Sustainable Urban Ecological Infrastructures:
Multi-Functionality and Long-Term Dynamics for Water Management

Research Supervision Habilitation (HDR) Thesis
University of Strasbourg - Sciences

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Glossary

BOD: Biochemical Oxygen Demand

BT: Biological Tide

COD: Chemical Oxygen Demand

CTW: Constructed Treatment Wetland

ES: Ecosystem Services

HDR: Habilitation à Diriger des Recherches (see also RDH)

HRT: Hydraulic Residence Time

IIED: International Institute of Environment and Development

IRGA: Infra-Red Gas Analyzer

LTSER: Long-Term Social-Ecological Research

NBS: Nature-Based Solutions

NH_4^+: ammonia

NTK: Total Kjeldahl Nitrogen

RDH: Research Direction Habilitation (see also HDR)

RTD: Residence Time Distribution

SDG: Sustainable Development Goal

SES: Social-Ecological Systems

TN: Total Nitrogen

TP: Total Phosphorus

TSS: Total Suspended Solids

UEI: Urban Ecological Infrastructure

UN: United Nations

WBCSD: World Business Council for Sustainable Development

WCED: World Commission on Environment and Development

WWTP: WasteWater Treatment Plant

WFD: Water Framework Directive

Introduction

You are about to read the dissertation I submit to get the "Habilitation à Diriger des Recherches", approximately translating into 'Habilitation for Research Supervision'. I understand this exercise as a way to demonstrate the ability of the candidate to actually carry out research in a personalized way. It is a starting point, not a final achievement so it will probably lack the wisdom of long established research. I will try to make this the least boring possible, and will strive to make it understandable. I beg my readers for kindness, but also for critical examination of this work. Practically, my dissertation will be articulated in three main parts.

I will first propose a synthesis of my past and present research activity. This will start with a synthesis of my PhD research activity, to present what I contributed to during this period. This will help me to present some reflections, and to point at a few methodological remarks emerging from this work. I implemented these remarks in my research activity since I came into position; I will synthesize it, structured in three main scientific fields. This will lead me to present my thoughts on my research topic to this day.

The second part of the manuscript will be devoted to the explanation of my research project. I will present the concepts I choose to rely on to carry out my work, reusing some I have already implemented in my current research activity and integrating new ones that help me to better conceptualize my research object. These concepts mainly stem from my work within the LTSER network in Strasbourg, and globally belong to the field of urban ecology. These work hypotheses will be articulated into research questions by merging my research work and the aforementioned concepts. The main objective is to study the multiple ecological functions of urban ecological infrastructures (UEI) and their dynamics over time. I will exemplify this with a research project we submitted recently.

The third part of the manuscript will be used to expose the way I consider supervision of young researchers. In my eyes, this activity appears fundamentally inseparable from leading a research project. I will use some of the work I initiated during my uni-

versity pedagogical degree to support this discussion.

Finally, a research work is never carved in stone: I will close this dissertation with a few perspectives and emerging research directions.

As a last thought for this introduction, I must insist on the fact that the research activity I analyze and use to move forward results from initiatives, encounters and a thorough yet enthusiastic team work. If my name is the only to appear here, one must keep in mind the credits are to be given to the research team(s) I was or am currently involved in. I would like to thank in no particular order all the interns, lab technicians, PhD fellows, and senior scientists that I worked with and that helped me to evolve on my professional path.

1 Synthesis of research activity

1.1 PhD research activity

In brief During my PhD, I carried out research in the field of applied microbiology. More specifically, the aim was to study the ability of *in situ* bioaugmentation[1] to help mitigating soil pollution caused by the use of herbicides in wine growing activity. This particular agricultural activity is today one of the most polluting ones: it represents only 3% of the agricultural area, but a bit less than 10% of pesticide sales[2]. Indeed in France, only 12% of vineyards are cultivated organically [3]. This intensive use of pesticides generates environmental disturbances: present studies reckon the resulting pollution level of vineyard soils [1]. The contact between soil and water triggers another disturbance, as water gets a part of this and ends up polluted as well [1].

The objective for this work was thus to alleviate herbicide and fungicide stress on vineyard soils and stormwater. To compensate for lab-scale experiments regularly expressed limitations (e.g. ill-suited study scale and soil conditions far from field ones), we set up lab experiments in wetland-mimicking microcosms, containing real polluted soil sampled from the field. We relied on microbial fantastic metabolic diversity and evolution capacity to turn down the chemical amount in soil and water. This hypothesis was tested through bacterial lab enrichment and subsequent bacterial inoculation of the microcosms. To complete the project, we added a natural sorption medium to increase contaminant residence time within the system, expecting this higher residence time would turn into higher contaminant mitigation. We carried out the study according to the following experiment design:

1. We identified lab bacterial species with the ability to mineralize one of the molecules we were handling ([2], during my Master's internship);
2. We selected low-cost sorption products to increase molecule residence time within the system ([3]);

[1] addition of lab-cultivated bacteria to a given medium
[2] http://uipp.org/Ressources/Publications/; accessed on July, 8th 2020
[3] https://agriculture.gouv.fr/infographie-lagriculture-biologique-en-france, accessed on July, 8th 2020

3. We performed the same type of degradation experiment as in step 1, but using a bacterial consortium selected from *in situ* polluted vineyard soil ([4]);

4. We completed the experiment design by microcosm degradation experiment ([5], [6]). The aim was to increase components residence time with the sