm)	Annual rainy days
Average	803.7	150.9
Standard deviation	135.0	17.3
Maximum	1,227.1 (1960)	196 (1979)
Minimum	506.0 (1884)	113 (1953 et 2011)

Figure 1: Rainy days and annual totals since 1881 at the Lyon-Bron station of Météo-France.



The Hess-Brezowsky catalogue for the study of rainfall patterns

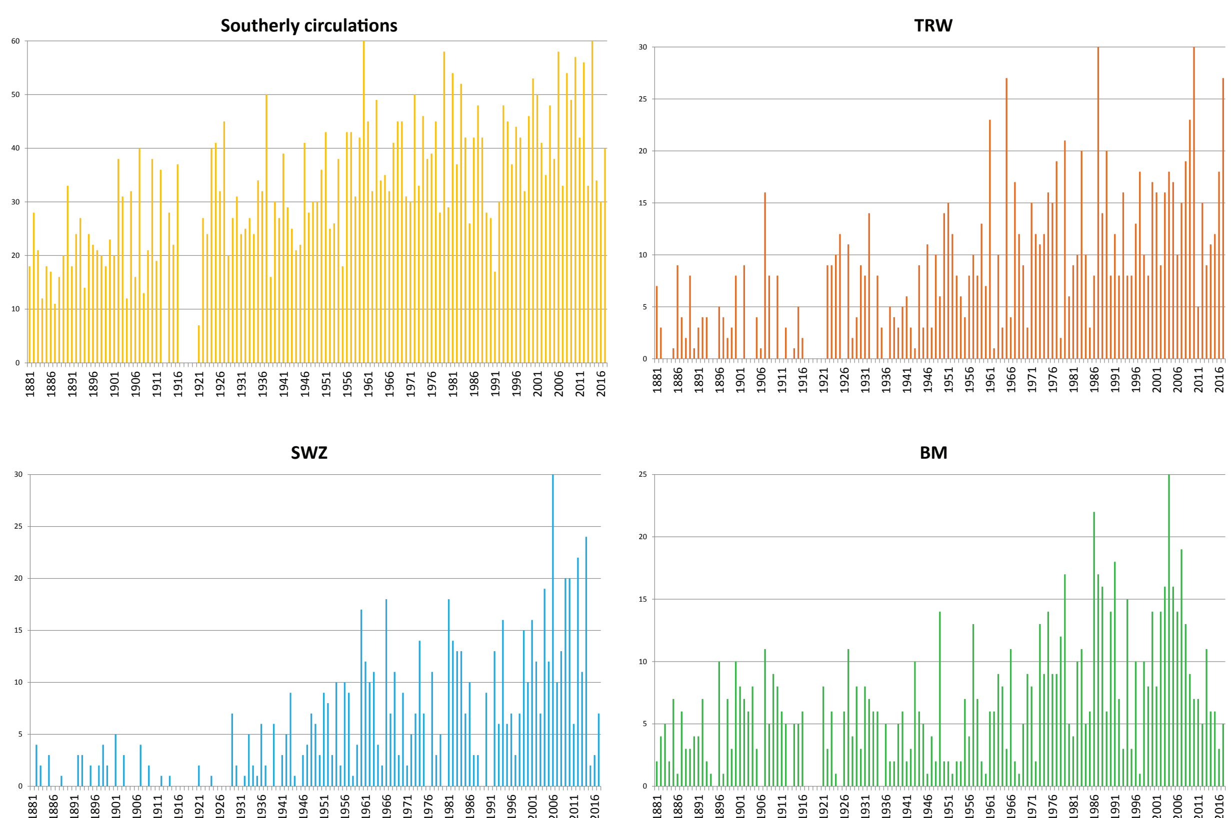
The Hess-Brezowsky catalogues for the determination of weather patterns in Western Europe are numerous. The classification methods, the oldest of which date back to the middle of the 20th century, are diverse and their origins, objectives and applications vary. An evaluation of the main existing catalogues has led to the Hess-Brezowsky classification (Gerstengarbe and Werner, 1999). It is based on 29 types of situations (Großwetterlagen: GWL), which can be grouped into five main atmospheric circulation types (Großwettertypen: GWT). The data from the rain gauges of Météo-France has been used to identify rainfall since 1881 and those of the mainland and OTHU allow the nature of the events to be identified in detail since 1988. The trends are analysed using several statistical tests.

Over a century, an evolution of atmospheric circulations favouring notable rainy episodes

When comparing rainy days with dry days, 31% of the circulations causing rainy days are from the West (compared with 24% for dry days), 24% of rainy days are from the North-West and North (compared with 25% for dry days), and 22% of rainy days are from the South (compared with 14% for dry days). North-easterly and easterly flows and situations with a centre of action over Central Europe were the least frequent to lead to rainy days with 11% (compared to 12% for dry days) and 12% (compared to 24% for dry days).

There are also strong evolutions of the types of circulation on rainy days between 1881 and 2017. Indeed, we see a stagnation or a decrease of all types, except for the southerly circulations, which show a strong and constant increase (fig. 2).

Figure 2: Circulation types during rainy days in Lyon from 1881 to 2017 (respectively from top to bottom and from left to right: Southerly flow, TRW 'Talweg over Western Europe', SWZ 'Southwestern flow, cyclonic' and BM 'Ridge of high pressure over Middle Europe').



Relationships between circulation types and precipitation types

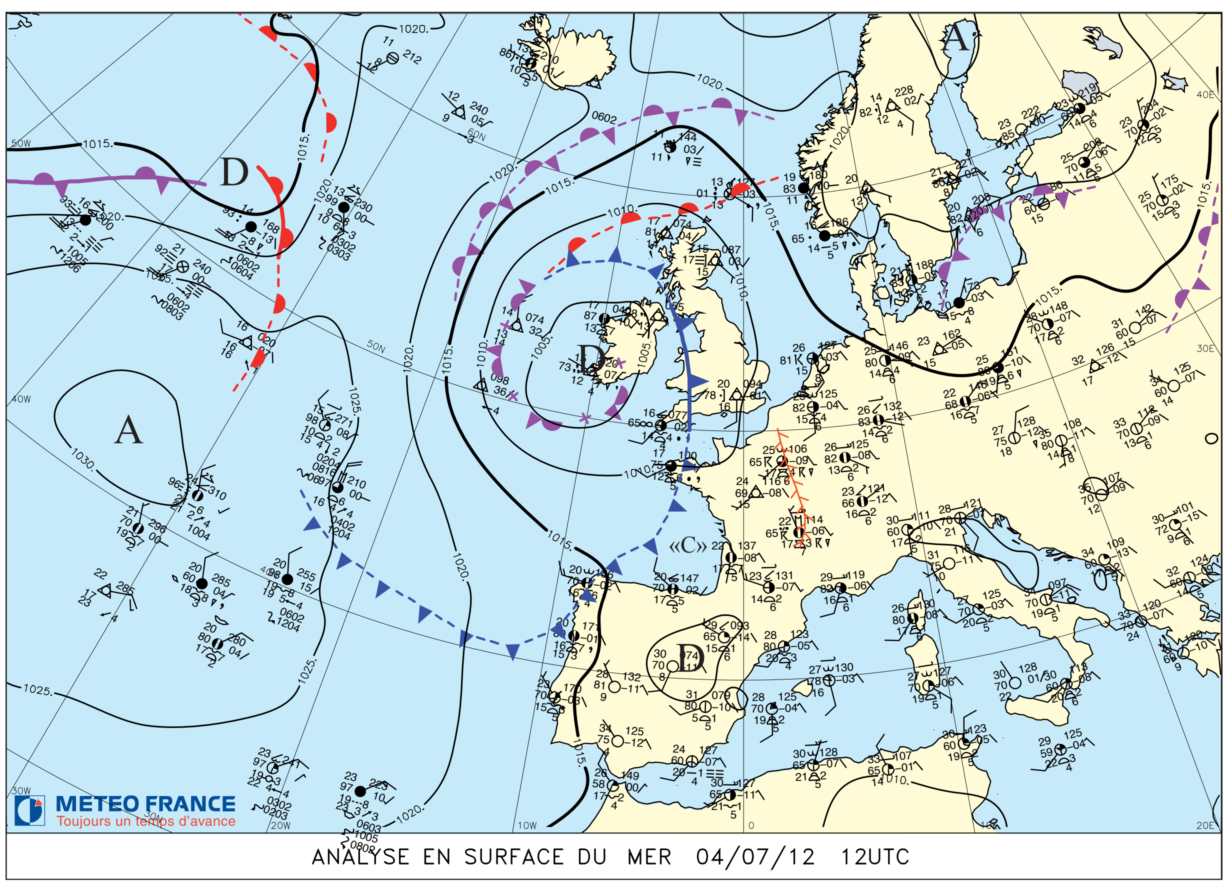
The characteristics of the rainfall can be known precisely since 1988, thanks to the network of the Lyon metropolis. Studies have shown that the most intense rainfall is the cause of the majority of flooding problems (60%). Therefore, samples of the 100 most remarkable rainfalls in terms of intensity, accumulation and duration since 1988 have been created, to be compared with the concomitant traffic types.

The results of these analyses reveal that the rains with the highest accumulation are characterised by a majority of southerly flows, present in more than half of the precipitation (56%). More specifically, at the level of the GWLs, we note that the TRW circulation type "talweg over Western Europe" alone is present for 29% of this precipitation (Figure 2). The second circulation type is the westerly flow, which is present in only 19% of the situations. The same observation is made when we look at the 100 longest rains of the period 1988-2017. 45% of these rains are found during southerly flows (of which 29% are TRW - Figure 2), and 22% during westerly flows.

The situation is very different when studying the circulations during intense precipitation. Southern circulations are still the most present, but only at 34%. Central European centric situations, which are only present at 11.6% on rainy days, occur at 23% during these intense rains. A closer look at the GWLs reveals that the BM GWL "ridge of high pressure over middle Europe" is the most represented with 13% of the most intense episodes. It is closely followed by the GWL WZ «cyclonic westerly circulation», SWZ

The "south-westerly, cyclonic flow" and TRW "trough over Western Europe" (representative example in Figure 3), all at 11%.

Figure 3: Surface analysis of 4 July 2012 - Type of circulation «talweg over Western Europe» (source: daily climate bulletin of Météo France). During this particularly intense episode, the rain gauges of Mions and Givors recorded rainfall amounts of 12 mm and 9.2 mm in 6 minutes, respectively. Thunderstorms and lightning were recorded at the Lyon-Bron Météo-France station (the beginning of the day was marked by thundery rain already present over the south-west quarter). Before the arrival of the rain and thunderstorms, the sun had time to settle in and raise temperatures to around 30°C from Alsace to Rhône-Alpes, up to 31 to 33°C from the Rhône valley to Provence.



Towards an increase in remarkable rainfall events?

These relationships between circulations and types of precipitation should be considered with great attention in the context of climate change. The types of circulation causing the majority of heavy and intense rainfall are on the increase, in particular the southerly circulations and more precisely the TRW (Talweg over Western Europe), SWZ (south-westerly, cyclonic circulation) and BM (anticyclonic ridge over Central Europe) type of circulation.

The possible increase in heavy and intense rainfall is a factor that is now systematically accounted for in OTHU's research programmes aimed at optimising stormwater management strategies. Monitoring by the Observatory of centralised and source control facilities also allows the impact of these rainfall changes on these techniques to be studied and relevant stormwater management strategies to be proposed to operational staff.

In Brief...

The perpetual evolution of the global climate can have impacts on a local scale over short periods of time, particularly on precipitation and its characteristics.
An approach based on (large-scale) synoptic rainfall patterns in Lyon reveals that the circulations resulting in the heaviest and most intense rainfall are increasing.
This should not be overlooked in the design of future stormwater management facilities.

TO GO FURTHER

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- **Renard F., Alonso L.,** (2019). *Precipitation evolution in Lyon in the context of climate change: an increase in rainfall at risk according to two types of synoptic classifications* 10[h] International Novatech Conference, 1-5 July 2019, Lyon, France – lc.cx/renard2019b (in french)

3.3

What influence does the city have on rainfall?

Florent Renard, Lyon 3 University

The urban environment has a direct influence on the local climate. It modifies the regional conditions by attenuating or exacerbating them, without making them disappear. With the current trend of increasing urbanisation and in the context of climate change, it is necessary to understand the influence of the city on its climate and particularly on its rainfall, in order to better anticipate future developments

The origins of the urban climate

The urban climate is not uniform

The city has a local impact on its climate. The urban environment modifies the local climate and thus creates a new type of climate which can be found in Lyon (and all urban areas of the world). However, this urban climate is not uniform. It is made up of an infinite number of nuances that characterise urban microclimates. This local impact of the city on its climate must be distinguished from global climate change, which manifests itself through processes on distinct temporal and spatial scales. Like current global climate change, urban climate is primarily human-induced (Stocker *et al.*, 2013).

Urbanisation leads to a local increase in temperature

The city changes the exchange of water and energy with the atmosphere, compared to rural areas.

Soil sealing and mineralisation, together with the morphology of buildings and their materials and the heat from human activities (heating, air conditioning, car traffic), explain the origins of the urban climate. The most remarkable impact of the urban climate is the increase in urban temperatures. Indeed, a difference of a few degrees can be noticed under specific conditions between Lyon and its rural periphery. This naturally leads to a more pronounced thermal convection in the city than in the countryside.

Urbanisation promotes cloud formation and precipitation

The urban environment also affects the airflow and wind regime. In windy situations, the roughness of the urban environment causes a braking effect. This braking effect results in a convergence of the rural air towards the city, but also in an updraft.

In addition, the many domestic and industrial activities increase pollution and more particularly the concentration of dust and various aerosols. These particles in suspension in the atmosphere constitute a potential for additional condensation nuclei around which micro-droplets of water can clump to form or grow clouds. As a result, the process of coalescence, whereby droplets increase in size by capturing other water droplets, is also more frequent and more powerful. All these processes are conducive to a more frequent formation of clouds in cities than in the countryside and can thus lead to more frequent but also more intense precipitation (photo). It should be noted, however, that high-intensity rain cells are more related to large-scale processes than to microclimatic ones. They are most often associated with weather types with sufficiently strong winds to blur the local and thus urban effects.

Lightning during the thunderstorm of 13 April 2016 (source: Romain Weber - www.lyonmeteo.com)

A pilot study in the Lyon metropolitan area

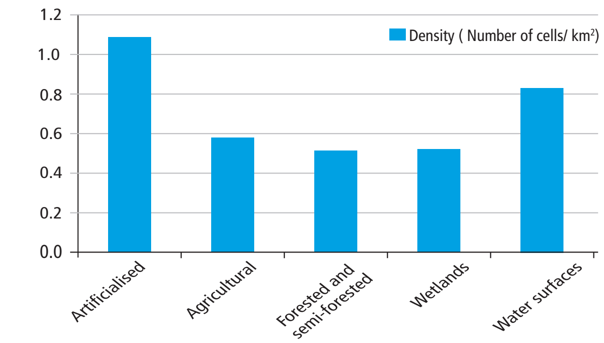
A pilot study, launched in 2014, to look at the effects of land use (and in particular the Lyon urban area) on the intensity and surface area of high-intensity rain cells. The rainfall data used came from the local weather radar of Météo-France (Saint-Nizier d'Azergues) adjusted with the help of rain gauges in the metropolis. A processing algorithm was used to determine the average centre of the rain cell, weighted by the rain intensity of each pixel. The area of the cell as well as the average and maximum rainfall intensities were also considered. Land cover data was provided by the Corine Land Cover database. The five most intense rainfall events of the period 2001-2005 in the Lyon Metropolis were analysed.

This enabled the identification of 109,979 centres of high rainfall intensity cells. These centres are distributed over the entire radar coverage area, from the southwestern Massif Central to Lake Geneva and the southern Vosges. Within a radius of 100 km around the radar, 49,663 high-intensity rain cells were detected.

Land use changes the characteristics of rainfall areas

When analysing the distribution of these high rainfall intensity cells, a much higher density can be observed above the artificial territories (1.1 cells/km²) compared to the agricultural territories, forests, and semi-natural environments (respectively at 0.6 and 0.5) (Figure 1). A multiple comparison method indicates that the intensity of the cells is highest above the artificial territories, with 28.4 mm/h on average, followed by the agricultural territories (27.8 mm/h) and then the forests and semi-natural environments 25.9 mm/h). Regarding cell areas, the tests indicate that the largest cells are located above agricultural land (6.3 km²), followed by man-made land (5.5 km²), and then forests and semi-natural areas (5.18 km²).

Figure 1: Density of intense rainfall cells according to land use – Artificial areas have more intense rainfall cells than other areas.



In Brief...

The study of the density, surface area and intensity of the rain cells of the five most intense rainfall events of the period 2001-2005 indicates that artificial areas are more frequently and intensely affected than other types of land use. These results confirm the theoretical concepts in literature. In order to continue the analysis, it would now be necessary to process several years of continuous data in order to solve the problem of selecting characteristic rainfall events, but also to gain more detailed knowledge of land use based on remote sensing results.

TO GO FURTHER

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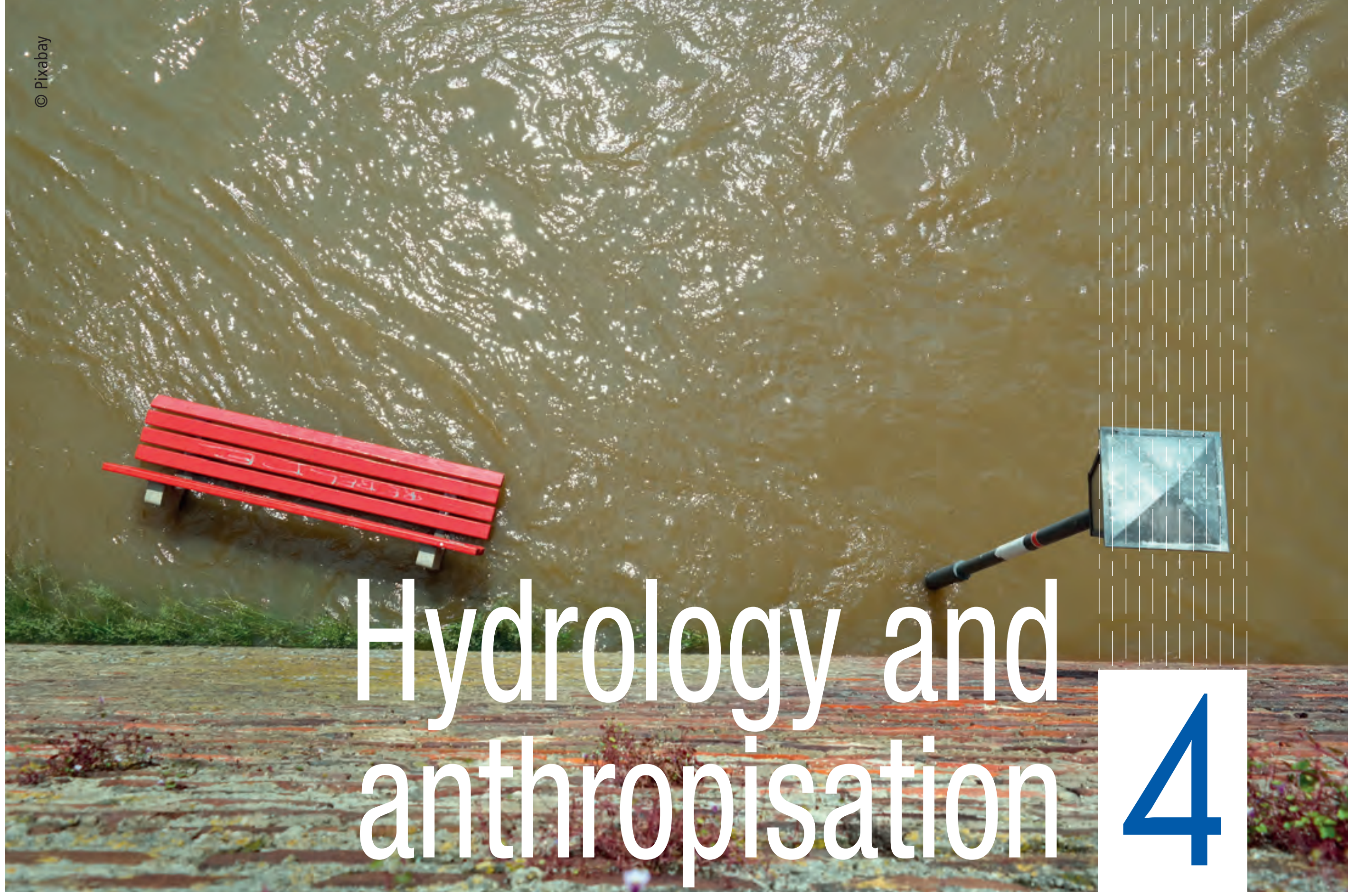
- **Renard F., Alonso L., Fitts Y., Hadjiosif A., Comby J.,** (2019). *Evaluation of the Effect of Urban Redevelopment on Surface Urban Heat Islands.* Remote Sensing, 11, 299. – DOI: 10.3390/rs11030299 – lc.cx/renard2019c (in french)
- **Stocker T.F., Qin D., Plattner G.-K., Alexander L.V.,** et al. (2013). Technical summary. In: *Climate Change 2013: The scientific evidence.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (dir. pub.)]. Cambridge University Press, Cambridge University Press, Cambridge, UK and New York – lc.cx/stocker (in french)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Hydrology and anthropisation 4

Global population growth is accompanied by an increase in the proportion of people living in urban areas. In France, this growth was 50% in 1945 and reached 80% in 2016. This urbanisation leads to changes in landscapes, which were initially natural, agricultural or forested, and has a strong impact on the natural water cycle in the affected catchment areas.

OTHU, illustrated in the following questions, has worked to study and quantify these impacts via long-term monitoring of several urban or peri-urban catchment areas. This work has made original contributions to the characterisation of surface artificialisation and the identification of water flows in peri-urban catchments. Several tools and methods combining long-term data collection and modelling have made it possible to quantify the impact of artificialisation on the hydrological cycle in catchment areas. Work has also focused more specifically on changes to groundwater resources and urban flooding.

4.1 What is soil artificialisation?

Isabelle Braud and Flora Branger, INRAE Lyon

Urbanisation modifies landscapes that were originally forested, agricultural or natural, leading to what is known as soil artificialisation. This notion of artificialisation is often wrongly considered as synonymous with the sealing of surfaces, whereas it refers to much deeper transformations that are not limited to what is visible on the surface.

The different components of soil artificialisation

Our definition: Artificialised soil is land that is subject to urbanisation

In the collective expertise conducted on the determinants and impacts of soil artificialisation, Béchet *et al.*, (2017) define "artificialised soils" as those that are neither natural, nor forestry, nor agricultural. Even if agricultural and forestry practices modify landscapes and soil functioning, a cultivated area is not considered to be "artificial": in this work, artificial soil is therefore soil subject to urbanisation.

The word urbanisation is regularly considered to be linked to the sealing or impermeabilisation of surfaces, due to the construction of buildings or roads. However, this is a simplistic view as the transformations brought about by urbanisation are more profound and affect landscapes as well as the structure, chemistry and biology of soils.

The underground compartment can also be artificialised

In addition to buildings, built-up areas include parks and gardens, sports, leisure and recreation facilities, industrial and commercial zones, as well as all the communication networks (roads, paths, public transport networks) that provide access to them. Another component, often invisible, concerns the modification of the soil structure via underground networks: drinking water supply, sewerage, and rainwater management networks, with the creation of trenches – where the natural soil is replaced by often coarser materials. New rainwater management techniques also introduce new elements into urban landscapes such as bioswales, infiltration trenches, rain gardens or green roofs. We can also mention sump-pumps which are used to remove water from basements or underground spaces in buildings. All these developments modify the surface and underground compartments and impact on the flow of water in rivers and groundwater.

Photo 1: Peri-urban landscapes: a mosaic of built-up areas, roads, rural areas or parks and gardens (source: Pixabay).

Mapping to quantify land artificialisation

To characterise the artificialisation of land, we generally rely on land cover or land use maps. Aerial and satellite imagery is increasingly used for this purpose, particularly with the advent of very high spatial resolution images (of the order of 50cm to one metre) which make it possible to identify different types of surfaces according to their spectral properties or to identify objects according to their morphological characteristics. Remote satellite sensing provides Land use information since the 1980s or so, but advances in sensor technology have led to an improvement of spatial resolution. Corrections are therefore necessary to compare maps produced at different dates.

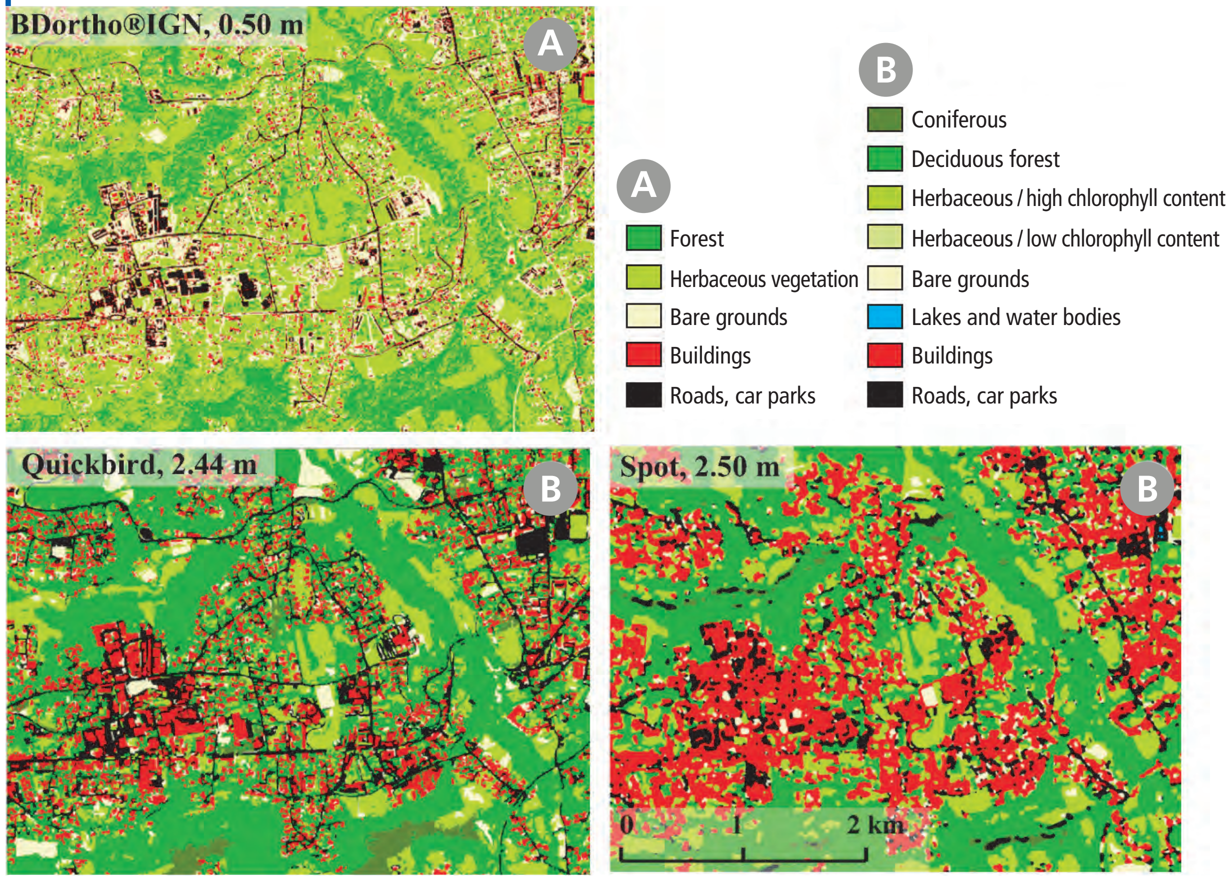
Moreover, artificialisation and sealing are not always synonymous. Parks and gardens are permeable, whereas natural surfaces such as rocky areas are quite impermeable. The mapping of land cover provides information on the physical properties of surfaces and thus on the permeability or impermeability of surfaces, whereas land use provides information on the use of plots (agricultural, residential, recreational areas, etc.).

The underground part of the artificialisation, invisible to aerial and satellite imagery, is more difficult to quantify. It is necessary to rely on specific maps, when they exist (maps of sewerage networks managed by local authorities and management bodies). In their absence, it is possible to work by association with surface data, for example by making the hypothesis that the sewerage networks follow the main roads.

Quantifying the level of surface sealing depends on the source of information used

As part of the ANR AVuPUR research project, soil artificialisation was characterised in the peri-urban Yzeron basin, one of OTHU sites. For this purpose, the information on the topography, geology and the paedology were collected. Contacts with the managers also made it possible to document the various sewage networks (rainwater, wastewater). Land use was mapped so that it is possible to

Figure 1: Land use mapping using aerial images (BR Ortho® IGN at 50 cm resolution) and analysis of Quickbird images at 2.44 m and Spot at 2.5 m over a sector of the Yzeron basin (adapted from Jacqueminet *et al.*, 2013).



Land use mapping online

The Theia portal[1] now systematically offers annual land use mapping, using Spot 5 and 7 images, that can be used to monitor the development of urban land use and the effectiveness of urban development policies, in addition to the data available in some communities.

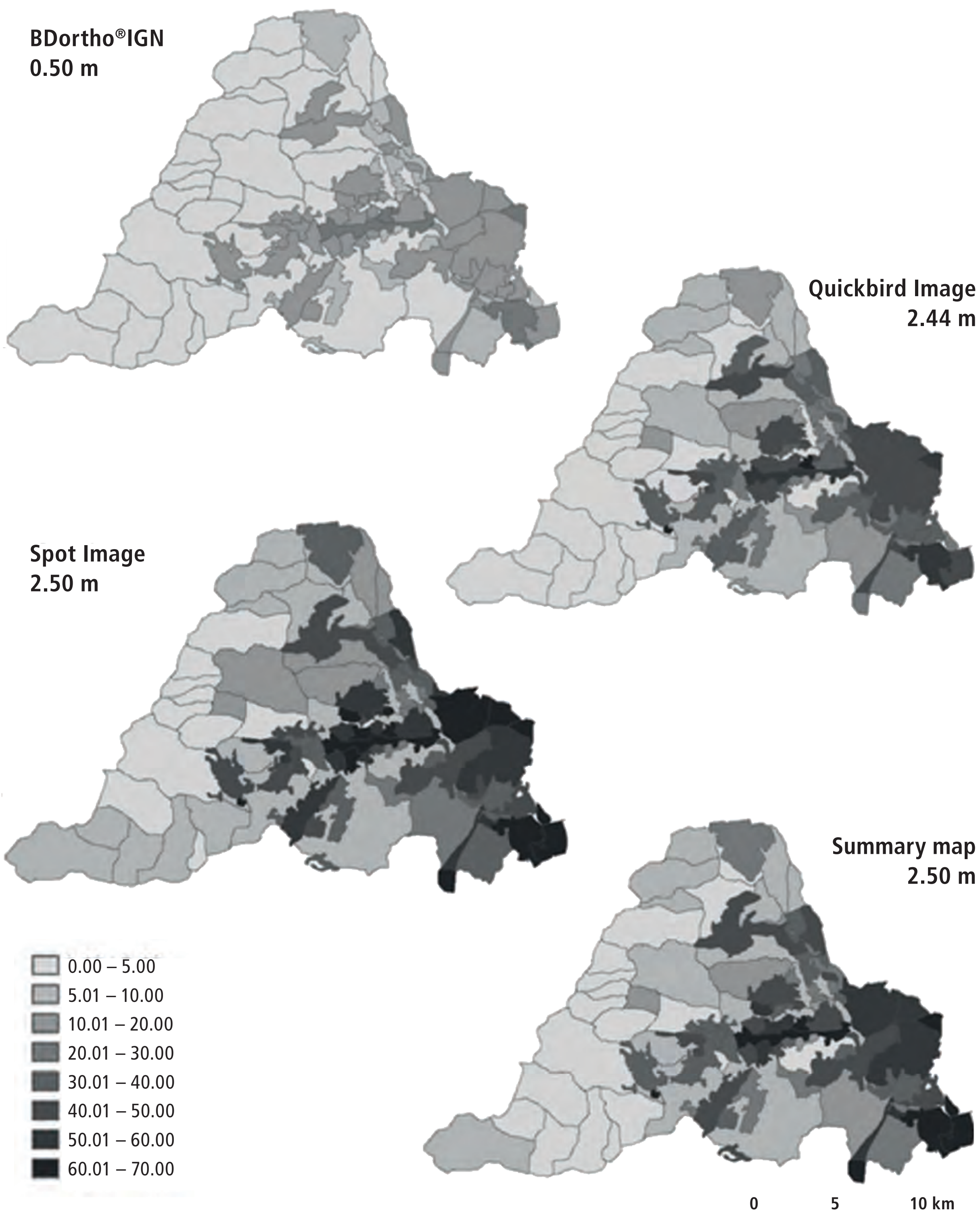
[1] lc.cx/theia

4.1

characterise the rate of soil sealing, and this information can then use in hydrological models which have been developed (see Question 4.2: *What are the consequences of soil artificialisation on the water cycle?*). Land use was also mapped retrospectively to parameterise a land-use evolution model and define prospective scenarios in 2030 (Dodane *et al.*, 2014).

To map land use, several sources of information were compared: the BDOrtho® of the IGN with a resolution of 50 cm; a spot image at 2.50 m and a Quickbird image at 2.44 m. Several land-use classes were defined, making it possible to distinguish between permeable and non-permeable surfaces (Figure 1). The different images provide additional information. For example, the BD Ortho® IGN

Figure 2: Percentages of non-permeable surfaces calculated by sub-catchment areas of the Yzeron using land use maps made from the BD Ortho® IGN at 50 cm resolution, and by analysis of Quickbird images at 2.44 m and Spot at 2.5 m (adapted from Jacqueminet et al., 2013).



allows the linear networks (paths, roads, highways) to be well characterised. Figure 2 illustrates the fact that the quantification of the degree of impermeabilisation is strongly dependent on the data source used. The simulations show that the total flow changes relatively little depending on the map used. However, the flow components (surface, subsurface, groundwater) are more strongly modified. This implies that, as the origin of the water is different, the transport of contaminants will be different depending on the data source used. The maps were then combined to generate a so-called "synthesis" map that best exploits the strengths of the different images.

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4.2

What are the consequences of soil artificialisation on the water cycle?

Isabelle Braud and Flora Branger, INRAE Lyon

Land artificialisation changes whether rainfall is destined for infiltration, runoff, evapotranspiration, or aquifer recharge. But how can we quantify and model the way in which it impacts the components of the hydrological cycle of urban or peri-urban basins? Today, the methods of artificialisation are changing and the evaluation of their consequences are even more complex: beyond the sealing and direct evacuation of rainwater by the "all-pipe" system, we are introducing more and more nature-based solutions to manage stormwater at the source (source control). It is therefore important to assess the impact of these new management methods at the level of the catchment area.

Artificialisation impacts all components of the hydrological cycle

The first impact of artificialisation is the sealing of soils, due to the construction of buildings or roads and the rain will run off them.

Beyond the impermeable surfaces, soil compaction and depletion reduce the permeability of the soil.

As the surfaces are impermeable, it is then necessary to collect the water, generally in pipes; this increases the speed of runoff and the concentration of flows towards low points.

Finally, the depletion of vegetation reduces the capacity to store, slow down runoff and evaporate water.

All these actions reduce the infiltration of rainwater into the soil. It leads to an increase in runoff volumes and runoff velocities. It can also change the components of stream flow, i.e. increasing the proportion from direct surface runoff, and reducing subsurface runoff (into the surface soil) and base flow (water from the emptying of deep soil reservoirs).

When this water reaches the receiving environment (watercourse) it causes a reduction in the time to peak of the flood and an increase in the flood volume (generating peakier hydrographs[1], see Figures 2 and 3).

However, artificialisation can have other effects on groundwater recharge and river base flows. The results of studies contrast, and some authors report an increase in groundwater recharge due to leaks in drinking water networks, the generalisation of septic tanks or the excessive irrigation of parks and private gardens (in the Santiago region in Chile), or alternatively the reduction of the water table. On the other hand, due to leaks, sewerage systems can have a drainage role for subsoil water, leading to a reduction in base flows in rivers.

The use of modelling is necessary to more precisely assess the impacts of artificialisation

Measuring rainfall and flows at characteristic points is often insufficient to quantify the components of the water balance. Distributed models can be used to estimate flows at different points on rivers and to determine water balances on different sub-catchments. Similarly, quantifying evapotranspiration, especially in complex environments, remains difficult experimentally and often requires modelling. To evaluate and compare different source control stormwater management strategies, distributed models[2], which explicitly represent landscape objects, are required. However, these models have yet to be improved to consider all the source control management methods.

The impacts of soil artificialisation are not limited to the water cycle

The impacts of soil artificialisation manifests itself equally in the flow of pollutants, upon the biodiversity of the subterranean and above ground environments and even upon the creation of urban heat islands, air pollution and noise pollution. These impacts are the action points described in the summary of collective scientific expertise INRA-IFSTTAR 2017 (lc.cx/bechet2017)

[1] See Wikhydro article: lc.cx/hydrogramm

[2] See Wikhydro article: lc.cx/modeledistrib

Photo 1: Visualisation of the impact of artificialisation during a heavy thunderstorm in July 2017 in Villeurbanne (69) – (19 mm).

The contributions of OTHU: the case of the Yzeron basin

Within the framework of OTHU, the Yzeron basin was studied with numerous flow measurements at different points in the basin as well as in the combined sewer system (Figure 2). The analysis of the data collected highlighted the following elements (Braud et al., 2013).

1 – Low-water support: the rivers are intermittent, but the presence of combined sewer overflows (CSO) leads to a reduction in the frequency of zero flows, the urban wet weather discharges (UWWD) being the only contributors to the flow during dry periods; the discharges from wastewater treatment plants also sometimes ensure a minimum flow in the rivers in other sub-basins.

2 – In combined sewer systems: a method of evaluating the share of clear water infiltrated into the sewer system shows that, in the combined sewer system of the Chaudanne basin, 30% of the annual volume corresponds to infiltration into the system, 40% to rainfall runoff, and the rest to wastewater (i.e. only 30%).

3 – Worsening of peak flows: Figure 3 illustrates that the hydrographs of the most urbanised basins (see Figure 2) are also the most peaked, demonstrating a rapid rate of change during the rise and fall of the flood.

Modelling tools have been developed, at different scales, to account for the complexity of peri-urban landscapes: mosaic of rural and urban plots, natural hydrographic networks, combined sewer networks and stormwater networks,

Figure 2: Share of agricultural areas, forest and buildings and roads for the different flow measurement stations on the Yzeron (based on data from Labbas, 2015).

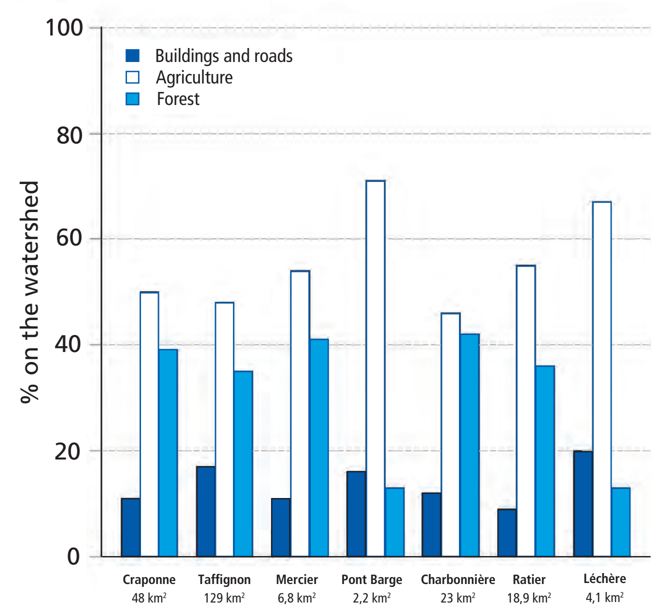
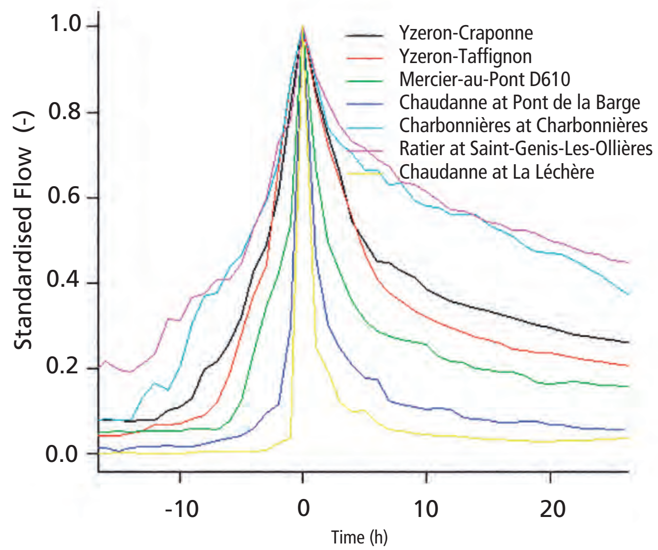


Figure 3: Typical standardised hydrographs for the different hydrometric stations of the Yzeron..

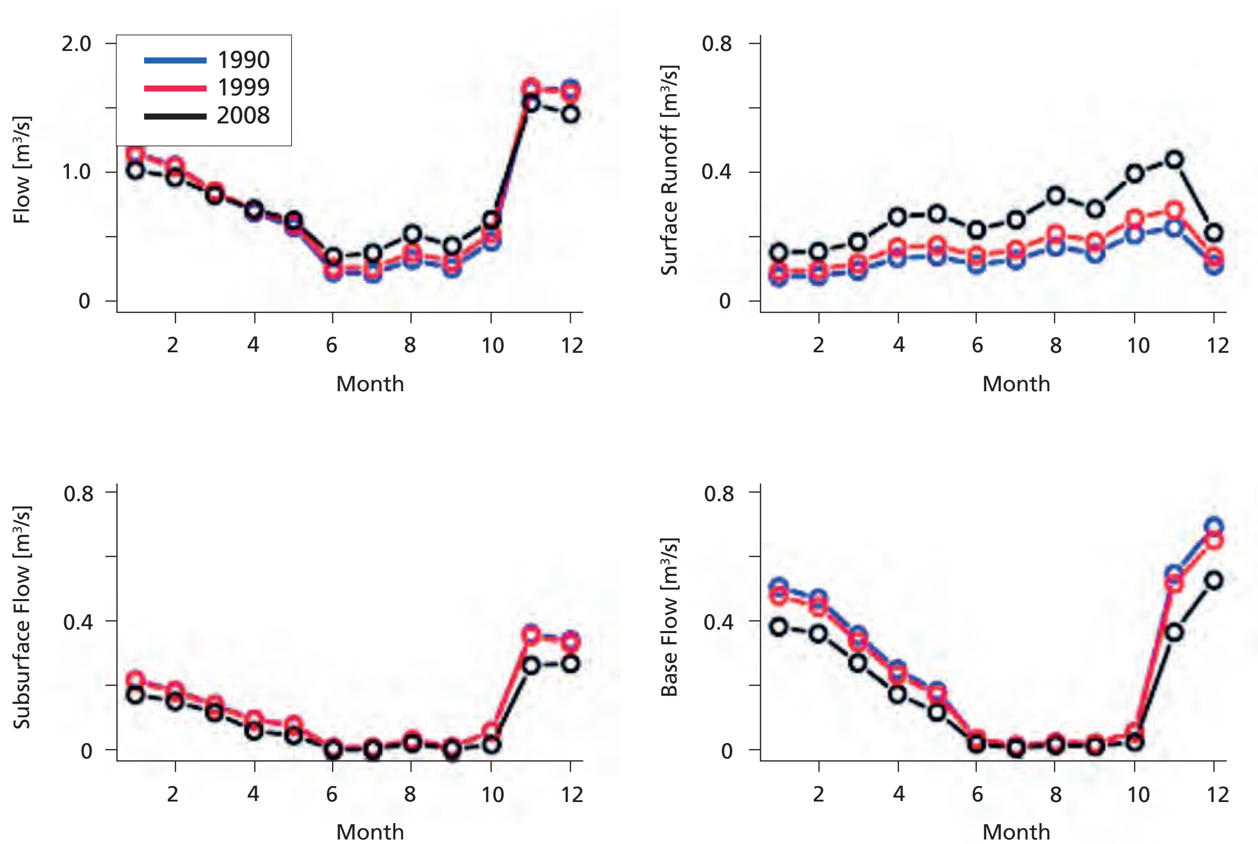


detention basins, etc. Figure 4 is the result of simulations on the Yzeron basin by the J2000 model (Branger et *al.*, 2012) of the impact of the evolution of urbanisation between 1990 and 2008 on the total flow and its components: surface runoff, subsurface and base flows. Although the total flow is minimally affected, artificialisation favours surface runoff to the detriment of base and subsurface flows.

The J2000P model (Labbas *et* al., 2015) integrates sewerage networks and CSOs into a model for characterising the functioning of hydrological response units. It has been used to assess the impact of different scenarios of future urbanisation (Dodane *et al.*, 2014) or stormwater management on the components of the hydrological cycle.

Initial tests on the scale of a basin such as the Yzeron suggest that the impact of water management methods (especially the disconnection of stormwater from the sewer system) on the hydrological regime is more important than the evolution of the sealing of surfaces alone (Labbas, 2015). This calls for further study of how a generalisation of source control or a disconnection of rainwater in this basin could limit the impacts of urbanisation on the hydrological cycle.

Figure 4 : Impact of the evolution of urbanisation between 1990 and 2008 on the monthly interannual flow of the Yzeron at Taffignon (129 km²) and its components: surface runoff, subsurface runoff and base flow.



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4.3

Do underground developments in cities impact water resources?

Guillaume Attard, CEREMA – Thierry Winiarski, ENTPE

The underground environment is still poorly understood. However, it is increasingly used by the city for the construction of facilities, for foundations, etc. It is also a resource of materials and energy. And when we know that this environment is also a drinking water resource for the inhabitants, the question of the impact of these infrastructures and uses on groundwater takes on its full meaning.

Increasing pressure of the city on the underground environment

The development of cities and the economy of land are putting increasing pressure on the vertical dimension of the city. Indeed, new buildings tend to be built higher and higher. But what about the underground space? This environment, which is poorly known and difficult to observe, is increasingly in demand. It is the preferred location for building foundations, of the communication network and the transport network (eg. Metro London Underground). It is also a development space that allows us to park our cars and install security systems. For as long as cities have existed, underground space has also been a resource for building materials and, more recently, for aggregates, an essential ingredient for concrete. This groundwater has also become an ever-developing geothermal resource. Finally, for several decades, urban groundwater has been the preferred medium from which drinking water is extracted: in Europe, more than 40% of the water distributed in drinking water networks comes from urban aquifers (Eiswirth *et al.*, 2004).

The city disturbs the flow and the physico-chemical quality of the groundwater

From a qualitative point of view, the construction materials of underground structures can alter the physico-chemical characteristics of urban groundwater (Chae *et al.*, 2008). On the other hand, from a quantitative point of view, the maintenance of structural stability in buildings requires the use of drainage systems with flows that can represent several million cubic metres annually (Vázquez-Suñé *et al.*, 2005). These disruptions to the flow of water can lead to soil compaction and possibly an increase in the flood risk due to rising groundwater. In neighbourhoods undergoing renewal, such as the Gerland district in Lyon, the construction of buildings with temporary phases of lowering of the water table (drop in the water level) also has a significant impact.

Furthermore, since Europe has committed to a 20% reduction in greenhouse gas emissions by 2020, geothermal energy is seen as a key resource. Ground-source heat-pump systems are an efficient way to exploit this energy (Lund *et al.*, 2011). The multiplication of these extraction systems tends to generate interference between installations (Herbert et al., 2013). Indeed, when the distance between two installations is not sufficient, the thermal influence zones can intersect and alter the performance of the systems with, for example, the formation of underground heat islands (Menberg, 2013).

All the pressures exerted by the city on the resource, i.e. the disruption of the water cycle, runoff, and the physico-chemistry of the water (Figure 1), show the interest in reviewing the governance of urban groundwater management. However, according to the work of Maire (2011), there is still no complete urban groundwater planning strategy. The lack of expertise and understanding of the interactions between groundwater infrastructure and the water resource is partly responsible for this gap.

Modelling to understand the impacts of urban development

The thesis work (Attard, 2017) undertaken as part of a scientific collaboration between ENTPE and Cerema aimed to better understand the impacts of underground developments on the urban groundwater resource. The following questions were addressed: what are the different types of underground structures encountered in the urban environment and what is their hydrodynamic behaviour? What types of impacts do they generate on flows and what is their influence on the quality of the water resource?

At what scale should these impacts be considered and are there cumulative effects when the urban subsoil is densely developed?

Figure 1: Representation of the nuisances and risks inherent in the interaction between underground works and urban groundwater – hot water injections are in orange and cold-water injections are in blue (after Attard, 2017).

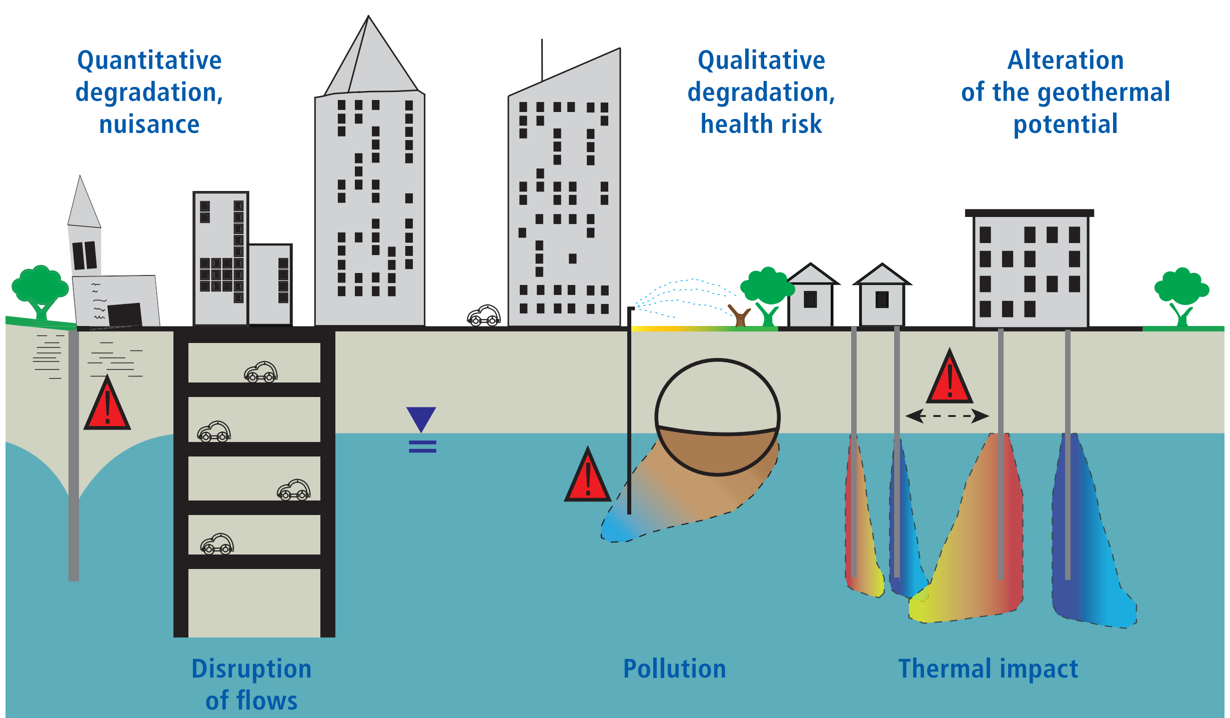
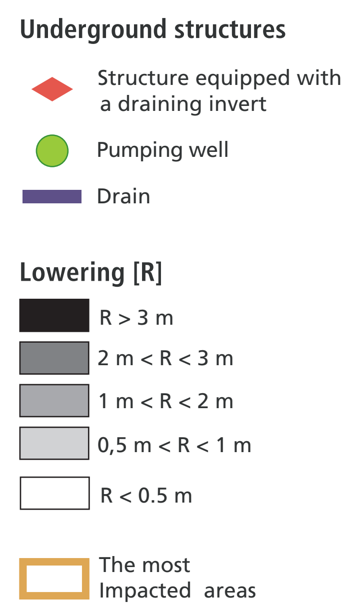
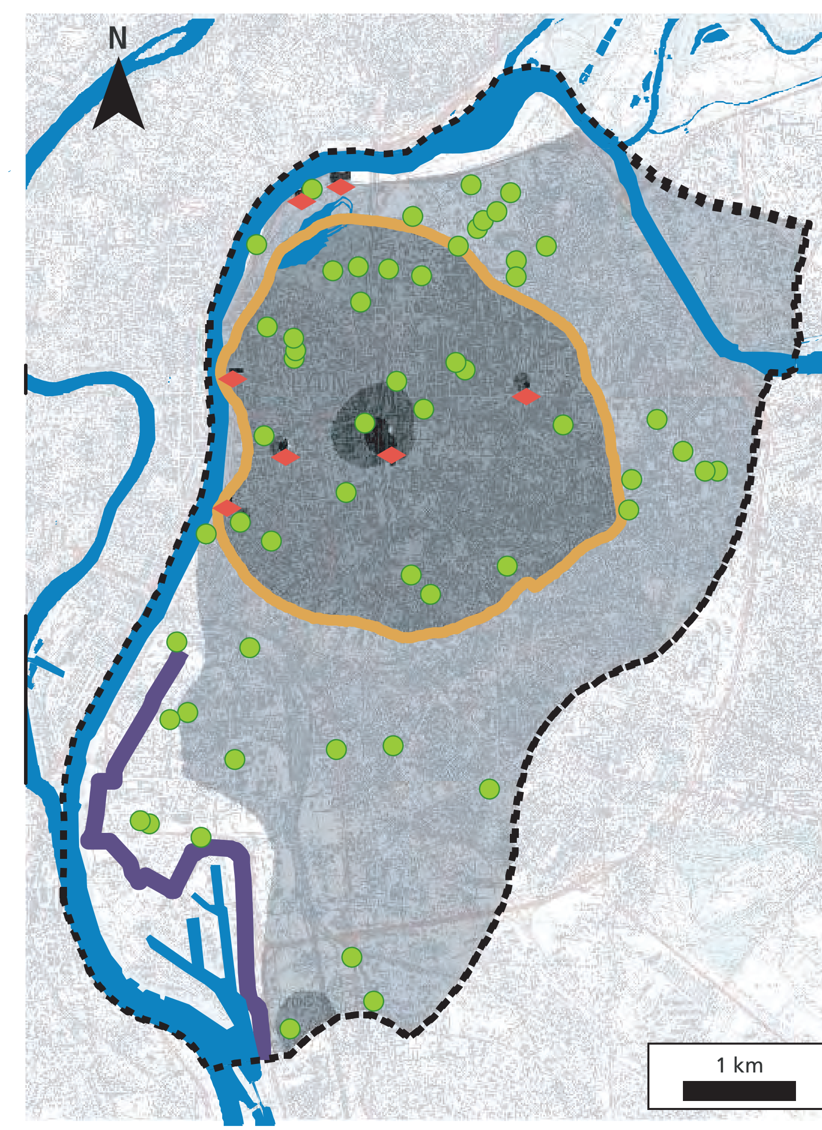


Figure 2: Cumulative impacts of the underground structures on the initial position of the free surface of the Lyon water table. The level of the water table is lowered by more than one metre overall and by more than 2 m in the most impacted area. Modified from Attard et al. 2016.

Lowering of the water table caused by the developments





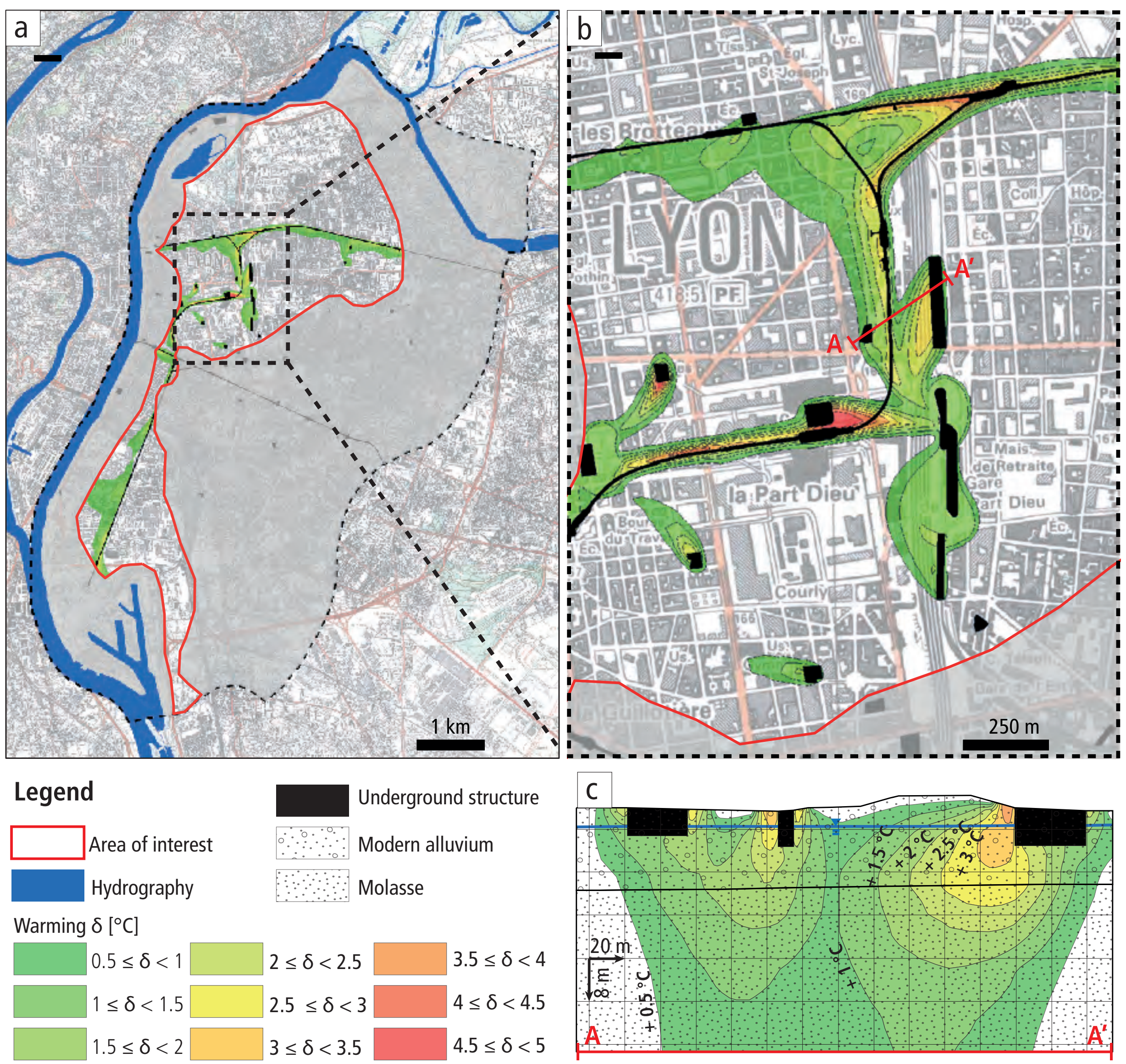
To answer these questions, a 3D deterministic hydrogeological modelling approach was conducted based on field data from the Greater Lyon Area. The results of this work showed that structures involving drainage systems are responsible for a significant fragmentation of urban underground flow systems, likely to modify the aquifer's recharge regime. They also reveal a marked cumulative effect of the structures on the water table drawdown ©, from 0.5 m to more than 3 m (Figure 2). The model also revealed an effect at the level of underground infrastructures that favours the communication of water at different depths, increasing the vulnerability of deep reservoirs (Attard *et al.*, 2016c).

Modelling the impact of infiltration at the plot level

In this PhD thesis (W. Pophillat 2022) an integrated modelling of the consequences, at the scale of small catchments and for current rainfall, of systematic use of infiltration practices at the plot level, with a focus on the underground compartment and vegetation. The modelling makes it possible to the interactions between the wells, underground structures, surface and underground compartments.

Finally, the individual and cumulative impacts of underground infrastructures on groundwater temperature were assessed. This analysis showed that these infrastructures could, due to their thermal influence zone, affect the potential geothermal potential of urban groundwater (Figure 3). These thermal influence zones could be integrated in the reflection of geothermal exploitation of urban groundwater to limit conflicts of use.

Figure 3: **(a)** Plan view of the thermal impact generated by the underground structures in Lyon. (**b**) Plan view of the cumulative impact in the Part-Dieu area where the model shows a warming of the water table by several degrees in some places. (**c**) Cross-sectional view around three underground structures shows that this warming affects the water table over several tens of metres. Modified from Attard *et al.*,(2016b).



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4.4

What are the impacts of soil artificialisation on water flow?

Isabelle Braud and Flora Branger, INRAE Lyon

The artificialisation of surfaces leads to profound changes in the structure of soils and landscapes. These changes influence the directions of rainwater flow and thus the transport of pollutants and the risk of flooding. It is therefore necessary to describe the links between artificialisation and flow directions in order to better manage stormwater.

Artificial land use changes flow directions and catchment boundaries

In natural, unmanaged environments, water flows from the top to the bottom following the topography until it reaches a river. To define the boundaries of a catchment at a given outlet (a point chosen on the watercourse), one must identify the direction of water flows at this point by following the topography (lines with the steepest gradient).

In the case of an urban or peri-urban catchment, various elements change the flow directions and thus the boundaries of the catchment areas, which often have several outlets. When overloaded, combined sewerage systems that normally carry wastewater and rainwater to the treatment plant will discharge their water into natural watercourses via combined sewer overflows (CSO).

In the case of a separate system, the stormwater collection system often discharges at StormWater Outlets (SWO) into natural watercourses and can also change the flow directions. In addition, road networks, especially in peri-urban areas, are often bordered by ditches that collect stormwater and modify the topography and therefore the flow directions. Finally, in interaction with the natural hydrographic networks, natural or artificial lakes (detention basins) must be considered, as well as all the landscape elements that are set up for source control of rainwater (ditches, infiltration trenches, etc.).

Figure 1: Steps in the method for defining the boundaries of a peri-urban catchment, its drainage network and contributing sub-catchments (adapted from Jankowfsky *et al.*, 2013).

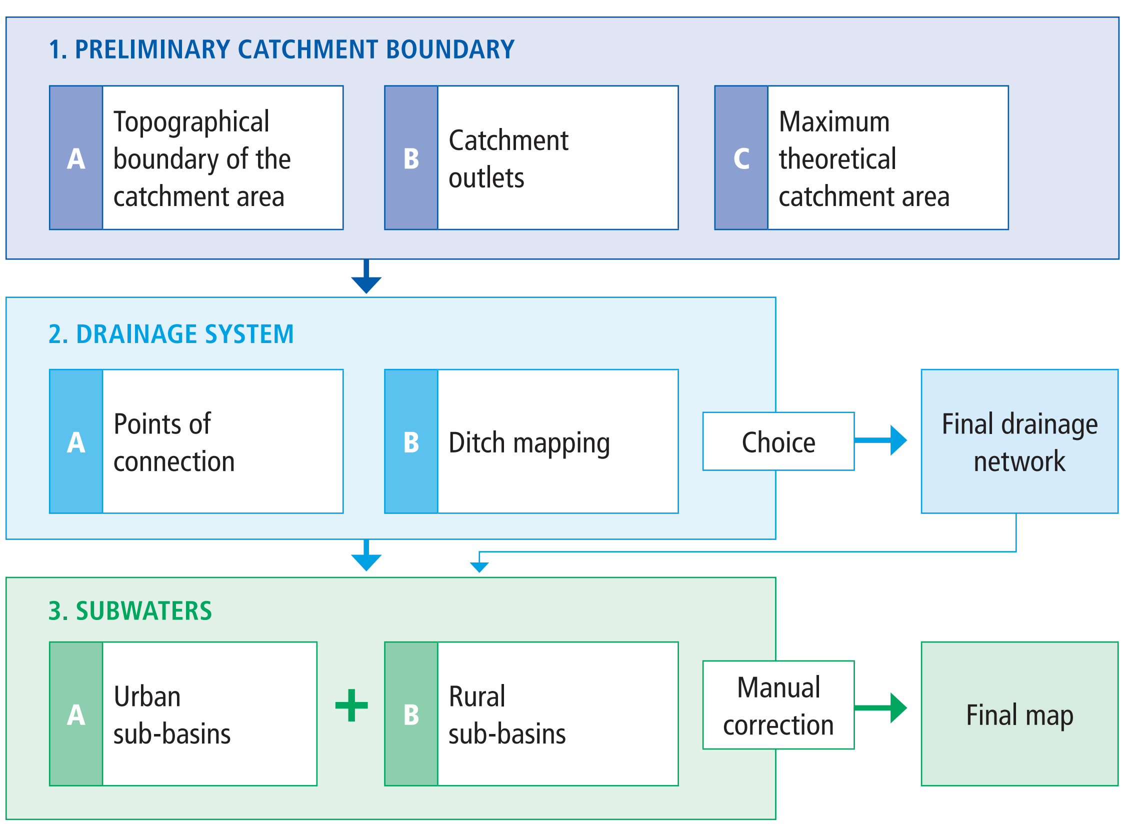
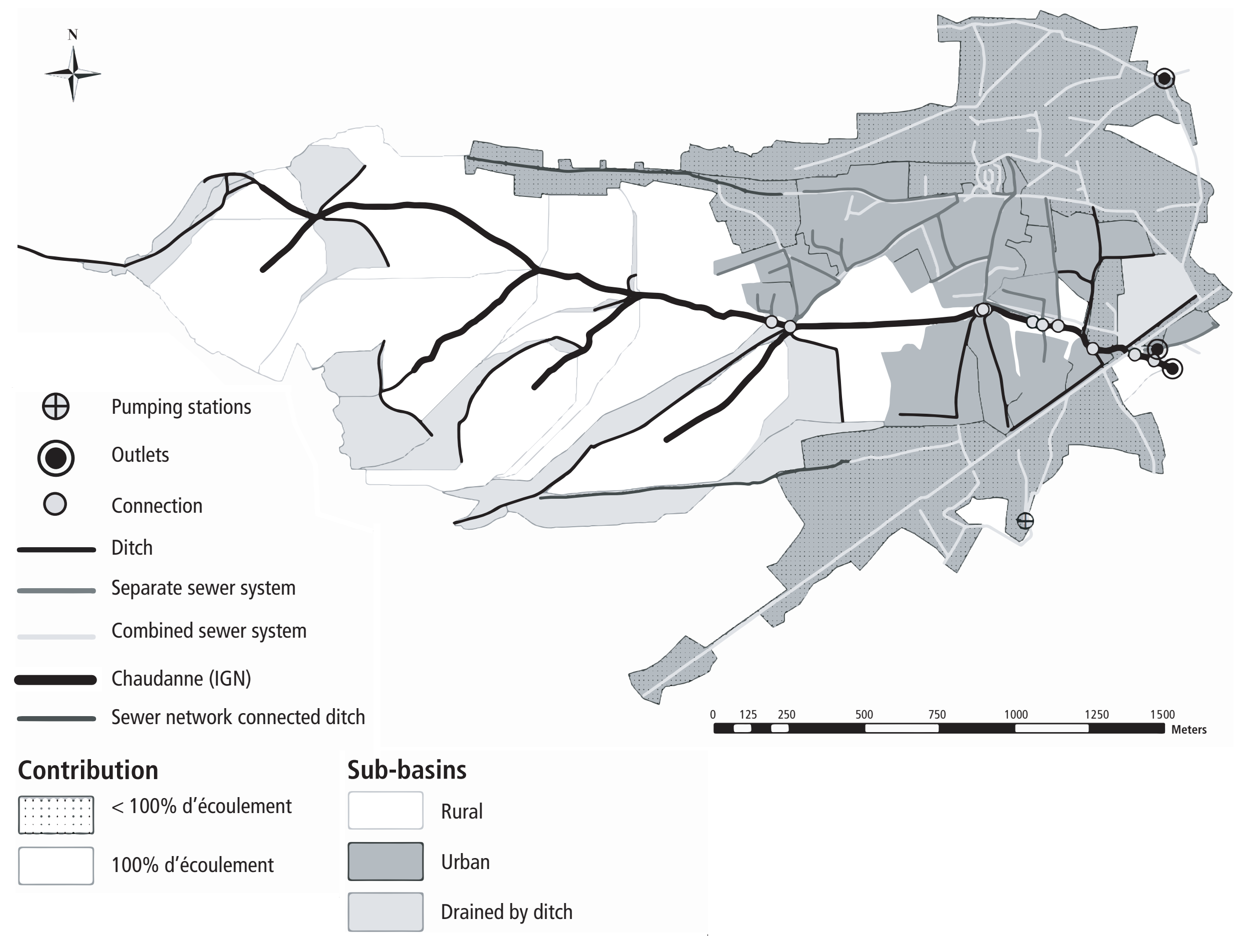


Figure 2: Final map of the Chaudanne sub-catchments and catchment boundaries under wet conditions. Urban sub-catchments are shown in dark grey, rural sub-catchments in white, and sub-catchments drained by ditches in light grey. The dotted sub-basins are only connected via CSO to the river. Subtracting the dotted areas from the basin area in wet conditions gives the basin area in dry weather (adapted from Jankowfsky *et al.*, 2013).



A method for defining the boundary peri-urban catchments and their sub-catchments

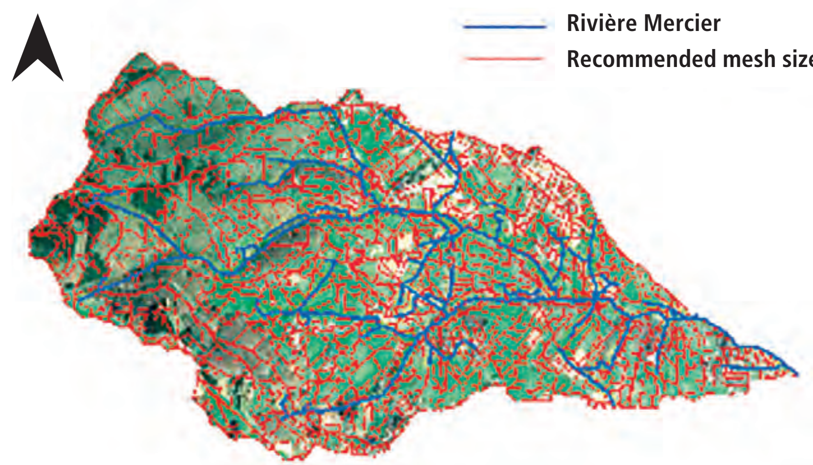
Within the framework of OTHU, a semi-automatic method has been proposed for defining the boundaries of a peri-urban basin and the rural, urban or mixed sub-basins that make it up (Jankowfsky *et al.*, 2013, Figure 1). A first step consists of determining the topographic boundary, the outlets and the total surface area of the basin (which accounts for ditches and sewage networks). For the topographic basin, conventional methods of watershed extraction using a Digital Terrain Model (DTM) can be used. All points of connection to the natural river network are identified. Ditches in rural areas can be added to this natural network. Areas of the catchment drained by a combined sewer system have at least two outlets: the first to the wastewater treatment plant (most of the time), the second to the river system via CSOs (during heavy rainfall events). These areas are added to the maximum surface area of the catchment. The catchment area depends on the flow conditions with a minimum area in dry conditions and a maximum area in wet conditions.

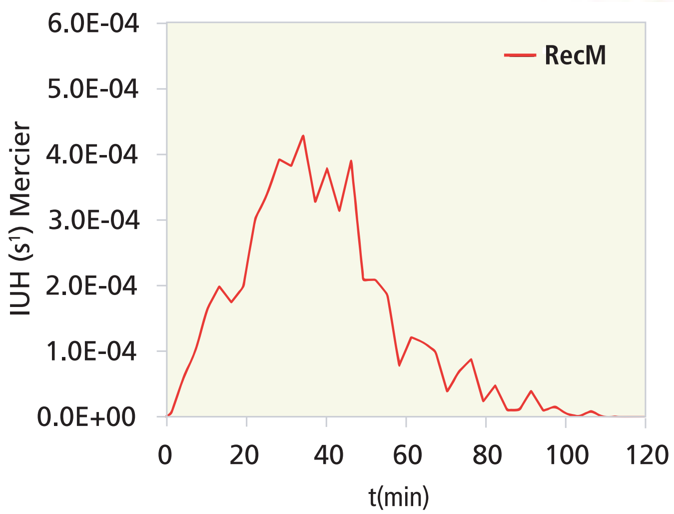
To better define the areas that are part of the catchment, field surveys are required to determine the direction of flow in the separate networks in order to eliminate areas draining outside the catchment. For urban areas, an object-based approach is used to link each cadastral parcel (a registered plot of land) to the nearest and lowest stormwater network, following the road network. Figure 2 illustrates the final result for the Chaudanne basin in Grézieu la Varenne. It can be seen that the final contours of the catchment area are irregular and different from the topographic contour of the catchment area.

Geo-PUMMA a GIS tool for the determination of flow directions in urban and peri-urban areas

To characterise flow directions in a complex urban and peri-urban environment, the Geo-PUMMA toolkit (Sanzana *et al.*, 2017) uses an object approach that relies on land-use mapping at the plot scale, accounting for urban and natural landscape features: cadastral or agricultural plots, recreational areas, squares, car parks, tree alignments, hedges, ponds, networks, as well as a delineation of buildings and vegetated areas. A high-resolution Digital Terrain Model (DTM) is required (maximum resolution 2 m) but these DTMs are now available through LiDAR (Light Detection and Ranging) surveys. The mesh of the basin is obtained by

Figure 3: (a) Drainage network for the Mercier (Yzeron) sub-basin calculated using Geo-PUMMA and (b) associated unit hydrograph (adapted from Sanzana *et al.*, 2017)





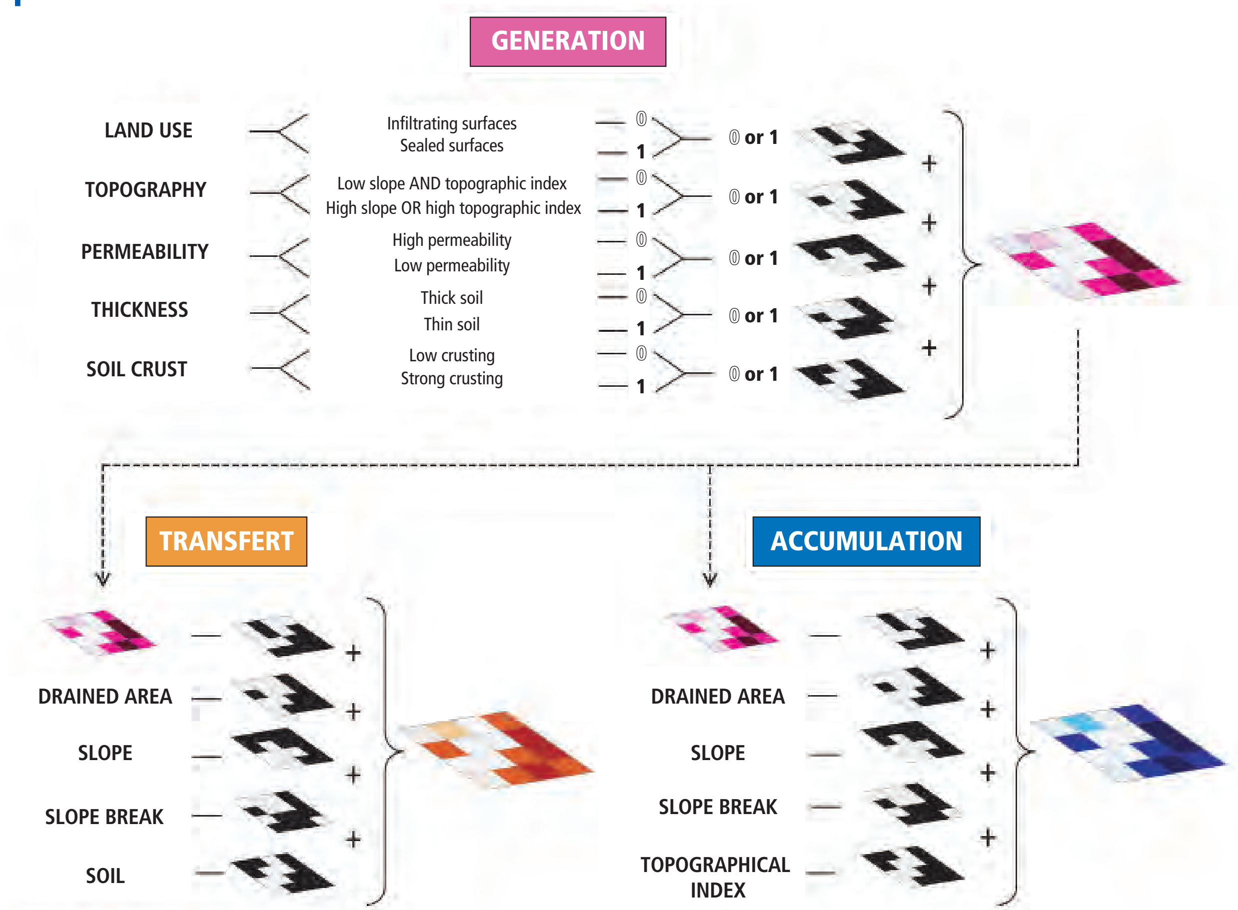
superimposing the initial geographic information layers. It is then improved to eliminate non-convex or too long plots that can disturb the algorithms for determining flow directions. Once the drainage network is known, a Unit Hydrograph can be calculated, which provides information on the water transfer times to the outlet (Figure 3). It is also possible to determine the proportion of surface runoff that transits through urban or rural areas, which is useful for determining the origin of possible contamination.
However, these tools are still in the realm of research.

The IRIP method: a tool to facilitate the implementation of the GEstion des Milieux Aquatiques et Prévention des Inondations (GEMAPI)

The management of intense rainfall runoff is the responsibility of local authorities. For peri-urban basins in particular, a territorial vision of runoff and therefore of flow paths is useful. The IRIP model (Indicateur de Ruissellement Intense Pluvial, Dehotin and Breil, 2011) produces maps highlighting the susceptibility of a catchment to produce, transfer and accumulate runoff. It relies on readily available cartographic information: topography, land use mapping and paedology. The resolution of the input data can be adapted according to the scale at which answers are sought. For each map, 5 indicators classified as favourable/unfavourable to runoff are defined (Figure 4) and summed to obtain a level of susceptibility (from 0 to 5) to runoff generation, transfer, and accumulation. The model includes an upstream-downstream dependency between the different points of the basin.

Several important results using the IRIP model. Firstly, the case studies showed that areas with a high susceptibility to runoff transfer also have a high potential for erosion and sediment transport. Secondly, the areas of runoff accumulation are favourable to flooding because the flows are slowed down there. The mapping provided by the IRIP model also makes it possible to identify wetlands, which can be used to limit the effects of flooding and the resulting pollution. It also highlights areas where source control detention or runoff and erosion control measures can be implemented. Areas favourable to transfer can be targeted for detention works, while sensitive constructions in areas favourable to accumulation are best avoided. These maps can therefore provide useful information for the implementation of the GEMAPI.

Figure 4: The different indicators and their combination to derive maps of susceptibility to runoff generation, transfer and accumulation (adapted from Braud *et al.*, 2020).



In Brief...

Water flow directions are impacted by land artificialisation. In urban areas, maps of sewerage networks allow these directions to be determined. The exercise is more complex in peri-urban basins, where the traditional tools for describing rural areas based solely on topography do not apply. OTHU has therefore developed several tools to delineate the boundaries of a peri-urban catchment, to determine the associated flow directions and to identify areas of a territory likely to contribute to runoff.

TO GO FURTHER

- **Dehotin J., Breil P.,** (2011a). Technical report of the IRIP project: mapping the flooding by runoff (Technical report). IRSTEA Hydrology-Hydraulic Research Unit - https://hal.inrae.fr/hal-02595951 (in french)
- **Jankowfsky S., Branger F., Braud I., Gironas J., Rodriguez F.,** (2013). Comparison of catchment and network delineation approaches in complex suburban environments. Application to the Chaudanne catchment, France. Hydrological Processes, 27(25), 3747-3761 - https://doi.org/10.1002/hyp.9506 (in french)

4.5

Does urbanisation make flooding worse?

André Paquier, INRAE Lyon – Emmanuel Mignot and Nicolas Rivière, INSA Lyon

Floods are the natural hazards that cause the most human and economic losses. However, the urban environment is particular, both from the point of view of vulnerability (population density, critical infrastructures) and of the hazard (concentration of flows in the network of streets, numerous obstacles, straight and possibly very steep streets). OTHU's work focused on hazard characterisation. The influence of urbanisation on urban waterways is a central issue.

The sewer network can aggravate or mitigate flooding

The role played by the sewer network in the management of flood flows is very variable according to the location of the flood and the intensity of the flood. In case of extreme flooding, the water passing through the sewer network can be neglected when compared to the surface flows in the city (e.g. the catastrophic flooding in Nîmes on the 3rd of October 1988 where the maximum rainfall recorded was 420 mm at Mas de Ponge, just above Nîmes. This value, equivalent to more than half the average annual rainfall, is underestimated because the rain gauge overflowed during the event).

On the other hand, in the case of more frequent floods, the overflow of the sewer network may be the source of the flood (especially in the basins or the downstream built-up areas), or on the contrary, it may be able to remove a significant volume of water from the surface through its gullies. However, the efficiency of these drains can be affected by blockages, for example by rubbish or dead leaves.

The Oullins OTHU site has shown that complex water exchanges can take place between the streets, the network and the urban river, during a flooding event with, for example, a specific operation of the different gullies (SI1, SI2 and SI3 on figure 1). In such cases, a representation of the flows within the sewer network, the exchanges with the surface, as well as the river must be included into the numerical calculations. This greatly complicates the simulation of the events but is necessary to create a reliable model.

The topography of streets and private plots influences the flow

The role of road and building geometry has also been studied (P.-H. Bazin thesis, 2013). We have shown that the topography of the cross-sections of the streets (height of the pavement, depth of the gutter, curved shape of the street) has an effect on the flooding which is negligible in case of a very high flood (such as in Nîmes in October 1988) but essential in case of a frequent flood (typically an annual or biannual event). Indeed, for an extreme flood, the water occupies the whole width of the street (from one façade to the one opposite) and will flood the whole of the downstream crossroads and end up into all the downstream streets; on the contrary, for a frequent flood, the curved shape of the street concentrates the water on one side of the street, only a part of the crossroad is flooded and the water invades the downstream streets only of this side of the crossroads.

Moreover, if the street network is the preferred place of the flow then the flow through theprivate plots and open areas can play two main roles:

1 – **store part of the water** during the event, such as a storage basin, especially if the volume available is large;

2 – **initiate new water paths** through the plots from a street to its parallel further downstream, possibly crossing sensitive areas (nurseries, hospitals, schools, old people's homes).

To accurately represent these water intrusions, it is essential to record the characteristics of the borders of private plots in the field, as described in figure 2. We have shown that in peri-urban areas, runoff through gardens or hedges can play a significant role in the distribution of flows at the global level.

The presence of fixed obstacles such as cars can increase the water depth

Finally, streets are rarely free of various obstacles, whether fixed (street furniture, signs) or mobile (vehicles). These obstacles can strongly modify the surface water paths. Their influence was studied in the laboratory on an OTHU site "reduced model of a crossroads" (Paquier, 2009). The results show that the presence of a fixed obstacle can significantly modify the distribution of flows within the streets. Figure 3

Figure 1: Map of the main pipes of the sewerage network, with SI1, SI2 and SI3 three gullies, in the flood-prone area of the Yzeron in Oullins in the suburbs of Lyon (from Bazin, 2013).

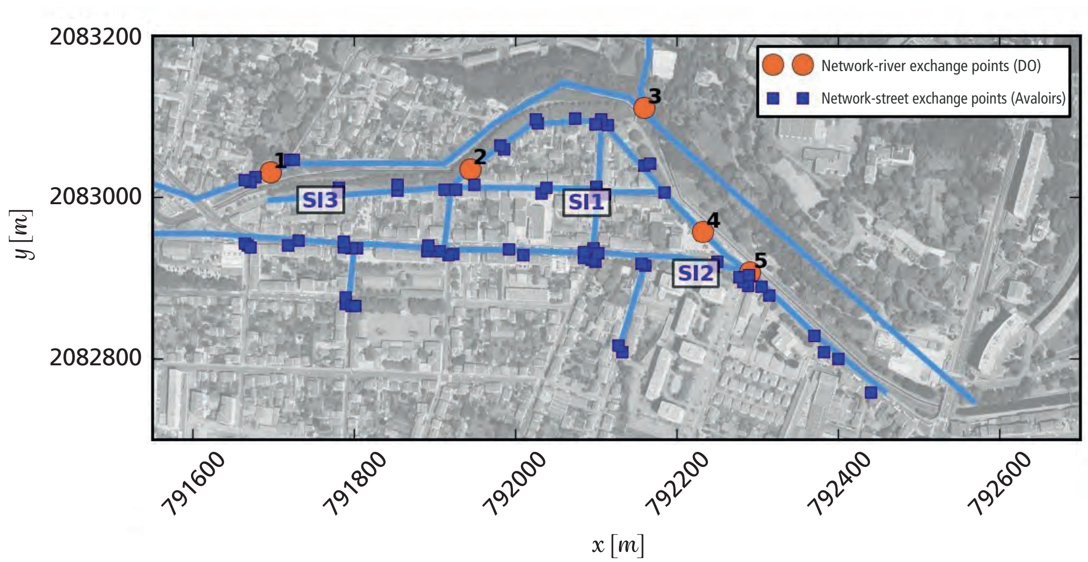


Figure 2: Field survey of the details of a neighbourhood in Oullins (69) with: per = permeable plant hedges, imp = impermeable walls, bar = semi-permeable barriers, low = low walls that can be crossed (after Bazin, 2013).

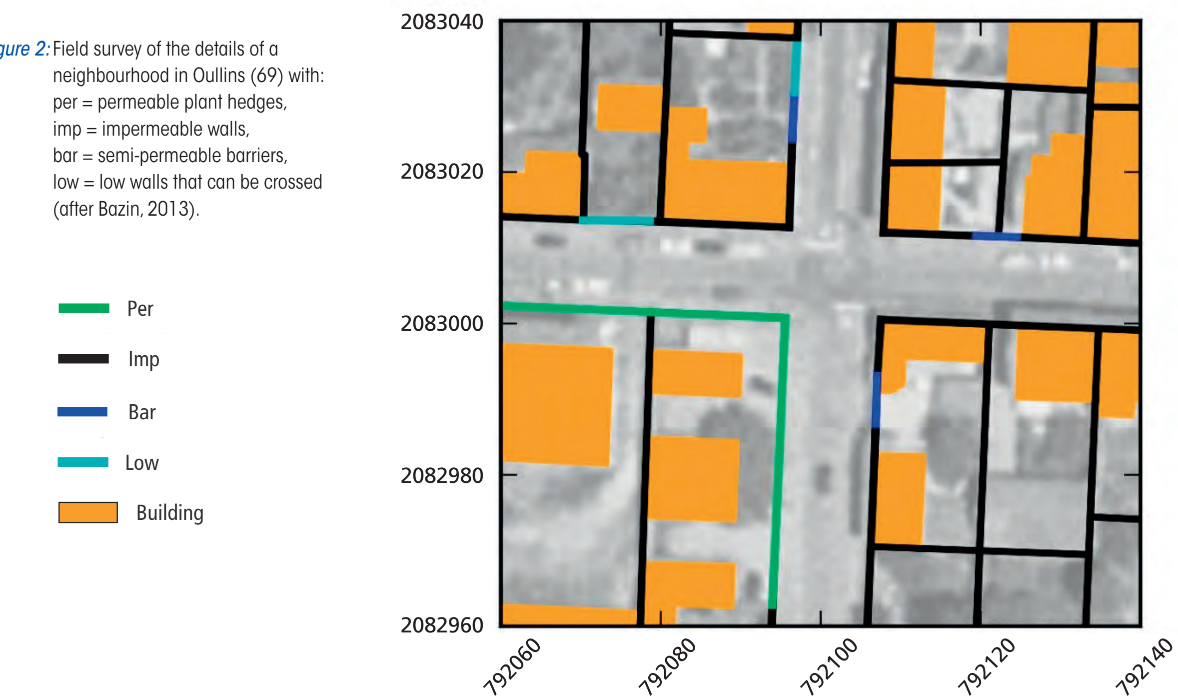
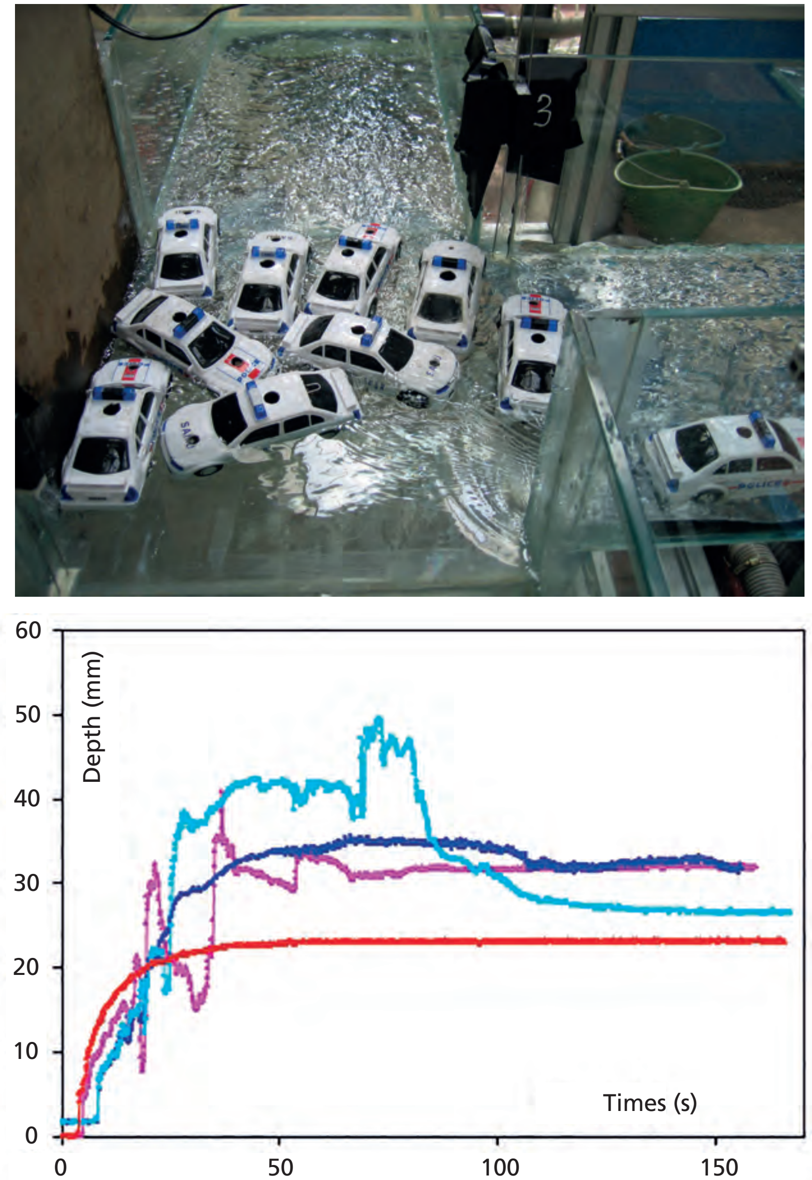


Photo 1: Flooding of a neighbourhood in Oullins (69) (source INRAE).

Figure 3: Modification of the flood wave by mobile obstacles: photograph of a laboratory test (top; scale 1:24) and evolution of the water depth (bottom) in the street in the absence (reference as red line) and presence of vehicles (source INSA Lyon).



shows the influence that blocked vehicles can have on the depth of water in a crossroads, measured in 1:24 scale tests. The depth can be more than doubled for a short period of time, but sufficient for, for example, significant amounts of water to penetrate buildings.

Which models are suitable for the simulation of stormwater flooding?

The simulation of stormwater flooding requires several types of complementary modelling.

The purpose of hydrological models is to determine the source of flooding in a given study area, i.e. the quantities of water coming from:

- upstream runoff;
- the overflow of the river within the area;
- the redistribution of rain through the roofs to the network and the streets of the study area.

Within the flooded area, different models can then be implemented, providing different information, depending on the scales or knowledge required.

The linear aspect of the buried network makes 1D models particularly suitable, provided that they are supplemented by laws linking depth and flow at the structures. For flows on the surface of streets, the most widespread codes are based on the flow equations averaged over the vertical (2D Saint-Venant equations; Paquier, 2009): they are called "2D-h". They benefit from an increasing amount of topographic data, particularly from airborne or terrestrial LiDAR, supplemented by increasingly detailed and widely accessible images. Moreover, 1D (network) and 2D-h (surface) models can be coupled (Bazin et al., 2014) to reproduce the complete dynamics of the flood. Using 2D-h models makes it possible to enlarge the simulation area by decreasing the calculation times. It does this by allowing for the buildings to be taken into account as it uses different porosity values in the simulation. This also reduces the resolution of the flow data locally, at the scale of the riparian environment or of the building. Conversely, 3D simulations suffer from prohibitive calculation times, which reserves them for local studies (around a structure for example).

To establish risk maps, the hazard characteristics (depths, flow velocities) provided by these models must be crossed with vulnerability maps. The intervention of human and social sciences is essential to add the behaviour of local residents (travel, possible or probable use of vehicles, perception of risk, memory, acceptability) in order to be able to propose evacuation plans, road modifications, protective structures, etc.

How can these models be used for crisis management?

The calculation capacities do not allow for a detailed simulation of an urban flooding event in real time, even more so as the dynamics of the flooding are rapid (a few hours or even a few minutes in the case of a localised storm on steep slopes). One solution is to establish a catalogue of simulations for synthetic events (corresponding to different hydrological conditions). In times of crisis, the simulated event that best corresponds to the event suffered is chosen to decide on the actions to be taken.

The uncertainty in the results of a simulation for a given event is linked to the limited representativeness of the model (insufficient calibration, insufficient or ill-adapted representation of certain processes). For use in forecasting, two sources of uncertainty are added: the estimation of the source volumes of the flood by the meteorological and hydrological models, and the method of interpolation or extrapolation from the predetermined scenarios closest to the current event.

Integrating data measured in the field ("data assimilation"), which can be transmitted almost instantaneously, is a means of automatically correcting forecasts; however, this method comes up against the reliability and representativeness of the transmitted data.

A correctly estimated uncertainty is essential for decision-making.

A life-size site and a "scale model"

The Oullins site is exceptional, with both heavy urbanisation and water inflow from either river overflow or local rainfall. It has the advantage of being included in the Yzeron catchment area, which has been monitored by OTHU for many years, which has enabled a very representative sample of urban flooding scenarios to be observed. As an essential complement, the workshop site "Free-surface channel junction model" sheds light on the mechanisms leading to these scenarios and provides estimates of simulation uncertainties.

TO GO FURTHER

- **Paquier A., Mignot E. and Bazin P.-H.,** (2015). From hydraulic modelling to urban flood risk. Procedia Engineering, Special issue "Toward integrated modelling of urban systems", 115, 37-44 – lc.cx/paquier2015 (in french)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Contaminants 5

The city is exposed to a wide range of contaminants as a result of its many industrial, commercial, domestic and recreational activities, as well as certain practices (for example, the use of cars with combustion engines, pesticides). These contaminants can be chemical (hydrocarbons, medicines, detergents) or biological (exogenous organisms from rubbish, spoiled food, faecal matter). They can be of concern for the health of the urban population because they can be toxic (endocrine disruptors, carcinogens) or infectious (through pathogenic bacteria and viruses). These contaminants can also have an environmental impact on urban systems and infrastructures. These contaminants can spread to urban areas via aerosols, meteoric waters, run-off, direct emissions or spills.

For several years, OTHU has been studying urban pollutants and microbiological contaminants in stormwater as a function of the intensity and frequency of wet weather events, but also of urban typologies, and quality of the urban sediments. Concentration of pollutants under particulate forms or among dissolved fractions have been investigated together with the microbiological quality of these matrices. The work illustrated by the following questions contributed to specifying the accumulation and degradation processes of some pollutants or decay of exogenous micro-organisms in a context of centralised stormwater management using settling and infiltration basins, but also within stormwater source control devices. OTHU has made it possible to develop innovative research on microbiological contaminants of urban surfaces, their hazards and evolution.

5.1

What pollutants are found in urban stormwater?

Sylvie Barraud and Jean-Luc Bertrand-Krajewski, INSA Lyon

Water flowing in urban areas during rain events carries a number of pollutants and contaminants that reach the aquatic environment and contribute to degrading its quality.
From the very beginning of the observatory, OTHU scientists have set up devices to measure the volumes, the nature of discharges and their characteristics so that strategies can be proposed to limit their impacts.
In this Question, we address the issue of chemical pollutants carried by stormwater. Microbiological contaminants are addressed in Question 5.3.

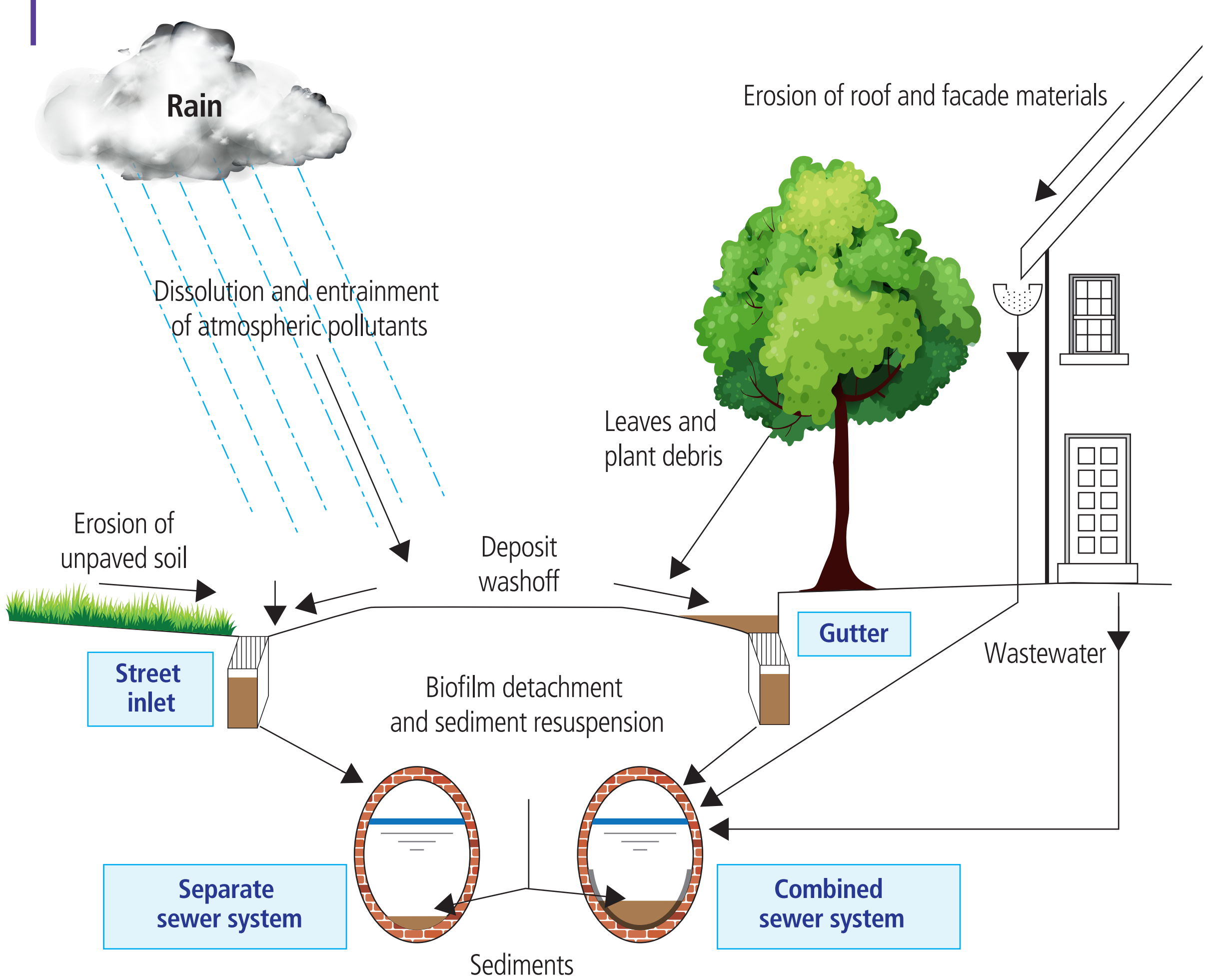
There is rainwater and rainwater

When addressing the issue of stormwater pollution, the very notion of stormwater can have different meanings depending on its position in the water cycle. It can be:

- rainwater that falls from the sky and is called meteoric water;
- water that runs off, washes off and erodes urban surfaces (stormwater runoff);
- or water collected by infrastructures (e.g. pipe networks).

Thus, runoff can be mixed with wastewater (in the case of a combined sewer system) or not (in the case of a separate stormwater system). All the discharges resulting from these processes are named urban wet weather discharges (UWWD), which are the subject of this question.

Figure 1: Mobilisation of pollutants by stormwater in urban areas (source : Chocat *et al.*, 2021).



Where do the pollutants come from?

Rainwater gradually becomes loaded with pollutants (Figure 1):

1 – firstly, by dissolution and entrainment of atmospheric pollutants (fine dust, aerosols emitted naturally or more often by nearby or remote human activities);

2 – then by runoff (wash-off of dry weather deposits, erosion of materials constituting the urban surfaces on which the runoff takes place or wash-off of substances used for the maintenance of these surfaces);

3 – finally, by the transfer of the pollutants resuspended in the various elements of the sewer system (detachment of biofilm, resuspension of deposited sediments).

What is found in stormwater runoff and UWWD?

Not surprisingly, we find substances used in human activities. In runoff as well as in UWWD, whether they come from a separate stormwater network or a combined sewer system, the main substances detected are the same.

These include:

- **trace metals** (from buildings, especially roofs, roads, and their equipment, and from wear and tear on metal parts in vehicles…);
- **hydrocarbons** (especially polycyclic aromatic hydrocarbons linked to urban heating and road traffic), some of which are carcinogenic;

Table 1: Total event concentration values (median, 10th and 90th percentiles and coefficient of variation) of stormwater sampled at the outlet of three different OTHU experimental sites: a traditional 90 m² impermeable car park (EcoCampus de la Doua), an industrial catchment with a separate stormwater network (Chassieu) and a residential catchment with a combined sewer network (Ecully) (sources: Becouze, 2010; Sébastian, 2013; Garnier, 2020).

			Car park runoff				Separate system (Chassieu)				Combined system (Écully)				NQE
			Q10	Median	Q90	CV	Q10	Median	Q90	CV	Q10	Median	Q90	CV	
Metals (ETM)	As	(µg/L)	0.4	**2**	10.5	123 %	0.7	**1**	2.6	57 %	1.3	**2**	3.7	45 %	0.83
	Cd**	(µg/L)	0.04	**0.2**	1.68	140 %	0.12	**0.3**	1.20	89 %	0.06	**0.1**	0.2	69 %	0.45
	Co	(µg/L)	0.2	**1**	7.1	120 %	0.9	**2**	14.1	127 %	0.4	**0,5**	0.6	50 %	-
	Cr	(µg/L)	2.3	**10**	46.6	109 %	3.7	**9**	16.0	50 %	1.1	**2**	2,.5	77 %	3.4
	Cu	(µg/L)	6.1	**23**	76.7	97 %	20.5	**32**	122.7	98 %	21.1	**36**	48.2	145 %	1
	Mn	(µg/L)	11.0	**107**	739.4	135 %	24.7	**58**	228.5	108 %	34.4	**45**	68.5	119 %	-
	Mo	(µg/L)	0.0	**0.0**	0.0	-100 %	0.3	**2**	25.8	161 %	0.6	**1**	1.4	29 %	-
	Ni*	(µg/L)	2.2	**7**	29.6	95 %	3.4	**9**	15.5	54 %	1.9	**2**	3.7	77 %	34
	Pb*	(µg/L)	1.4	**9**	50.8	126 %	4.7	**11**	57.5	109 %	2.2	**6**	11.8	178 %	13
	Sr	(µg/L)	24.6	**44**	148.9	79 %	46,.1	**74**	106.5	37 %	99.7	**166**	256.3	64 %	-
	Ti	(µg/L)	23.5	**442**	1532.2	112 %	19.0	**60**	202.1	88 %	35.9	**39**	54.7	72 %	-
	V	(µg/L)	1.9	**11**	48.6	112 %	2.3	**5**	8.2	47 %	1,.3	**2**	2.3	0 %	-
	Zn	(µg/L)	21.0	**105**	387.4	104 %	198.4	**259**	928,.8	79 %	76.3	**112**	163.4	71 %	7.8
	Ba	(µg/L)	7.4	**74**	293.2	117 %	23.7	**53**	812.9	210 %	22.6	**31**	44.2	70 %	-
Pesti-cides	Atrazine*	(ng/L)	0.0	**5**	112.5	150 %	0.2	**3**	135.1	175 %	0.5	**2**	90.1	215 %	2 000
	Diuron*	(ng/L)	0.0	**0.3**	45.8	207 %	1.1	**19**	53.2	92 %	0.2	**28**	45.6	80 %	1 800
	Bisphenol A	(ng/L)	126.4	**158**	353.2	49 %	406.1	**525**	731.9	25 %	nm	**nm**	nm	nm	-
Alkyl-phenols	4-Tert-Octylphenol*	(ng/L)	8.6	**19**	355.6	182 %	21.7	**39**	90.3	57 %	0.0	**5**	171.7	127 %	100
	4-Nonylphenol**	(ng/L)	140.9	**329**	434.2	44 %	258.8	**584**	1 231.7	55 %	0.0	**0.0**	0.0	0 %	2 000
HAP	Naphtalen*	(ng/L)	94.5	**211**	1 693.1	149 %	100.9	**238**	1 219.5	110 %	0.0	**4**	21.0	115 %	130 000
	Fluoranthen*	(ng/L)	29.5	**111**	297.5	77 %	65.6	**100**	201.0	48 %	47.9	**91**	181.5	75 %	120
	Benzo(b)fluoranthen**	(ng/L)	6.9	**60**	298.6	116 %	18.3	**58**	153.6	74 %	0.0	**50**	64.3	78 %	17
	Benzo(k)fluoranthen**	(ng/L)	6.9	**6.9**	6.9	0 %	6.9	**19**	52.0	79 %	0.0	**25**	44.1	70 %	17
	Benzo(a)pyren**	(ng/L)	11.7	**12**	83.6	118 %	9.1	**15**	75.5	98 %	0.0	**0.0**	19.5	245 %	270
	Indeno(1,2,3-cd)pyren**	(ng/L)	40.0	**40**	80.0	36 %	7.6	**46**	57.9	50 %	0.0	**48**	129.0	87 %	-
	Benzo(g, h, i)perylen**	(ng/L)	40.0	**40**	81.8	37 %	28.0	**55**	98.2	47 %	9.6	**51**	80.9	75 %	8.2
PBDE	B183**	(ng/L)	1.9	**6**	17.3	84 %	1.7	**2**	2.6	24 %	*nm*	***nm***	*nm*	*nm*	-
	B205*	(ng/L)	0.3	**11**	104.3	176 %	0.0	**0.4**	8.5	192 %	*nm*	***nm***	*nm*	*nm*	-
	B209*	(ng/L)	2.6	**50**	568.5	168 %	0.0	**60**	216.9	98 %	*nm*	***nm***	*nm*	*nm*	-
	Σ6PBDE	(ng/L)	2.1	**14**	67.5	123 %	1.9	**8.9**	13.8	68 %	*nm*	***nm***	*nm*	*nm*	140
			min	average	max		min	average	max		min	average	max		
TSS	Total Suspended Solids	(mg/L)	21.3	**140**	1 075.7	125 %	22.0	**144.0**	1 421.0	88 %	13.0	**260**	1 433.0		50

nm: not measured – * priority substance – ** priority hazardous substance (European Water Framework Directive)

[1] La The median is a central statistical value for which 50% of the samples have a concentration below it and 50% above. Q10 is the 10th percentile. It gives an idea of the low values of the samples (10% of the samples have a concentration that is below Q10). Q90 is the 90th percentile. It gives an idea of the high values of the samples (90% of the samples have a concentration that is lower than Q90).
The coefficient of variation measures the degree of variability of the samples. It is the standard deviation divided by the sample mean. If a CV = 150% it means that the standard deviation is 1.5 times higher than the sample mean.

Photo 1: Stormwater runoff on an impermeable surface (source GRAIE).

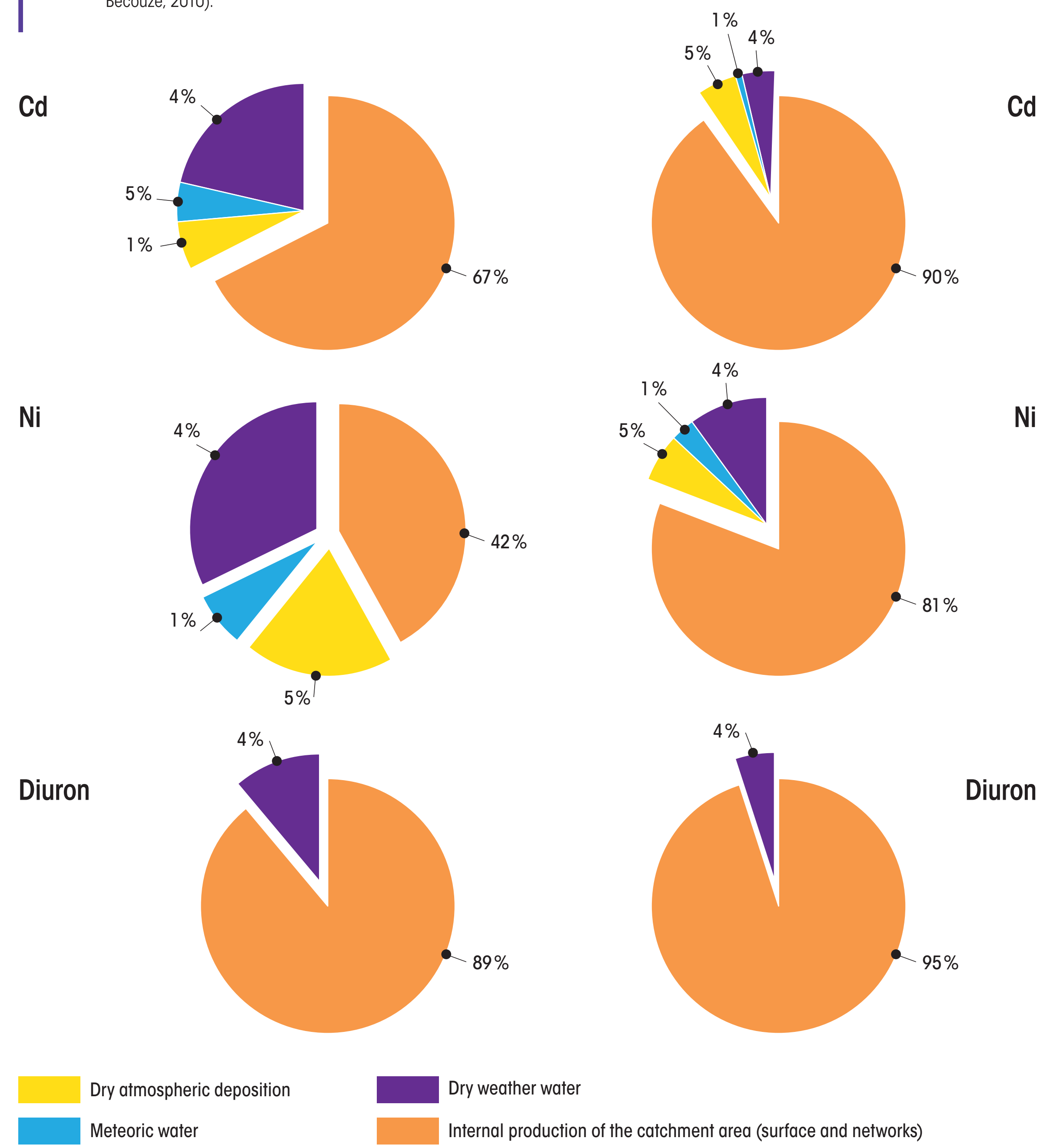
- **additives** such as flame retardants or alkylphenols used in many urban materials;
- **cleaning products** such as pesticides, fungicides;
- or, to a lesser extent, **nutrients** (e.g. nitrogen products).

OTHU has made a major contribution to the databases on pollutants in the various compartments (from meteoric water to discharges) by developing specific metrological devices (e.g. for estimating dry and wet deposition), for acquiring event mean concentrations (EMCs) taking into account the whole chain of uncertainties from sampling to laboratory analysis (see Questions 2.3 and 2.4.).

Pollution levels in runoff and UWWD are significant and highly variable

Pollutant concentrations can be significant. Table 1 gives orders of magnitude observed for total concentrations (dissolved and particulate fractions) at three OTHU experimental sites: the first one collecting runoff from a small traditional impermeable car park of about 90 m² (La Doua EcoCampus), the second site draining a 185 ha and 70% non-permeable industrial area by means of a separate storm sewer system (Chassieu) and finally a 245 ha and more than 40% non-permeable residential area drained by a combined sewer system (Écully).

Figure 2: Examples of mass balances for three pollutants (cadmium, nickel, diuron) at OTHU experimental sites of Ecully and Chassieu, France (source: Becouze, 2010).



Concentrations of metals and polycyclic aromatic hydrocarbons (PAHs) are high at all sites. Other substances are measured in lower concentrations but are endocrine disruptors, such as diuron or some brominated flame retardants (PBDEs), which are now known to have effects at low doses.
Even if the median concentrations of pollutants in stormwater separate systems seem to be higher, the variability of the concentrations, whatever the site, is very high (coefficient of variation is often over 100%). A major characteristic of stormwater pollution is its great variability, not only from one site to another, but also from one event to another for the same site without any simple relationship with the characteristics of the rain events (duration, rainfall average intensity or duration of previous dry weather periods, etc.). The variation in pollutant concentrations within each rain event is also very important (see Question 5.2).

Table 2 : Examples of dissolved fraction values (medians, 10th and 90th percentiles) of pollutants sampled at the outlet of the Chassieu catchment equipped with a stormwater separate system and of the impermeable car park of the Doua Campus. The darker the median cell, the more particulate the pollutant; the lighter the pollutant cell, the more dissolved it is (Garnier, 2020).

		Car park runoff			Separate system (Chassieu)		
		Q10	Median	Q90	Q10	Median	Q90
Metals (ETM)	As	4	12	41	21	35	49
	Cd**	1	5	32	5	31	91
	Co	1	4	17	2	23	60
	Cr	0	1	11	5	10	41
	Cu	2	8	51	7	18	54
	Mn	0	3	45	3	7	32
	Ni*	2	6	64	9	27	63
	Pb*	0	1	4	2	3	13
	Sr	17	50	94	59	78	94
	Ti	0	0	3	0	0	3
	V	2	10	52	5	21	43
	Zn	0	3	35	11	36	78
	Ba	5	12	100	7	26	82
Pesticides	Carbendazime	13	99	100	73	99	100
	Atrazine*	45	99	100	100	100	100
	Diuron*	0	97	100	53	93	100
	Bisphenol A	82	93	97	84	91	98
Alkylphenols	Nonylphenol-1-carboxyled*	50	71	93	96	99	99
	4-Tert-Octylphenol*	8	44	72	43	57	90
	Octylphenol-mono-ethoxyled	29	79	96	84	99	100
	Octylphenol-di-ethoxyled	20	67	87	61	71	98
	4-Nonylphenol**	12	85	93	13	53	92
	Nonylphenol-di ethoxyled*	13	88	98	51	68	94
	Nonylphenol-mono-ethoxyled*	22	54	86	57	86	97
HAP	Naphtalen*	0	7	34	2	61	91
	Acenaphten**	25	44	66	25	35	100
	Fluoren**	7	43	68	26	61	79
	Phenanthren**	1	3	40	17	24	40
	Fluoranthen*	0	4	72	5	9	20
	Pyren**	0	1	90	4	12	24
	Benzo(a)anthracen**	0	13	25	0	0	3
	Chrysen**	0	3	25	0	1	5
	Benzo(b)fluoranthen**	1	5	25	0	0	17
	Benzo(k)fluoranthen**	25	25	25	0	0	25
	Benzo(a)pyren**	4	25	25	0	0	25
	Indeno(1,2,3-cd)pyren**	13	25	25	0	0	23
	Benzo(g,h,i)perylen**	13	25	25	0	0	44
	ΣHAP light	3	8	44	9	43	65
	ΣHAP heavy	3	8	38	3	5	20
PBDE	B183**	3	15	56	0	2	70
	B205*	0	3	19	4	51	94
	B209*	0	1	7	0	1	1

Due to the large volumes of runoff likely to be produced by rain events, the discharge can be a major source of pollutants and micropollutants to surface aquatic bodies. For example, in Chassieu, comparable fluxes are measured for some micropollutants (e.g. zinc) between a rainfall event and the daily discharge from the Feyssine wastewater treatment plant (300,000 population equivalent).

Figure 2 illustrates some contrasting cases of mass balances calculated for Ecully and Chassieu.

The atmospheric contribution to pollutant flows is low

Mass balances of pollutants were established for the Chassieu and Écully OTHU sites, distinguishing between the contributions of meteoric water, dry atmospheric deposition, dry weather water (i.e. wastewater), and the internal production of the catchment (surfaces and networks). They show that the contribution of pollutants coming from meteoric water and dry atmospheric deposition does not exceed 25%, while the share of meteoric water alone does not exceed 20% and is most often less than 10%.

Pollution is often particulate but not only…

Pollutants such as metals and PAHs are mainly present in the particulate fraction and are generally bound to particles that can be easily settled. The TSS parameter is important for quantifying particulate pollution. Stormwater TSS have a fine particle size (median diameter d50 < 50 µm) but its significant density (generally 1,700 to 2,400 kg/m^3) giving good settling properties.

Some micropollutants, such as pesticides and bisphenol A, and to a lesser extent alkylphenols, are mainly present in the dissolved fraction. These pollutants are particularly important to monitor because they are more difficult to intercept by centralised detention or infiltration infrastructures.

Table 2 provides some orders of magnitude of the dissolved fractions of various pollutants measured at the outlets of the Chassieu separate stormwater system and of a small car park on the Doua EcoCampus.

In Brief...

**Pollution of stormwater is significant and highly variable: from one site to another, from one rain event to another for the same site and within rain events.
This pollution increases as water runs off and over urban surfaces, and the atmospheric contribution is small.
An effective mechanism for reducing pollution is therefore to act at the source by limiting runoff and systematic collection with networks by favouring, for example, on-site infiltration or evapotranspiration by planting more vegetation on urban surfaces. Pollution is mostly particulate (and thus highly settleable) but it is not only in this form!
Some micropollutants, such as pesticides and bisphenol A, and to a lesser extent alkylphenols, are also present in the dissolved fraction in Urban Wet Weather Discharges (UWWD) and are therefore potentially mobile.**

TO GO FURTHER

- **Becouze C.,** (2010). *Characterisation and estimation of priority substance flows in urban discharges during rainy weather on two experimental catchments.* PhD thesis, INSA Lyon, 308 p. (in french)
- **Garnier R.,** (2020). *Alternative stormwater management systems: Contribution to the analysis of joint performance in quantitative hydrology and micropollutant trapping. Comparison between source systems and centralized systems.* PhD thesis, INSA Lyon, 318 p. - lc.cx/garnier2020 (in french)
- **Sébastian C.,** (2013). *Stormwater detention basin in urban environment: performance in micropollutant trapping.* PhD thesis, INSA Lyon, 354 p. (in french)
- **Chocat B., Bertrand-Krajewski J.-L., Barraud S.,** (2021). Pollution from urban rainfall discharges. *Techniques de l'Ingénieur* – article W 6 800v2. (in french)

5.2

Does it make sense to base an urban wet weather discharge control strategy on the first-flush principle?

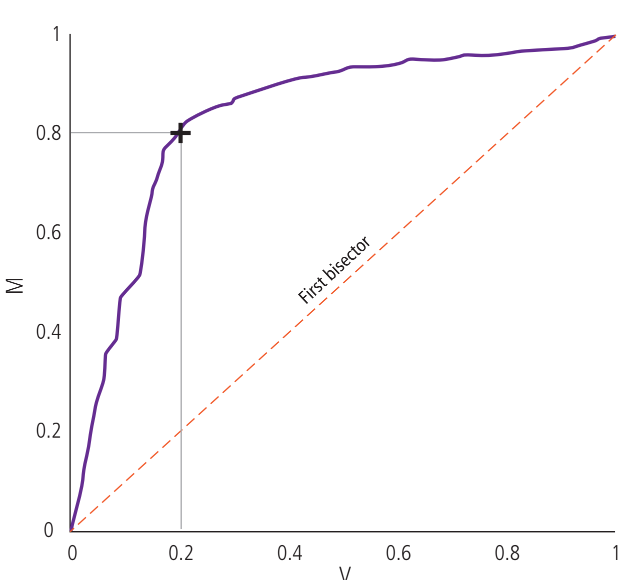
Sylvie Barraud and Jean-Luc Bertrand-Krajewski, INSA Lyon

The encyclopaedia of urban hydrology and sewerage (Chocat *et al.*, 1997) defined the first flush effect as "the concept that water passing through a stormwater separate system or combined system would be much more polluted at the beginning of a rain event than during its course". Using previous definitions dating back to the 1970s, the encyclopaedia definition nevertheless introduced a critical look at the concept by using the conditional tense. Indeed, the concept of first flush has suffered from inaccuracies and misinterpretations since its inception, which have led to inadequate management strategies and futile debates.

The limits of the concept

Inaccuracies: it is true that in many cases concentrations of pollutants in stormwater are higher at the beginning of a rain event than at the end, although this is not systematic given the high variability of the processes (see Question 2.2: *Why is long-term monitoring of the quality of urban wet weather discharges necessary?*). But neither "higher concentrations" nor «onset of events» are quantified in the existing definitions of first flush, which is problematic.

Figure 1: Schematic diagram of a curve showing the mass fraction of pollutants (M) as a function of the fraction of stormwater runoff volume (V). This curve is illustrative and purely theoretical.



Misinterpretations: the main one is the insidious and biased shift from an observation related to concentration (in mg/L) to an interpretation in mass (in kg). Network operators have indeed seized on this notion of first flush to justify investments aimed at treating only the supposedly most polluted part of the stormwater runoff volume, i.e. that which would take place at the beginning of the rain. The hypothesis put forward is that the treatment of the first volumes of stormwater runoff would be sufficient to protect the aquatic environment. In fact, it turns out that these first volumes, even if concentrated, generally only represent a small fraction of the total mass of pollutants generated by a rain event. This misinterpretation of the first flush concept has therefore led to the construction of low volume infrastructures, but also of low efficiency infrastructures...

What method should be used to implement the evidence of a possible first flow?

Several methods have therefore been proposed in the literature to correctly quantify a first flush effect with regard to mass and to evaluate its frequency of occurrence. The most commonly used approach for urban discharges consists of establishing dimensionless curves, known as M(V) curves, which represent, for each event, the fraction of the total mass of pollutants transported (M) by a given fraction of the stormwater runoff volume (V).

Thus, a first-flush effect could be proven and relevant to base a discharge control strategy if, for the vast majority of the rain events at a given site, more than 80% of the mass of the monitored pollutant (M = 80%) would be contained in, for example, the first 20% of the volume (V = 20%) (Figure 1).

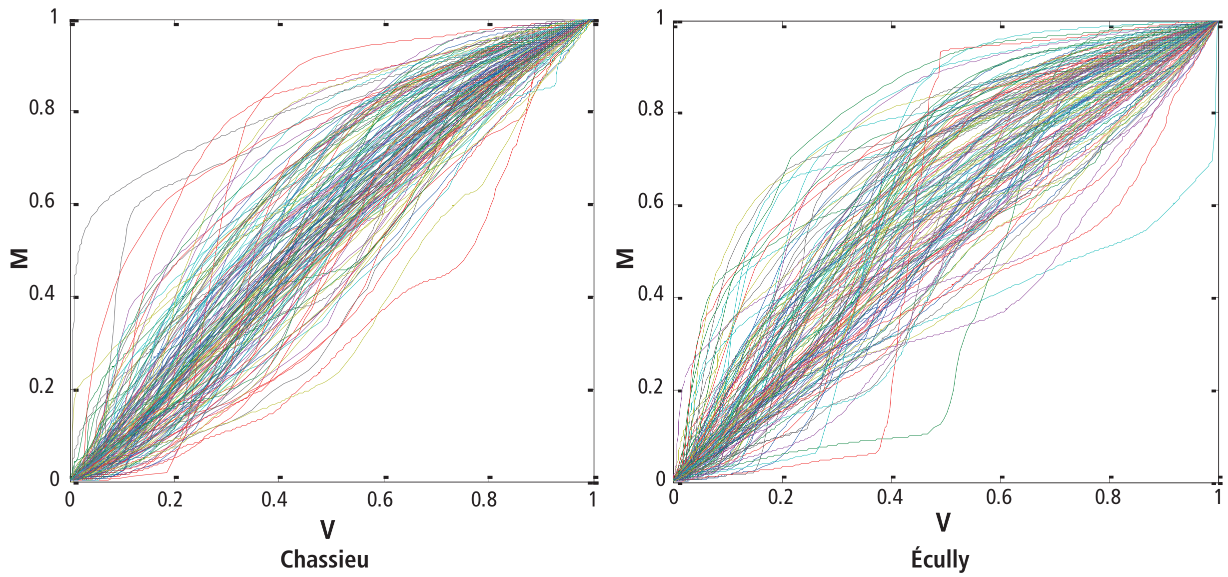
On this basis, several indicators were used to search for a possible first flush. These are:

(i) the relative mass M of the pollutant corresponding to 20% or 30% of the volume: this is the most frequent indicator because of its direct interpretation.

(ii) the maximum difference noted Max-MV between the M(V) curve and its first bisector.

(iii) the coefficient b in the power law approximating the curve M(V) as $M = V^b$.

Figure 2: Curves of pollutant mass fraction (M) versus stormwater volume fraction (V) for 162 complete rain events in Chassieu (left), for 148 complete rain events in Ecully (right) (Barraud *et al.*, 2015).



Treating the first flush: a false "good idea"

As it is very costly in terms of analysis to monitor various pollutants for a large number of rain events at the same location, M(V) curves are, most of the time, produced for global indicators (e.g. TSS or COD) that are easier to monitor continuously (see Question 2.4: *Continuous measurement and sampling: why do we need to go beyond regulation?*).

Let's take the example of TSS concentrations estimated continuously with a 2-minute time step from turbidity at the outlets of the Chassieu stormwater separate system and Écully combined. TSS concentration is a good indicator of particulate pollution of other contaminants such as heavy metals or polycyclic aromatic hydrocarbons (PAHs).

Figure 2 shows the M(V) curves for the Chassieu and Écully sites, based on 162 and 148 complete and good quality data rain events from 2004 to 2011 respectively. It shows a wide dispersion of these curves around the first bisector, thus confirming the absence of a systematic first flush effect. These OTHU datasets are corroborated by other data obtained at various sites in France and abroad.

In the vast majority of cases, it is therefore not justified to treat only the first fraction of the volume, either for combined or stormwater separate systems, as the first flush phenomenon is both too little recurring and too little marked. Other strategies (source control or detention/settling) are much more effective (see Question 7.1: *Why infiltrate stormwater?*).

Looking for the first flush?

Like many simple misconceptions, the first flush idea has a long life, although many M(V) curves have been published for more than 20 years for various sites and have all led to the same conclusion: the frequency and amplitude of the first flush in mass are too low to make it a relevant strategy for managing urban wet weather discharges by simply intercepting "the first part of the stormwater volumes". If, despite everything, you hear that this would be the case somewhere on a sewer system, invite the operator to first establish the M(V) curves of a few dozen rain events on this site before investing in works that would only be based on a belief.

TO GO FURTHER

- **Métadier M., Bertrand-Krajewski J.-L.,** (2012). The use of long-term on-line turbidity measurements for the calculation of urban stormwater pollutant concentrations, loads, pollutographs and intra-event fluxes. *Water Research*, 46(20), 6836-6856. doi:10.1016/j.watres.2011.12.030. – lc.cx/metadier2012 (in french)
- **Barraud S., Sun S., Castebrunet H., Aubin J.-B., Marmonier P.,** (2015). *Study of the evolution and variability of the quantities and quality of urban water in rainy weather over the last decade - Capitalisation of OTHU chronicles (CHRONOTHU Project).* Rapport de convention 2013-2882 – Agence de l'Eau Rhône Méditerranée Corse, Lyon, France, 92 p. – lc.cx/chronothu (in french)

5.3 What are the microbiological contaminants of urban wet weather discharges and their related health hazards for urban dwellers?

B. Cournoyer, D. Blaha, W. Galia, V. Rodriguez-Nava, B. Youenou, R. Bouchali, Y. Colin, A. Aigle, A. Meynier Pozzi, E. Bourgeois, J. Voisin, R. Marti, S. Ribun, A. Gleizal, C. Bernardin-Souibgui, F. Vautrin, B. Tilly, L. Marjolet, UMR Écologie Microbienne Lyon (LEM), BPOE Team, VetAgro Sup, University Claude-Bernard Lyon 1, CNRS & INRAE

The dynamics of emission, dissemination, settlement and decay of pathogenic micro-organisms in cities remain poorly understood. Urban wet weather discharges (UWWD) can carry multiple microbial contaminants which can spread among the connected rivers and groundwater. The related health issues justify the development of relevant indicators and assays to assess the microbiological quality and hazards of urban waters and reduce the impact of UWWDs by optimising management practices and favouring the decay of these organisms.

Why study the microbiological quality of UWWD?

Urban wet weather discharges (UWWD) are of health concern because of the biological contaminants that they can carry. These waters can contain nutrients for micro-organisms such as fecal matters, hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), and other chemicals. These are often associated with micro-organisms coming from, amongst others, household wastes, faecal and food matters, industrial releases, and other sources at the origin of their occurrences. The microbial contaminants in UWWDs can be pathogenic and represent a health hazard to humans, i.e. they can provoke infections (dermatitis, ear infections, lung infections, etc) and epidemics in the context of recreational or professional activities.

Within the framework of OTHU, research actions have been developed on:

1 – **the diversity of bacterial pathogens** carried by the UWWDs;

2 – **their ecology** in relation to field parameters, including their capacity to persist or even develop over urban surfaces, in the various compartments of the receiving watercourses and in rainwater detention or infiltration systems;

3 – **their level of risk** (infectious dose and virulence).

Figure 1 shows the main areas of investigation on this theme within OTHU. These aspects have been studied in different compartments:

(i) at the level of urban surfaces;

(ii) of runoff water;

(iii) at the outlet of runoff overflow pipes and stormwater networks;

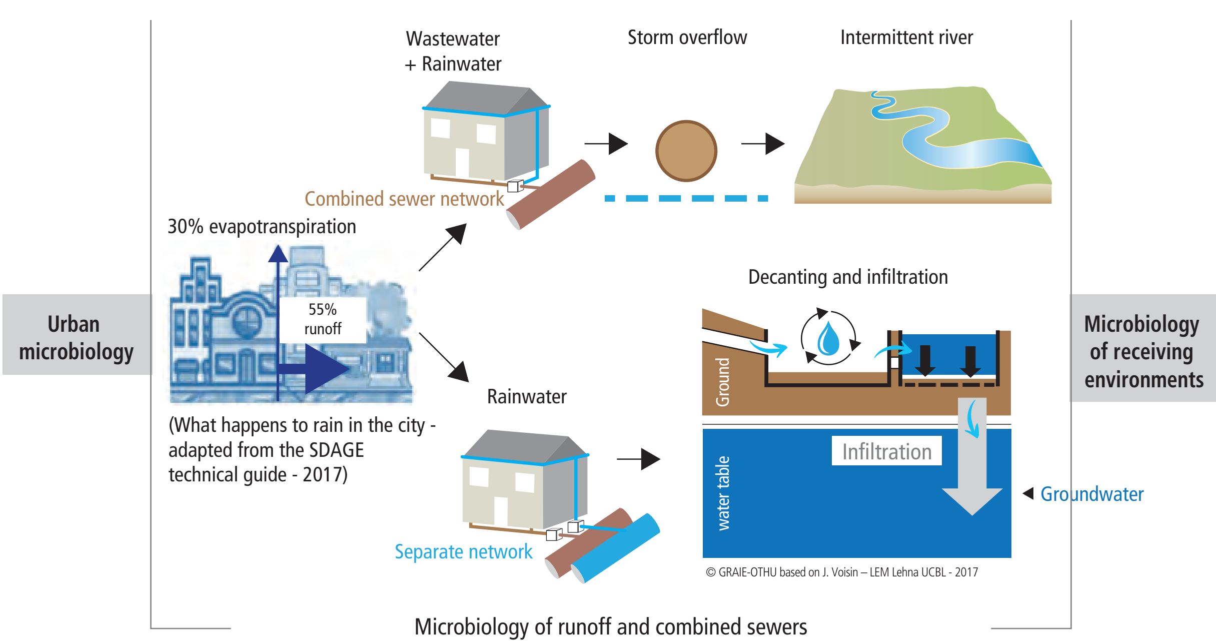
(iv) in peri-urban rivers receiving combined sewer overflows;

(v) at the outlet of separate stormwater networks;

(viii) in runoff detention and infiltration basin, and

(ix) in the underlying water table of infiltration ponds.

Figure 1: Master plan of OTHU's activities in the fields of urban microbiology and the assessment of microbiological hazards to humans related to UWWD management practices. The impact of overflows from the combined sewer system is mainly studied at the Grézieu-la-Varenne site, and that of runoff from urban catchment areas discharging into detention-infiltration systems and the Lyonnaise water table via the Django-Reinhardt site in Chassieu.



Which pathogens or indicators should be monitored to assess the microbiological quality of urban water?

Standard methods have important limitations

To assess the microbiological quality of urban water, several micro-organisms can be monitored. Standard methods for estimating the concentrations of certain bacterial species, viruses and protozoa have been developed, such as NF EN ISO 7899-2 for intestinal enterococci. However, these detection methods have limitations either in terms of their predictive capacity or sensitivity. The general rule is to use bacterial indicators of faecal contamination, such as E. coli or intestinal enterococci, which make it possible to estimate risks of contracting gastroenteritis (under a bathing condition exposure scenario). However, these indicators do not allow to define the nature of the pathogen likely to cause gastroenteritis nor do they allow to infer the occurrences of pathogens associated with other pathologies.

DNA fingerprinting to assess microbiological water quality

Complementary tools must be developed to assess the sanitary quality of urban water and aquatic environments. This led OTHU to initiate studies on the occurrences of pathogenic species over city surfaces, runoff and sediments. A toolbox to perform microbiological quality assessments of urban waters and sediments was developed.

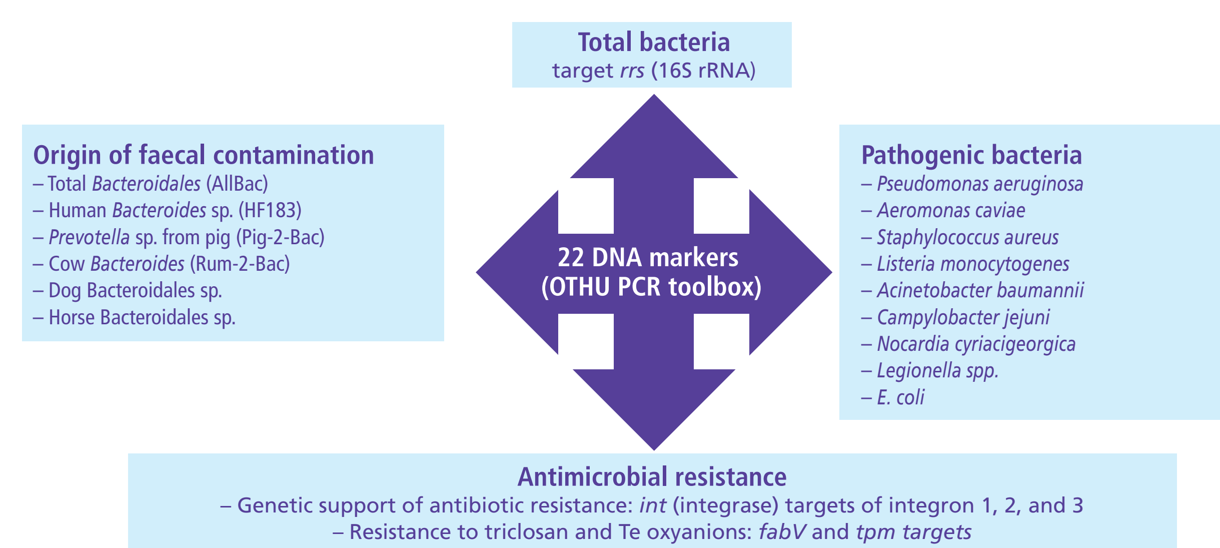
DNA "meta-barcoding" and qPCR (polymerase chain reaction quantification of a DNA segment) approaches have been developed and used to qualify the microbial diversity of various systems implemented for the management of urban waters, as shown in Figure 1 (Aigle *et al.*, 2021; Colin *et al.*, 2020; Marti *et al.*, 2017b, 2017a; Navratil *et al.*, 2020; Voisin *et al.*, 2018). The principle of these tools is to identify and track a bacterial species through its "genetic barcode".

More precisely, these approaches make it possible to follow the nucleotide variations among marker genes systematically found in a microbial group of interest. Bacteria are thus characterised by the analysis of these variations within housekeeping genes such as the one encoding the 16S rRNA, an essential component of ribosomes allowing the translation of genes into proteins, but also other genes including those involved in human cell infectious processes. Within the framework of OTHU, several DNA markers have been developed, including new "meta-barcoding" targets allowing specific differentiation of species (Aigle *et al.*, 2021; Pozzi *et al.*, 2021a; Vautrin *et al.*, 2021).

This information was subsequently used to define sentinel species for the evaluation of quality of certain environments, including the Lyon aquifer, the Yzeron watershed and urban runoff and sediments. Methods for monitoring DNA traces by quantitative PCR were developed or validated for monitoring these sentinels. Figure 2 shows the current OTHU PCR toolbox.

The toolbox of Figure 2 is constantly evolving, and recently several hundred reference genes to monitor antibiotic resistances have been added according to Stedtfeld *et al.* (2018). Sequence analysis of the gene encoding the 16S rRNA of the detention basin of the Django-Reinhardt (Marti *et al.*, 2017b) and the Chaudanne (Grézieu-la-Varenne) sites have made it possible to identify genera likely to contain pathogenic species including, in order of abundance,

Figure 2 : OTHU toolbox for DNA fingerprinting (qPCR) of bacterial targets for microbiological quality assessment of urban waters and receiving environments. These tools are described in: Bernardin-Souibgui *et al.*, 2018; Bernhard and Field, 2000; Best *et al.*, 2003; Colinon *et al.*, 2013; Gassama Sow *et al.*, 2010; Gaze *et al.*, 2011; Layton *et al.*, 2006; Marti *et al.*, 2017a, 2017b; Martinon and Wilkinson, 2011; Mieszkin *et al.*, 2010, 2009; Nogva *et al.*, 2000; Riedel *et al.*, 2015; Seurinck *et al.*, 2005.



Mycobacteria > *Pseudomonas* > *Acinetobacter* > *Aeromonas* > *Nocardia* > *Enterococcus* > *Escherichia* > *Staphylococcus* > *Streptococcus*. Methodologies have been developed within the scope of OTHU's work for monitoring pathogenic species within these genera but also for monitoring bacterial species that are indicators of human or animal faecal contaminations (see figure 2). New "meta-barcoding" methodologies have been designed to allow the monitoring of pathogenic forms within the Pseudomonas, Acinetobacter, and Aeromonas (Aigle *et al.*, 2021) but also Actinobacteria of the genus Nocardia (Vautrin *et al.*, 2021). The first two genera are known for their involvement in the dissemination of antibiotic resistance genes.

What have we learned from the long-term observations of bacterial communities and pathogenic forms?

Relationships between socio-urban variables and the microbiology of a watershed

The relationships between individual and collective activities within neighbourhoods and the composition of bacterial communities in runoff water were studied for several catchments in Lyon. Data acquired from DNA extracted from runoff and sediments collected from avenues, streets and cul-de-sacs of the sampling sites shown in Figure 3 allowed to differentiate the sub-catchments according to technical devices and uses (Bouchali *et al.* 2022, 2024). Figure 3 shows the observed distribution patterns of DNA traces tracked by the OTHU PCR toolbox for the Mi-plaine industrial area of Lyon feeding the Django-Reinhardt detention and infiltration basins.

Bacteria of faecal origin (E. coli and intestinal enterococci) were found over the entire urban catchment, which indicated that there is an increase in exogenous bacteria induced by the behaviours within the neighbourhood.

Significant occurrences of human and canine faecal contamination were revealed by qPCR assays (OTHU toolbox) over the Mi-plaine area and were linked to night-time activities. A high prevalence of P. aeruginosa was observed, suggesting that this pathogenic species is adapted to the urban living conditions. This led to the initiation of an eco-genomic study to evaluate the impact of the city on the evolution of this species.

Figure 3: Aerial overview of the Mi-Plaine industrial and commercial zone towards Eurexpo (a center for social and large scale show events, and concerts). The zone is the home of about a hundred companies, restaurants, hotels, but also some agricultural plots. The picture illustrates the intense sealing of the zone with numbers of roads and buildings, and a high density. The two stormwater networks of this urban watershed are represented by the green and orange lines. The outlets of these networks are a detention basin and a rainwater infiltration system (named Django-Reinhardt; indicated in yellow at site23). The coloured asterisks indicate the distribution of pathogenic species, markers of faecal contamination (Bacteroides from humans or dogs) and genetic supports of antibiotic resistances (integrons 1, 2 & 3), enumerated by classical approaches with selective media or by molecular approaches based on the monitoring of DNA signatures using the OTHU toolbox.

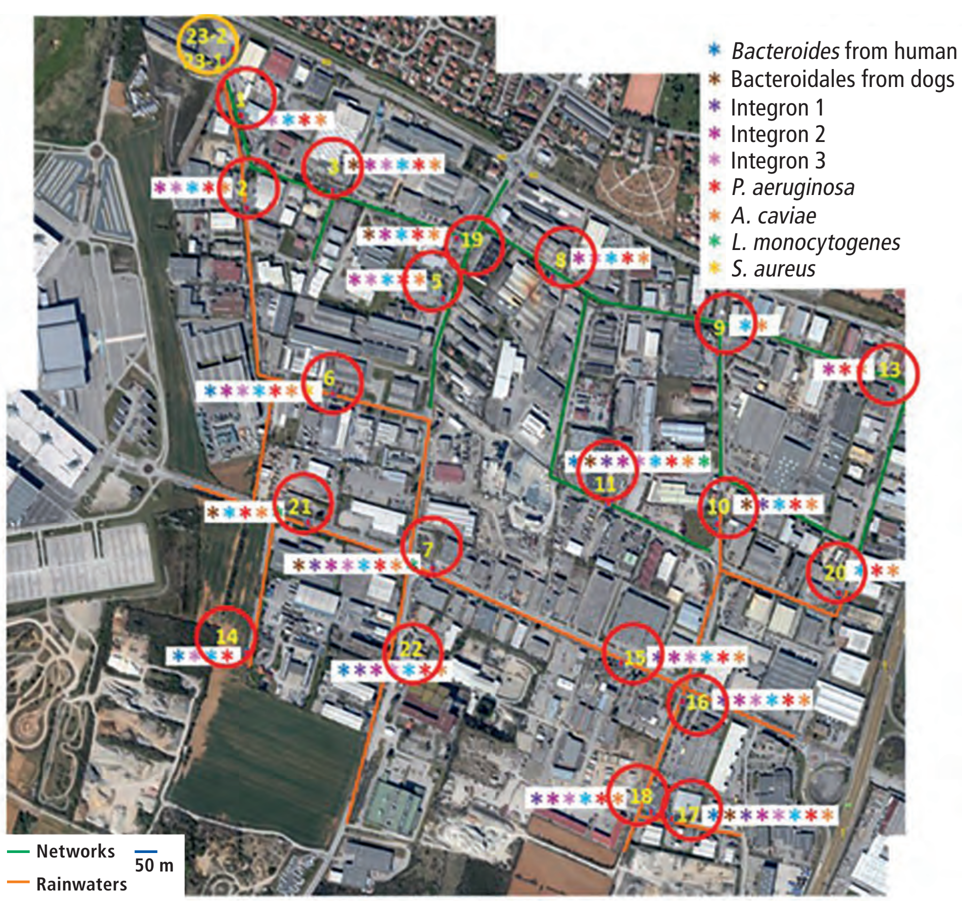
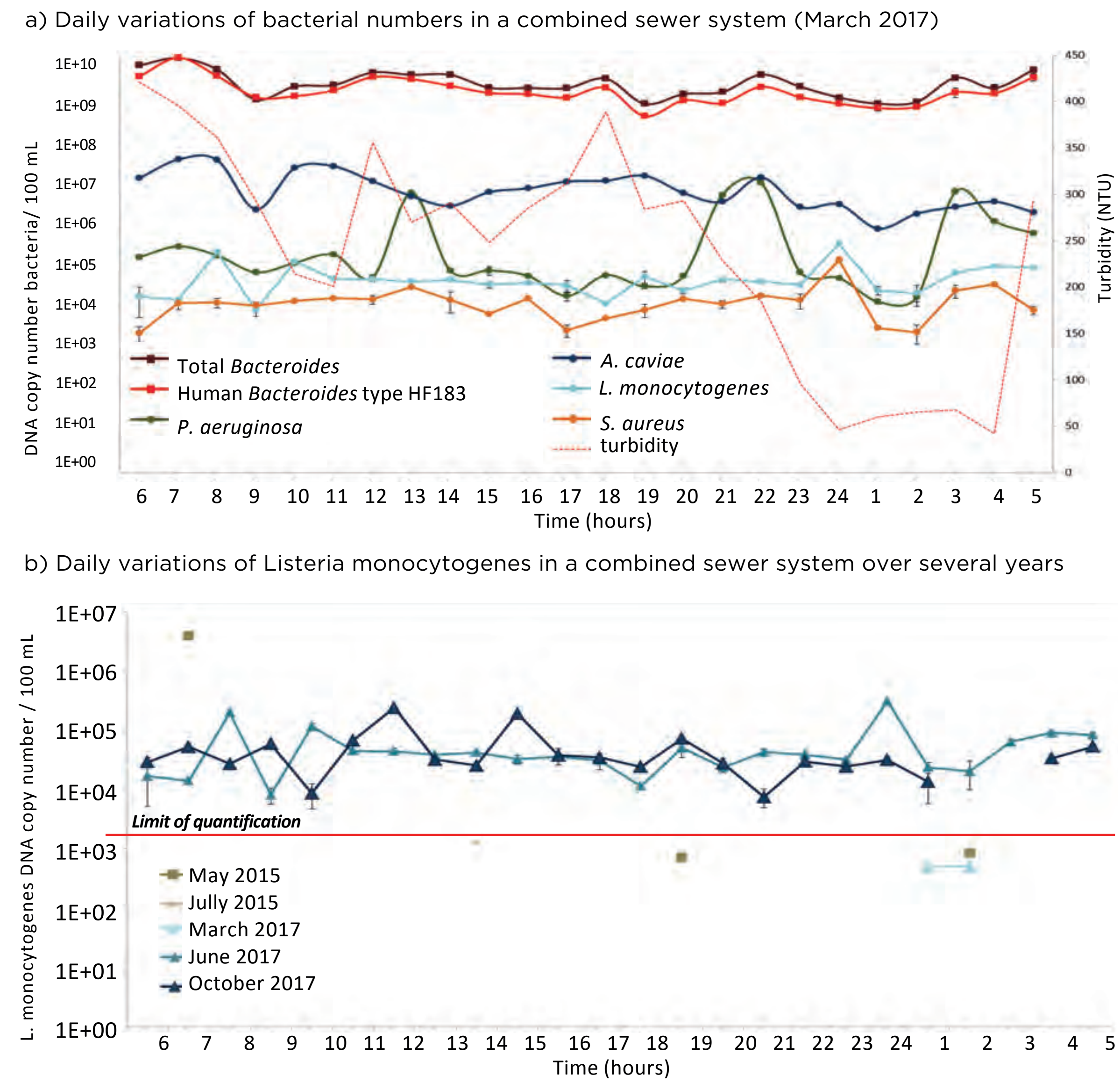


Figure 4: **Use of the OTHU PCR toolbox to qualify the microbiological quality of an intermittent watercourse contaminated by a combined sewer overflow device during heavy rains** (OTHU site in Grézieu-la-Varenne).
(a) 24-hour qPCR counts of waters transiting in a combined sewer network for several bacterial markers,.
(b) qPCR counts of Listeria monocytogenes species in the waters of a combined sewer network over several years of observation. Variations from year to year are observed.



Environmental DNA analyses to assess the microbiological quality of urban waters and sediments, and of peri-urban catchments

Every living organisms contains DNA and some specific DNA imprints: this is what allows the police to identify a criminal from a hair left at the scene of a crime. In the same way, it is now possible to isolate DNA from a simple water sample in the laboratory and analyse certain genetic targets to estimate the microbial diversity of the collected sample, and to predict the functions performed by these organisms. These approaches are used by microbial ecologists because of the intrinsic difficulties of analysing microscopic living forms.
The study of environmental DNA makes it possible to analyse microbial diversity through meta-barcoding (DNA sequences) approaches and qPCR assays, and to infer the occurrences of particular taxonomic groups in a field sample. It opens up immense prospects for the development of relevant DNA targets for assessing the hygienic and ecological states of outdoor settings.

The definition of the occurrence rates of pathogenic bacterial species in the discharge of a combined sewer overflow (CSO).

Long-term observations have been carried out on the water of a combined sewer network and on overflow waters from such a sewer impacting an intermittent watercourse in the Yzeron catchment area. Work to clarify the impact of these combined sewer overflow (CSO) discharges on the natural microbiomes of a watercourse has been performed (Marti *et al.*, 2017b; Pozzi *et al.*, 2024). Figure 4 shows the daily variations of bacterial species within a combined sewer network that have been monitored with the "OTHU PCR toolbox", including the monitoring of the Listeria monocytogenes species over several years. These results show specificities in the species distribution patterns over a given day, with some groups strongly correlated to the presence of faecal contamination but not all. Other species, such as Aeromonas caviae, correlated with emissions from other sources like road runoff. These microbiological data can be used to predict the presence of certain bacterial species in CSO discharges according to the time of day. Long-term observations of L. monocytogenes were observed to increase during the 2017 drought period. Only long-term observations make it possible to detect this type of phenomena (thanks to OTHU!).

Estimates of the amount of bacteria discharged from a CSO during an overflow could also be made. Average loads of 1 billion cells of P. aeruginosa, E. coli and intestinal enterococci per overflow were deduced, confirming the microbiological hazards associated with this practice. This work has shown persistence of these spillover bacteria in benthic sediments as a function of stream temperature and flow rates (Navratil et al., 2020; Pozzi et al., 2024). Aquatic macrophytes and some inert media in the vicinity of the CSO were also found to be contaminated with these species.

Detention basins allow significant reductions of certain pathogenic micro-organisms.

Runoff can induce a resuspension of urban deposits and contribute to the dissemination of micro-organisms of health concerns from the surface to a groundwater table. The detention basin of the Django-Reinhardt site was used as a source of urban deposits representative of the activities in the upstream catchment of the Mi-plaine area. The evolution of the bacterial diversity of the basin deposits was studied as a function of their residence time (from 2010). These analyses were carried out using the "OTHU toolbox" and the 16S rRNA and tpm (encoding the thiopurine methyltransferase) meta-barcoding approaches. Significant relationships were observed between the chemistry of the detention deposits and the occurrence of potentially pathogenic *Aeromonas* and *Pseudomonas* species (Aigle *et al.*, 2021). The phytopathogenic species *P. syringae* was favoured by the growth of plants over the old detention basin deposits and the accumulation of naphthalene. Interestingly, the most hazardous species showed a significant die-off in the detention basin aged deposits. This suggests that detention practices and incubation of urban sediments among detention basins can achieve significant reductions in pathogenic cell lines that are carried by runoff. Good management of sediment maturation times can therefore reduce microbiological hazards. However, this does not apply to all species. *P. aeruginosa* did not show a significant decline during the observation period (e.g. Bernardin-Souibgui *et al.*, 2018). This species may be transferred to the infiltration basin used to discharge runoff to the groundwater table in the area as demonstrated in Colin *et al.*, 2020.

Some species can flow down into the groundwater if the filtering media are poorly designed or maintained. However, little is known about the thickness and composition of the porous media of the vadose zone (unsaturated zone = soil thickness above the aquifer) of infiltration basins and bioswales that can prevent the transfers of micro-organisms from runoff and contaminations of aquifers. Microbiome studies via meta-barcoding approaches were carried out to infer transfers from a catchment down to the aquifer.

The percentage of "genetic" similarity of bacterial communities between runoff and groundwater allowed inferring the percentage of bacterial transfers between the surface and the subsurface (Colin *et al.*, 2020). Significant abundances of *P. aeruginosa* were observed in the groundwater downstream of the runoff infiltration zone of the Django-Reinhardt site. Nine tpm genotypes of *P. aeruginosa* were found. The P. aeruginosa in the aquifer were compared to those in the infiltration-detention basins and the catchment area. A common type was observed between the catchment and the aquifer. These results suggested that surface *P. aeruginosa* can spread down to the groundwater despite a significant thickness (>10 m) of the vadose zone.

By comparing the similarity indices of several stormwater infiltration basins in the Lyon Metropolis, we have shown that the transfer of bacteria from the surface to the water table depends on water transit time: the longer the water transit time, the more different the communities are (Voisin *et al.*, 2018; Pozzi *et al.*, 2021b). Thus, the bacterial detention capacity of the unsaturated zone increases with the water transit time and could be optimised when designing infiltration structures.

Infectious agents, pathogenic forms and virulence: what are we talking about?

An infectious agent is a pathogenic organism responsible of an infectious disease (virus, bacteria, etc.). The pathogenicity of an infectious agent measures its ability to cause disease in a host organism. Virulence refers to the ability of an infectious agent to grow in an organism (invasiveness) and to secrete toxins (toxicity).

In the results presented, the pathogenic species identified are presumed to be virulent but may contain non-virulent forms, hence the importance of isolating these urban forms and verifying their virulence in the context of interaction studies with human cells or using alternative host models such as nematodes, plants and laboratory mice. These assays have also been carried out in the framework of OTHU in recent years (Bernardin Souibgui *et al.*, 2017; Vautrin *et al.*, 2021; Bouchali *et al.*, 2024).

In Brief...

Urban water can be a key component of the epidemiological cycle of the most versatile pathogenic bacteria such as *P. aeruginosa.*
While CSO can contribute to their dissemination, centralized detention-infiltration systems tend to to induce a decline in the majority of these undesirable species.
OTHU has developed and validated a wide range of bacterial markers for assessing the microbiological quality of urban waters and of the connected environments. Long-term observations of these bacterial populations should make it possible to identify management practices that can reduce the spread of these pathogenic forms, prevent the dissemination of their genetic content, including certain antibiotic resistance genes, and reduce human exposures.

5.4

How can we determine the pollution levels of sediment in stormwater detention basins?

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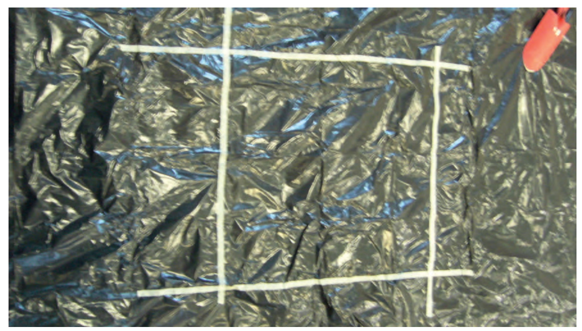
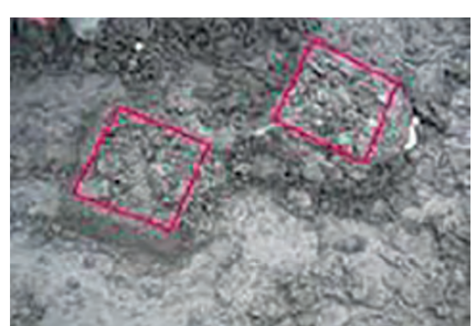
In addition to their role in flood prevention, detention basins allow for the trapping of pollutants present in runoff water, such as hydrocarbons and heavy metals, through sedimentation. However, questions remain about the risks associated with the remobilisation of volatile and/or toxic substances during wet weather periods. The operators of these basins are also concerned about the optimal frequency of cleaning and the management of sediment disposal. To answer these questions, It is necessary to have precise data on the physical and chemical characteristics of these sediments.

Figure 1: Sampling procedure using the quartering method.



(1) Mixing zone

(2) Dividing the heap into 4



(3) Mixing of the 2 opposite quarters

How to sample the sediments?

The constitution of a homogeneous sample

The method used to sample the sediments is quartering. This method reduces the sample size and homogenises the collected sediments for different analyses. The sediments are homogeneously distributed over an area of 50 cm x 50 cm. This square is then divided into 4 quarters and the two opposite quarters are spread out. The other two quarters are mixed on the surface of the square. The same process is carried out 4 times (figure 1). Finally, the collected sediments are sieved to 2 mm, to eliminate coarse elements (stones, leaves) and to obtain homogeneous samples.

The importance of sample packaging and storage conditions

The samples are then packed in a plastic bag for the analysis of particle size, water content, density and metallic trace elements and in amber glass containers for the analysis of organic micropollutants. Indeed, the sample packaging material as well as the storage conditions are of great importance and depend on the analyses planned later (Schiavone *et al.*, 2011). For example, polymeric materials (crystal polystyrene, polyethylene or Teflon) are required for the analysis of metals, whereas the analysis of organic contaminants, especially the more apolar ones, requires the use of glass containers. In addition, samples should be refrigerated during transport, protected from light, and delivered to the analytical laboratory within 24 hours of sampling. A temperature between 2 and 8°C is recommended.

Which parameters should be measured and for what purpose?

Physico-chemical parameters to characterise the sediments

Understanding the hydrology of the basin requires a particle size analysis, which allows the distribution of particles by diameter classes to be determined quantitatively. Indeed, several studies have shown that particles become finer the further away they are from the water inlet to the basin. There are many methods for determining particle size, but one of the most reliable is laser particle sizing for the finest particles (Delanghe-Sabatier D., 2011).

An analysis of volatile organic matter is also necessary. This is classically determined by loss on ignition [calcination at 550°C (EN 12897)] and more rarely by determination of total organic carbon, the latter being more accurate and reliable than the former.

Detention basin sediments have very high organic matter levels compared to river sediments. These levels are close to those of suspended solids found in stormwater runoff.

This parameter gives an indication of the contamination of the sediment. Indeed, the sorption of pollutants on the sediment matrix is essentially correlated to the organic matter of the sediment.

Pollutant analyses to assess the danger and identify the sources of pollution

Heavy metals, or trace metals, occur naturally but in very small quantities in soils (in the order of mg/kg), water and air. However, human activities are the source of higher concentrations. Due to their toxicity, several of them need to be monitored, in particular cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), mercury (Hg) and arsenic (As).

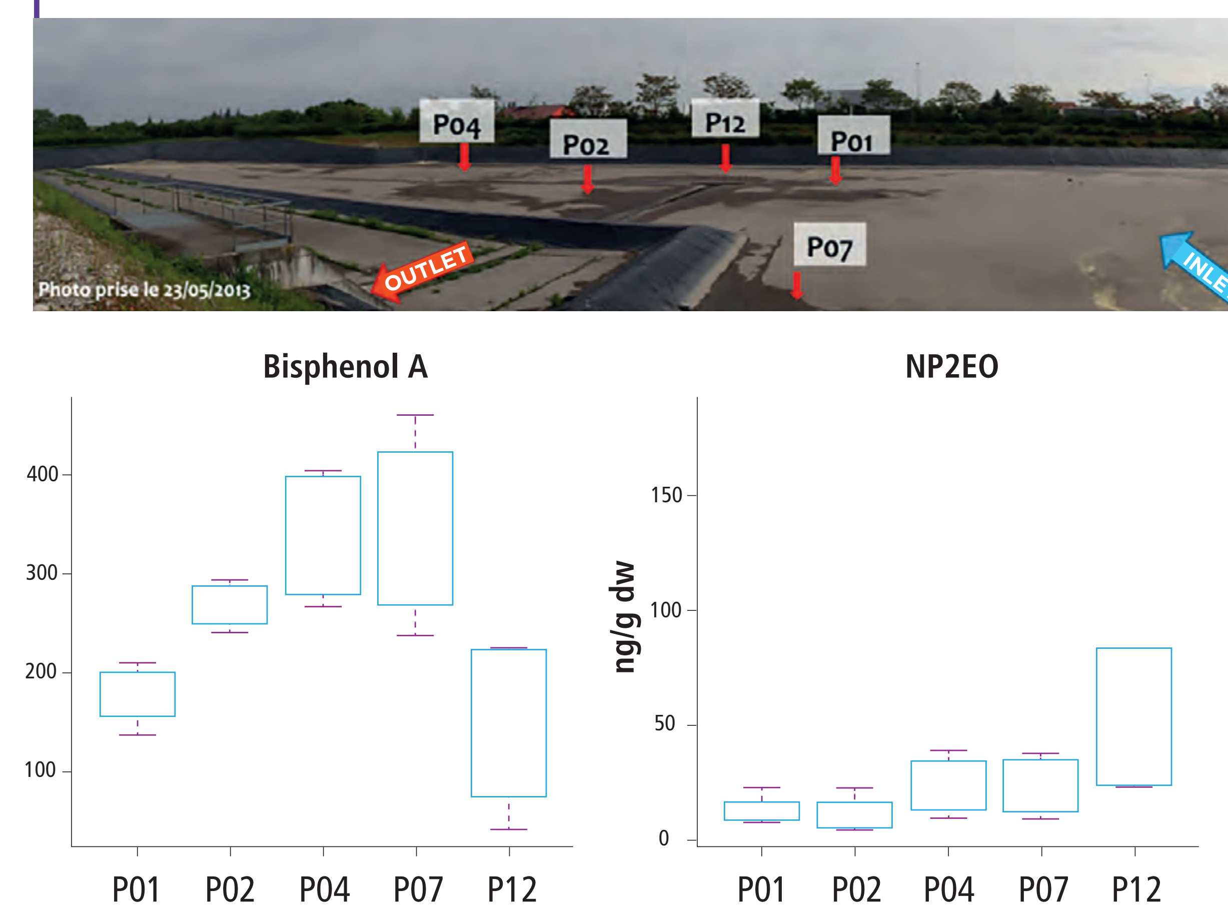
In addition, the analysis of these metals helps to identify sources of pollution. For example, zinc is a trace element characteristic of pollution linked to run-off from roads and motorways. Roadside verges are also loaded with cadmium and zinc, linked to tyre wear.

It is also relevant to measure organic pollutants. Unlike heavy metals, these are not naturally present in the environment, apart from a few hydrocarbons. As the concentrations sought are extremely low (in the order of µg/kg - or ng/g -, i.e. 1,000 times lower than for metals), their analysis requires sensitive and specific methods, the technique of choice being mass spectrometry.

The analysis of organic pollutants provides information on potential pollution sources: industrial activities, agriculture, road traffic, but also domestic activities.

Persistent Organic Pollutants (POPs), such as polycyclic aromatic hydrocarbons (PAHs), have been studied since the

Figure 2: Spatial heterogeneity of organic pollutant concentrations: photo of the Django-Reinhard detention basin and concentrations of Bisphenol A and Diethoxylated Nonylphenol (NP2EO) (P01: inlet, P02: centre, P04: gutter/outlet, P07: outlet, P12: hydrocarbon pit).



1990s and are covered by two international texts, the Aarhus Protocol, signed in June 1998 and amended in 2009, and the Stockholm Convention, signed in May 2001. Conversely, so-called emerging contaminants, which are not subject to regulation, have only recently been studied and are a cause for concern due to their toxicity, persistence and diversity. This group of contaminants includes substances used in large quantities in everyday life, such as medicines, cosmetics, detergents and plastic additives.

The main results of OTHU

In-depth monitoring of the sediments accumulated in the Django-Reinhard detention basin (Chassieu) has been carried out in the framework of various projects, in particular the ANR CABRRES project. In the latter, various classic parameters were studied [granulometry, organic matter, metallic trace elements, polycyclic aromatic hydrocarbons (PAHs), pesticides, brominated flame retardants (PBDEs) but also some emerging pollutants such as alkylphenols, ethoxylated alkylphenols and bisphenol A.

Levels of sediment contamination that justify precautions during disposal

All the metals analysed (Cd, Cr, Pb, Cu, Ni, Zn) were found in the sediments in relatively high concentrations. Depending on the metal in question, the orders of magnitude varied by more than a factor of 1000, from µg/kg for Cd to g/kg for Zn.

Furthermore, our results show that the sediments were poorly contaminated with pesticides and polybrominated diphenyl ethers (PBDEs).

Only three of the targeted pesticides were detected (chlorpyrifos, diuron and isoproturon) and in low concentrations. These low levels may indicate a decreasing use of these substances due to regulatory changes. But they may also be the result of the low efficiency of such a detention basin to trap these substances which are mainly in the dissolved phase.

In contrast to pesticides and PBDEs, the sediments were largely contaminated with alkylphenols and bisphenol A. This can be explained by the ubiquitous presence of these substances in construction and automotive materials. At some points in the basin, these levels of contamination were above the predicted no-effect concentration (PNEC), a threshold above which the risk to ecosystems is considered significant. Thus, precautions must be taken during the removal (wearing masks and gloves is strongly recommended) and disposal of these sediments.

Significant differences between the different areas of the basin

This study also showed a spatial heterogeneity in the physico-chemical characteristics and pollutant contamination of the sediments within the basin. The sediments at points P01 (inlet) and P12 (rough oil separator) had a higher particle size and a lower organic matter content than the points furthest from the inlet (P02, P04 and P07). These characteristics may explain the lower concentrations of bisphenol A at these points (Figure 2). This phenomenon was also observed for the three heavy metals, cadmium, lead and zinc.

But not all pollutants followed this trend: diethoxylated nonylphenol NP2EO was quantified at higher concentrations at point P12 (Figure 2), where a rough oil separator is located. The fact that this point probably includes anaerobic (oxygen-free) areas may be an explanation for this difference. Indeed, NP2EO only degrades to 4-nonylphenol in the presence of oxygen: its degradation is therefore probably less rapid at this point in the basin. This observation supports the idea that it is not advisable to install low-capacity or settling rough oil separators in detention/settling basins, since they create zones in which little or no degradation of pollutants takes place.

The contributions of ecotoxicology

Physico-chemical characterisation only gives a partial picture of the potential toxicity of a sample.

These analyses are far from exhaustive, and only biological tools such as bioassays can highlight the toxic effects of a group of pollutants (cocktail effect). The ostracode bioassay (microscopic crustaceans), used as part of the CABRRES project for example, proved to be suitable and showed that fresh sediments from a stormwater detention basin were more ecotoxic than mature sediments.

Work in microbial ecotoxicology based on the development of new DNA markers has also made it possible to refine these studies. New sentinels of ecotoxic effects have thus been identified (Aigle *et al.*, 2021).

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5.5

How can we study the processes of the use and contamination of stormwater management structures incorporated by urban developments?

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In addition to their hydraulic function, alternative stormwater management structures are infrastructures whose other functions will depend on the way in which the urban public uses the associated public spaces. The objective of this article is to propose a method to observe the urban uses and activities at the origin of microbiological and even chemical contamination of water. This is the case whether the runoff feeding these structures is at the source, such as bioswales, or centralised, such as detention or infiltration basins.

The urban environment is made up of technical structures and devices

There is no social activity that does not require structures (Toussaint, 2009). Public spaces are no exception to this rule. They are made up of structures and technical and spatial devices that make the city practicable. In concrete terms, the urban public needs to move around to go to work, to do their shopping, to have leisure activities, etc. To do this, they need roads, signage, cycle paths and vehicles for travel activities, pavements, benches, litter bins, green spaces for leisure activities, etc. All these structures and devices are available to urban people and at the same time contribute to urbanisation: in this sense, they can be called Technologies for Urban and Spatial Planning (TUSP).

Wastewater and stormwater management facilities also represent a set of structures and technical devices such as infiltration basins, detention basins, bioswales, underground networks (combined or separate network), specific facilities (CSOs, connections, reed filters, etc.). These structures are more or less closed or open to the public, integrated or not into public spaces and sometimes landscaped (parks, public gardens, squares etc.).

Our behaviours, aptitudes and abilities to use structures to solve a problem in action respond to common rules of use. When behaviours are regular, we can speak of practices (Toussaint, 2009), which establish the rules of use of the structure.
It is then a question of describing the ways in which the public use the objects in their environments, in the regularity (practice) or in the creation of actions, a new form of behaviour and aptitude with regard to the objects. At the same time, it is necessary to understand how these urban installations call for certain activities.

Describing the uses of these objects poses several methodological difficulties

To grasp the way in which objects call for action, practice and use requires a methodology of rigorous and systematic observation of the times of activity. Activity is in fact profoundly temporal; it is inscribed in various rhythms and durations. In their temporal characteristics, activities can thus be regular or temporary, seasonal, event-based, daytime or night-time, etc. These levels of temporality can become entangled and make it difficult to observe activities and to design them. Each of these temporalities provides information on the dynamics that take place in daily urban social activity. The observation of activities therefore poses methodological difficulties:

1 – **Activities are not visible or comprehensible in their entirety,** but in sequences. They are the result of the unfolding of a set of actions in space and time. When a person travels to work, he or she starts from a point A, both spatial (the home) and temporal (the time of departure). They leave their home, cross their street, take their bike, car or public transport, go through this or that street, listen to music, etc. Thus, the activity of 'moving to one's place of work' generates a certain number of courses of action that are sequences of this activity. In situ observations (Toussaint, Vareilles, 2011) make it possible to describe these sequences very precisely, courses of action in which the urban public mobilise the technical and spatial objects in their environment (car, bicycle, streets, headphones, etc.).

2 – Since the activity is always situated, **the observer is spatially and temporally arbitrary** in relation to the observed activity. To take the idea of travelling to work again, if the investigator has set his observation field on a street with separate facilities (lane, cycle track, pedestrian lane), he will only observe the sequences 'cycling', 'driving' or 'walking'. His observations will therefore constitute an arbitrary sequence and defined in time (time, day of the week of observation) and space (place of observation) of the activity.

This is the case for the "moving around" (Toussaint, Vareilles, 2013).

3 – The objects and the facilities they constitute support **multiple simultaneous and successive activities.** The street with separate facilities in our example is a good illustration of the idea that a facility simultaneously accommodates different travel activities (sometimes shopping, breaks, etc.) and that these follow one another over time.

The need to take into account the factors that uses into account

To overcome these methodological difficulties, many explanatory factors of activities can help to make them meaningful to the observer. First, activities are never random, they are fixed in social agendas: at certain times, days or seasons, one can expect to observe sequences of certain activities at the expense of others. In the morning 'rush hour', for example, we are likely to see mainly travel activities, whereas over the course of an afternoon we may observe strolling or shopping activities. Also, the social typologies articulated to the urban typologies are significant for the actor as well as for the observer from the social belonging of the people and the neighbourhoods but also from the urban morphology of the terrain. For example, all squares have in common that they are undeveloped public spaces, limited by buildings, served by communication routes and equipped with street furniture or kiosks (status, kiosk, toilets etc.). However, depending on the type of ground surface (tarmac, grass, paving stones, etc.), the type of street furniture (benches, litter bins, children's playground equipment) and their configuration, the squares will not call for the same activities. Thus, the square, whether it is in a dense urban centre, on the outskirts of the city, in a working-class or gentrified neighbourhood, will not host the same types of social activities, their same variety or their same intensity.
The social and urban morphology of the site allows for certain behaviours to be expected.

Applications and methods: towards a model of urban uses

A survey methodology applicable to different study areas

We have constructed a survey methodology capable of being applied to heterogeneous study areas while accounting for precise characteristics relating to the different temporal aspects of the observation, the objects and devices to be observed and the criteria for describing the study areas (including the social and urban morphology). It is then a matter of squaring them by establishing precise observation points with a defined survey perimeter for each. Table 1 summarises our methodology, applied and adapted to three study areas, the Chassieu Mi-Plaine industrial zone (catchment area associated with a detention/infiltration basin), the Part-Dieu district (separative developments, sustainable drainage systems (SuDS)) and Grézieu-La-Varenne (storm water overflow).

Let us take the case of the study carried out within the framework of the ANR CABRRES project. Our research problem concerned the impact of social activities in an industrial zone on the microbiological and chemical quality of runoff water collected in a detention and infiltration basin. We used this method by considering the observation perimeter, the areas of runoff of rainwater rushing into the grates present at each observation point.

These gullies correspond to the points where run-off water samples were taken by the microbiology team. In addition, we added as variables the activities of the businesses adjacent to

Table 1: Summary of the survey methodology (Claire Mandon, 2019).

For each observation point (= sampling point)	Types of observations	Timing and observation sessions for each point		Objectives
Observation of the objects and technical devices forming the facilities	Identification of TUSPs and descriptions of planning configurations	1 session per field		Identify TUSPs and design configurations + determine thresholds (sealing/ demarcation between private and public space)
Observation of stormwater runoff perimeters	Identification of runoff directions through observation points (gullies)	1 session per field		Understand (1) how rainwater drains to (2) identify areas where traces and waste left by objects in activities are washed away
Sequential observations of social activities in public space **30 min / point / session**	Description of social activities in the public space and: • TUSP mobilized • Waste/traces left behind • Activity flows • (counting vehicles - soft modes - pedestrians)	ZI Chassieu (20 points) • 6am-10am: 2 sessions • 12:00-14:30: 1session • 16h30-19h30: 1session • 7pm-11pm: 2 sessions	Part-Dieu (12 points) and Grézieu- La-Varenne (4 points) • 7.30-9.30am: 3 sessions • 10am-12pm: 3 sessions • 12:00-14:00: 3 sessions • 14:30-16:30: 3 sessions • 17:00-19:30: 3 sessions • 8pm-00am: 3 sessions	Identify the (1) **different temporalities of the activities** (morning, noon, leaving work, evening) – (2) their **regularities or frequencies** – (3) whether or not there are **any inferences** between the observed activities and the waste/traces found
Monitoring of economic activities	Census of businesses and shops included in the observation perimeter	Zi Chassieu 1 business census session	Part-Dieu and Grézieu-La-Varenne 1 business census session	Identify the companies or businesses present around the observation points - their size - their activity times - their types of activities

the perimeter and their permeability in terms of the threshold between private (business) and public spaces. The objective was to understand whether the activities of the companies had an impact on the microbiological contamination of the public space.

The same applies to the other two study areas (ANSES IOUQMER Programme, 2016-2020) where the method was adapted mainly to the temporalities of the social activities to be observed. Indeed, the exploratory surveys carried out in the Part-Dieu district and the commune of Grézieu-La-Varenne revealed that the times of urban activity differ from those in the Z. I. de Chassieu. For example, work-related activities and rush hours start earlier in the day in Chassieu than in the other two areas.

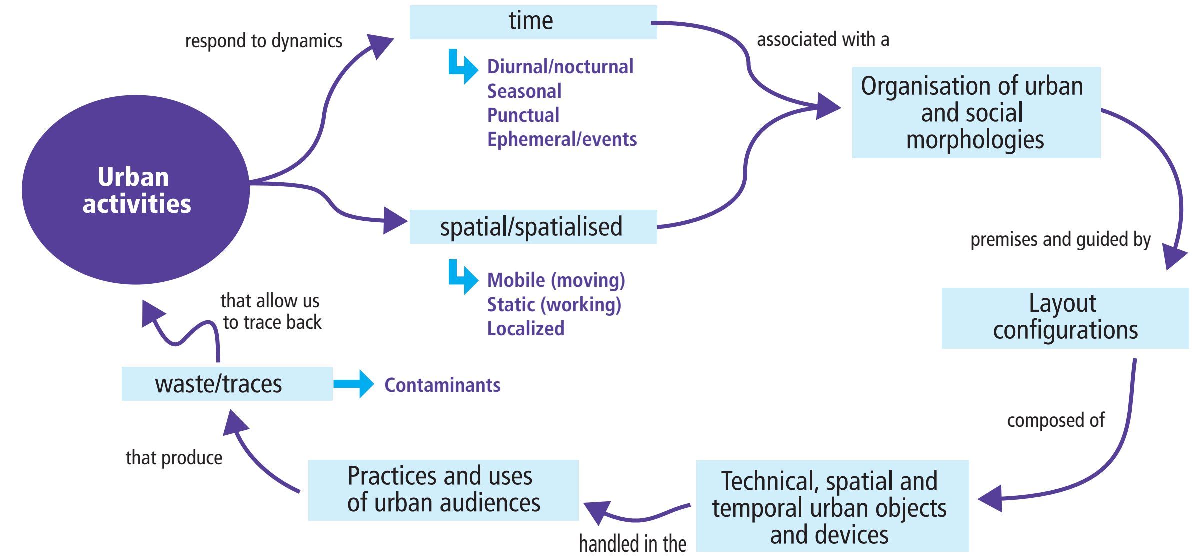
This methodology required a minimum of two field investigators in view of the density of simultaneous and systematic observations to be carried out on the selected observation points. To visualise the types of data that were produced as a result of these surveys, Figure 1 shows a summary of the data collected at two observation and sampling points in the Chassieu industrial zone. The activities and waste have been grouped by type to allow the identification of categories of relationships between activities, mobilised objects, waste, and traces produced. Also indicated are the directions of the runoff (i.e. the observation perimeter), private spaces and the types of thresholds (design devices for separating private and public spaces).des activités sociales à observer.

Activities and objects can of course cause contamination of run-off water, but how can they be used?
The results obtained in the CABRRES project showed that the objects mobilised, and the traces left during these social activities were one of the sources of microbiological contamination of rainwater. A porosity was also observed between private and public spaces (runoff from private areas to public spaces). The design of public spaces with stormwater management facilities should be considered in relation to the surrounding social activities that may be a source of contamination of the stormwater runoff feeding them.

The work carried out on the three sites of the Lyon Metropolis has enabled the construction of a database bringing together all the observation data. This database lists nearly 115,000 people using public spaces and the objects and devices that make them up, everyday objects (cars, telephones, cigarettes, etc.), and the waste and traces produced when handling them. This database is currently being processed and analysed using the analysis model shown in Figure 2. The results will be available in 2021 (INSA Lyon thesis, Claire Mandon).

Figure 1: Summary of observation data from points 17 and 18 in the Chassieu industrial zone (source: Google Earth, 2016).

Figure 2: Analysis model for human activity observation data (Claire Mandon thesis).



In Brief...

Alternative stormwater management facilities and associated urban development are very much in demand.
They require consideration of the possible impacts of social activities on the chemical and microbiological quality of the runoff feeding these facilities. They require reflection on the possible impacts of social activities on the chemical and microbiological quality of the runoff water that feeds these structures.
Urban developments, both supports and vectors of social activities, must be designed to limit the impact of human activities.
This article proposes a reflection and a methodology to identify the sources of contamination of public spaces and run-off water.

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Impact 6

Urbanisation, and in particular the increase in impermeable surfaces, leads to functional (usage) and structural (catchment morphology) transformations which, in turn, have numerous effects on the aquatic environments (watercourses, water table, etc.).
These effects can be observed both on the natural ability of these environments to manage floods and on the morphological dynamics and chemical and biological quality of the receiving environments.
The chapter shows that, depending on the methods of water management in an anthropised environment and the nature of the receiving environments, the effects and therefore the impacts can be very different and require adapted monitoring.

6.1

What is the impact of stormwater infiltration basins on groundwater?

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Arnaud Foulquier, Grenoble Alpes University

Infiltration Drainage Systems for stormwater management reduce flooding and contribute to the recharge of groundwater by infiltrating runoff. But to ensure that, these practices can be maintained over time, it is necessary to assess their impacts on groundwater quality. This is particularly true in the case of infiltration basins of moderate surface areas (less than 1 hectare/ 2.47 acres) but collecting water from catchment areas of several hundred hectares

The need to evaluate the hydraulic and ecological performance of infiltration structure

Artificial infiltration of rainwater runoff, implemented in many cities around the world, is an effective way to limit the volume of runoff during wet weather events. The main goal of these practices is to minimise the risk of flooding while contributing of the recharge of urban aquifers that are used heavily for drinking water, irrigation, or industry. Sustainable management of these practices relies on our ability to evaluate the performance of infiltration structures, both from a hydraulic point of view (capacity to infiltrate surface water flows) and from an ecological point of view (capacity not to degrade the chemical and biological quality of groundwater). While hydraulic performance is relatively easy to evaluate, characterising the impact of infiltration structures on groundwater quality requires the implementation of an appropriate sampling device and monitoring method.

What experimental set-up is needed?

OTHU's work has led to the development of a monitoring system that can isolate the impact of a centralized infiltration structure on groundwater quality. This requires the installation of two piezometers positioned respectively upstream and downstream of the infiltration structure (figure 1). To carry out water sampling even during major fluctuations in the height of the water table, these piezometers must be cored over several metres in the saturated zone. The piezometer located upstream (upstream piezometer on figure 1) corresponds to the «reference» piezometer. It allows the local characteristics of the groundwater not subject to rainwater infiltration to be determined. As the plume of rainwater generated by the infiltration basin can partly extend into the water table upstream of the structure, the piezometer should not be positioned upstream of the structure in order to ensure that it is outside the plume's zone of influence.
To limit the likelihood of a pollution source being present between the structure and the infiltration structure the upstream piezometer should not be located too far from the structure. A compromise must therefore be found depending on the land use upstream of the structure. The second piezometer is located immediately downstream of the infiltration basin (downstream piezometer in Figure 1) to intersect the plume of rainwater generated by the structure. This positioning allows monitoring (e.g. temperature) and sampling of the rainwater as it arrives at the surface of the water table, after it has passed through the infiltration bed and the unsaturated zone. The permeabilities of the fluvio-glacial sediments of the Lyon area (between 7.10-3 and 2.10-2 metres per second) are very variable, so the downstream piezometer must be placed as close as possible to the infiltration point, for example on the banks of the basin, in order to maximise the chance that the piezometer will intersect the plume. To compensate for any positioning errors, tripling the number of piezometers downstream of the facility can compensate for positioning errors and therefore ensure a more reliable assessment of the impact of the facility.

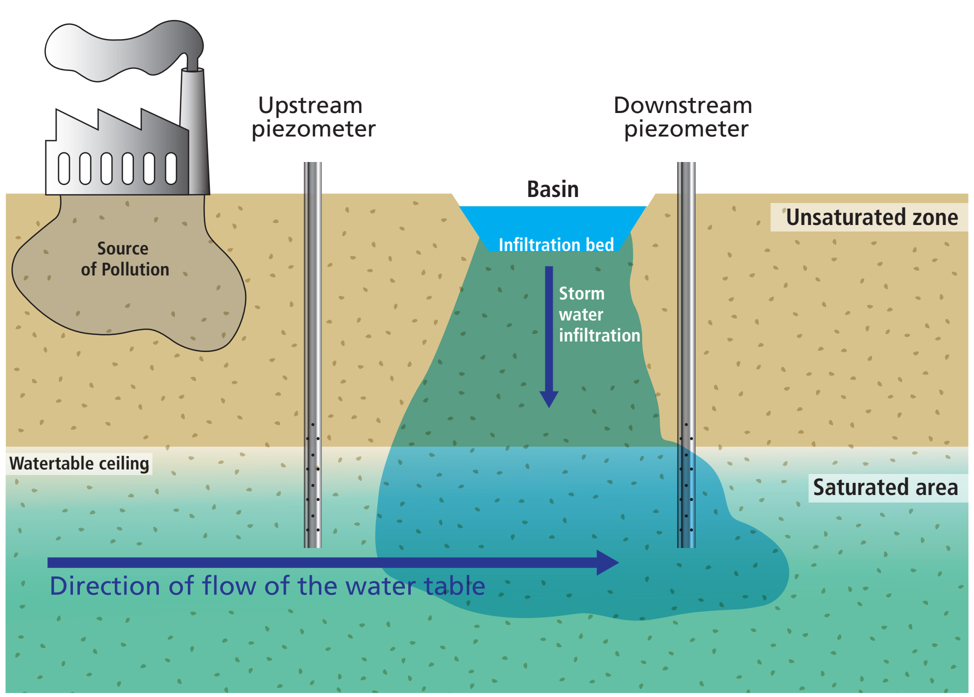


Figure 1: Positioning of the monitoring piezometers in relation to the infiltration structure.

What parameters should be measured and for what purpose?

Detecting the influence of rainwater

Measurements of parameters such as chloride (a conservative tracer) and electrical conductivity can detect the presence of stormwater runoff in the groundwater. These two parameters are generally accepted to be good tracers of stormwater since the chloride concentration and electrical conductivity of stormwater (~ 5 mg Cl-/L; ~ 100 µS/cm) are much lower than those of groundwater (~ 25 mg Cl-/L; > 600 µS/cm for the East Lyon groundwater).

Assessing the biogeochemical functioning of the facility

The measurement of these parameters must allow the structure-function to be characterised with respect to the processes of detention and degradation of the organic matter in the stormwater runoff, the infiltration bed and the unsaturated zone. These parameters correspond to dissolved organic carbon (DOC), the different forms of nitrogen (nitrates, nitrites, ammonium), phosphates and dissolved oxygen

Detecting pollutants specifically associated with stormwater runoff

Analyses of compounds such as hydrocarbons and heavy metals contained in rainwater runoff and resulting from the leaching of urban surfaces should make it possible to assess whether the infiltration bed and the unsaturated zone constitute an effective filter for these pollutants. In the case of the East Lyon water table, it is essential to also measure volatile organic compounds (e.g. solvents) as these are regularly detected at concentrations above the quantification thresholds for analysis. Depending on the type of land-use, it could also be necessary to test for pesticides.

It should be noted that, within the framework of OTHU, other contaminants are looked at using the same experimental devices. Therefore, new methodologies are being implemented to assess the impacts of the work on the microbiology of the water tables (by incubation of artificial supports - see Question 2.7: *Which bioindicators to measure the impacts of urban wet weather discharges on the receiving environments?*), and on easily water-soluble chemical contaminants such as pesticides or drugs (by incubation of specific adsorption membranes). For example, the use of adsorption membranes makes it possible to concentrate certain chemical pollutants that cannot be measured in the dissolved phase due to their low concentrations.

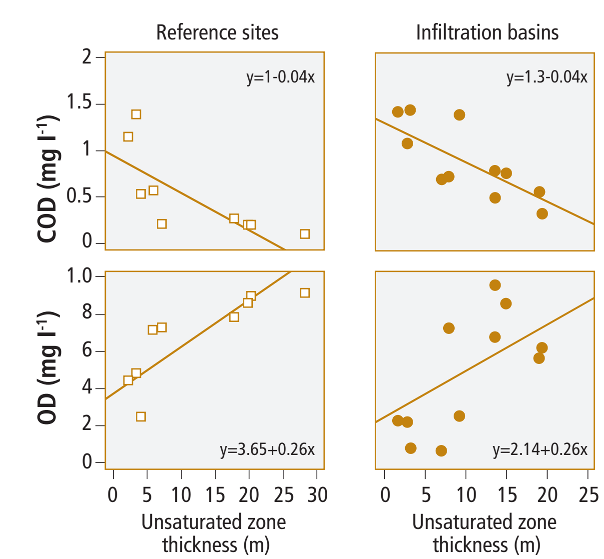
The main OTHU results

The importance of the thickness of the unsaturated zone to filter and degrade pollutants

On the sites of the East Lyon area, the infiltration bed of the basins and the unsaturated zone constitute an efficient filter for the detention of compounds such as hydrocarbons and heavy metals brought by stormwater runoff. However, the artificial infiltration of stormwater runoff leads to a considerable increase in DOC being transferred to aquifers. The organic compounds associated with this DOC can be problematic in water used for human consumption, as chlorination of water loaded with dissolved organic matter produces organochlorine compounds that are often carcinogenic. Under the ponds, DOC values are higher than for reference areas not subject to artificial infiltration. Thus, in eleven infiltration structures in the Lyon urban area, it was shown that the increase in DOC concentrations measured in the water table under the structures was on average 0.3 mg/L (+30%) compared to reference areas (Figure 2).

A stormwater/groundwater mixing model showed that during infiltration events most of the biodegradable DOC is efficiently degraded in the unsaturated zone. This degradation of DOC by aerobic micro-organisms is accompanied by a decrease in dissolved oxygen, which explains the lower dissolved oxygen

Figure 2: Evolution of Dissolved Organic Carbon (DOC) and Dissolved Oxygen (DO) concentrations in groundwater as a function of unsaturated zone thickness for reference (left column) and artificial rainwater recharge (right column) sites.



6.1

levels under the structures compared to the reference sites (Figure 2).

The results obtained indicate that beyond a thickness of 3 metres, the unsaturated zone is an effective filter for degrading the majority of readily biodegradable DOC before it reaches the groundwater table. Furthermore, a sufficiently thick unsaturated zone allows proper oxygenation of the groundwater, which is important in several respects. Deoxygenation of the water can lead to increased mobility and transfer of chemical compounds (phosphate ions, ammonia ions, heavy metals) from the surface of the ponds to the groundwater, changes in the microbial communities in the groundwater, as well as the production of reduced compounds that can damage metallic pumping equipment.

The thermal disturbance of the groundwater increases with the surface area of the catchment area of the structure

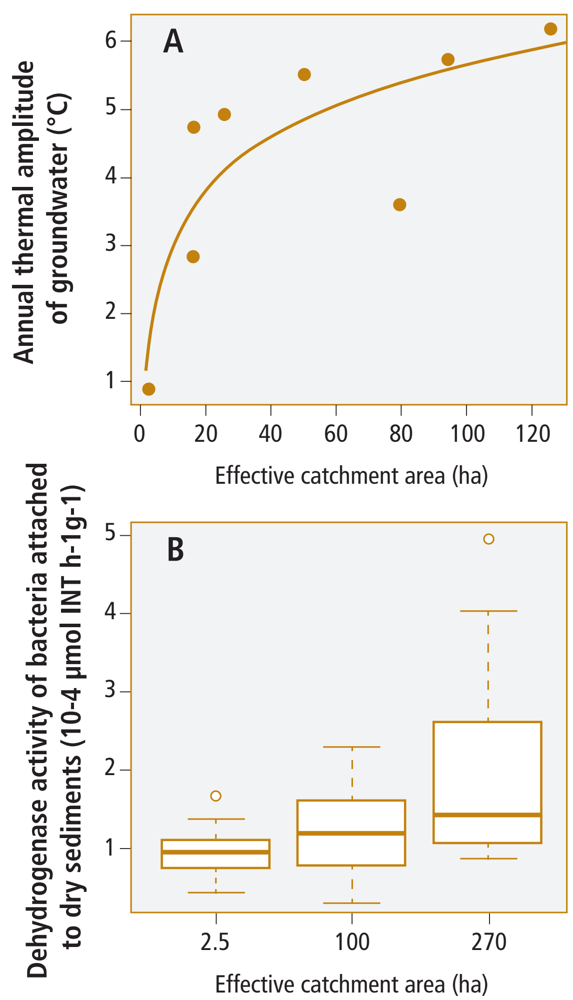
Until now, there was little data to assess the influence of the surface area of the catchment area connected to the structure on the intensity of the disturbance caused by the artificial infiltration practices of stormwater runoff. In the absence of artificial infiltration, groundwater is very stable in terms of temperature, with an average value of around 13°C and an annual thermal amplitude generally lower than 1.5°C in the Lyon area. On the other hand, the considerable increase in the flow of infiltrated water results in heat transfers and leads to a strong disturbance of the thermal regime of the water tables. This disturbance from artificial infiltration increases with the size of the catchment area connected to the structure and therefore with the volumes of water infiltrated (Figure 3A). Although during recharge episodes, temperature variations at the water table rarely exceed 3°C, the annual thermal amplitude is on average 9 times greater than that observed at the reference sites. For some sites, this increase in amplitude leads to the groundwater temperature being maintained at values above 20°C for periods of up to 3 consecutive months. Such high groundwater temperatures can be problematic for groundwater quality, for example by encouraging the development of opportunistic pathogenic bacteria.

The relationship between the size of the catchment and the annual temperature range shows that a change from an effective catchment area of 5 to 20 ha leads to a change in annual temperature range from 2.2 to 3.8°C (Figure 3A).

In addition to this, despite the low proportion of biodegradable DOC being added to the water table during rainfall events, the multiplication of these small quantities by the infiltrated water flows allows a stimulation of the microbial compartment (in the first metre under the water table) which increases with the size of the catchment for basins with unsaturated zones of less than 3 metres (figure 3B).

However, as long as the minimum thickness of unsaturated zone (i.e. greater than 3 m) is respected in the case of the East Lyon water table, which ensures effective detention of most the easily biodegradable DOC, then it does not seem relevant to recommend a particular size of catchment area, particularly from the point of view of thermal disturbance. However, for basins with a thin unsaturated zone, a thermal disturbance is being generated even for small catchment sizes (20 ha), a real attenuation of thermal amplitudes would require the installation of source control infiltration systems. However, our results need to be moderated according to the permeability of the land. If our conclusions are valid for the basins studied on the East Lyon water table, it would probably be necessary to reconsider the effectiveness of an unsaturated zone greater than 3 metres for subsoils with higher permeabilities or presenting a structuring (presence of preferential paths) favouring the speed of water and solute transfers from the surface of the basins towards the water table.

Fig. 3: Evolution of the annual thermal amplitude of groundwater (A) and of the dehydrogenase activity of bacteria attached to sediments in basins with an unsaturated zone of less than 3 metres (B) as a function of the surface area of the catchment connected to the structure.

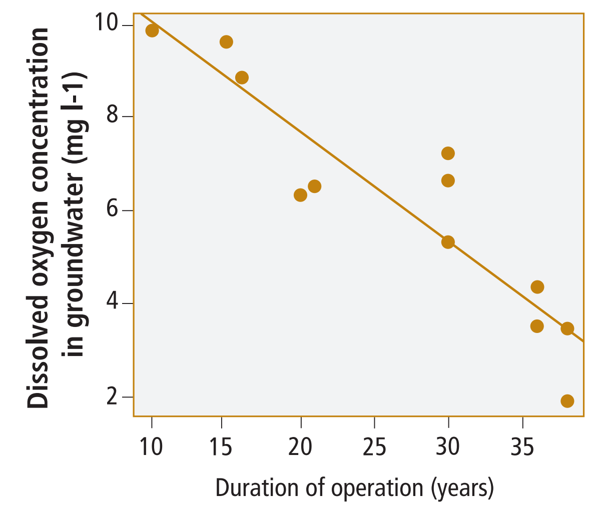


Infiltration basins have an "ecological lifespan"

Analysis of dissolved oxygen logs for 12 sites has established a relationship between the duration of infiltration works operation and the average oxygen content of the water table (Figure 4).

This relationship suggests that the organic matter accumulated in the infiltration bed and the unsaturated zone leads to deoxygenation of the infiltration water, which becomes increasingly important the longer the structure is in operation. Given the negative impact of deoxygenation on the chemical and biological quality of the water table, it is necessary to limit this situation as much as possible.

Fig. 4: Evolution of average dissolved oxygen concentrations in groundwater as a function of the duration of operation of the structure.



Towards a better understanding of impacts at the scale of the structures and the water table

The work and results presented here mainly concern the local impact of artificial infiltration on the functioning of the water table. There is not a lot of data currently available to assess the geographic coverage of disturbances generated long distances downstream of the structure. Future research should enable the extent of the pollution plume to be characterised more precisely, while at the same time enabling the influence of the characteristics of the structures on the extent of this plume to be defined. The use of hydrogeological modelling tools is a promising avenue for quantifying the impact of infiltration of rainwater runoff on the quality of the water table at the scale of the structures and the water table of the East Lyon area. This assessment work could also be facilitated and completed by the development of new approaches to quantify chemical and microbiological contaminants in the water table.

Monitoring of water tables to improve structure management

The groundwater monitoring method developed within OTHU framework can be used to provide answers to a number of questions associated with the management and design of structures. For example, it is possible to determine whether the organic matter accumulating in the bed of the infiltration basin has an impact on the ecological quality of the water table, based on measurements of dissolved oxygen concentrations in the water table. This development can be used to create a cleaning schedule for the infiltration basins.

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6.2

What are the impacts of urban wet weather discharges on small rivers?

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Since the beginning of the 2000s, OTHU has been carrying out work on the peri-urban Yzeron catchment area to the west of the Lyon conurbation, in order to provide solutions against the impacts of urban wet weather discharges (UWWDs) on small headwater streams basin.

Impacts of various kind

The impact of an UWWD results from a combination of geomorphological, hydrological, biogeochemical and biological processes in the watercourse, in response to the suspended solute and solute fluxes of the discharge.

Disruption of the hydrological functioning of small rivers

UWWDs change the flooding regime. The frequency of small floods, periods of high water, and the return periods. The flood at the origin of a notable geomorphological evolution known as a 'morphogenic flood' (capable of modifying the shape of a river section) can become annual whereas it was biennial (Wagner and Breil, 2013). Compared to runoff on rural or natural surfaces, rainwater runs off more rapidly on urban surfaces, mobilising volumes that can be significant (low infiltration, rapid transfer into the drainage network and then into the environment). The effect of UWWDs is therefore dependent on the impermeability of the catchment area (Schmitt *et al.*, 2016) and on the greater or lesser proportion of urban surfaces connected to the main drainage network. During the dry season, the dilution capa

An increase in the frequency of erosion

The most marked geomorphological dysfunction is the phenomenon of bank and riverbed erosion, which poses management problems such as destabilisation of structures (e.g. culverts, bridges), land losses, lowering of the piezometric level, biological impoverishment through erosion of the hyporheic zone (permeable river bottom) and bank erosion. It should be noted that the latter only poses problems in the presence of human activity. In other cases, this process must be allowed to take place without hindrance because it is fundamental to the functioning of a river, which naturally exhibits erosion and deposition.

Photo 1: UWWDs pipe - see the large size of the pipe compared to the width of the river from combined sewer overflows (CSOs) in the Yzeron basin with discharges into watercourses in urban areas - Ruette Mulet (Source: P. Breil, INRAE, 2002).

OTHU has shown that in the Yzeron basin, UWWDs increase the frequency of erosion in small rivers by a factor of 2.5 and the volumes of sediment removed by 77% (Wagner and Breil, 2013; OTHU Fact Sheet 13). These massive removals, containing a large proportion of sand, significantly increase downstream sediment deposition (silting) in the main branches of the river system where the energy is lower. This greatly alters fish habitats: disappearance of spawning grounds, filling in of pools, etc. Aquatic invertebrates and plants are also impacted by a very mobile sandy substrate representing a constraint for fauna and flora. The erosion in a peri-urban context generally develop to a depth of 1 to 2 m, but can reach 4 m. The hydro-morphological typology of the watercourses is a necessary step to establish a reference to measure these impacts and characterise the adjustment dynamics. The different types of watercourses do not, in fact, have the same sensitivity to erosion (Grosprêtre, 2011; Schmitt *et al.*, 2016). This requires the implementation of methodologies that allow the definition of full-bore flows assessing the flow capacity of the minor bed just before overflow, which evolve under the effect of agricultural and urban activities. Regional hydrological modelling is one of the solutions tested in OTHU to establish references.

Organic and toxic pollutants

The impact of UWWDs is partly linked to the input of organic matter. This induces self-purification processes that consume dissolved oxygen, which is vital for aquatic fauna (invertebrates and fish). UWWDs also bring nutrients in the form of ammonium ions or phosphates (e.g. fertilisers) as well as toxic substances such as heavy metals and synthetic organic compounds such as drug residues, detergents, or pesticides.

OTHU has shown that pollutants accumulate in specific areas of the porous stream sediments: the hyporheic zone of riffles[1] (Namour *et al.*, 2015). This contributes to the creation of anaerobic (oxygen-free) zones that produce greenhouse gases, such as methane and nitrous oxide or hydrogen sulphide, which results in putrid odours for local residents. The measurement of gas flows produced by microbial biodegradation activity has been the subject of a field prototype (Breil *et al.*, 2018).

Excessive nutrient inputs encourage the proliferation of algae that produce DO during the daytime phase through photosynthesis but consume oxygen during the nighttime phase and during respiration. Understanding the alternation of these cycles is therefore crucial to avoid a drift towards eutrophication. Finally, the input of toxic pollutants by UWWDs can lead to the disappearance of pollution-sensitive species in these small rivers (reduction in biodiversity).

Release of pathogenic bacteria

UWWDs release bacteria that are pathogenic to humans and can cause severe illness if ingested or in contact with the skin. DNA analysis showed that the lineages of the species present in the surface layer of the stream sediments were close to those present in the combined sewer system, signifying survival of these organisms in the receiving environment, but at a low rate probably due to competition and highly diversified physico-chemical conditions (Marti *et al.*, 2017). Indeed, these bacteria can persist for a long time in the porous matrix or on plant supports. In addition, the periodicity of UWWDs maintains a pathogenic population, which is resuspended during small floods. Less documented is the impact of these pathogenic bacteria on the biological community of the watercourse and in particular on the microbial populations involved in self-purification.

[1] Among the various types of flow features, which correspond to optimal hydro-morphological structures for dissipating flow energy with a length of between 1 and 10 times the full width, riffles are characterised in low water by a shallow depth and a relatively high slope, surface granulometry and turbulence compared to adjacent features.

The use of oligochaete worms to measure biological impacts

OTHU assesses the impact on living populations using standardised indicators recommended in the French Water Quality Assessment System (SEQ-EAU). These biologically based indicators (invertebrates, vertebrates, plants) such as the Standardised Global Biological Index (IBGN) provide information on the physico-chemical nature of the pollution by assessing the presence and absence of pollutant-sensitive and pollutant-resistant species.

However, the IBGN does not concern the hyporheic compartment, located a few decimetres into the porous sediment of the watercourse and which constitutes a storage zone for pollution and its possible self-purification (Namour *et al.*, 2015). Within the framework of OTHU, the quality of the hyporheic zone as well as the exchanges between surface water and groundwater were assessed through the study of oligochaete worms (oligochaetes) (Lafont *et al.*, 2010; Schmitt et al., 2011). The in-depth knowledge of the species allows them to be used as a biomarker of the direction of water exchange and pollution between surface and groundwater, and to define the way in which the organisms respond to environmental factors. This association between species, functions and specific habitats of oligochaetes is called a functional trait (FTr). Oligochaete assemblages can thus be used to characterise the hydrogeological functioning and the nature of the pollution of the hyporheic environment. Several studies show the effect of physical clogging of this hyporheic zone by UWWDs (reduction of exchanges between surface water and groundwater), by biological films, which reduces the capacity for self-purification, and reflects organic contamination.

Thus, from OTHU work, it was possible to produce ecological indicators based on interstitial oligochaete species in superficial and hyporheic coarse sediments to assess the ecological quality of a porous sediment and the origin of a physico-chemical impact.

Alteration of the self-purification capacity of small rivers

This work has also shown that the ecological impacts of UWWDs are partly linked to the exchange capacity between surface water and groundwater or hyporheic water, a capacity which is itself linked to the hydro-geomorphological types and features of the sector under consideration. The excess of organic matter brought by the UWWDs can lead to biological clogging which reduces exchanges between surface water and the hyporheic zone. In addition, the additional energy given by the UWWDs increases erosion of the banks and

Photo 2: Taking water and fauna samples from the deep sediment, measuring exchanges between the water table and the watercourse, monitoring the quality of the water in the sediment, experimental watercourse of the Chaudanne at Grézieu-la-Varenne (source: P. Breil, INRAE, 2006).

the bottom of the bed, which can cause physical clogging by fine sediments further downstream. These effects linked to UWWDs locally alter the self-purification capacity of small rivers and generate costs for the protection of banks, in the event of destabilisation of riparian structures.

Impact indicators associated with UWWDs

Based on OTHU's results, it is now possible to propose impact indicators that allow the analysis of changes in relation to the natural functioning of the watercourse (table 1).

Position CSO discharge points in areas suitable for self-purification

Stormwater disconnection, source control, sustainable urban drainage (SuDS) and water treatment before discharge are all strategies for reducing the impact of UWWDs on the environment. In addition, it is possible to work on the watercourse itself, by choosing the sectors where CSOs are placed on the watercourse according to their self-purification capacity.

Indeed, a watercourse has a natural capacity for self-purification (physical, chemical and biological) that varies and is not consistent from upstream to downstream, resulting in the river having resistance or resilience to UWWDs. OTHU has made it possible to develop the understanding for segmenting a watercourse into zones with homogeneous self-purification capacity. The hydro-morphological types are characterised by frequencies of hydro-morphological features and levels of sensitivity to erosion (OTHU Fact Sheet No. 14, Schmitt et al., 2004). In less sensitive, high-energy, coarse-sedimented areas, the hyporheic zone is the preferential location for microbial activity and biodegradation. The capacity for biodegradation is modulated by the intensity of the flows of water and substances through the hyporheic zone. The intensity of the exchanges are particularly linked to the interactions between the flow and the features (riffle, flat, wet).

Table 1: Impact indicators associated with Urban Wet Weather Discharge (UWWD).

Types of impacts	Impact indicators associated with UWWDs
Hydrological	Frequency of discharges increasing, particularly that of summer freshets due to centralised and punctual discharges. Duration of low water levels increasing.
Geomorphologica	Frequent erosion of headwater streams downstream of UWWD. Tendency for silting of the main branches of the downstream hydrographic network linked to an increase in sandy deposits from erosion (clogging of spawning grounds, pools, etc.).
Hydraulics	Decrease in hydraulic conductivity of porous sediments in clogged areas.
Physico-chemical	Installation of anoxic reducing media: absence of oxygen, presence of ammonium and nitrite, production of greenhouse gases (N_2O, CH_4 & CO_2) and toxic gases (H_2S, NH_3). Sedimentary concentrations of mineral compounds more than three times those of the bottom natural geochemical characteristics of the catchment. Presence of synthetic organic compounds.
Bacteriological	Infiltration of pathogens in fine sediments.
Hydrobiological	Presence of species associated with hypoxic or anoxic clogged environments, i.e. with little or no oxygen (polluted "sludge" type).

Photo 3: Barrier devices on the Yzeron basin: on the left old (2005) porous weir on the Chaudanne at Grézieux- la-Varenne; and on the right new (2020) porous weir (porous spur) on the le Ratier (source: P. Breil INRAE).

Operationally, there are three types of river sections:

- sections with low self-purification capacity, which have a low sediment content and sometimes outcropping bedrock. They transfer pollution downstream. Without specific arrangements before discharge, discharge into these sections should be avoided;
- regeneration sections that are in contact with a slope or valley bottom alluvial water table. These sections should be protected from future discharges as they also provide dilution;
- sections with an active hyporheic zone and an accompanying water table. They are suitable for developments in the bed to increase the capacity for self-purification. The latter is sometimes physically altered by concrete work on the watercourse in an urban environment. It must therefore be recreated or compensated for.

UWWDs should take place in those hydro-morphological areas that are best suited to biodegrade pollutant inputs and least susceptible to erosion, i.e. those types of river sections with high energy and coarse sediments. In medium-energy areas, it is possible to enhance the natural biodegradation process by working on appropriate developments that stimulate the self-purifying capacity of the watercourse.

An experimental approach: stimulating the self-purifying capacity of the watercourse

OTHU experimented with the possibility of restoring and even increasing the self-purification capacity of a small river by acting on the hydro-geomorphology of the bed. A first prototype composed of three porous sills made of wooden logs placed just downstream of a storm spillway and spread over 67m made it possible to naturally create sandbanks from the granitic arenas of the basin. The geometry and porosity of the sills favoured the infiltration and filtration of the polluted water, particularly during low flows. The trapped pollution (organic load, nitrogen salts and phosphates) can then be naturally self-purified by the microbial flora hosted in the sandy sediment.
During flooding, the sediment is reworked and the mixing allows a significant flow of dissolved oxygen into the deeper layers. Monitoring over a year has shown the almost total elimination of biodegradable pollution from the urban wet weather discharges (UWWDs) discharged and intercepted by this device (photo 3). More resistant pollution (e.g. metals and certain synthetic organic compounds, such as PCBs) persists and remains naturally trapped in the sediments.

TO GO FURTHER

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6.3

What are the hydrogeomorphological trajectories of peri-urban rivers?

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Urbanisation is generally associated with flooding and degradation of river water quality.
These phenomena take place over generally short periods of time, on the scale of a wet weather event. On longer time scales, from a few years to several decades, adjustments in river morphology are also taking place as flooding progresses, linked to soil artificialisation/ sealing and increased stormwater runoff.

Soil sealing leads to erosion of peri-urban watercourses

Numerous research studies have highlighted these phenomena of rapid morphological adjustment (change over a few years) in connection with urbanisation, soil sealing and therefore increased runoff (Table 1). Most of the time, these adjustments take place in the direction of incision, i.e. erosion of the minor bed leading to a significant increase in the depth and width of the watercourse. These stretches are generally characterised by a very deep, U-shaped channel (photo 1). Other indicator can also be a sign of this phenomenon in the field, such as a sudden increase in the size of the riverbed downstream of urban discharges (storm spillway, ditch or road culvert, etc.), or destabilisation of the banks by erosion, revealing the roots of the riverine vegetation.

Important economic and environmental consequences

An eroded river concentrates the flow in a single, rather straight channel, similar to a dammed river. These hydromorphological changes amplify the intensity of floods, and thus increase the risk of flooding downstream of these rivers. These areas are often densely populated and therefore associated with significant socio-economic issues. The risk of destruction of infrastructure (bridges) and networks (e.g. road, rail, electricity) by erosion of the banks and the bottom of the riverbed is also increased. This phenomenon of erosion of the minor bed is generally associated with the lowering of the water table which accompanies the river flows outside of wet weather events, thus reducing the quantity of water available and reducing its access for the populations of densely populated areas (figure 1).

From an environmental point of view, the erosion also leads to an ageing of the alluvial forests and a drying up of the wetlands which are no longer fed by the alluvial water table and/or by the frequent overflows of the river.

The self-purification capacity of urban watercourses The self-purification capacity of urban watercourses also tends to decrease, due to the reduced diversity of geomorphological features. These watercourses then become much more sensitive to urban discharges. Finally, downstream of the eroded sections, one can sometimes observe significant deposits of sand, which add to the pollution of urban discharges and lead to significant ecological impacts (e.g. clogging).

Table 1: Hydromorphological trajectories of peri-urban rivers studied in the scientific literature (after Chin, 2006 and Gregory, 1987).

	Hydromorphological adjustment variable	Geomorphological trajectory*	Number of studies considering this variable (in %, out of 58 studies)
Change of profile in across the river	Capacity at full tilt**	74 % + 86% + 60% + 100% +	66 50 34 14
Planimetric and altimetric changes	Minor bed width Minor bed height Ratio between width and height of the minor bed Sinuosity of the watercourse Slope of the minor bed	100% - *** + et -	10 5

* trend towards an increase (+), decrease (-);
** The capacity is expressed in square metres of water, which is the limit of the minor bed or main channel of the watercourse, beyond which the flood flow spreads into the floodplain. The capacity is expressed in m^2. It is associated with a wetted width (m) and a water height (m) at full flood;
*** trajectory towards river rectification.

Photo 1: Example of morphological adjustment of a river in the Yzeron basin (source: O. Navratil): the bed of the watercourse is strongly eroded, with a typical "U" shape, the banks are strongly eroded and steep, revealing the roots of the riverine vegetation.

The causes of erosion explained through the example of the Yzeron catchment area in western Lyon

A river that is very sensitive to erosion phenomen
The Yzeron catchment area currently has very dense urban areas in its downstream part near Lyon, less dense and more fragmented peri-urban areas in the middle part and the zones that remain rural are upstream.

A series of land use maps for the period 1904-2000 (Cottet, 2005) shows that the Yzeron basin was very rural at the beginning of the 20th century, and until the 1950s-1960s, with many meadows and ploughed areas (Figure 2). Sedimentological analyses and dating in the banks of eroded streams show that very large quantities of sediment were exported from these ploughed areas and slowly filled in the valley bottoms with very sandy and easily remobilised materials (Delile *et al.*, 2016). With the rural decline in the second half of the 20th century, the agricultural areas decreased significantly and the forests recolonised the slopes. The sedimentary input from ploughing then fell sharply, leading to numerous erosion points in the river, the most spectacular of which are at the head of the basin, in the old sandy deposits. Thus, almost one third of the erosion points (as a percentage of the total length of the sections eroded) are situated in the Monts du Lyonnais where urbanisation has developed very little (Groprêtre, 2011).
These historical elements explain the very high sensitivity of the Yzeron and its tributaries to erosion.

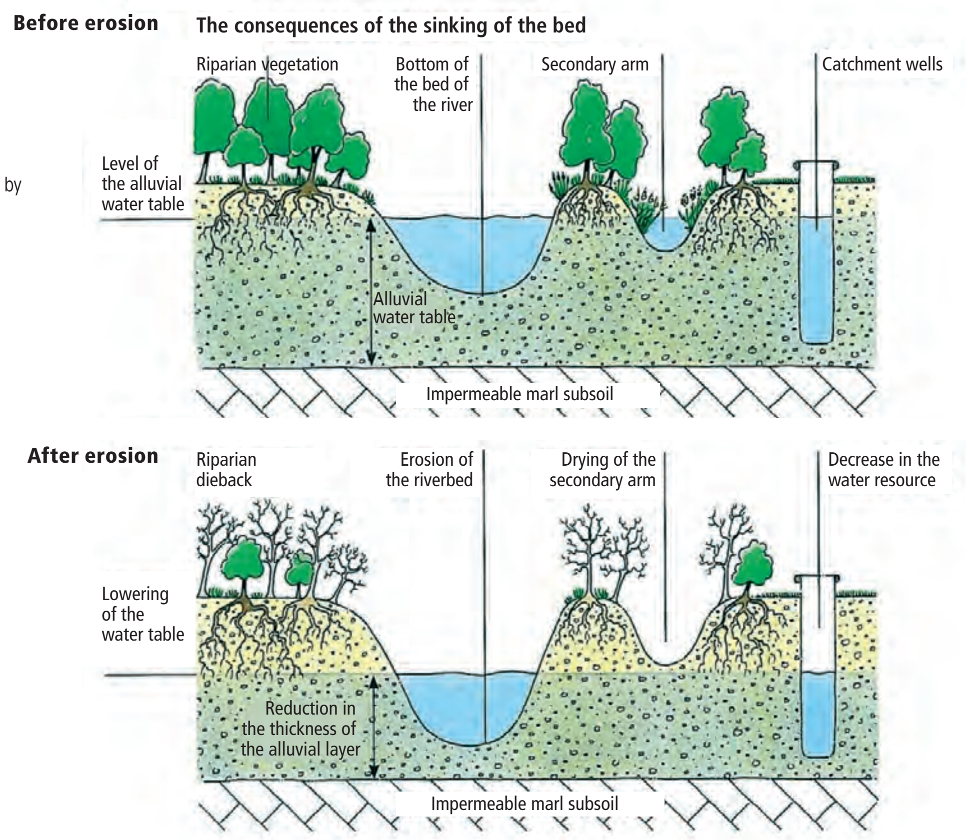
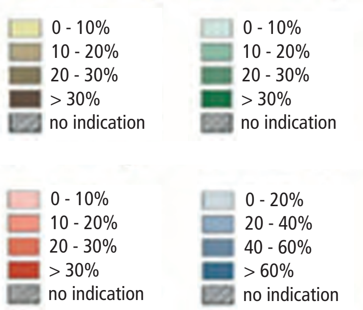
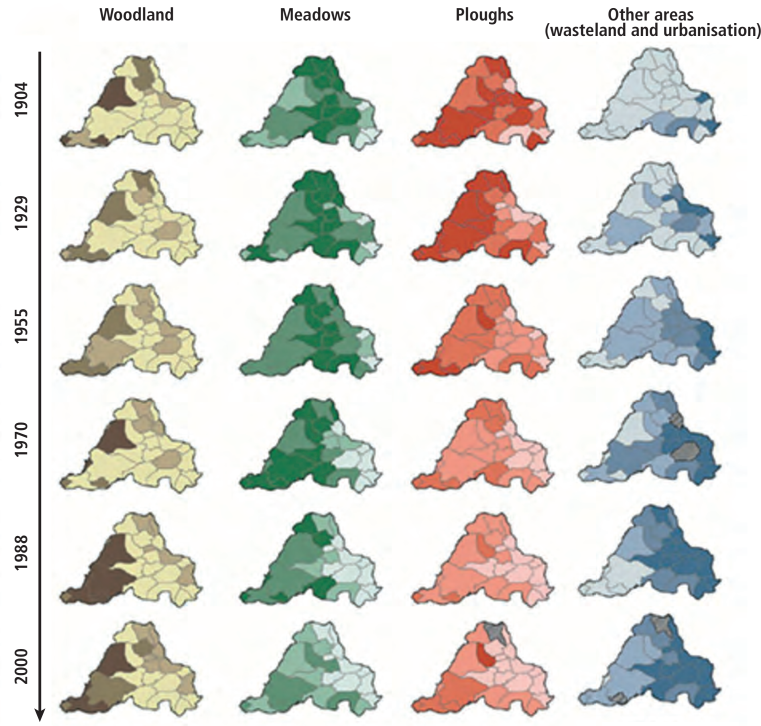


Figure 1: Impact of river erosion.(Source: drawings by Philippe Coque for Frane).

6.3

Figure 2 : Evolution of land use from 1904 to the present day in the Yzeron catchment area: woodland, grassland, ploughland, wasteland and urbanisation.
Source: Gropřêtre (2012) based on Cottet (2005).





Sealing and storm overflows as causes

Since the 1960s and 1970s, urban populations have been moving to rural areas and settling there permanently. The urbanised surface area of the Yzeron basin thus increased from 21% in 1970 to 36% in 2008. On these built-up areas, infiltration and evapotranspiration decrease, while the volumes of runoff increase significantly. This rainwater is then partly collected by a combined sewerage system equipped with storm overflows to relieve it. The Yzeron basin has a total of 70 storm overflows which are triggered several times a year. The impact of these discharges on the flood regime is very significant. Hydrometric measurements show that frequent flood flows can be multiplied by more than 3 or 4 downstream of storm overflows.

This increase in the intensity of frequent floods has important consequences for the sediment flows and morphology of urban rivers. Indeed, these floods are by definition very morphogenic, i.e. they are responsible for most of the multiannual sediment transport and thus shape the morphology of the watercourse over the long term (its gauge, the wavelength of its meanders and the alternation of riffles and pools). The increase in the intensity of these frequent floods is an element in the explanation of the significant erosion points observed downstream of urbanised areas (Grosprêtre, 2011).

A second significantly penalizing factor is the presence of storm overflows. The water discharged by these structures is very lightly loaded with coarse sediments (gravels, pebbles), generally carried by the river and which shape its morphology. The watercourses into which the storm water is discharged then find themselves in a situation where there is a sediment deficit, therefore acceleration of sediment erosion in the river itself, leading to erosion and widening of the river: this is known as "hungry water". A new hydromorphological equilibrium is rarely achieved in these rivers, even several years after the sealing of the catchment area.

The contributions of OTHU to diagnose and explain the erosion

First method: measuring sediment transport

To diagnose these morphological adjustments, a first approach consists in measuring and comparing the solid transport by scouring of rivers located in contrasting contexts in terms of urbanisation (e.g. a peri-urban site and a rural site), but nevertheless presenting similarities from a geological, climatological, slope, catchment size[1] point of view. However, these studies are rare because they are very difficult to carry out: they involve taking measurements for several years before the land use changes (or calibration period), and then several years after the developments, while the morphological adjustments take place. The only examples available in the literature point in the direction of higher sediment production in urban rivers. Gropřêtre's (2011) work, carried out in the Yzeron basin, also showed that erosion points were a major source of fine sediments and contributed to downstream river ecosystem degradation, via clogging and silting. Various operational recommendations were then formulated to limit these impacts.

Second method: study of the morphology of the watercourse

Another method is to compare the morphology of rivers in predominantly rural and urban land use contexts across a region with similar climatic and geological characteristics. For example, Figure 3 shows two sections with equivalent catchment areas but different levels of urbanisation. A clear difference in morphology is already visually apparent: the peri-urban river has a much greater width and height of the minor bed than the rural site, with a comparable catchment area. A regional approach was therefore developed and applied to the

[1] This so-called "matched catchment" method was introduced in hydrology to compare, over the long term, the effects of land use change *ceteris paribus*.

Figure 3 : Example of two sites, rural and peri-urban, with equivalent catchment areas. The peri-urban river has a greater width and height of the minor bed.

Rural site: Yzechau
BV surface: **22 km²** - Urbanisation: **1,1%**

Peri-urban site: Ratier
station BV surface: **17.4 km²** - Urbanisation: **7%**

Yzeron river basin (Navratil *et al.,* 2013). 19 river reaches were selected with contrasting catchment sizes and urbanisation rates. On these reaches, topographic and hydraulic measurements were carried out on 10 to 20 cross sections to estimate different hydromorphological indicators. A statistical analysis of these data allowed us, in the case of the Yzeron, to identify four variables that discriminate between rural and urban watercourses according to hydromorphological criteria. On average, urban streams in the Yzeron basin are 30% wider and deeper than rural streams, with an 80% greater full flow[2] and a 50% wider low-water bed. No differences were identified for the variables of slope and granulometry of the sediment present in the bottom of the minor bed.

Discharges to small rivers should be reduced to reduce their erosion

We also found that the intensity of erosion increased with the rate of sealing of each river basin. Finally, even though widening and erosion affects both small and large rivers, the most important erosion points are located on the smallest rivers located downstream of storm overflows or road discharge points.

Thus, measures to reduce erosion will primarily involve a significant reduction in discharges into these small urban rivers. However, one difficulty in the diagnosis lies in knowing whether the erosion observed is linked to urbanisation or to a combined effect of other phenomena, such as the multi-secular history of land use in the drained areas mentioned above (Gropřêtre, 2011). As a result, quantifying these adjustments remains a complex process based on detailed knowledge of the terrain and the historical context of the catchment area.

Soil sealing and flood intensities

Numerous studies from the scientific literature (e.g. Hollis, 1975) have shown that flood regimes are unevenly affected by soil sealing. While the intensity of very frequent floods (< 1 year) is multiplied by 20, that of the annual flood is multiplied by 10, and that of the ten-year flood by 3. The explanation is as follows: during these rare hydrological events, the non-artificial soils are saturated with water and then behave like impermeable soils. These results were confirmed on the Yzeron river.

TO GO FURTHER

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[2] That is, the flow just before the overflow of the minor bed into the floodplain.

Infiltration 7

Infiltration as a method of rainwater drainage in urban and peri-urban areas is nowadays highly popular. But while water has been channelled for decades, why would a change in practice be promoted today? What interest and potential risks could it present? This is a field that OTHU has explored extensively and in an original way by studying the circulation of rainwater feeding infiltration systems from its production (runoff water) to its impact on soils and groundwater.

In the following questions we discuss the results obtained on OTHU, particularly those related to clogging, the added value of vegetation and the biodiversity that may be associated. Aspects related to pollution are addressed in question 7.2, while the impacts on the water table are available in chapter 6.

7.1

Why infiltrate rainwater?

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The use of infiltration techniques is now booming, both in France and abroad. This renewed interest has given rise to a parallel fear of the potential for groundwater pollution, as well as a risk of worsening flooding during intense rainfall events. Yet, infiltration of rainwater can limit the negative consequences of urbanisation and protect against the very real risks induced by the classic "all-pipe" management system.

Urbanisation disrupts natural rainwater circulation processes

The renewed interest in infiltration comes, in part, as a reaction to traditional urbanisation and stormwater management: massive sealing, collection of water from impermeable surfaces, channelling and rapid evacuation of this water to pipe networks and then to the surface environment. The diagrams in Figure 1, which are widely available in the literature, illustrate the distribution of water flows before and after urbanisation, in broad strokes. They show a drastic decrease in infiltration into the subsoil, both deep infiltration, which allows the water table to be fed when it exists, and sub-surface infiltration, which contributes to the feeding of vegetation and/or surface water (e.g. rivers). Traditional stormwater management also leads to a significant increase in the flows resulting from runoff.

Infiltrate to replicate the natural stormwater cycle

Quantitatively, the idea of infiltrating rainwater has the advantage of reproducing the natural processes of rainwater circulation and allows:

- limit what is likely to produce flooding in the city, i.e. peak flows (large quantities of water arriving in a very short time) and the volumes of runoff to be managed;
- contribute to the recharge of groundwater which serves for other uses (irrigation, drinking water supply, etc.), upport to the surface water system etc.);
- help infiltrate and store rainwater in the top soil for the most frequent rainfall events
- to reduce pressure on downstream systems, limit the frequency of storm water discharges and the degradation of surface water;
- create favourable conditions for the reintroduction of vegetation in the urban environment (Figure 2). As infiltration systems are often vegetated, they can promote evapotranspiration and contribute to producing islands of coolness during hot spells, or increase or maintain biodiversity.

Source control solutions are generally designed for routine rainfall events. By slowing down the flow, they contribute to making water more often visible in the urban landscape; even if their role in the management of extreme events is less, they do not aggravate the risks of flooding by runoff or by overflowing networks.

Infiltrate to reduce pollution flows

As rainwater washes off urban surfaces, it becomes loaded with various pollutants. Thus, the renewed interest in infiltration has led to the parallel fear of chemical pollution or bacterial contamination of groundwater.

However, we have shown in OTHU that, in terms of pollutant management, the idea of infiltrating rainwater has many advantages. **Infiltration allows:**

- **limit surface wash off and pollutant transport:** this is particularly true for source control rainwater infiltration systems;

Figure 1: Main quantitative processes related to the urban water cycle between natural and urbanised surfaces. Percentages are indicative (source: FISRWG (1998)). The values in the figure give trends but should not be taken literally.

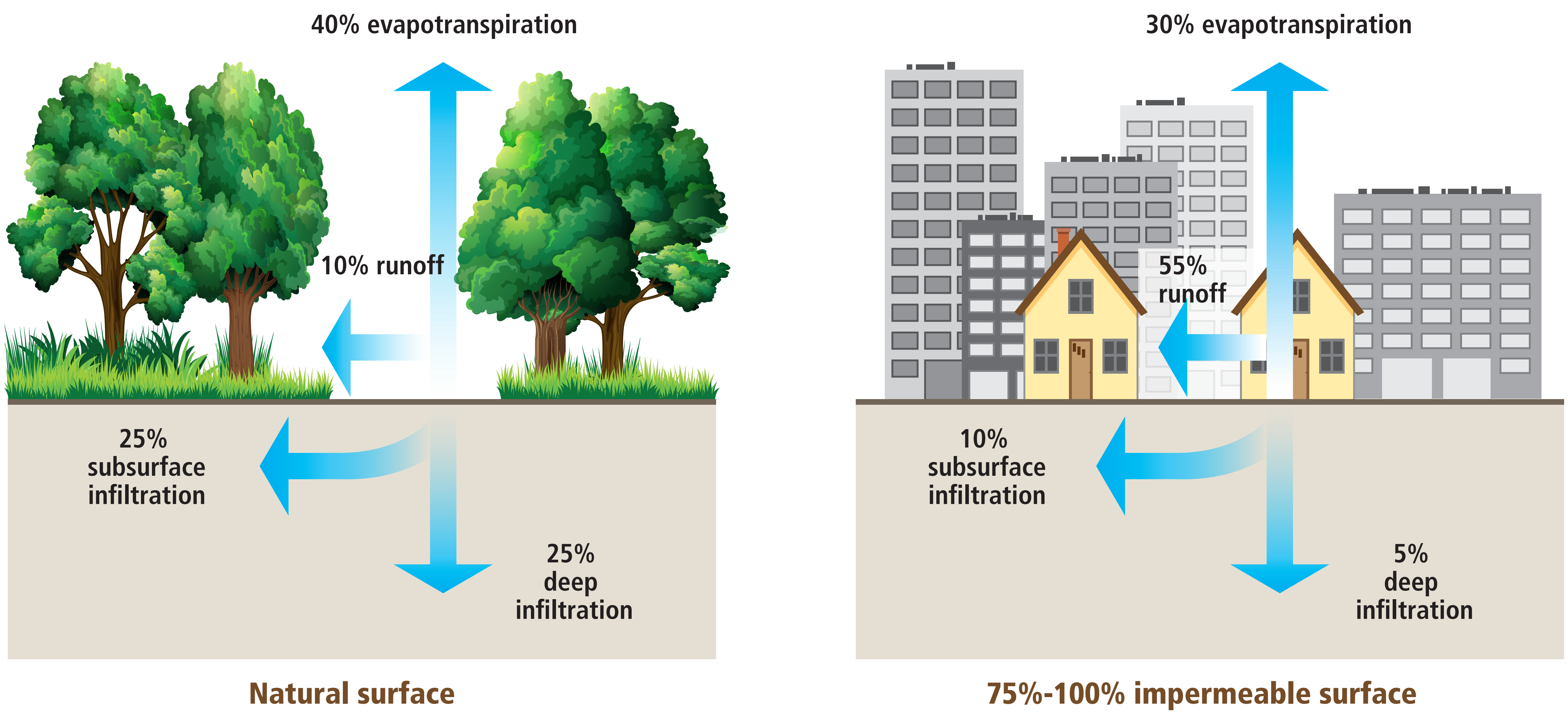


Figure 2: Various infiltration systems within the development (© Graie - UCBL).

- **limit the amount of water from runoff and therefore the amount of pollutants discharged to outlets (sewers or surface water).** Infiltration systems, which are often vegetated and composed of specific substrate, are particularly good at retaining water from frequent light rainfall, thus contributing to the discharge of small quantities of water and pollutants at the outlet of the structure.

For example, on the La Doua Ecocampus, the project owner set up various rainwater management systems using infiltration, including an experimental bioswale draining a car park with a conventional asphalt section and a partially permeable "stabilised" section. This site, over two and a half years of observation, shows that this system intercepts 98% of rainfall with a total precipitation height of less than 15 mm, without any restitution of water by exfiltration (bottom or side infiltration).

- **to help "filter" pollutants such as heavy metals or hydrocarbons, with an effective surface trapping that depends little on the nature of the soil, and to limit the percolation of metallic pollutants or hydrocarbons towards the groundwater.**

The physical, physicochemical or biological processes linked to the percolation of water in the substrates forming the body of the structures (notably the vegetated substrates) or the supporting soil, can be seen as an added value for the treatment of stormwater, notably for a majority of hydrocarbons and heavy metals (see Question 7.2 *What role does the soil play in the trapping of pollutants?*).

Beware, however, of dissolved pollutants such as pesticides which, in the case of centralised systems (e.g. infiltration basins), are not trapped and could percolate. There is no other solution for them than to reduce their use in these situations. So if you want to get rid with these pollutants… the best way is not to use them.

[1] Stabilised soils are a mixture of fine gravel, sand and sometimes a cementitious binder.

Infiltration ok but not in my backyard

When stormwater source control solutions are mentioned, a common response is "but in my backyard I can't infiltrate". Even if the groundwater table is fairly shallow or the soil is not very permeable, infiltration or detention can still be used for current rainfall, which corresponds to total rainfall depths of a few mm. Infiltration then takes place spontaneously through vegetated surfaces and can also be helped by the installation of infiltration systems such as bioswales, rain gardens or tree pits. These elements perform a dual function of rainwater management and enhancing the landscape.

TO GO FURTHER

- **Barraud S., De Becdelièvre L., Bedell J.-P., Delolme C., Perrodin Y., Winiarski T., Bacot L., Brelot E., Soares I., Desjardin-Blanc V., Lipeme Kouyi G., Malard F., Mermillod-Blondin F., Gibert J., Herbreteau B., Clozel B., Gaboriau H., Seron A. Come J.-M., Kaskassian S., Verjat J.-L., Bertrand-Krajewski J.-L., Cherqui F.,** (2009). *L'infiltration en questions* – Guide édité dans le cadre du projet ECOPLUIES – ANR PRECODD - lc.cx/ecopluies (in french)

7.2

What role does the soil play in trapping pollutants?

Sylvie Barraud, INSA Lyon - Laurent Lassabatère, ENTPE -
Florian Mermillod-Blondin, CNRS University Lyon 1

When stormwater drains off urban surfaces, it washes off contaminants such as heavy metals, hydrocarbons or pesticides. The renewed interest in infiltration has therefore given rise to the fear of pollution and deep contamination of soils and groundwater. But deploying stormwater infiltration solutions does not mean injecting rainwater directly into the groundwater. And the soil plays a definite role in trapping pollutants, which goes beyond mere filtration. But what exactly is it?

What processes are implemented?

The main processes that water encounters as it percolates into the soil are summarised in Figure 1. The soil can be a natural soil in place from which the structure has been excavated: this is the case for an infiltration basin. It can also be composed of an added substrate, such as the topsoil of a vegetated swale for example.

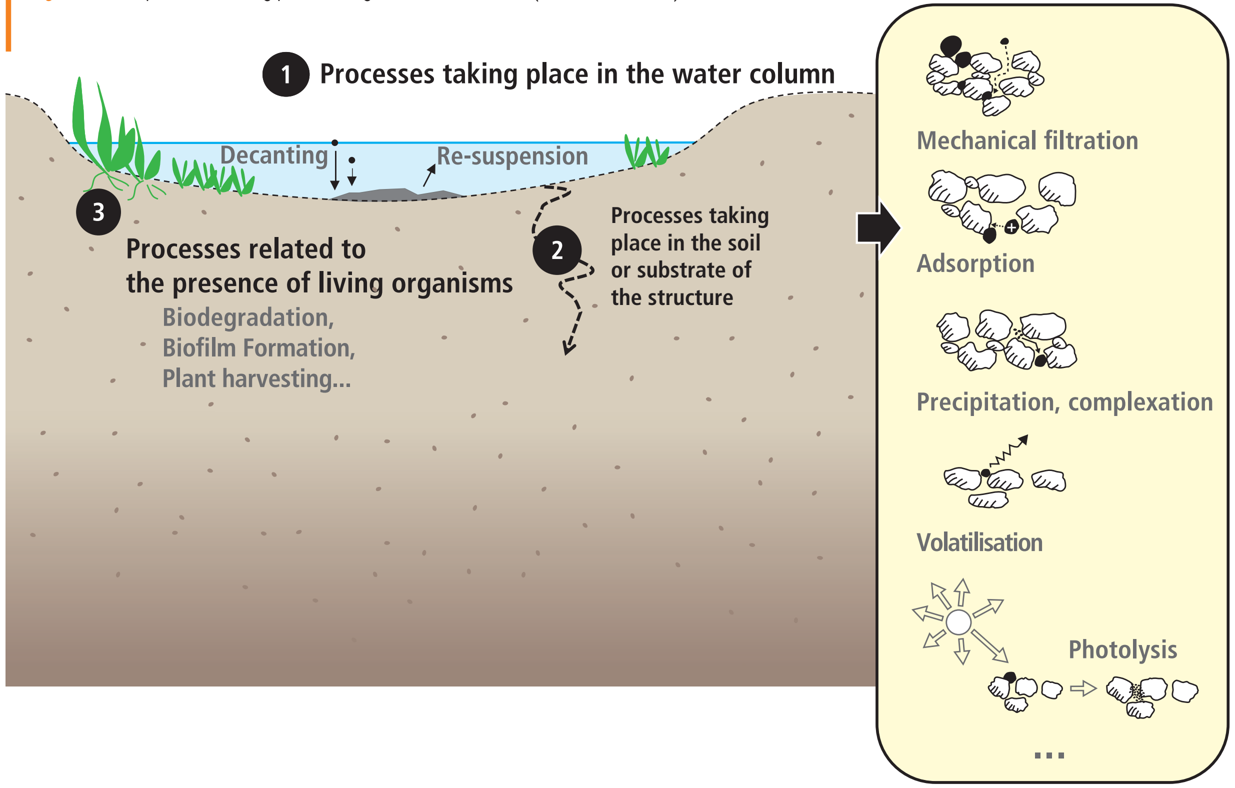
The processes of detention, mobilisation or transport of pollutants are complex and varied (Martinelli, 1999). In a very schematic way, these processes can occur (Figure 1):

1 – in the water column, during and following rainfall events. This is the purpose of the decantation of particulate pollutants with possible resuspension of deposits;

2 – within the soil or substrates in which the flows take place. In this case, the phenomena mobilised can be:

- Mechanical filtration: filtration and detention of particles present in the stormwater in the pores of the soil or substrate. It should be noted that settled deposits can themselves act as filters,
- Adsorption: the process of fixing (electrostatically or chemically) the pollutants on the surfaces of the soil particles or substrate,
- Precipitation and complexation, which result from changes in the state of the pollutants,
- Degradation by photolysis (degradation by daylight) or volatilisation which affects organic substances,
- Transfers in the soil for pollutants in dissolved or colloidal forms.

Figure 1: Main processes taking place during rainwater infiltration (source: S. Barraud).



Whether in the water table or in the soil/substrate, living organisms (plants, micro-organisms, etc.) can act on several processes (biodegradation, bioaccumulation of pollutants in the organisms themselves, mobility of pollutants).

Some of the processes that retain pollutants in the soil or substrate are not very significant. This is the case for photolysis or volatilisation. This is also the case for the removal of pollutants (especially metals) and their accumulation by plants present on centralised infiltration systems (see box below).

In the rest of this article the processes of reducing the concentration of pollutants in stormwater in the soil are discussed. It should be remembered that the predominant factor of sustainable drainage systems (SuDS) is the reduction of the volumes of water runoff, and therefore the masses of associated pollutants.

Particulate pollutants are mainly retained in the surface layers

A large proportion of the pollutants from runoff are in particulate form (e.g. heavy metals, hydrocarbons). These pollutants are clearly stopped in the topsoil layers or in the structure/soil interfaces when the materials making up the structures are very permeable. This is the case, for example, of trenches filled with coarse aggregates and whose water infiltration takes place in the underlying soil (Proton, 2008).

Work on several infiltration basins in the East Lyon plain formed by fluvioglacial deposits (Dechesne, 2002; Le Coustumer, 2008) indicates that only the first 30 centimetres are affected by significant heavy metal and hydrocarbon pollution after more than 10 years of operation (Figure 2).

For these same pollutants and over a period of eight years, Le Coustumer (2008) and Gonzalez-Merchan (2012) showed that the polluted parts tended to become homogenised over the entire surface of the basin and that the concentrations no longer changed over time. However mass accumulation was clearly visible. The surface layer therefore seems to act both as a filter layer and as an adsorbent layer for these pollutants.

These pollutants have sometimes been detected very locally at great depths (of the order of 2-3 m (Winiarski, 2006)) in the Django Reinhardt infiltration basin. Nevertheless, the levels were low, slightly above the local soil geochemical background and well below those of polluted topsoils. These particular migrations were also observed at certain specific points in a basin. The detailed analysis of these points showed that the movement could be due to preferential paths and/or very permeable areas (hydraulic conductivity > 10^{-2} m/s). Recommendations were drawn from this in the guide *L'infiltration en questions,* (Barraud et *al.*, 2009).

The extraction of heavy metals from soils by vegetation alone (or phyto-extraction) is not very active… but the soil/plant complex is beneficial

Saulais (2011) was able to establish mass balances of zinc, cadmium and copper on the vegetation present in different infiltration basins. Her study clearly shows that, whatever the area considered and the present vegetation, the surface layer represents the major metal storage site. The root and aerial parts of the plants capture less than 4% of the total intercepted mass.

Thus, the vegetation of infiltration basins, for example, taken alone, will not necessarily bioaccumulate the metals present in the contaminated soils of infiltration basins. However, the presence of vegetation in combination with the soil or substrate in place can limit the transfer of pollutants (e.g. by promoting decantation, adsorption… or by removing water and associated pollutants - see question 8.6: *How to design an effective sediment and particulate pollution trapping basin?*). It also provides real added value in limiting clogging (see question 7.4: *What is the role of vegetation in the clogging of infiltration systems?*).

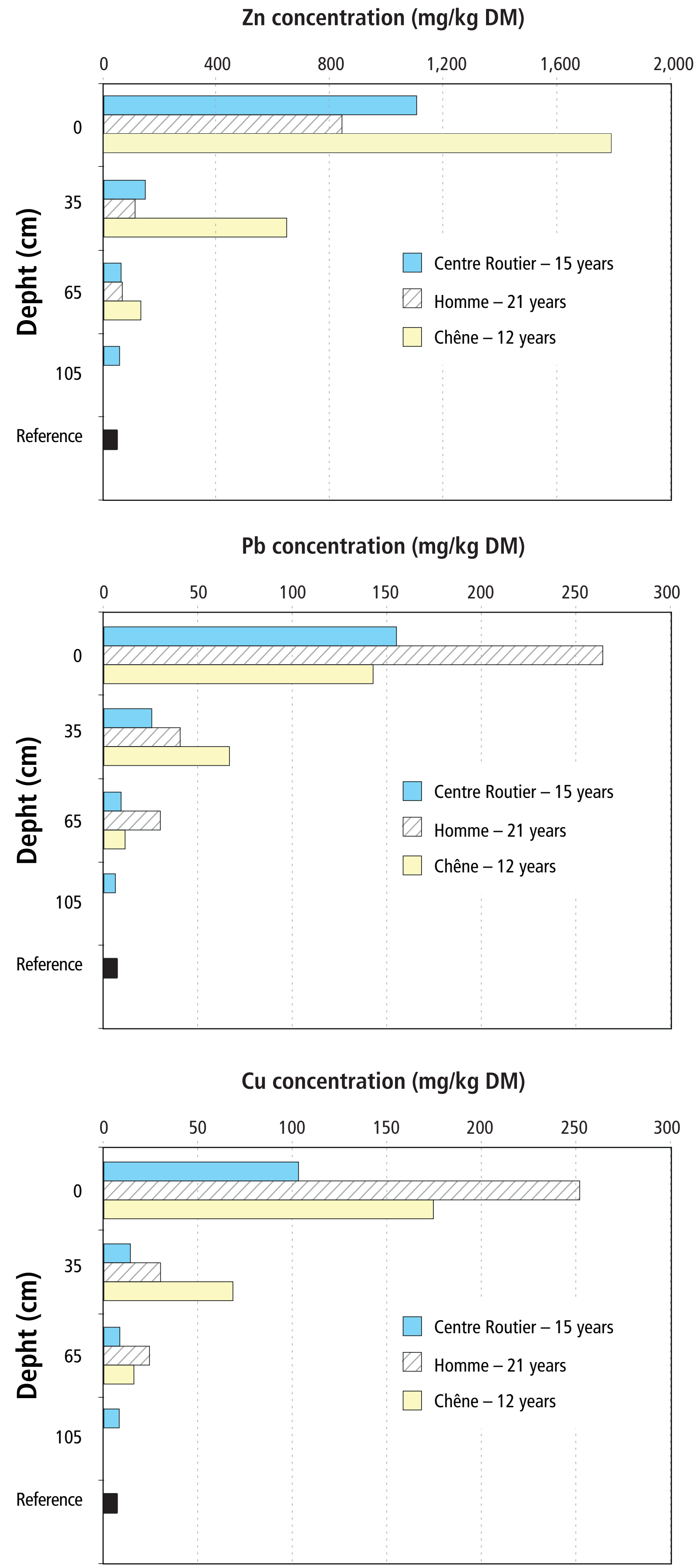
The metals and hydrocarbons retained do not migrate into the water table and are not easily remobilised

Finally, in order to «close the loop», water sampling campaigns upstream and downstream of an infiltration basin in the groundwater with an unsaturated zone (2-3 m - Datry, 2009) showed that the heavy metals and hydrocarbons present in the runoff water discharges did not reach the water table. It was, of course also the case on the Django Reinhardt basin whose vadose zone is 13 m deep. (see Question 6.1: *What is the impact of rainwater infiltration basins on the water table?*).

These field observations were supplemented by laboratory experiments.

Laboratory column studies whose composition is that of the bottoms of infiltration basins and underlying soils (Badin, 2009, Nogaro and Mermillod-Blondin, 2009) indicate that the pollutants present in the soil are released only to a limited extent during the percolation of water through the columns, for different types of simulated rainfall (normal or stormy). Consequently, the risk of remobilisation of pollutants seems low for pollutants such as heavy metals and hydrocarbons.

Figure 2: Heavy metal concentrations measured at four depths in the soil of three infiltration basins in eastern Lyon with their number of years of operation (Dechesne, 2002).



Coustumer (2008) also found a lack of metal transfer in biofilters for different types of substrate composition and different types of vegetation.

While the underlying soil plays a key role in these processes, its capacity to retain metal and hydrocarbon pollutants seems to be more related to infiltration capacities, which should not be too high (i.e. a soil that is too highly permeable does not allow for the maximisation of soil-contaminant exchanges needed to trap pollutants), rather than to the type of soil or the design of the systems. The conclusions drawn in OTHU are now largely corroborated by multiple studies internationally (see Tedoldi *et al.,* 2016). Overall, scientific work has demonstrated we can assume that the soil or substrate in which, filtration and adsorption processes occur are a good filter for heavy metals and hydrocarbons and more generally for particulate pollution.

What about other micropollutants and contaminants?

These results must be completed for other types of pollutants that have only recently been investigated, notably micropollutants (see Chapter 5: Contaminants).

For pesticides, which are present in mainly dissolved form, the transfer processes in soils are the most significant. These compounds unsurprisingly cross the unsaturated zone of infiltration systems with a risk of groundwater contamination but mainly for centralised (end of pipe) systems (Marmonier *et al.,* 2013; Pinasseau *et al.,* 2020). Concerning micro-organisms, Badin (2009) has shown on soil columns composed of infiltration basin bottoms that bacteria were likely to migrate. More recent knowledge on OTHU shows that the bacterial communities found in the groundwater downstream of an infiltration basin are different from the bacterial communities present upstream (Voisin *et al.,* 2018). These community changes do not seem to be related to a transfer of bacteria present in stormwater runoff but rather to an environmental modification of the conditions in the water table itself (e.g. enrichment in dissolved organic matter - Voisin, 2017; Voisin *et al.,* 2020).

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- **Datry T.,** (2003). *Urbanisation and groundwater quality: responses of underground aquatic ecosystems to rainwater infiltration practices. PhD thesis from the University of Lyon 1* – lc.cx/datry2003 (in french)
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7.3

How does an infiltration system get clogged and how long does this take?

Sylvie Barraud, INSA Lyon

Clogging is the counterpart of the effectiveness of infiltration structures in stormwater pollution treatment. The particles fix the particulate contaminants. The fact that these contaminants are fixed at the surface means that they are not found deeper in the soil or in groundwater. But over the long term this trapped materials are prone to clogging and affect the hydraulic performance of the systems that needs to be accounted for to maintain proper infiltration conditions.

Know the dynamics of clogging in order to delay it

The management of rainwater by infiltration is rapidly developing today via permeable devices integrated into urban developments (basins, rain gardens, swales, trenches, porous reservoir pavements, etc.). A recurrent issue is their durability over time, particularly through the reduction in their permeability (progressive clogging) which can call into question their hydraulic functioning.

Clogging is indeed an inherent phenomenon of infiltration. If it is unavoidable, it is important to know the spatial dynamics (where does clogging occur most?), the temporal dynamics (how long does it take?) and the predominant factors, in order to delay it and to take it into account during design and/or maintenance.

The scales at which infiltration occurs and the pressure exerted on the structures have a direct influence on the spatial and temporal distribution of clogging. A differentiation is thus made between centralised and source structures.

How can the temporal evolution and spatial distribution be assessed? The assets of OTHU

An original method has been developed and used in different technical and climatic contexts by OTHU. It has the advantage of evaluating global clogging and has benefited from measurements over long periods. It consists, under certain hypotheses generally required to infiltrate rainwater[1], in calculating a hydraulic resistance[2] based on an operating principle (Bouwer model). The calibration is carried out based on continuous monitoring of the inlet flows, water levels and temperatures in the structures. The method also requires three-dimensional modelling of the geometry of the structure, which is relatively simple to obtain by topographic survey.

The evolution of the hydraulic resistances over time is measured from the evolution of the capacity of the structure to infiltrate water heights of the order of one metre. The resistances are normalised at 20°C to avoid the effects of temperature, which affects the viscosity of the water. The method also makes it possible to distinguish between bottom and wall resistance. It is well suited to centralised systems that may have significant water depths.

Other measurements carried out within the framework of the observatory are also valuable, including:

- continuous measurements of turbidity (transformed into TSS concentrations) which, in addition to the measurements of inlet flows, allow the behaviour of the systems to be analysed in the light of their stresses (masses of sediment brought in and volumes of water entering);
- monitoring of the vegetation and organisms present in the clogged layer, which makes it possible to assess their role in the clogging.

What was learnt?

The clogging of the infiltration works is very superficial (photo 1). It forms a "skin" whose development is favoured by the input of suspended solids, mainly composed of organic matter[3]. On small structures, the layer is generally much less visible because these inputs are less significant.

On centralised structures, progressive clogging that can be delayed by vegetation

In centralised structures, the phenomenon develops primarily in the areas that are most hydraulically stressed. Over time, the zone of influence of clogging extends to occupy the entire bottom surface. As a last resort, the walls provide the main part of the infiltration. Since they also constitute a significant part of the surface area, clogging of the bottom may not be a problem for the hydraulic functioning of the system during rainfall. According to the observations made on basins in the east of Lyon based on fluvio-glacial soils and equipped with upstream decanting devices, the clogging is rather progressive and generally quite long (more than 10 years).

For example, fine monitoring over 8 years of the hydraulic resistance of the Django-Reinhardt basin shows that clogging is very gradual (figure 1a) and that it occurs mainly at the bottom of the structure (figure 1b).

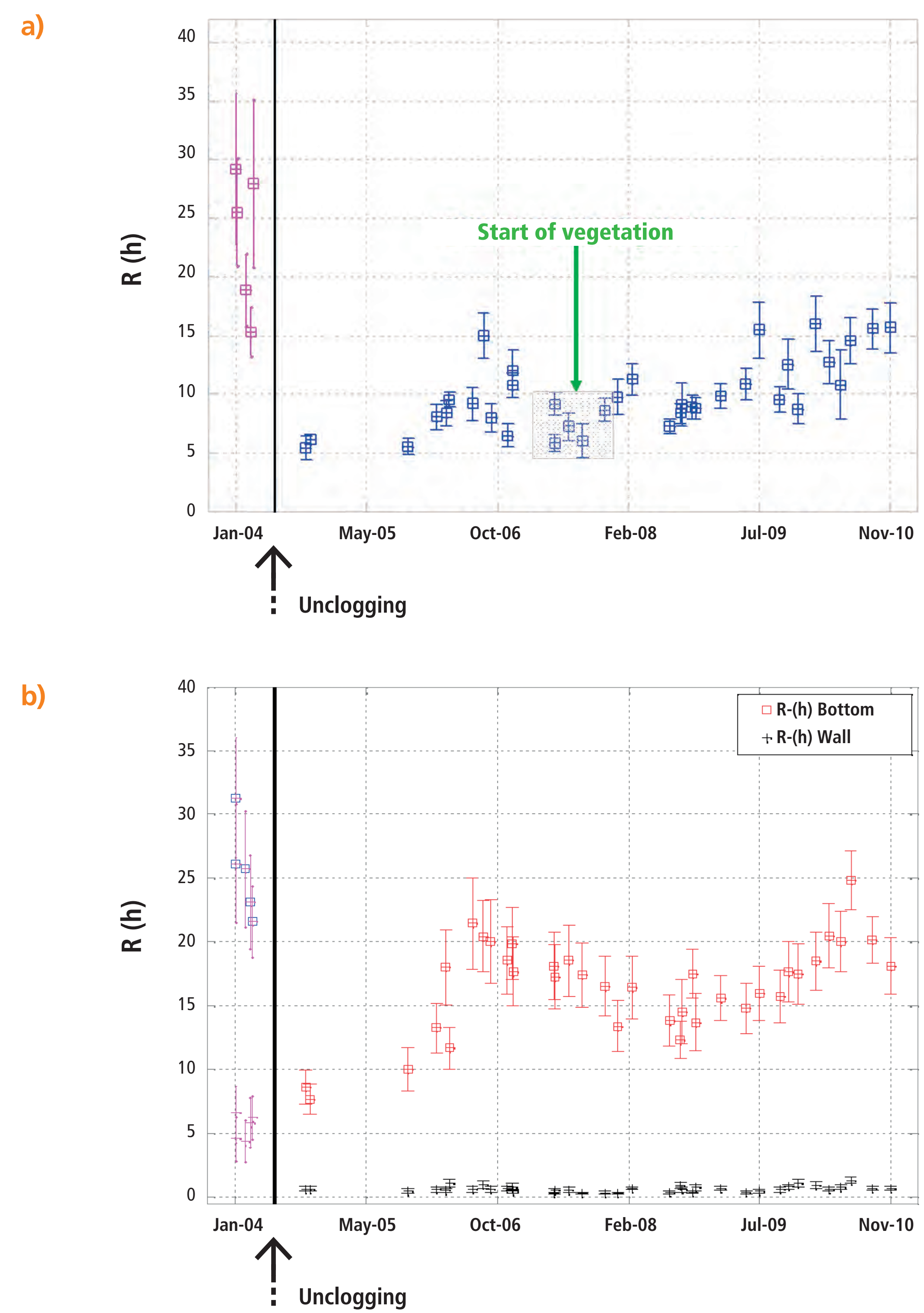
[1] Presence of a slightly clogged layer, underlying medium with high hydraulic conductivity, unsaturated zone far from the bottom, presence of a water layer during wet weather events.

[2] The hydraulic resistance is the time required for a unit amount of water to pass through the clogged layer under a unit load. The higher the resistance, the more clogged the device.

[3] The higher the resistance, the more clogged the structure.

This study also revealed that clogging can be slowed by the presence of vegetation. Long-term monitoring allowed us to identify a drop in hydraulic resistance over a period of about a year (in 2007), during which spontaneous vegetation invaded the bottom of the structure (photo 1) without this drop being attributable to a drop in water or TSS inputs measured continuously.

Figure 1: **(a)** Evolution of the global hydraulic resistances R(h) with their uncertainty, **(b)** Evolution of the bottom and wall resistance. (Source : Gonzalez-Merchan, 2012).



Photos 1: **(a)** State of the vegetation in the Chassieu-Django-Reinhardt basin between the 2004 clogging (top) and **(b)** in 2007 (bottom), when clogging began to decrease. (Source : Gonzalez-Merchan, 2012).

WHERE DOES THE CLOGGING COME FROM?

Photo 2: Clogged layer on the Django-Reinhardt basin (source: ENTPE).

Three types of clogging can occur:

- **physical** (most common): linked to the input of solid particles (suspended solids strongly present in stormwater) and to compaction (e.g. water loads, trampling);
- **biological:** due to the development of micro-organisms (algae, fungi, bacteria, pro- tozoa) on the surface of the infiltration system;
- **chemical:** involving the precipitation and dissociation of minerals that can lead to the development of bacteria that reduce the porosity of the medium. As this clogging is closely linked to the previous ones, it is difficult to study it in isolation.

Similar conclusions for source control structures

In source control structures, clogging is highly dependent on the design. For example, Proton (2008) clearly shows that clogging occurs only at the bottom of the structure and that the structure clogs over a period of about six years (observation made under accelerated loadings). Over the same period, the vertical sides are not affected.

Other experiments on the hydraulic conductivity at saturation of 38 vegetated biofilters an age of less than 7 years conducted in collaboration between OTHU and the FAWB (Facility for Advancing Water Biofiltration) (Le Coustumer *et al.*, 2009) revealed superficial clogging. The hydraulic conductivity decreases by a factor of 2 for structures with high initial conductivity (> 200 mm/h (~5.10^{-5} m/s)) but remains high. For structures with low initial hydraulic conductivities (< 12 mm/h (~3.10^{-6} m/s)) these appear to remain relatively constant but fairly low despite the presence of vegetation which plays a role in maintaining the initial permeability (see Question 7.4: *What is the role of vegetation in the clogging of infiltration systems?*).

TO GO FURTHER

- **Barraud S., Le Coustumer S., Perrodin Y., Delolme C., Winiarski T., Bedell J.-P., Gibert J., Malard F., Mermillod Blondin F., Gourdon R., Desjardins V., Brelot E., Bacot L.,** (2006). Guide Technique : *Recommandations pour la faisabilité, la conception et la gestion des ouvrages d'infiltration des eaux pluviales en milieu urbain.* 62 p. – lc.cx/guideinfiltration (in french)
- **Gonzalez-Merchan C.,** (2012). *Improving knowledge on clogging of stormwater infiltration systems.*. PhD thesis INSA Lyon. lc.cx/gonzalez2012 (in french)
- **Le Coustumer S.,** (2008). *Clogging and detention of trace metals in stormwater infiltration systems.* TPhD thesis INSA Lyon / Monash University – Melbourne, Australie. lc.cx/lecoustumer2008 (in french)

7.4

What is the role of vegetation in the clogging of infiltration systems?

Sylvie Barraud, INSA Lyon – Jean-Philippe Bedell, ENTPE

Vegetation in basins, swales, biofilters and other infiltration systems, whether intentionally or spontaneously planted, can play a beneficial role in limiting clogging. However, not all plant species are equally effective in optimising or maintaining soil qualities with respect to rainwater infiltration.

Key finding: Vegetation delays the clogging of infiltration systems

Vegetation plays an important role overall in delaying the clogging of infiltration systems, despite the contribution of organic matter and solids to their surface. Indeed, it contributes through the root systems of plants and the movement of stems under the effect of the wind, to the creation of macropores, improving the infiltration capacity of the soil.

Focus on the role of vegetation in centralised structures: the case of the Django-Reinhardt basin

The Django-Reinhardt infiltration basin is a perfect example. Indeed, the monitoring of clogging carried out within the framework of OTHU between 2004 and 2010 made it possible to identify a significant slowing down of the evolution of the overall hydraulic resistance[1], following the spontaneous vegetation of the bottom (see Question 7.3: *How does an infiltration system become blocked?*).

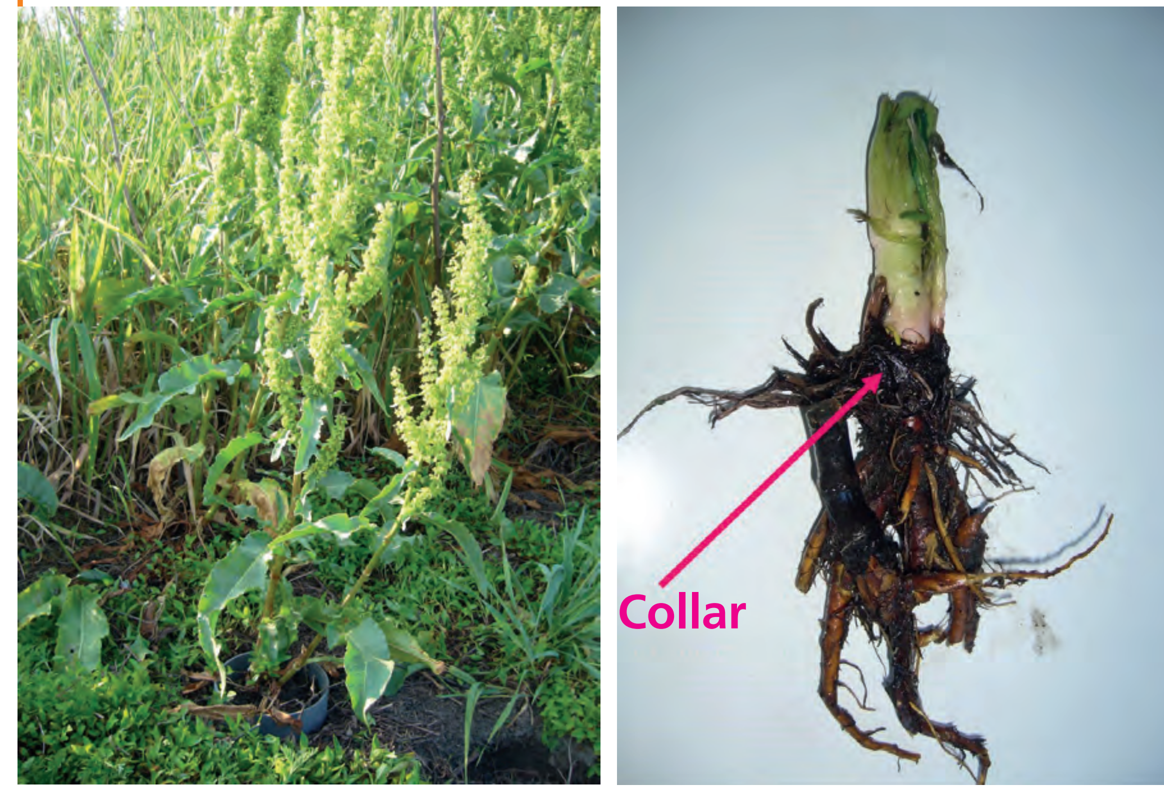
Importance of plant morphology

An in-depth analysis of the nature of the vegetation present and its co-evolution with the characteristics of the soil in the clogged areas of the structure was carried out over two years and at different seasons. It shows that not all species give the same infiltration performance to the soil support and that the morphology of the roots, of the stems and the soil/plant relationship plays an important role. For example, of the three species that grew most in the studied basin (*Polygonum mite, Phalaris arundinacea* and *Rumex Crispus*), *Phalaris Arundinacea* (figure 1) performed best, with an infiltration capacity (at saturation) through its vegetated horizon about twice as high as the infiltration capacity of the nearby bare soil. Its rhizomes and stolons (creeping aerial stems) that form through the surface layer effectively create macropores and facilitate water transfer through the clogged layer (Gonzalez-Merchan *et al.*, 2014).

Figure 1: *Phalaris Arundinacea* has a very high infiltration capacity, thanks to the characteristics of its root syste (Gonzalez-Merchan, 2012).

[1] The hydraulic resistance is the time required for a unit amount of water to pass through the clogged layer under a unit load. The higher the resistance, the more clogged the device.

Figure 2 : *Rumex Crispus* performs poorly in terms of infiltration, due to the characteristics of its root system (Gonzalez-Merchan, 2012).



In contrast, *Rumex Crispus* was the least successful. It has a coarser root system, but above all is characterised by the development of a collar at the stem/root connection, where sediments accumulate. These characteristics make it more "hermetic" to water and its infiltration, thus favouring local decantation (figure 2).

Permeability changes with plant growth and the seasons

Observation of the plant growth stages revealed that the planted areas infiltration capacity showed a significant evolution between each stage of the plant life. The plant metabolism is modelled on the seasonal rhythm in accordance with the nutritive resources (water, quantity of light, nutrients, etc.). During the growth and reproduction period, the hydraulic conductivity[2] at saturation in the vegetated areas is significantly higher than during the resting period.

These studies suggest that the establishment of vegetation can help improve infiltration conditions at certain times, particularly in the summer (June to September) during heavy rainstorms. This can be particularly noticeable as the alternation of dry and wet weather in conjunction with the development of vegetation modifies the surface soil structure. This alternation creates favourable conditions for the formation of micro-cracks that induce preferential infiltration through the surface horizon (photo 1).

However, the establishment of vegetation is not sufficient to completely restore the infiltration conditions on an already very clogged layer.

Photo 1: Example of soil microcracks during the summer period.

[2] Hydraulic conductivity is a measurement of the ability of a porous medium to allow a fluid to pass through it under the effect of a unit pressure gradient. Depending on the temperature (viscosity of the fluid) and the existing water content in the medium, this hydraulic conductivity is often used at saturation and 20°C, which is the case here. The higher the conductivity, the less clogged the system is.

7.4

Focus on the role of vegetation in decentralised systems such as wetlands or biofilters

The importance of plant morphology is also noticeable for source control structures

Morphology, particularly that of the root parts, was also highlighted in OTHU/ FAWB (Facility for Advancing Water Biofiltration) work in Australia on laboratory pilots (Le Coustumer, 2012). The study showed, for example, that the plant *Melaleuca ericifolia* (Figure 3a) compared to four other types including *Carex apressa* (widely used for for swales or raingardens revegetation - Figure 3b) was much better at maintaining initial soil hydraulic conductivity. The explanation given for this higher performance is again morphology. *Melaleuca* is a shrubby plant with large roots that do not form rootlets like *Carex* (photo 2).

Planting a substrate is always more effective in combating clogging regardless of the vegetation than leaving it bare

Despite the varying performance of the five plant species studied with respect to clogging, none of the planted beds of the five species performed worse than a bare substrate subjected to the same stresses.

Figure 3: Photos of *Carex apressa* and *Melaleuca ericifolia* and evolution over time (72 weeks) of the hydraulic conductivities of the pilots planted with *Carex* and *Melaleuca* (mean and 95% confidence interval) (Le Coustumer, 2008).

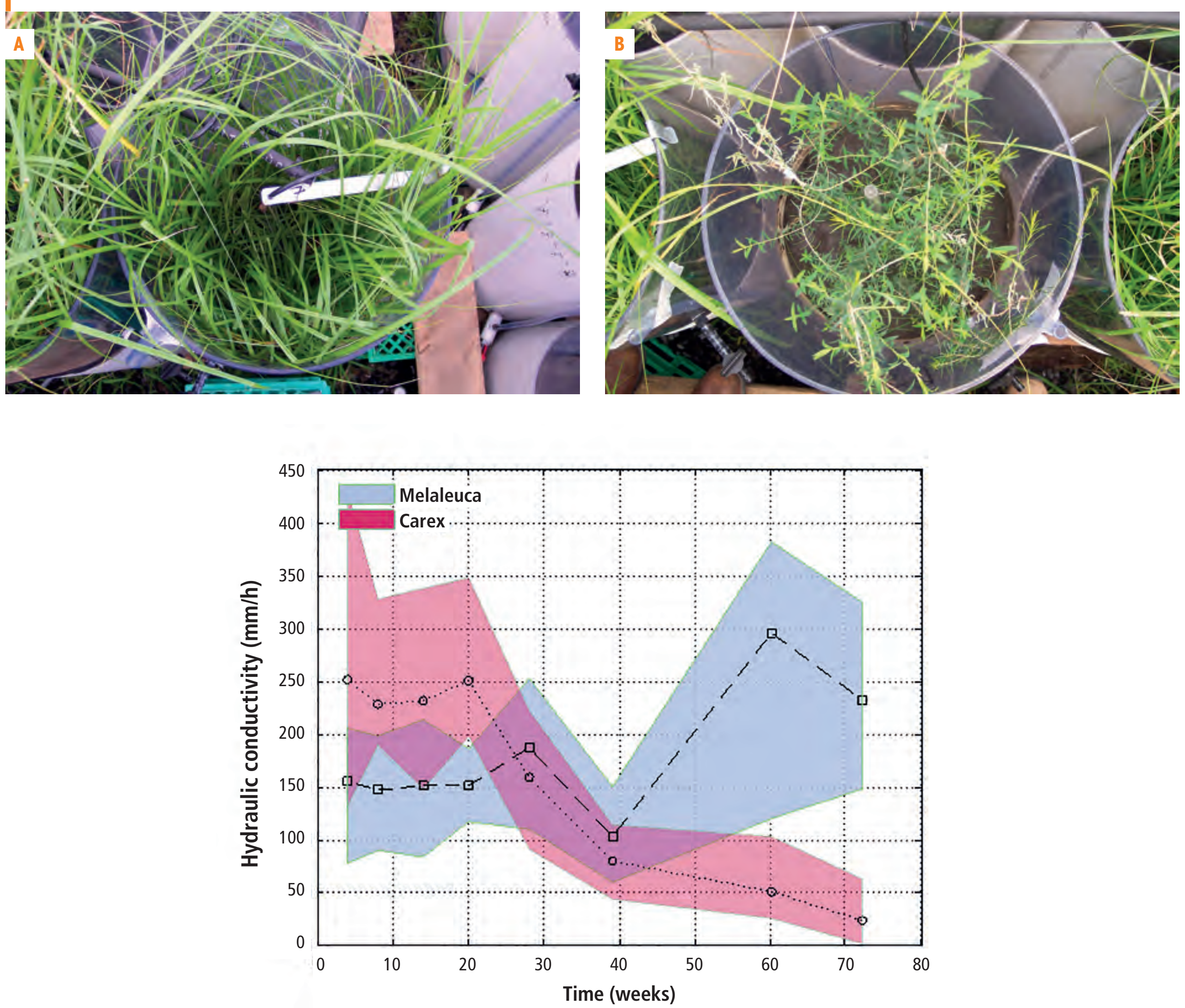


Photo 2 : Root system of *Carex* (left) and *Melaleuca* (right) (Le Coustumer, 2008).

In Brief…

If vegetation, whether spontaneous or deliberately planted, does not perform in the same way depending on the morphology of the plants and their condition over time.
The presence of this type of vegetation can only be beneficial in terms of the clogging of a soil receiving rainwater. Its presence can only be beneficial with regard to the clogging of a soil receiving rainwater.

TO GO FURTHER

- **Gonzalez-Merchan C.,** (2012). *Improving knowledge on the clogging of stormwater infiltration systems.* PhD Thesis INSA Lyon. TEL-00943422 – lc.cx/gonzalez2012 (in french)
- **Le Coustumer S.,** (2008). *Colmatage et rétention des éléments traces métalliques dans les systèmes d'infiltration des eaux pluviales.* Thèse de doctorat INSA Lyon / Monash University – Melbourne, Australie – lc.cx/lecoustumer2008 (in french)

7.5

What is the role of fauna in the clogging of infiltration systems?

Florian Mermillod-Blondin, CNRS University Lyon 1 – Géraldine Nogaro, Laboratoire National d'Hydraulique et Environnement R&D EDF – Jean-Philippe Bedell, ENTPE

Particles carried by rainwater and deposited in infiltration works often lead to progressive clogging of the systems. Just like with revegetation, also encouraging the presence of aquatic invertebrates such as oligochaete worms can be an ecological engineering approach to limiting soil clogging.

The presence of worms reduces the amount of organic matter present in the infiltration systems

To determine the impact of fauna, laboratory experiments were conducted with tubificid oligochaete worms (e.g. *Tubifex tubifex* species) and sediments collected from the IUT infiltration basin on the la Doua Campus in Villeurbanne (Mermillod-Blondin *et al.*, 2005). The results clearly showed that the presence of tubificid worms increases respiration in the system by up to 35%, indicating a higher mineralisation of organic matter in the presence of worms (figure 1). In addition, the presence of tubificid worms significantly stimulates the exchange of nutrients from the sediment to the water column, increasing the release of ammonium (+200%), phosphates (+300%) and dissolved organic carbon (+500%).

The stimulation of organic matter consumption by worms is also linked to a stimulation of microbial communities by invertebrates. Indeed, significant increases in the percentage of active bacteria and hydrolytic microbial activity involved in the degradation of organic matter were measured in sediments in the presence of worms (figure 2).

In conclusion, the oligochaetes create galleries that will stimulate the exchange of water and solutes between the free water and the pore water contained in the sediments. The increase in these exchanges leads to a stimulation of the mineralisation process of the organic matter. To encourage the presence of invertebrates can therefore be an ecological approach to reducing the amount of organic matter present in stormwater detention/infiltration systems.

Figure 1: Fluxes measured in experimental systems in the absence and presence of tubificid worms (Mermillod-Blondin *et al.*, 2005).

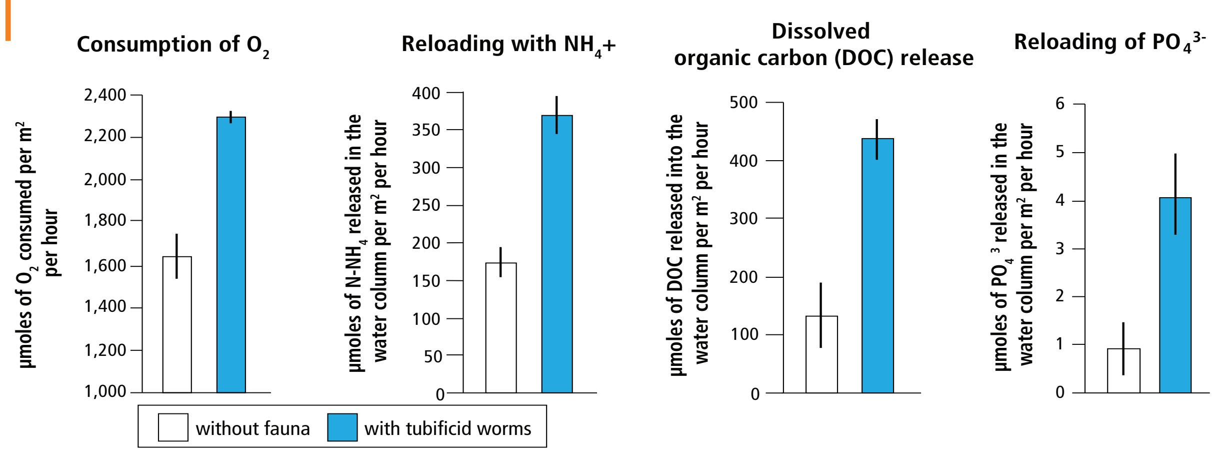


Figure 2: Percentage of active bacteria and hydrolytic activity measured on 4 sedimentary horizons in systems with or without tubificid worms (Mermillod- Blondin et al., 2005).

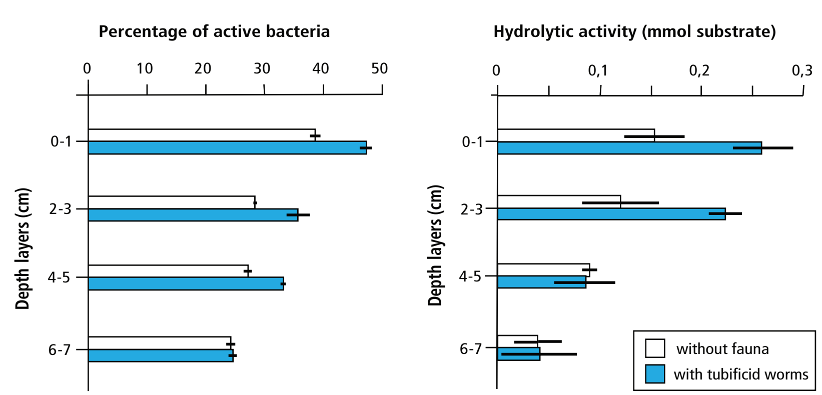


Figure 3: Experimental systems obtained in the presence of tubificid worms (left) and in the presence of chironomid larvae (right). Photo source: Géraldine Nogaro, LEHNA.

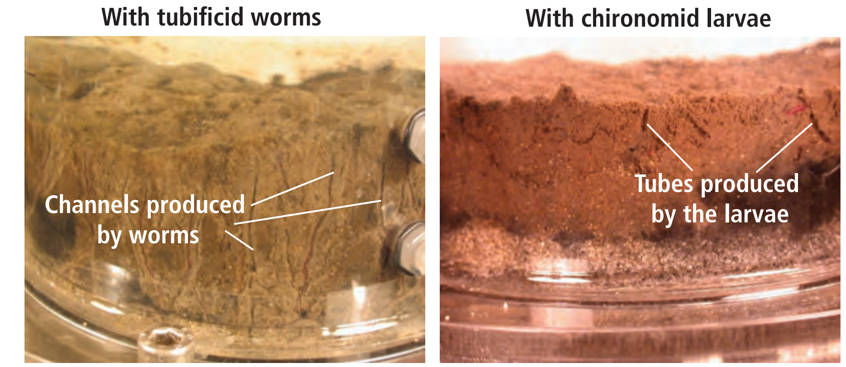


Figure 4: Experimental systems obtained in the presence of tubificid worms with the sediments of the Django-Reinhardt basin (left) and the IUT basin (right). Source Géraldine Nogaro, LEHNA.

Some aquatic invertebrates can increase the permeability of urban sediments

Following the work carried out on the degradation of organic matter by invertebrates, column experiments aimed to evaluate the role of aquatic invertebrates on the infiltration capacity of systems clogged by sediments from several sites. In the IUT sediments, the experiments revealed that the activity of tubificid worms prevented clogging of the columns, whereas no effect was measured with chironomid larvae. The observation of invertebrate activity (figure 3) shows a deep action of tubificids which produce vertical galleries (which pass through the clogged sediment layer) whereas chironomids (e.g. *Chironomus riparius* species) produce U-shaped tubes which do not pass through the clogged sediment layer. Thus, the calculated permeability is 17.7 cm/h with tubificid worms compared to 0.33 cm/h without fauna. These results are very significant and show a positive effect of certain organisms on hydraulic permeability depending on their type of bioturbation activity.

However, these encouraging results must be moderated because the effect of worms on clogging depends on the type of sediment in place. Results obtained on the clogging phenomenon with sediments collected in the Django-Reinhardt infiltration basin indicate that worms cannot decolonise all types of urban sediments (Nogaro and Mermillod-Blondin, 2009). The very high proportion of very fine sediments (< 10 µm) in this basin creates a significant clogging and a very hard layer that the tubificid worms cannot penetrate (Figure 4 shows a comparison between the activity of worms on the sediments of Django-Reinhardt and the sediments of the IUT). The importance of invertebrates in reducing the clogging phenomenon must therefore be put into perspective depending on the characteristics of the sediments deposited.

In Brief...

In aquatic environments, sediment fauna, such as oligochaete worms or chironomid larvae, play a significant role in the degradation of organic matter on the surface of infiltration systems.
In addition, in some cases it can have a positive effect, but not always, on the infiltration capacity of the soil by creating tubes, galleries and burrows in the fine sediments, thus limiting the clogging of the systems.

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7.6

What biodiversity is found in urban infiltration systems and what does it reveal?

Laëtitia Bacot, Graie – Pierre Marmonier, Florian Mermillod-Blondin, CNRS University Lyon 1 – Jean-Philippe Bedell, ENTPE

Source control stormwater management structures are often nature-based solutions and, in all cases, spaces and facilities that constitute true urban islands of biodiversity. Indeed, compared to other urban spaces, they present particularities in terms of physical configurations, uses (or non-uses) and presence of water, and they host fauna and flora communities different from those present in the traditional urban fabric.

Stormwater management basins encourage the development of biodiversity

Infiltration/detention basins are of particular interest at OTHU. They have two physical characteristics which favour communities of organisms:

- a flat bottom, potentially floodable for part of the year or for short periods, where fine and organic sediments can be deposited;
- edges with gentle to steep slopes, contrasting with the background with a more mineral composition with low humidity.

Both parts are often vegetated, whether intentionally in a landscape approach or spontaneously after a period of time, and host a wide range of animal species, particularly insects. They are therefore heterogeneous and original habitats because they are not very common in urban and peri-urban areas.

However, the biodiversity that develops there is not always desired and can generate nuisances for local residents and conflicts between inhabitants and water managers. Its description and the study of its dynamics are therefore essential to its management and acceptance. The first question we have to answer is to describe the organisms present: what biodiversity can be found in these systems?

Within OTHU in the Lyon Metropolitan Area, numerous studies have been conducted on biodiversity, its dynamics and its evolution. They have on vegetation, terrestrial and soil invertebrates, and mosquitoes. Vertebrates are also present (ducks, rats, etc.) and will be studied in the coming years.

Floristic biodiversity of infiltration basins

Vegetation dynamics were studied for 2 years on 18 detention/infiltration basins (Saulais M., 2011), from the point of view of the dominant plant species but also of the quality of the soils, considering the levels of bio-accumulated metal contaminants in their tissue (GESSOL Programme).

The composition of the floristic community is multifactorial.

The observations reveal that a majority of the basins have vegetation typical of environments that are particularly poor in nutrients, characteristic of a soil of anthropic origin that has formed very quickly at the bottom of the system.

The first explanatory factor is the availability of water, which depends in particular on the way the basin operates and is supplied.

The depth of soil and sediment also plays a key role in the establishment and diversification of the plant community. For example, some plants harvested from a single basin, such as Iris pseudacorus, have strong requirements, needing a minimum of 21 centimetres of sediment and water for their development. Others do not have such requirements for soil thickness and are more widespread in the basins studied, such as *Rumex* of the *Polygonaceae* family, which was present in 88% of the basins.

The third factor is the type of urban environment where the basin is located. The land use and the activities developed within the catchment area have an influence on the presence or absence of species. For example, the concentration of pollutants in run-off water from industrial areas probably explains, plants like 1 do not develop in these areas.

Finally, the management and maintenance of the installations (cleaning, mowing, etc.) also has a significant effect on the plant biodiversity in place.

There is a spatio-temporal dynamic of the vegetation

In addition to the composition of the communities, we were able to study the dynamics of the flora over more than 10 years, from the point of view of its richness and the abundance of the dominant species in two contrasting types of vegetated basins: Minerve where the vegetation was planted intentionally and Django-Reinhardt which was naturally colonised by vegetation.

For Minerve, the planted basin, we observed a marked spatial gradient between upstream (near the rainwater inlet) and downstream (where this water infiltrates into the infiltration

Figure 1: Distribution of water content in the Minerve infiltration basin and visualisation of the development of this flora in the Minerve basin.

bioswales). Indeed, the organic matter content, the thickness of the sediment deposited, and the content of trace elements brought by the rain decrease from upstream to downstream, which directly influences the floristic composition. The 10 years of monitoring have also highlighted a change in the plant community, with a regression of "heliophytes" (plants that seek out waterlogged soils) in favour of species typical of meadows in drier soils, often considered as pioneer species (first organisms to colonise an environment after it has appeared). This dynamic is not anecdotal: since 1999, more than 93% of the species initially established have disappeared. However, a stabilisation has been observed since 2008, with little variation in helophyte diversity (only 12.5% of the variation in the number of these species).

For Django-Reinhardt, the initially non-vegetated basin, the spatial structuring of the soil quality is less clear, but we also found areas with varying levels of organic matter and heavy metals. The plant community that has colonised this basin shows a high heterogeneity of ecological strategies. In this community we find both:

- Euroecious» species (species with a wide ecological spectrum) that can colonise many habitats;
- pseudo-metallophyte species (withstanding high levels of trace metals in the soil);
- macrophytes living in wet soils (*Typha latifolia, Phragmites australis, Iris pseudacorus, Phalaris arundinacea*) or even wetlands (*Rumex* sp.);
- but also, pioneer species typical of dry grasslands (of the *Asteraceae, Poaceae, Brassicaceae* family) when moving away from the family) when moving away from the most area.

The number of species has remained fairly stable since 2008, but there has been a decrease of almost 50% in the cover rate of macrophytes, which are now reduced to 3 species: *Phalaris arundinacea, Typha latifolia* and *Schoenoplectus tabernamontanii.*

These changes can be explained by the modification of incoming water flows. Indeed, the control strategy of the Lyon metropolitan area for the reduction of process water discharges from the companies present in the area has reduced the dry weather arrivals in the basin: these previously contributed to a certain recurrent moistening of the soil and sediments in certain places in the basin, and therefore to the development of macrophytes.

Faunal biodiversity: focus on the health of invertebrates

Terrestrial invertebrates are particularly abundant on the edges of basin

The terrestrial invertebrate community, mainly arthropods (invertebrates characterised by a segmented body), was described in 7 basins during a summer period. These were

Photos 1: **A** : *Iris pseudacorus,* Marsh iris – **B** : *Typha latifolia,* Broad-leaved sledgehammer (source: GRAIE et ENTPE).

7.6

Photos 2: Quadrat of earthworm extraction using the mustard test.

In Brief...

Invertebrates are abundant in stormwater management works. Due to the composition of the community and its richness, they can be good indicators of the functioning of the structures: soil quality, maintenance of the flows or stagnation of water.

sampled by trap tubes placed both at the bottom of the basin (372 tubes) and at the edges (343 tubes). The most striking results were the higher abundance of organisms on the edges (6083 individuals in total) than on the bottom (only 4474 individuals collected). The sloping edges of the infiltration basins are therefore very favourable habitats for fauna living on the soil surface. It should also be noted that ants and spiders are the most abundant groups of terrestrial invertebrate communities, both on the bottom and on the edges of the structures. These organisms, some of which are predators, participate in the control of the communities developing in the basins. They therefore play a complex ecological role.

The composition of earthworms is indicative of the quality of the soil and its characteristics

Soil invertebrates, mainly earthworms, were also studied during a counting and identification campaign carried out on two infiltration basins: Django-Reinhardt and Le Carreau.

The total abundance of earthworms collected per sampling quadrat (1 m^2 - Figure 3) shows strong variations with values ranging from 1 to 300 individuals. This variability is observed in the two infiltration basins studied and can be correlated with the thickness of sediment deposited at each point. The species composition is quite similar from one quadrant to another within the same basin but varies strongly between basins.

From the point of view of its composition, the earthworm community is first of all characterised by the absence of anechoic worms (which explore the soil through vertical galleries) but limited to endogeous and epigeous worms (which make horizontal galleries on the soil surface or sub-surface). The proportion of these two groups varies between the two basins: the Django-Reinhardt community is characterised by 60% endogeans and 40% epigeans, whereas in the Le Carreau basin, an inverse distribution is observed between the two ecological groups with 80% above ground and only 20% that were soil-dwelling. The presence of many «juvenile» earthworms in both ponds also illustrates that reproduction does take place in these artificial systems.

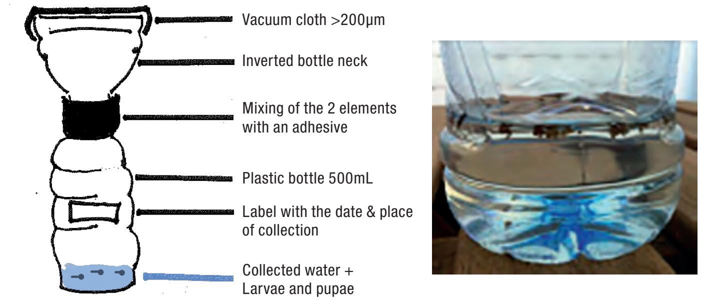
The fauna living in the soil, such as earthworms, are therefore interesting to analyse because, in addition to their role as a soil engineer (gallery, aeration, etc.), and chemical reactor (recycling of organic matter, trace elements, phosphorus, etc.), it is also a bio-indicator of soil quality and provides information on the characteristics of the soil itself.

Why are we interested in biodiversity in urban infiltration systems?

The biodiversity present in infiltration systems (flora and fauna) is rich and diverse. It can be a relevant indicator of the functioning of stormwater management structures, and this can be achieved through regular observations and inventories and their interpretation.

It is also interesting to note that this bio-diversity can be considered as positive or negative depending on the public and ecosystems considered. Often, it is a question of finding the best compromise between what is desirable for biodiversity, what is technically and economically possible and what is compatible with the lifestyle and perception of city dwellers.

Figure 2: Home-made mosquito larvae emerger - for subsequent adult identification.



SuDS techniques do not contribute to the development of the Tiger mosquito

The fauna living in the water retained in the basins is often not very diverse, but sometimes includes well-known and feared insects, such as mosquitoes.

This is a sensitive issue, as SuDS in urban areas are sometimes suspected of contributing to the development of these mosquito populations, which are a real nuisance and even a potential health risk for local residents.

Within the observatory, mosquito larvae were sampled over several seasons in areas that remained wet in 15 structures: detention basins, infiltration basins, green roofs and bioswales.

The first important conclusion of this study is that wetlands and green roofs, if properly designed and maintained, are not suitable breeding grounds for tiger mosquitoes because the water infiltrates or evaporates in less than 24 hours whereas it takes around 5 days for a larva to develop. As a result, in the basin, only those areas that remain permanently wet, due to their specific function (e.g. settling pit in a detention basins) or lack of maintenance (sediments that impede water evacuation), revealed the presence of mosquitoes. A total of 4 indigenous species were sampled (e.g. *Culex pipiens*), none of which are pathogen vectors. No tiger mosquitoes (*Aedes albopictus*) were found in SuDS.

Another important finding is that the most productive breeding areas for mosquitoes are the most artificial areas, mainly those with concrete bottoms and banks, which are the most productive breeding areas because they have no predators.

The two most important conclusions of this study are that: (1) if properly maintained, bioswales and green roofs are not breeding grounds for these organisms and (2) the emptying time of the structures, generally less than 24 hours, and in all cases less than 5 days, including at low points with residual water, does not allow the development of pathogen-carrying mosquito species.

In Brief...

Plants are mainly distributed in the basins according to hydrological factors, i.e. water availability. The height of the sediment, the typology of the catchment area of the structure (typology, types of activities...) are factors that also influence the presence or distribution of certain plant families or species. The management of structures (cleaning, mowing, etc.) also has a significant effect on plant biodiversity.

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Works 8

Urban water management (wastewater and stormwater) is carried out through infrastructures designed to intercept or collect, store, transfer to the open surface or infiltrate into urban soils the flows of water and pollutants.

These infrastructures are said to be either centralised (installed in or downstream or combined sewerage network) or decentralised (source control stormwater management structures). Their good hydrological functioning and pollutant abatement (reduction, control or elimination) is closely linked to their design.

The long-term observations carried out within the framework of OTHU have made it possible to better understand the processes governing their operation and to formulate recommendations on their design and on the management of the sediments.

In this chapter, the functions of strategic centralised and decentralised urban water management facilities are recalled. Their operation is described. The associated design rules as well as the methods for managing the sediments present in certain structures (in particular the detention-settling basins) are also explained.

8.1

The combined sewer overflow: an ally of sewerage networks, an adversary of the environment?

Gislain Lipeme Kouyi, INSA Lyon

Installed in combined sewer systems, overflows protect downstream structures and treatment plants against overloads caused by certain rain events. But these structures are also criticised for their pollutant discharges, which contribute to the degradation of aquatic environments.

What is a combined sewer overflow?

A combined sewer overflow (CSO) is a diversion structure that allows an upstream flow to be directed to at least two downstream destinations. Installed in a combined sewer system, it protects the downstream system against significant hydraulic overloads during wet weather events. Its main role is to cushion the excess volume that cannot be accommodated at the treatment plant. During an intense wet weather event, the CSOs may discharge untreated water into the aquatic environment (urban wet-weather discharge - UWWD). These discharges contribute to the degradation of the environment (discharge of micropollutants - Weyrauch *et al.*, 2010, discharge of microorganisms including pathogens - Passerat *et al.*, 2011). CSOs were not initially designed to be instrumented and their geometries are not standardised. As shown in Figure 1, they consist of one or more upstream pipes and a bypass chamber that allows part of the upstream flow to be directed towards the natural environment (discharged flow) and another part towards the treatment plant (retained flow).

Their management is essential to control their discharge and to take appropriate measures to protect the receiving aquatic environments. These measures include, for example, the installation of equipment for the recovery of macro-waste, the installation of storm water basins or reed filters as proposed in the ANR SEGTEUP project (extensive system for the management and treatment of urban water during rainfall events - with the support of OTHU). However, their management requires a control of their hydraulic functioning (figure 2), but also and above all, of their polluting discharges.

The functioning and role of an CSO

The hydraulic operation of an CSO depends on its typology and the boundary conditions of the structure, i.e. mainly the flow rates and water levels upstream and downstream of the CSO considered.

CSO categories

The typology of CSOs is difficult to specify. Based on geometry, they can be classified into two broad categories: i) CSO with threshold and ii) CSO without threshold.

i) **Weir CSOs** include those with side or end weirs. These weirs can be "high" or "low", depending on whether the height of the weir or scoop is higher or lower than the top generatrix of the downstream pipe carrying the retained flow to the treatment plant.

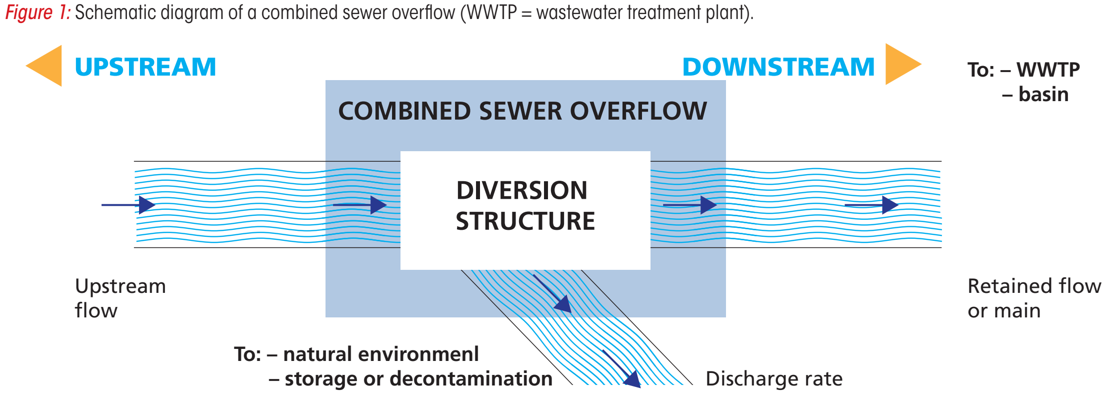
ii) **The CSOs without a weir** correspond, for example, to diffluences: the upstream flow is separated into at least two downstream flows conveyed by two different pipes, one pipe carrying the retained flow and the other the spilled flow. They also correspond to the CSOs with an opening: lateral, frontal or at the invert (bottom of the structure). The CSOs with an opening at invert level are called leaping weir.

Analysis of the functioning of a CSO

The operation can be analysed:

- by setting up measuring instruments: monitoring of water levels, flows, pollutant concentrations (e.g. monitoring of suspended solids or biochemical oxygen demand at 5 days - BOD5);
- using cameras: collection of videos then use of these to visualise and interpret the flows;
- by modelling.

Figure 1: Schematic diagram of a combined sewer overflow (WWTP = wastewater treatment plant).



Most often, these structures operate under riverine, torrential, or a combination of both, resulting in a hydraulic surge (sudden rise in water level in the direction of flow when it changes from torrential to riverine). To know if a flow is fluvial or torrential, the Froude number must be calculated. The Froude number is a dimensionless number that compares inertial forces to gravitational forces. It is given by the formula:

$$\frac{U}{\sqrt{gD_h}}$$

where U is the average velocity of the flow, g is the acceleration of gravity, Dh is the hydraulic diameter of the flow, which is obtained by dividing the wetted cross-section of the flow by the width of the associated free surface (mirror width). If the Froude number is less than 1, it is called a fluvial regime, and if it is greater than 1 it is called a torrential regime.

The functions of a CSO

Regardless of its geometry and mode of operation, a CSO must perform three main functions:

- in dry weather, allow the wastewater flow to pass through without spillage and without reducing the flow velocity too much in order to limit the settling of suspended solids in the effluent;
- in wet weather, allow the reference flow to pass through, i.e. the maximum flow allowed downstream, without discharge;
- finally, to discharge the excess flow in wet weather (above the reference flow) to relieve the network downstream, without loading and without causing decantation in the upstream pipe.

The masses of pollutants released during spills are extremely variable

Two CSOs are monitored within the framework of OTHU: the Grézieu-la-Varenne CSO and the Écully CSO. For the Écully CSO, Figure 3 illustrates the variability of the masses of suspended solids and COD (chemical oxygen demand) discharged. These discharges are sometimes very low but can also reach several hundred kilograms during certain wet weather events. This example shows us the interest of continuous monitoring; indeed, if only a few events are sampled, for example events 3, 19 and 28, this leads to a very high underestimation of the masses of pollutants spilt; conversely, if event 16 is sampled, the assessment will also be biased because this case corresponds to an exceptional spill over the period considered.

Should we continue to install combined sewer overflows?

CSOs have a complex operation and are difficult to equip. Their discharges contribute to the degradation of natural environments. The management of existing CSOs already poses many difficulties in terms of instrumentation and monitoring, and it is therefore legitimate to question the relevance of building new ones. To avoid building new CSOs and thus greatly reduce discharges into the natural environment, priority could be given to source control management systems. The Conscéquans project (financed by ZABR/AERMC) will partly answer this question.

Figure 2 : Lateral CSO in operation (City of Fontainebleau). The discharge rate, indicated by the red arrow, is variable along the weir with a higher discharge rate downstream of the weir - the green arrow indicates the direction of flow and symbolises the upstream flow rate.

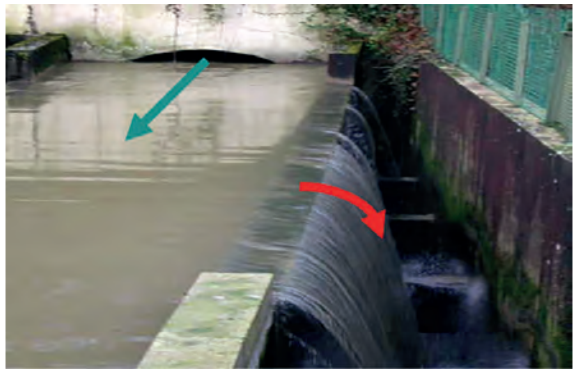
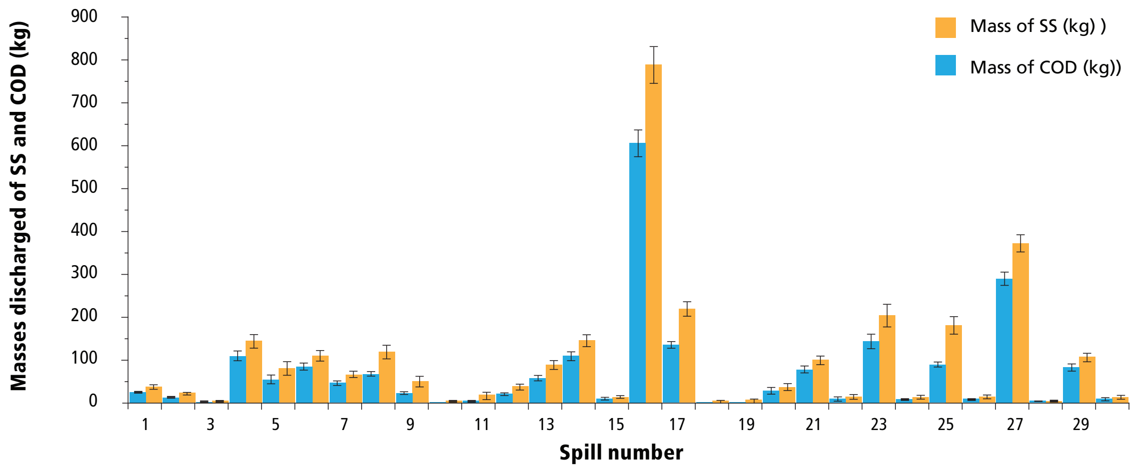


Figure 3: Masses of TSS and COD for the 30 spills measured at Écully in 2004 (Bertrand-Krajewski *et al.*, 2008).



8.2

Intersections in sewer networks: complex flow structures to understand and manage?

Emmanuel Mignot, Nicolas Rivière, Gislain Lipeme Kouyi, INSA Lyon

The recovery of the good ecological status of aquatic environments cannot be achieved without optimising the operation of collection systems. However, the 300,000 km or so of wastewater and sewer networks under our feet are far from being a long, quiet river: the bends, chutes, confluences and diffluences lead to the formation of flows that are complex to measure and to control.

The problem of intersections

Duct intersections are very common structures in sewer systems. They include:

- Confluences (also called junctions), with two upstream flows merging into one downstream flow (Figure 1);
- Diffluences (or bifurcations), with an upstream flow that separates into a downstream flow (often in line with the upstream branch) and a lateral flow (Figure 2).

Confluences result from the fact that sewer systems collect multiple point source discharges and/or runoff and convey them to the treatment plant or other downstream treatment facilities. These waters mix at confluences in increasingly large discharges. Diffluences, on the other hand, are mainly encountered at combined sewer overflows (CSOs) in sanitation. These two types of intersection (confluence and diffluence) lead to the formation of locally three-dimensional and complex flows, with two major problems:

- an impact on the reliability of measurements made downstream of intersections;
- an impact on the behaviour of the particulate and dissolved pollutants transported.

Figure 1: Diagrama **(a)** and photograph **(b)** of flow structures in confluences (top views). (Source INSA Lyon)

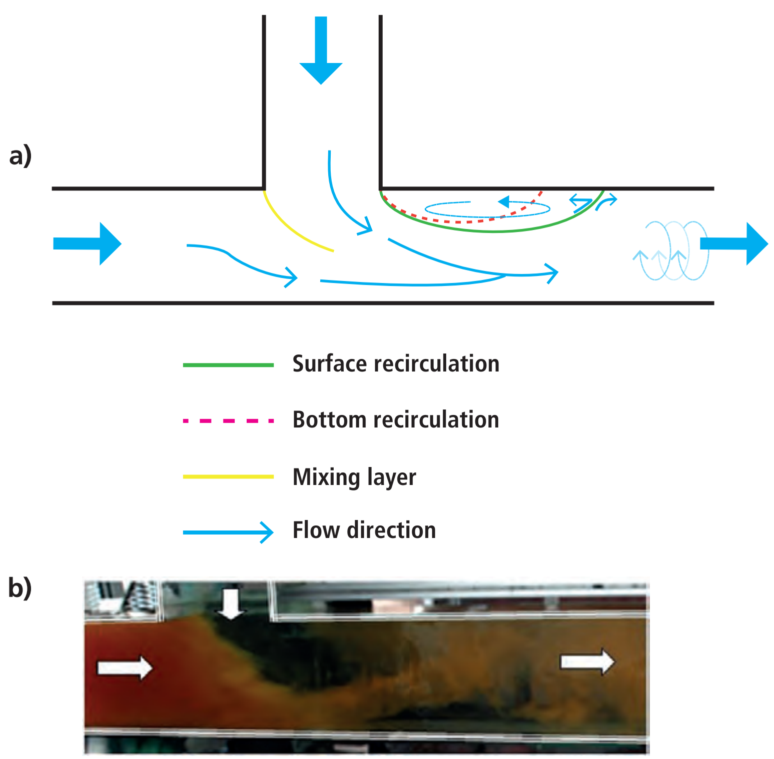
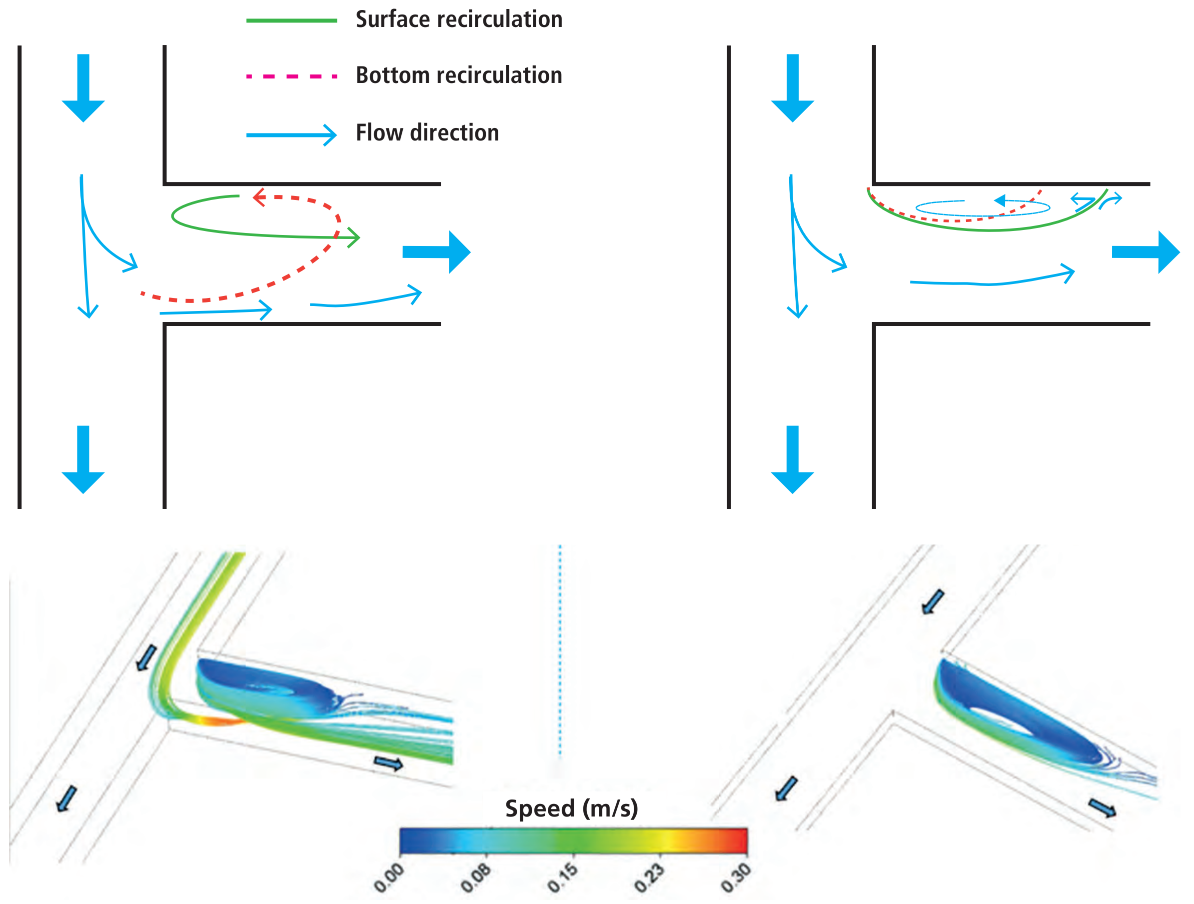


Figure 2: Details of flow structures in diffluences (top) with an illustration of the streamlines (after Momplot *et al.* 2017).



The flow pattern depends on the type of intersection and on the hydraulic and geometrical characteristics of the network

Although confluences and diffluences can also be found in rivers (and these are the subject of numerous studies), their characteristics are different in sewer networks, particularly because they are manufactured structures:

- the shapes of the sections are often very simple: rectangular, trapezoidal, circular or ovoidal sections are common;
- the width to depth ratios are low, of the order of 1 (rather 100 in rivers);
- the corners are generally sharp and clear at intersections.

One might imagine that the flows are also simple, but this is not the case!

The flow patterns that occur in these intersections differ greatly between confluences and diffluences, and according to the geometry (typically the angle of the intersection) and to the discharges involved. The hydrodynamics of these flows has been extensively studied in the laboratory, especially for simplified cross-sections with a large intersection angle and large water depths, typical of sewer systems. In particular, the following complex flow structures can be found.

In confluence

At confluences (Figure 1), a recirculation zone forms within the downstream branch (on the side of the lateral branch), accompanied by an acceleration zone on the remaining part of the section (Mignot *et al.*, 2012). Furthermore, if the velocities of the two upstream flows differ sufficiently, a mixing layer is observed at the interface between the two flows within the intersection. Finally, complex secondary flows take place in the downstream branch, which can persist over long distances; this downstream recirculation can notably take the form of a helix occupying most of the section.

In diffluence

In diffluences (Figure 2), a large recirculation zone characterises the lateral branch, which can take two different forms depending on the geometric conditions and the upstream flow. The flow is strongly three-dimensional, and is subject to a greater centrifugal force at the surface than near the bottom. This makes it easier for the flow to turn towards the side branch near the bottom than at the surface. This process is responsible for the Bulle effect, i.e. a fraction of the sediments flow rate entering the side branch that can be significantly higher than the fraction of the liquid discharge.

Intersections make flow measurement complex

From an operational point of view, the first problem linked to intersections concerns the measurement of flow. This is complicated by the presence of three-dimensional flows, particularly because it is difficult to link the velocity measured locally with the mean velocity, i.e., once multiplied by the cross-sectional area, the liquid discharge.

Regarding the measurement of flow at confluence, El Bahlouli *et al.,* (2017, Figure 3) showed that, when using a bottom-mounted Doppler sensor, a distance of about 10 times the duct width downstream of the confluence is required to estimate the discharge with an error of the order of 5%, for an average aspect ratio (width to depth ratio between 2 and 4). However, if the flow is shallow or very deep ("width/depth" ratio < 2 or > 4), this error increases to 15 or even 20%, even for much greater distances.

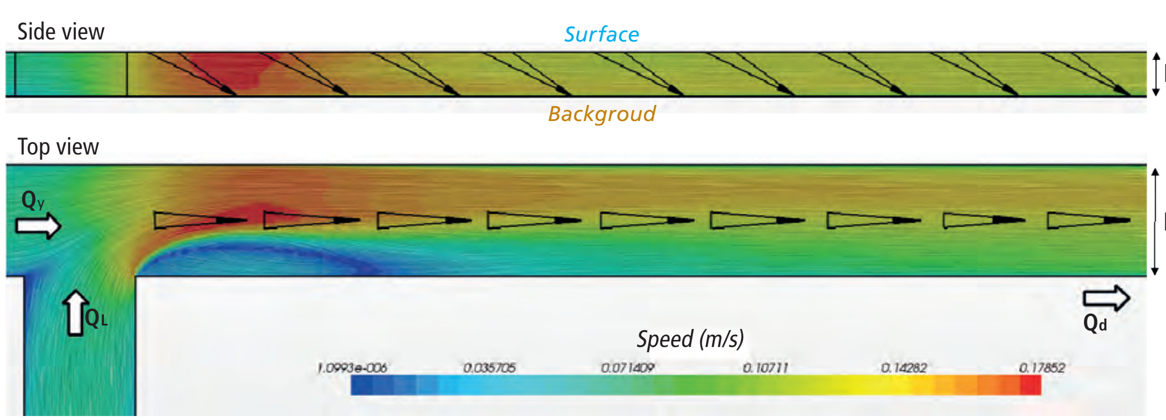
In the diffluence, the measurement of the flow within the lateral branch is made particularly complex by a very marked three-dimensional character of the flow and the presence of the recirculation zone. The estimation of the discharge, in particular within CSOs, requires the use of specific structures, such as Venturi channels or calibrated devices such as the DSM-flux type (see Question 2.6: *How to measure the discharge from a combined sewer overflow?*).

Intersections can cause an accumulation of pollutants

With regard to particulate transport, laboratory work - some of which is carried out within the framework of OTHU - has confirmed the presence of specific deposits in the storage zones, for both diffluences and confluences. These storage areas, particularly within the recirculation zones, can be the source of an accumulation of pollutants: floating pollutants on the surface, particulate pollutants deposited on the bottom, or dissolved pollutants.

In addition, many authors are beginning to look at the efficiency of mixing downstream of confluences, this mixing being made particularly complex by secondary flows in the downstream branch of confluences and in the side branch of diffluences (Figure 1a).

Figure 3: Velocity field of the flow in a confluence, with in black the measurement volumes seen by Doppler sensors located at different distances from the confluence (source : El Bahlouli *et al.,* 2017).



In Brief...

Sewer networks have many peculiarities, notably pipe intersections, which make the flows locally highly three-dimensional with strong velocity gradients. This leads to difficulties in measuring the discharges but also to potential accumulations of pollutants in recirculation zones.

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8.3

Sustainable Drainage Systems – a relevant alternative

Sylvie Barraud, Hélène Castebrunet, Gislain Lipeme Kouyi, INSA Lyon – Elodie Brelot, GRAIE

Sustainable Drainage Systems (SuDS), referred to as Alternative Techniques (AT) in France, include a multitude of solutions for integrated and decentralised management of urban stormwater management. They are based on solutions favouring infiltration, temporary storage and/or evapotranspiration, such as nature-based solutions for example.
There is a growing tendency to rectify the terminology to speak of source control management solutions or decentralised solutions to go beyond a purely technical vision based on a catalogue of preconceived technologies. The idea is to manage rainwater as a resource for urban development and not as a technical problem to be got rid of.

A variety of solutions

SuDS as well as AT refers to a set of solutions that respond to a major evolution in the strategy of stormwater management in development since the 1970s: from a strategy based on the rapid evacuation of drained stormwater through pipe networks, we have progressively moved to a strategy of runoff control and management as close to the source as possible (source control).

In France, the first responses, particularly in a context of urban expansion and new towns, were the construction of detention and infiltration basins, often at the outlet of a network (end-of-pipe or centralised solutions not very well integrated in urban areas (photos 1, a and b). Since then, and especially in a context of densification and reconstruction of the city on the city, source control solutions have been developed, in multiple forms both in terms of geometry and materials, such as vegetated infiltration bioswales, green roofs, rain gardens, pavements with a reservoir structure, trenches, tree pits (photos 1, c and d).

The use of these management approaches is widely shared internationally and can be found under such terms as: AT (Alternative Techniques), LIDS (low impact development systems), BMPs (best management practices), SuDS (sustainable drainage systems), WSUD (water sensitive urban design), SCM (stormwater Control Measures) or NBS (nature based solutions) (Fletcher *et al.*, 2014).
The term "Alternative Techniques" used in France for sustainable drainage systems is not that ideal, for two reasons:

- because a "technique" has a main service function, which would be stormwater management, whereas, beyond stormwater management, the importance and diversity of other functions and services rendered go far beyond the simple response of a technical work,
- because a solution presented as an "alternative" (i.e. to all-pipe) always refers to this traditional mode of evacuation which should not constitute a reference anymore.

The other terms used, such as SuDS, LIDS and BMPs, are not that ideal either and have their own issues. Their relevance is discussed in Fletcher *et al.*, 2014.
Thus, the generic terms decentralised, or source control stormwater management strategies vs centralised solutions will be used to cover the set of solutions addressed here.

Multiple functions

Source control stormwater management strategies are supposed to meet several objectives:

- control flood risks;
- ontribute to the natural recharge of groundwater and rivers, and therefore of water resources;
- preserve the quality of natural environments and water resources;
- limit the costs of collective water management infrastructures;
- promote/optimise facilities by making them multi-functional;
- make cities more resilient to global change in particular when vegetated NBS are used.

The multi-functionality of decentralised stormwater management solutions allows the fulfilment of different levels of functions, including:

Primary functions and services

- avoid run-off, concentration of water and pollutant flows, and adapt to different climatic events;
- promote water detention, infiltration, evaporation and evapotranspiration and, if runoff occurs, slow it down and temporarily store water to control downstream flows;
- reduce stormwater pollution, through processes of settling, filtration, adsorption and natural biological degradation.

Functions vis-à-vis the overall system

They relieve traditional stormwater management systems by reducing the impermeable areas or by disconnecting stormwater from existing pipe networks. This helps to avoid or limit the discharge of large amounts of water into watercourses during rainy events, thereby reducing the discharge of pollutants and minimising the geomorphological and biological disturbance of these watercourses.

They also avoid an exponential increase in the size of the structures and operating constraints, thus reducing costs.

Co-benefit functions

Far from being negligible, these functions are real added values. They can indeed be:

- support of biodiversity and contribution to urban coolness islands in particular when vegetated nature-based-solutions are used;
- integration in multi-functional spaces promoting landscape quality enhancement (e.g. sports grounds, urban parks, introduction of green spaces in dense urbanised areas, etc.).

Alternative technique… the alternative is far from being just technical and is gradually becoming the main way to manage rainwater.

Photo 1a: Non-integrated centralized infiltration basin (Django-Reinhardt basin, Chassieu).

Photo 1b: Centralized infiltration basin (IUT Villeurbanne).

Photos 1c et 1d: Bioswales collecting water from bicycle paths and pedestrian walkways (INSA campus, Villeurbanne).

c

d

What has OTHU studied and contributed?

From the outset, OTHU researchers have worked on evaluating the performance of these stormwater management systems, taking advantage of its strong interdisciplinary approach and long-term monitoring to measure their impacts. However, OTHU operational and research partners first focused on the monitoring of centralised detention-infiltration systems, as they are particularly developed in the Lyon metropolitan area, with high stakes on their possible effects on groundwater. This is the case of the Django-Reinhardt basin (basin infiltrating on less than one hectare the stormwater drained by a surface of 185 ha, more than 70% of which is impermeable), as well as more than ten other basins of the same type in eastern Lyon. The monitoring led to the deployment of highly innovative and, above all, highly integrated metrological equipment (combining measurements of different kinds). The research provided answers to the following questions:

- the role of pre-treatment devices on the management of water, solids (decantation) and pollutant flows;
- the physico-chemical, microbiological characterisation and then the treatability of the sediments trapped in these devices or at the bottom of infiltration basins (see Chapter 5: Contaminants);
- the role of centralised infiltration devices on pollutant trapping and the potential bio-physical-geo-chemical impact of stormwater infiltration on the groundwater (see Chapter 6: Impacts);
- the evolution of clogging over the long term and the role of vegetation and soil invertebrates in this evolution, (see Question 7.4: *What is the role of vegetation in the clogging of infiltration systems?* and Question 7.5: *What is the role of fauna in the clogging of infiltration systems?*);
- the long-term trends, particularly in surface and groundwater temperatures, in relation to changes in air temperatures;
- the definition and evaluation of performance indicators.

With its knowledge and expertise, OTHU then engaged in the specific instrumentation of decentralised management solutions.

In addition to the hydrological aspects, the issue of multifunctionality was also addressed from a sociological (uses) and anthropological (practices of the organisations responsible for management) point of view. The question of the obstacles to the adoption of these solutions was also addressed. The analysis of the perceptions and modes of representation of these devices and their treatment function by different categories of actors and users was further developed (see Chapter 1: Strategy).

More recently, research has compared source control systems with centralised systems in terms of their role with respect to micropollutants (metals, pesticides, PAHs, alkylphenols and derivatives and brominated flame retardants). (See Question 8.5: *How effective are sustainable drainage systems with regard to micropollutants?*).

Today, research on the performance of source control structures is continuing and is being extended through the implementation of process modelling within the structures (internal processes describing their behaviour with respect to water and pollutant flows) or modelling on a larger scale (district or city, for example) to assess the impact of decentralised urban scenarios. The effects of vegetation on the microclimate of neighbourhoods drained by vegetated decentralised solutions are also being studied.

8.4

What are the factors influencing the operation and design of an infiltration structure?

Gislain Lipeme Kouyi, INSA Lyon – Laurent Lassabatere, ENTPE – Sylvie Barraud, INSA Lyon – Nelly Maamir, Lyon Metropolis – Rafael Angulo Jaramillo, ENTPE

Whether they are centralised (basins) or at the source (source control: bioswales, infiltration trenches, permeable concrete car parks, etc.), infiltration structures must allow rainwater to be infiltrated while retaining the pollutants transported by this water.
The performance of these structures is highly dependent on certain factors related to their design and maintenance, which it is essential to know and control to achieve optimal operation.

Filtration and infiltration...

The operation of an infiltration structure can be characterised in technical terms by two main functions: the "infiltration" function of water and the "filtration" function of pollutants. The first function is the infiltration of rainwater as a means of drainage in urban operations to protect against a given level of flood risk. Infiltration of water can also contribute to the recharging of the water table, if any, and/or to the recharge of the surface layers of soil and the vegetation therein. The devices must be designed to avoid prolonged stagnation of water on the surface and thus delay clogging. The second function, commonly referred to as filtration, even if this is an abuse of language (see question 7.2), aims to promote the detention and/or degradation of pollutants in the surface soil horizons so as to transfer as little as possible of the pollutants from runoff.

The evaluation of short and long term hydrological and pollutant interception performance (including clogging effects) has been the subject of much research at OTHU for centralised schemes. The main results obtained on the different aspects are presented in Chapter 7.

More recently, research has also investigated the question of the performance of source control infiltration systems (OFB-Micromegas project carried out in connection with the Matriochka project in Nantes and Roulépur in Paris, which are the result of the OTHU,OPUR and ONEVU observatories). The results are presented in the Question 8.5. *How effective are alternative structures in regard to micropollutants?* To date, there are still unknowns concerning the operation of source control structures in the long term and the impact of certain design choices and maintenance strategies that would make it possible to develop rigorous asset management methodologies.

Nevertheless, this research has highlighted a number of factors influencing the operation of the structures, which need to be taken into account in the design and operation phases.

Factors affecting design and the operation of an infiltration structure

The ratio between the infiltration surface of the structure and the surface area of the drained catchment (active / contributing surface)
The idea is that one should not try to infiltrate on small surfaces quantities of water from catchment areas draining large surface areas. Infiltration works are in fact "concentrators" of water and pollutant flows, especially when they are centralised. The concentration effect is all the greater as the surface area of the drained catchment is larger than the infiltration surface area.

This ratio should be at least a few percent. It is sometimes preferable to have a high ratio, but this obviously raises questions about the availability of space to infiltrate under good conditions.

The characteristics of the catchment areas
The activities and the size of the drained catchment area obviously condition the flows and the nature of the pollutants/contaminants. For chemical pollutants, it is unfortunately not possible to associate, even qualitatively, a type of urbanisation with approximate pollution levels. Concentrations as well as masses are extremely variable from one event to another with a variability greater than that from one site to another.

However, it will be important to pay attention to possible inputs of pollutants (e.g. use of plant protection products on the structures or in the vicinity) or to inputs of fines (nearby building sites, types of eroded surfaces, etc.) so as not to clog up the infiltrating surfaces prematurely.

Soil properties under the infiltration structure
The hydraulic conductivity (permeability) of the soil is obviously a key factor. First of all, the soil must have sufficient hydraulic conductivity (permeability). In addition, the unsaturated zone must be thick enough. This zone acts as a buffer zone between the soil surface and the water table and allows most of the degradation and detention of pollutants. It is this zone that mainly provides the "filtration/detention" function for pollutants. A minimum thickness of 1 to 2m is often agreed upon.

The nature of the soil must also be conducive to the presence of water: some soils, whether superficial or not, have mechanical behaviours that prohibit infiltration or at least limit it. In terms of stability, the risk of soil dissolution can be significant in gypsum soils for example and prohibits any punctual and centralised infiltration. Similarly, the phenomenon of shrink-swell can lead, in certain soils such as soils rich in clay, to mechanical disorders in the surrounding structures. This phenomenon is not necessarily prohibitive as it can also favour the stability of structures. Each soil must be studied on a case-by-case basis.

Inputs and their impact on soil properties
The contribution of suspended matter by stormwater runoff is one of the factors that leads to a progressive clogging of the structure. A sedimentary layer can form on the surface and thus slow down infiltration and facilitate the settling of solid matter on the surface. This surface layer therefore reduces infiltration and harms the "infiltration" function. At the same time, as it is made up of fine particles, it favours the adsorption of certain pollutants and is therefore beneficial for the "filtration" function. Note that clogging can also be biological (see Question 7.3: *How does an infiltration system get clogged and how long does this take?).*

In addition, the presence of water in the soil and the surface sedimentary layer makes these places suitable for plant colonisation. Vegetation has a strong influence on the functioning of a structure. The development of the root system improves the "infiltration" function. Indeed, by developing in the sediment and the underlying soil, the roots create macropores, favouring the infiltration of water towards the lower horizons. This positive effect on the "infiltration" function can be translated into a potential negative effect on the "filtration" function, with a risk of pollutant migration linked to the creation of preferential flow paths. However, overall, the observations made in OTHU show that the presence of vegetation has a beneficial effect, for both centralised and decentralised systems, this is linked to the soil/vegetation complex which is particularly effective in combating clogging and retaining particulate pollution (see Question 7.4: *What is the role of vegetation in the clogging of infiltration systems?*).

Moreover, the evolution over time of the inputs and the ecological continuity lead to the constitution of a dynamic ecosystem favourable to the development of biodiversity and strongly dependent on local conditions (geology, climate, etc.). These ecosystems are also a priori subject to global changes and in particular to the current climate warming. Studies carried out on OTHU over long periods show that the effects of temperature variations are all the more sensitive the more centralised the systems are with insufficient unsaturated zones (see in particular question 6.1: *What is the impact of stormwater infiltration basins on groundwater?).*

Recommendations for infiltration works

To ensure that these infrastructures function properly, we recommend that they be installed on permeable surface geological formations. In the Lyon region, a large part of the reservoirs is based on a very permeable fluvioglacial deposit, which allows this condition to be met. It is also necessary to ensure that the "infiltration" function is maintained over time by monitoring clogging and its negative effect on this function. At the same time, it must be ensured that the infiltration capacity does not affect the filtration and treatment capacity of the structure so that the risk of pollution of the water table is reduced. It is commonly accepted that maintaining at least one metreof unsaturated zone in the case of a centralised infiltration structure will ensure that most of the pollutants are filtered. It is also important to ensure that the centralised infiltration structure is located away from vulnerable areas in terms of water quality (catchment wells, etc.). Infiltration works should be operated considering the evolution of the system as a whole, including the effects of vegetation, global changes and anthropogenic forcing.

Source control structures have a higher filtration and detention capacity for micropollutants
Various stormwater management systems were compared in terms of their "infiltration" and "filtration" functions. For the latter, we compared three source control management systems (car park equipped with a pavement with a reservoir structure with a permeable coating, an infiltration trench and a bioswale) to a traditional impermeable car park in order to get an idea of the level of performance in terms of micropollutant removal of infiltration systems compared to an impermeable traditional system. The following findings were established at the end of this study: (see also Question 8.5: *How effective are alternative structures in regard to micropollutants?*).

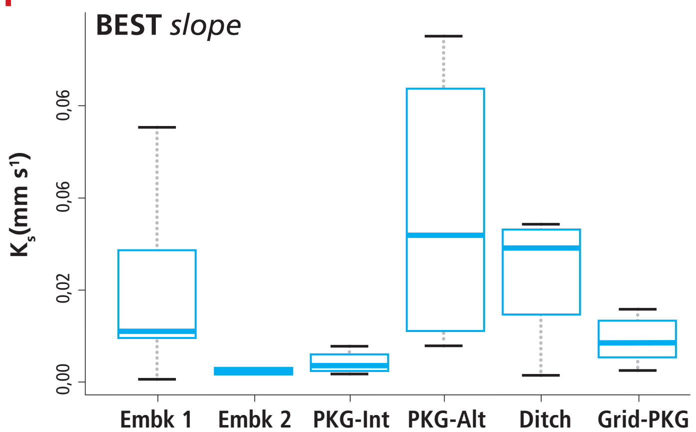
- a significant effect on water infiltration and the reduction of runoff volumes to be managed;
- very effective removal of particulate and even dissolved micropollutants in these small systems;
- higher efficiency for decentralised than centralised systems;
- even higher efficiency of vegetated systems.

A vegetated infiltration system with topsoil as a support seems to be more effective. These results need to be confirmed in the long term.

The Beerkan test to evaluate the infiltration capacity of draining surfaces or the bottom of structures
Many solutions use draining surface coatings (permeable asphalt, permeable concrete, permeable paving stones, grass slabs, etc.) or infiltrate through surface of natural or added soils which must be checked periodically for their permeability.

The Beerkan test is used to assess the permeability of such surfaces. It consists of placing a ring on the ground and pouring successive volumes of known water (often 100 or 200 ml) into the ring. The infiltration time is then noted for all volumes of water. The ratio of "volume of water infiltrated" to "infiltration time" quantifies the infiltrated flow and gives a good idea of the infiltration capacity of the pavement or the infiltration surface present. This technique is very simple. It can be easily deployed on a larger scale to compare infiltration

Figure 1: Ks (saturation hydraulic conductivity) estimates for various techniques allocated to stormwater infiltration on the EcoCampus (Bouarafa *et al.*, 2019).



- **Embk1** and **Embk 2:** vegetated garden slope reference structures.
- **PKG-Int:** Intact asphalt drainage car park.
- **PKG-Alt:** Drainage car park in weathered asphalt.
- **Ditch:** Ditch
- **Grid-PKG:** Car park with a grassed alveolar covering (or grassed slab).

Photo 1: Minerve vegetated infiltration basin on the Portes des Alpes site - Lyon Metropolis (source: UCBL Lehna E3S).

areas between them (spatial variability within a structure or comparison between structures). The test is however more adapted to small permeable surfaces found in source control infrastructures where the permeable surface is flat and not very extensive.

For example, tests were carried out for various permeable pavements or structure surfaces on the La Doua Ecocampus site (figure 1): on surfaces of ditches, trenches, draining car parks and platforms, etc. and on natural control surfaces (grassy surfaces). The aim was to compare these types of surfaces in terms of infiltration capacity. It was found that draining car parks guarantee a high level of permeability after about ten years. On the other hand, the honeycomb structures do not have better permeability than the car park permeable pavements and are less permeable than the adjacent grassy surfaces.

It should be noted that for large, centralised structures (a few thousand m²), a method of measuring clogging "in situ" has been developed by OTHU teams and gives a realistic idea of their overall clogging conditiions.

Recommendations to limit clogging in the design of structures

The ANR Ecopluies programme has resulted in a set of recommendations for the feasibility, design and management of rainwater infiltration structures in urban areas (Barraud et al., 2006). Thus, to limit clogging, it is recommended that the design of the structures:

- to take into account mainly the clogging of the bottom and less that of the edges;
- to take the highest possible "Infiltration Surface/ Contributing surface " ratio (never go below 1%);
- for centralised structures, to avoid the permanent supply of water in dry weather, which favours the development of biofilm;
- protect the bottom of the structures with vegetation with sparse roots or with granular material that protects against light and therefore against biofilm development;
- when rehabilitating a site, to control any sediment removal and earthmoving operations, so as not to bury clogged layers and compact the soil.

8.5

How effective are sustainable drainage systems in regard to micropollutants?

Sylvie Barraud and Hélène Castebrunet, INSA Lyon

If you were disappointed not to be able to see concrete results in Question 2.5 on the problems of measuring the effectiveness of Sustainable Drainage Systems (SuDS) in terms of micropollutant trapping, here is something to ease your frustration and to show you the trends observed.

SuDS reduce contamination of discharges

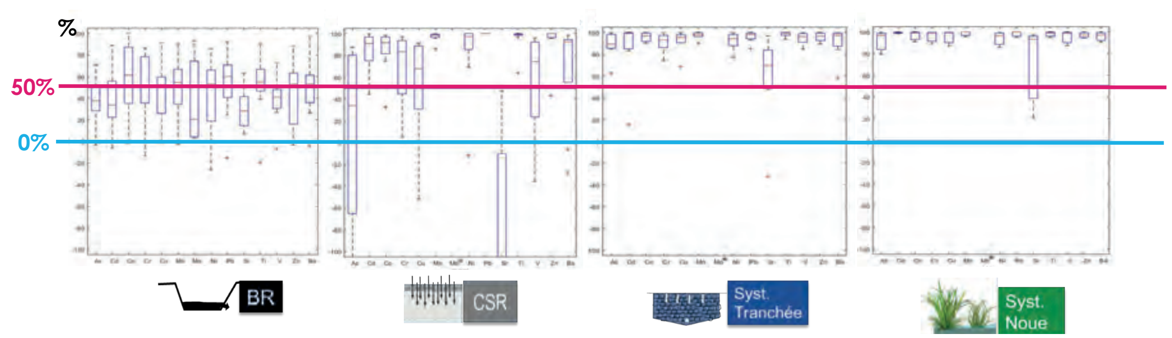
SuDS as a stormwater management solution are promoted as they are supposed to reduce water flows and contamination of surface and groundwater environments:

- either by decantation: in the case of centralised systems such as detention-settling basins;
- or by limiting emissions, leaching and/or by trapping, filtration, decantation: in the case of source control systems such as bioswales, pavements with a reservoir structure, green roofs, wells, biofilters, trenches, tree pits, etc.

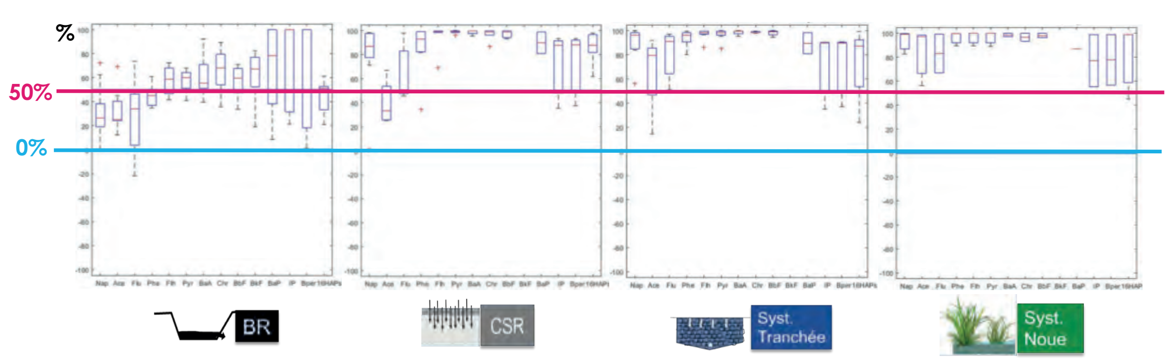
But are these SuDS actually effective against micropollutants?

Figure 1: Reductions in mass per active square metre for all sites and for the four sites and for the families of micropollutants.
Detention basin abatements are evaluated between inlet and outlet (comparison of a traditional pipe system vs. detention basin outlet).
The reduction of pollutants on the source control devices are evaluated in relation to a reference surface (comparison of a traditional car park vs. a car park equipped with a permeable reservoir pavement, a bioswale or a gravel trench). (Source: Garnier, 2020).
RB = Detention Basin, PRP = Permeable reservoir pavement, GT = Car park with gravel trench, BS = Car park with bioswale.

Reduction in mass/active m² of Metal discharges



Reduction in mass/active m² of PAH discharge



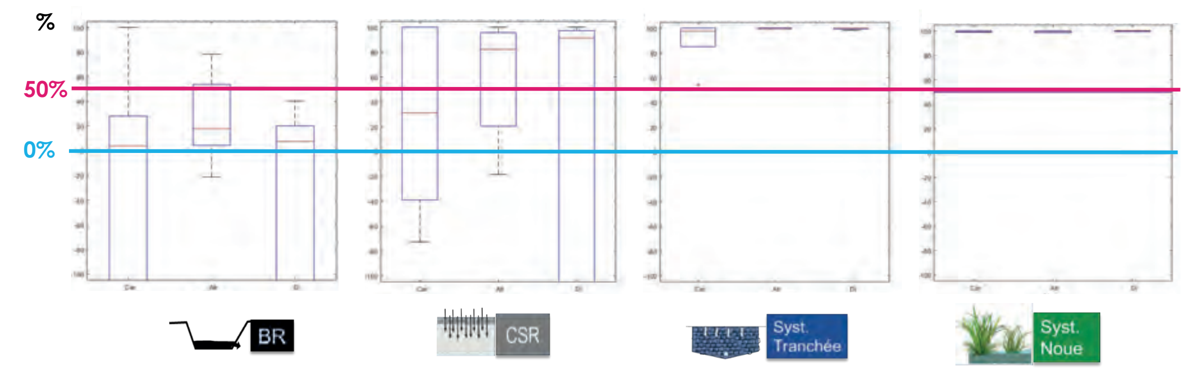
List of PAHs analysed: Nap | Ace | Flu | Phe | Flu |Pyr |BaA |Chr| BbF |BkF| BaP |IP| Bper| 16HAPs

The evaluation principle: a comparison of SuDS and traditional structures

The effectiveness of SuDS with regard to micropollutants is one of the issues that OTHU has been addressing since 2010. Its evaluation, as discussed, is concerned with the gain or loss of performance compared to a traditional rainwater management system. In other words, OTHU researchers wanted to know whether sites using SuDS discharge more or less micropollutants than sites without them.

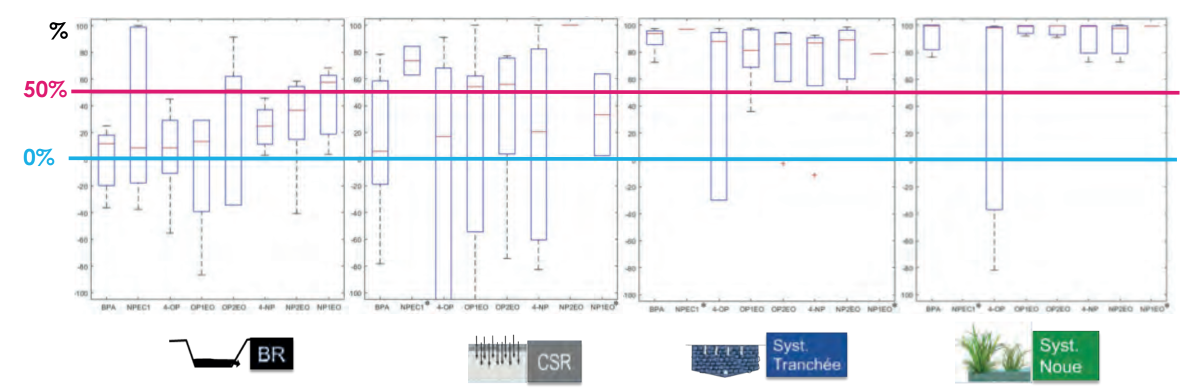
For this purpose, the event efficiency was analysed in terms of water volumes, concentrations and masses of micropollutants (per active square metre) so to compare the devices with each other. Micropollutants are considered from six main families (PAHs, metaloid/metals, bisphenol A, alkylphenols, pesticides and PBDEs) selected for being frequently detected in rainwater (see Question 5.1: *What pollutants are found in urban stormwater?*).

Reduction in mass/active m² of Pesticide discharges



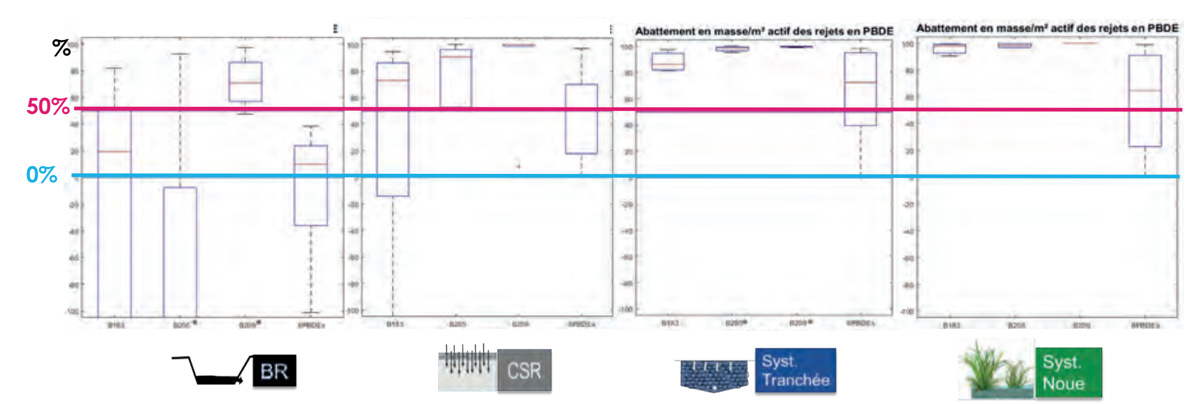
List of Pesticides analysed: Carbendazim, Atrazine, Diuron

Reduction of Alkylphenol discharges in mass/active m²



List of Alkylphenols analysed : BPA, NPEC1, 4-OP, OP1EO, 4-NP, NP2EO, NP1EO

Reduction in mass/active m² of PBDE releases



The research was based on monitoring:

- of three source control systems draining runoff water from car parks on the LyonTech la Doua campus in Villeurbanne: Two are car parks of the same construction of approximately 300 m², the water from which is evacuated, one by a planted swale (bioswale) and the other by a gravel trench. The third is a car park with a reservoir pavement with a permeable surface of 94 m². The structures are completely sealed at the bottom for experimental purposes. A reference zone with a traditional asphalt pavement allows a comparison of water and pollutant flows;
- a centralised system (Django-Reinhardt detention basin) which drains 185 ha, about 70% of which is impermeable, by means of a separate network. Here again, the comparison with a traditional system (stormwater sewer system flowing into the basin) is used as a reference for measuring efficiency.

The main trends observed

Micropollutants are present in the stormwater collected by traditional systems used as a reference for the study.

Micropollutants are present both at the inlet of the detention basin (i.e. at the outlet of the catchment area) and at the outlet of the impermeable car park. All the substances searched for were detected at least once at one of the sites, with the exception of dibenzo (a, h) anthracene (a PAH).

The water is unsurprisingly loaded with metals or metalloids (As[1], Cr[1], Cu[1], Pb[2], Zn[1] and Cd[3]), heavy ones (Fluoranthene[2], Benzo (b) fluoranthene[3] ou Benzo (g, h, i) pérylene[3]) with concentrations close to or exceeding the EQS values (Environmental Quality Standard)[4]. On the other hand, they are relatively lightly loaded (values often below the EQS) with pesticides, alkylphenols and PBDEs, even though these three families of pollutants are very often present. All of the concentrations measured are within the range of literature values when they exist.

Finally, there is no major difference between the concentration ranges observed at the outlet of the centralised catchment (inlet of the detention basin) and at the outlet of the source control structures. For some substances, however, higher median concentration values can be observed at the inlet of the detention basin, which can be explained by the large size of the catchment area.

Source control techniques appear to be more effective than the centralized system in reducing micropollutant flows

The efficiencies (in mass per active square metre) of the detention basin are, for almost all substances, lower than that of source control structures (Figure 1). In fact, the settling capacity of the basin, although it has a significant impact on pollution in the particulate phase (substances mainly bound to suspended solids such as metals, PAHs or some PBDEs), appears to be less effective than the processes occurring during the percolation of water in infiltration source control systems, all families of pollutants taken together. For example, the vegetated substrate in the swale is particularly effective. However, one should not jump to conclusions about the role played by vegetation (see Question 7.2: *What role does the soil play in trapping pollutants?*): the decrease come mainly from the vegetated bed (and not from the vegetation alone) coupled with a high-volume abatement (water absorption).

It should be noted that for substances that are mainly in the dissolved phase, such as pesticides, the concentrations are not reduced by the detention basin. For some of them (carbendazim, diuron), releases have even been observed. In this case, the reduction of emissions will be achieved by reducing the volumes discharged or, better still, by stopping the use of pesticides.

Finally, the detention basin, although less efficient regarding micropollutants, remains more efficient than the traditional network system, particularly for metals and PAHs, with positive efficiencies (Figure 1).

Volume reduction is an effective lever for limiting polluting discharges

The effectiveness of the devices studied in terms of micropollutant abatement is measured, for each rainfall event, by their ability to reduce concentrations (biophysical-chemical processes) and the quantities discharged in mass. The latter obviously depends heavily on volumes, the masses being calculated for each event as the product of an average event concentration by the volume. Thus, reducing the volumes of water discharged is a first step in limiting the pollutant flows leaving the systems.

The detention basin is watertight and therefore retains a small volume of water after each rainevent. Thus, only the settling treatment process reduces the flow of pollutants. For this reason, the efficiency of the basin is only considered to be adequate for particulate pollutants such as metals and PAHs. Conversely, the car park equipped with the bioswale (even if it is sealed at the bottom) shows very high reductions (close to 100% in median) for practically all the selected pollutants.

The substrate of the swale often absorbs the entire volume generated by rainfall (63% of the rainfall measured), showing its high water detention capacity for small amounts of rainfall which is evaporated afterwards.

[1] Substance to be monitored according to the order of 17 October 2018

[2] Priority substance according to the Water Framework Directive, dir 2013/39/EU

[3] Priority hazardous substance according to the Water Framework Directive, dir 2013/39/EU

[4] EQS = The Water Framework Directive defines, in its Article 2, the Environmental Quality Standard (EQS) as "the concentration of a pollutant or group of pollutants in water, sediment or biota that must not be exceeded in order to protect human health and the environment".

In Brief...

Volume reduction is a real lever for limiting micropollutant flows. It can therefore be judicious to develop a strategy of volume reduction by using infiltration and vegetation. The vegetation system performs well for most substances. The metropolis of Lyon has understood this: it recommends disconnecting water from the network for rainfall of less than 15 mm (80% of annual rainfall in its territory) and widely promotes the concept of the "permeable city".

TO GO FURTHER

- **Garnier R.,** (2020). Alternative stormwater management systems: Contribution to the analysis of joint performance in quantitative hydrology and micropollutant sequestration. Comparison of At the source - centralised system. PhD thesis from INSA Lyon. 318 p. – lc.cx/garnier2020 (in french)
- **Sébastian C.,** (2013). *Stormwater detention basin in urban environment: performance in micropollutant trapping.* PhD thesis from INSA Lyon. 318 p. – lc.cx/sebastian2013 (in french)

8.6 How to design an effective sediment and particulate pollution trapping basin?

Gislain Lipeme Kouyi, INSA Lyon

Detention-settling basins consist of storing stormwater runoff for a certain time period in order to allow the water to be cleaned by settling. But for these structures to be truly effective, several factors must be taken into account during the design phase.

What is a settling basin?

Structures dedicated to managing water flows and ensuring the depollution of stormwater runoff through solid-liquid separation by settling are called detention-settling basins. The detention-settling basins studied in the framework of OTHU are called "dry" (as opposed to "wet").

The widely used "dry" basins are designed to drain after 24 to 30 hours so that they can be operational during the next rainfall event. In general, detention-settling basins have three main functions that should be considered in the design of the basin:

- protect downstream areas from flooding;
- to allow for runoff cleanup through solid-liquid separation by decantation;
- avoid the resuspension of the deposits.

These last two functions are complementary to reduce the risks of pollution downstream, whether surface water or groundwater, and to limit the risks of clogging if an infiltration basin is connected downstream.

There are several key factors to consider

To estimate the dimensions of these basins for hydraulic purposes, several methods are commonly used in France: the rainfall method[1], the volume method[2] or to dimension and simulate them: the flow method[3].

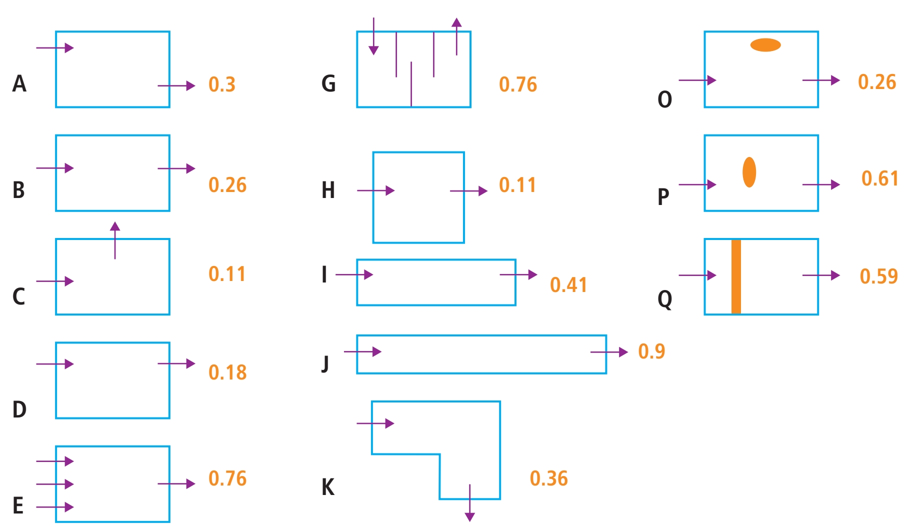
However, these methods do not allow for the evaluation of any pollution treatment efficiency. One of the major aspects to take it into account qualitatively is to try to ensure quiet (non-turbulent) conditions in the detention basins.

An earlier study based on modelling (Persson, 2000) shows the impact of pond design on pond efficiency; the ponds were all the same capacity, input load and output regulation level (Figure 1). It identified concrete elements that could be used in a simple way:

- **Number of inputs:** it is preferable to have several inputs rather than just one (Model E, Figure 1).
- **Basin geometry** with a high length to width ratio In the case of rectangular basins, it is preferable to build a basin that is longer than it is wide (in model J in Figure 1, the basin is 12 times as long as it is wide).
- **Interior design:** in order to reduce turbulence, slow down the flow and lengthen the drying time, it is advisable to compartmentalise the pool by installing partitions or to install baffles (G), although the latter configuration is not optimal for maintenance.
- **Regulation:** the output flow rate must be regulated correctly to avoid short-circuiting and thus avoid very short residence times (less than 4 hours). Several regulation devices exist, such as valves equipped with a float (see Figure 3). It can be added that the output flows also benefit from being distributed.

[1] lc.cx/methodepluies – [2] lc.cx/methodevolumes – [3] lc.cx/methodedebits

Figure 1: Examples of geometry for the case of detention ponds (plan view) according to (Persson, 2000). The indicator gives an overall score to the basin in terms of efficiency. The recommended models are : E, G, I, J, P, Q. The depths are included between 0.5 and 2 m. The length to width ratios for the E, I and J models are 2, 4 and 12 respectively.



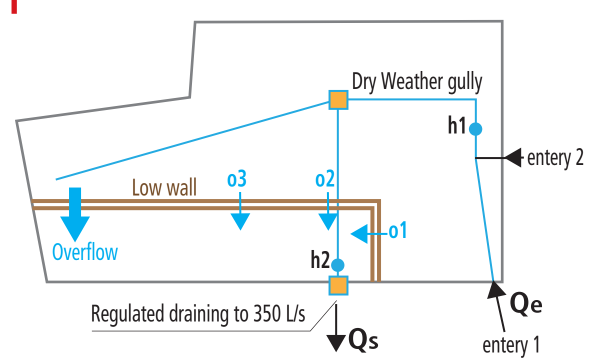
A basin rehabilitated to improve its performance

The Django-Reinhardt detention-settling basin is located at the outlet of a 185 ha industrial catchment area, 70% of which is sealed. This basin has a surface area of about 1 ha and a maximum volume of about 32,000 m³ (figure 2). The "length to width" ratio is about 3. The basin has two inlets, one of which is predominant (inlet 1 in Figure 2). The outflow goes into an infiltration basin with a circular pipe 600 mm in diameter. This pipe is equipped with a control valve (Figure 3), with an outlet flow rate regulated at 350 L/s. It is an open basin that must be dry between two rain events.

A drop in performance beyond 5 years of sediment accumulation

The hydraulic operation of this structure and its behaviour with respect to pollution were then studied in the context of several thesis works (A. Torres, H. Yan, C. Gonzalez-Merchan, C. Sébastian, X. Zhu) and research projects (ANR Ecopluies, ANR Cabrres, Gesol, BRtox, etc.) which used continuous measurements of TSS concentrations at the outlet. The results obtained show that the design of the basin makes it possible to fulfil the three main functions, provided that the sediments are not allowed to accumulate in the basin for more than 5 years. After 5 years of accumulation, the trapping efficiency drops from 80 to 50% (re-drainage of part of the deposited sediments).

Figure 2: Simplified schema of the Django-Reinhardt detention-settlement basin.



Qs: outlet flow (to the infiltration basin) – **Qe:** inlet flow
o1: port no. 1 – **o2:** port no. 2 – **o3:** port no. 3
h1: water level sensor no. 1 – **h2:** water level sensor no. 2
Dry weather settling tank

Continuous measurements of turbidity transformed into TSS concentrations at the inlet and outlet and the little deposition observed at the time in the basin clearly showed that it was not a satisfactory design for trapping sediments and associated pollutants. It was therefore rehabilitated in 2004 with the aim of improving its performance in trapping particular pollutants. It was first partitioned by a low wall. Three openings through the partition wall and an overflow were added to the basin in order to extend the residence time and improve the efficiency of trapping particulate pollutants before transfer to the infiltration basin.

This is complemented by Question 8.7: *How do you assess the trapping efficiency of a detention-settling basin?* and Question 8.5: *How effective are sustainable drainage systems in regard to micropollutants?*, including the Django-Reinhardt detention basin, for a wide range of both dissolved and particulate pollutants.

Figure 3: Float valve at the outlet of the Django-Reinhardt detention-settling basin.

3D modelling as a design tool

3D modelling is an approach that makes it possible to predict the accumulation zones within this type of structure (see the results of the ANR CABRRES project - lc.cx/cabrres). This three-dimensional approach lays the foundations of an operational tool for the design of detention-settling basins of various shapes (not only rectangular) with the aim of storm water runoff treatment.

WARNING

It is not recommended to install oil pits or small settling pits within the detention-settling basins. This type of arrangement favours the enrichment of certain microorganisms, including pathogenic species, without improving the interception capacity of particulate pollutants.

8.7

How to assess the trapping efficiency of a detention-settling basin?

Gislain Lipeme Kouyi, INSA Lyon

The main functions of stormwater detention and settling basins are to protect downstream areas from flooding and to trap particulate pollutants with the goal of preserving the quality of the environment. However, many of these basins were initially designed with the sole objective of attenuating peak flows. As a result, their pollution control efficiency is highly variable and can only be assessed on a case-by-case basis.

Trapping efficiency is variable and depends on several factors

Over the last two decades, research has been carried out to improve the performance of detention-settling ponds in trapping particulate pollutants and micropollutants (Torres, 2008; Sébastian *et al.*, 2015). This trapping or interception efficiency depends on several factors, including:

- the geometry of the structure;
- tthe bio-physical-chemical characteristics of particulate pollutants;
- the hydrodynamic behaviour of the basin. Thus, depending on their design, these structures can be inefficient or very efficient, with abatement rates of up to 90%.

Quantifying the rate of removal of particulate pollution by a detention basin can be done in two ways:

- or by measuring the masses at the entrance and exit of the structure;
- or by modelling the hydrodynamic behaviour of the structure and the transport of particulate pollutants within it.

In-situ sensors to assess pollutant loads

The use of pollutant load measurements makes it possible to evaluate the efficiency of the structure in trapping particulate pollutants. Until recently, suspended solids and chemical oxygen demand (COD) loads were estimated exclusively from laboratory analyses of samples collected during rainfall events. This practice has several limitations: low temporal representativeness, transport, conservation and preservation of samples, delays in obtaining results, etc. Indeed, due to the high experimental and analysis costs, only a few samples can be collected for each event (normally up to 24 samples due to the technical constraints of automatic samplers) and only a few events per year can be measured. The results thus obtained do not provide precise or complete information on the dynamics of pollutant flows (Bertrand-Krajewski *et al.*, 2008).

An alternative solution is to use in situ sensors with short data acquisition steps and capable of providing time series that can be converted into TSS and COD concentrations. Among the existing sensors on the market, only turbidimeters and UV-visible spectrometers seem to be able to be used in situ with an acceptable level of reliability, considering the specific conditions of pipe systems (Gruber *et al.*, 2006). On the basis of these measurements, specific methods are applied to evaluate the equivalent concentrations of TSS and COD and their respective uncertainties (Bertrand-Krajewski, 2004).

3D modelling can also be used to assess trapping efficiency

A 3D hydrodynamic model of the Django Reinhardt detention-settling basin was developed in order to simulate the spatial distribution of sediments. The 3D model developed makes it possible to take the settling and resuspension of the sediments in place and entering into account, for a given inlet flow. Settling and resuspension are accounted for by comparing the turbulent kinetic energy (linked to the flow) and the kinetic energy transported by the particles (calculated from their fall velocity). If the kinetic energy carried by a particle is greater than the flow-related kinetic energy, then the particle settles; otherwise, it is resuspended. Figure 2 shows the spatial distribution of sediments within the settling tank. The simulated spatial distribution ("green" particles) is consistent with that observed since 2006.

The interception efficiency of particulate pollutants was also re-produced by modelling (Yan et *al.*, 2014). This model lays the foundations for an operational tool for designing detention-settling basins with the objective of depollution.

Figure 1: Comparison of measured and modelled efficiencies for different sediment densities (Yan *et al.*, 2014).

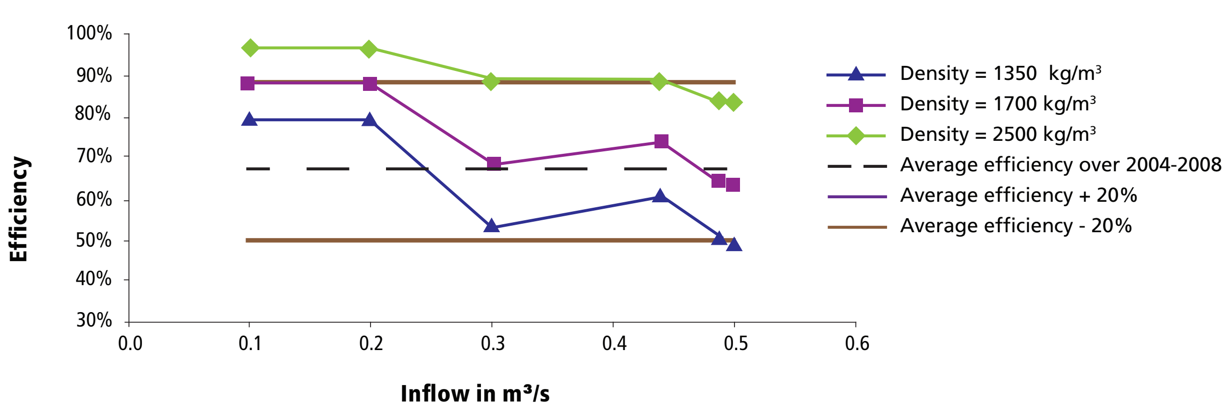
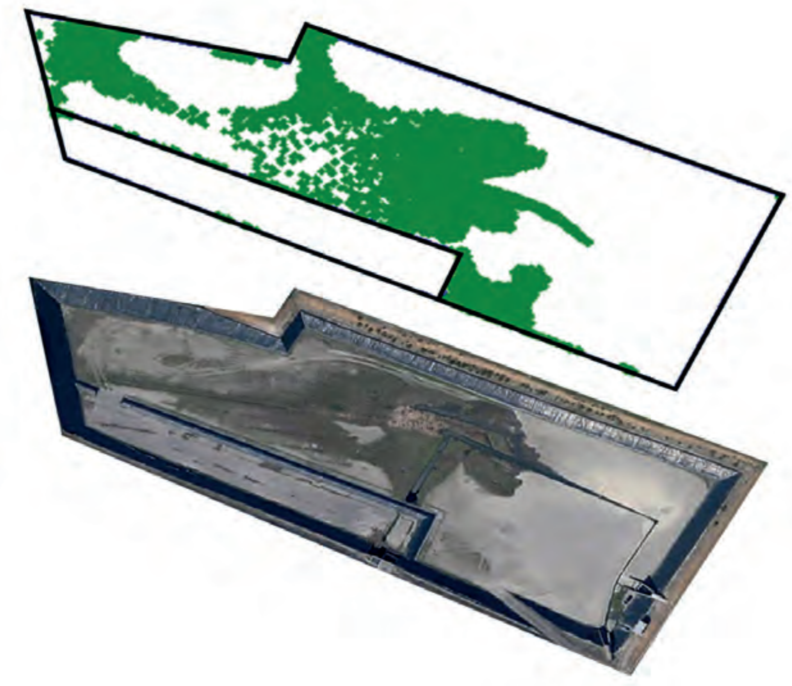


Figure 2: Comparison of simulated (green) and observed deposition areas in the Django-Reinhardt basin.



In Brief...

The implementation of a continuous monitoring of turbidity with a fine time step (2 minutes for the case of OTHU Django-Reinhardt site) at the inlet and outlet of the structure and the 3D modelling of hydrodynamics and solid transport allow access to the rate of trapping of particulate pollutants. This trapping efficiency depends mainly on the geometry of the structure and the physico-chemical characteristics of the particulate pollutants transported.

TO GO FURTHER

Estimation of TSS concentrations from turbidity:

- **Bertrand-Krajewski J.-L., Barraud S., Lipeme Kouyi G., Torres A., & Lepot M.,** (2008). Continuous measurements of particulate pollutant flows in urban wastewater networks: issues, methods, application examples. *La Houille Blanche*, 4, 49-57 – https://doi.org/10.1051/lhb:2008039 – lc.cx/bertrand2008 (in french)

3D modeling of hydrodynamics and solid transport within a retention-settling basin:

- **Yan H., Lipeme Kouyi G., Gonzalez-Merchan C., Bécouze-Lareure C., Sébastian C., Barraud S., Bertrand-Krajewski J.-L.,** (2014). Computational Fluid Dynamic modeling of flow and particulate contaminants sedimentation in an urban stormawater detention and settling basin. *Environmental Science and Pollution Research*, 21(8), 5347-5356. https://doi.org/10.1007/s11356-013-2455-6 – lc.cx/yan2014 (in french)
- **Yan H., Vosswinkel N., Ebbert S., Lipeme Kouyi G., Mohn R., Uhl M., & Bertrand-Krajewski J.-L.,** (2020). Numerical investigation of particles' transport, deposition and resuspension under unsteady conditions in constructed stormwater ponds. *Environmental Sciences Europe*, 32, 76. Open access https://doi.org/10.1186/s12302-020-00349-y – lc.cx/yan2020 (in french)

8.8

What are the elements to be considered for the management of sediment in detention basins?

Gislain Lipeme Kouyi, INSA Lyon – Claire Gibello, Nelly Maamir, Lyon Metropolis – Laure Wiest, ISA – Jean-Yves Toussaint, Sophie Vareilles, EVS – Benoit Cournoyer, Vetagro Sup /University Lyon 1 CNRS– Yves Perrodin, ENTPE – Céline Becouze-Lareure, Roannaise de l'eau – Sylvie Barraud, INSA DEEP

Like many local authorities, the Metropolis of Lyon has considerably increased its stock of stormwater detention or infiltration structures and is confronted with the management of the sediments that are deposited in them. The questions it raised with OTHU researchers included the following: How should the structures be designed? Should they be cleaned? How often? In what season? Which cleaning technique should be used? Do specific treatment/ recovery channels exist? These questions have been used to direct the CABRRES multidisciplinary research programme, which has provided operational staff with important answers.

Some rules to optimise the design of structures

Initially designed for hydraulic needs, stormwater detention-settling and infiltration structures have various and varied geometries. However, this geometry largely influences the settling process. The 3D hydrodynamic modelling developed within the framework of CABRRES makes it possible to understand the operation and to optimise the design or rehabilitation of structures. It has shown that some shapes are more suitable than others for intercepting pollution by settling.

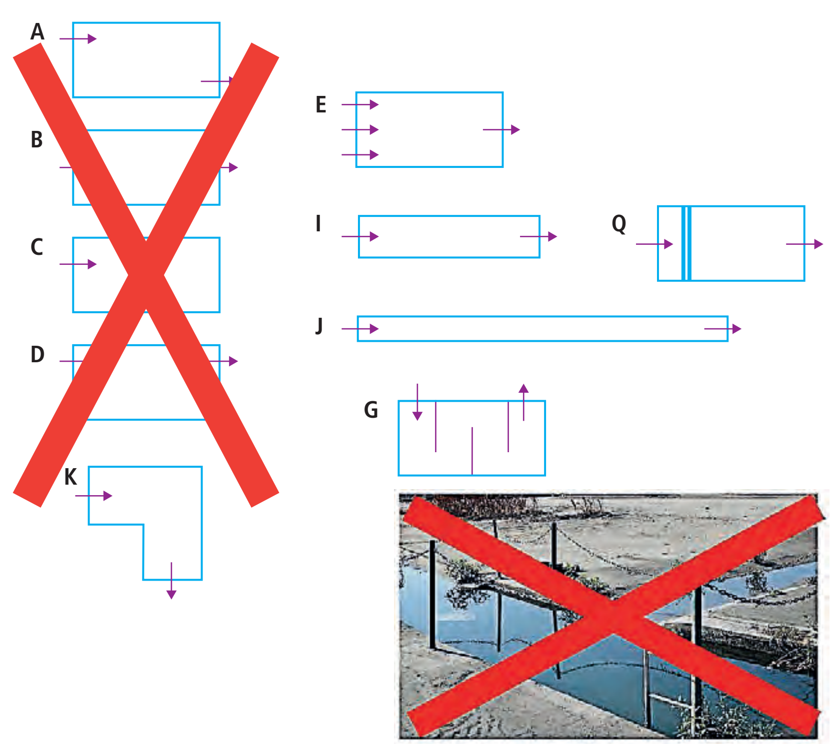
Thus, the geometry of the structure should allow for a residence time of at least 3 hours in the detention basin. As explained below, internal settling pits within a basin should also be avoided.

Figure 1: Some rules for better design of settling ponds

Have several entries rather than one. In the case of a single entrance, implement heatsinks or other forms of obstacle to slow down the flow.

Building a longer pool than wide (length to width ratio of 12 for a pool rectangular for example).

Compartmentalise the pond by installing low walls or partitions or by installing baffles, to reduce turbulence, slow down the flow, lengthen the residence time and avoid resuspension.



Persson (2000)

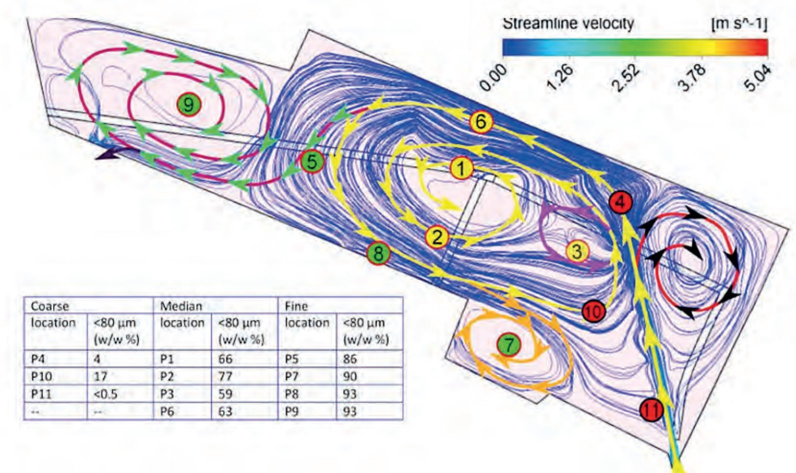
Several lessons for limiting pollution and toxicity of sediments

The sampling methods and chemical and biological analyses used and developed in CABBRES have proved to be relevant and have revealed pollution of the sediments (see Question 5.4: *How can we determine the pollution levels of sediment in stormwater detention basins?*) The latter are mainly contaminated by Polycyclic Aromatic Hydrocarbons (PAHs), metals and some PolyBromoDiphenylEthers (PBDEs: flame retardants). They contain few pesticides because they are mainly in dissolved form (Sébastian, 2013). 4-Nonylphenol (a compound of the alkylphenol family) and bisphenol A are also recurrently found. These sediments are also very high in iron.

The results confirmed that the installation of a settling pit within the detention structure should be avoided (Figure 1). This is because the accumulation of contaminants in the pit develops a culture broth that increases the toxicity of the sediments, as evidenced by the mortality observed during

Figure 2: Illustration of the tools and methods developed within OTHU for sediment management
(a) 3D hydrodynamic model.
(b) Technique for sampling pond sediments by quartering (see OTHU data sheet no. 27: lc.cx/ficheothu27).
(c) Ostracod (microcrustacean) biological model known and standardised (ISO 14371 standard) to qualify the sediments of the detention-settling basins, and to decide on the right time for cleaning, and to prioritise the sediments according to their quality.

a



Coarse		Median		Fine	
location	<80 µm (w/w %)	location	<80 µm (w/w %)	location	<80 µm (w/w %)
P4	4	P1	66	P5	86
P10	17	P2	77	P7	90
P11	<0.5	P3	59	P8	93
--	--	P6	63	P9	93

b

c

the ostracod bioassay (microscopic crustaceans). In addition, the pit favours a particular bacterial population, different from that of other points inside or outside the tank, including pathogenic colonies (including *Pseudomonas* or *Nocardia*).

Regarding cleaning, it seems that a frequency of 5 years is a good compromise: this period allows a certain homogenisation of the sediments and a reduction in ecotoxicity due to their maturation. Beyond 5 years, the trapping efficiency decreases. The ostracode (seed shrimp) test is a promising bioindicator for deciding when to carry out cleaning, even if it does not necessarily give access to a threshold value: the reference mortality level must be taken into account. Further research is needed to refine these elements.

The location, nature and layout of urban development influence the pollution of run-off water that feeds into the works

Within the framework of CABRRES, a socio-urban survey was carried out on the industrial catchment area connected to the Django-Reinhardt detention-settling basin. The objective of this survey was to establish a link between the substances mobilised in human activities, the particulate, chemical and biological contamination of the runoff water and that which is then found in the sediments of the detention-settling and infiltration basins.

Urban facilities (avenues, streets, cul-de-sacs, etc.) are the support and the condition for activities. In other words, the place where the activity takes place (the support) and the layout and nature of the urban facilities (the condition) directly influence the activities that will take place. For example, the presence of waste (food packaging, hygiene waste, human excrement, etc.) in the streets and cul-de-sacs was observed to be strongly linked to the night-time parking of heavy goods vehicles. Indeed, the survey revealed a problem with the hygienic needs of lorry drivers (microbiological analyses confirm a high level of faecal contamination in the area). The more isolated corners therefore allow and call for practices that have no other spaces or devices to be carried out. Therefore, the installation of litter bins, toilets, or even water points or reception areas for trucks could improve the situation.

Finally, a flexibility between public and private spaces has been observed, contributing to the contamination process of public space (runoff from private space flowing into the street).

Prospects for the management and treatment of dredged sediments

In order to identify the possibilities of sediment management and recovery as well as possible treatment needs, a DESIR project (Development and Evaluation of Sustainable Management Strategies for Stormwater Infiltration and Detention Basins - lc.cx/desir) started in 2020.

In Brief...

Some keys to management:

- Designing or rehabilitating structures without a pit decantation and with a residence time of at least 3 hours.
- Clean with a frequency of about 5 years, with a protective mask, rather in winter to avoid the risk of aerosolisation and to benefit from a lower activity of bacteria.
- The treatment of sediments by maturation is promising. Further research is needed.
- Urban development and the activities that take place there have an influence on the contamination of sediments. It is also possible to act at this level.

Tools and methods are available to support communities in managing sediments.

TO GO FURTHER

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- **ANR CABRRES research programme**. Chemical, microbio logical, ecotoxicological, spatio-temporal characterisation of contaminants in urban stormwater detention basins: assessment and management of associated environmental and health risks - 2012-2017 – lc.cx/cabrres (in french)

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Abbreviations

The abbreviations used in the book are defined below:

DNA: Deoxyribonucleic acid, containing the entire genome

EMC: Event Mean Concentration

DOC: Dissolved Organic Carbon

SEQ-EAU: French Water Quality Assessment System

BOD5: 5-day Biochemical Oxygen Demand

COD: Chemical Oxygen Demand

CSO: Combined Sewer Overflow

SWO: StormWater Outlets

SuDS: Sustainable Drainage System

DSM-flux: Device for Stormwater and combined sewer flows Monitoring and the control of pollutant Fluxes (DSM - Spill Monitoring and Control System)

FAIR: Findable Accessible Interoperable and Reusable

FTP: File Transfer Protocol (protocol for exchanging files over the Internet)

GEMAPI: GEstion des Milieux Aquatiques et Prévention des Inondations (Management of Aquatic Environment & Flood Prevention)

PAH: Polycyclic Aromatic Hydrocarbons

HMI: Human Machine Interface

IWA: International Water Association

LiDAR: Light Detection and Ranging

TSS: Total Suspended Solids

DTM: Digital Terrain Model

MV: Mass-Volume (curves)

NTU: Nephelometric Turbidity Unit

EQS: Environmental Quality Standard

DO: Dissolved Oxygen

TUSP: Technologies for Urban and Spatial Planning

OFB: Office Français de la Biodiverite (French Office for Biodiversity)

OTHU: Observatoire de Terrain en Hydrologie Urbaine (Field Observatory of Urban Hydrology)

PBDE: PolyBromoDiphenylEther (flame retardants)

PCR: **P**olymerase Chain Reaction

PNEC: Predicted No Effect Concentrations

POP: Persistent Organic Pollutants

UWWD: Urban Wet Weather Discharges

GIS: Geographic Information System

WWTP: Wastewater Treatment Plant

FAWB: Facility for Advancing Water Biofiltration

IBGN: Standardised Global Biological Index

ONEVU: Observatoire Nantais des environnements Urbains (Nantes Observatory of Urban Environments)

OPUR: Observatory of Urban Hydrology in Île-de-France

tpm: transcript per million

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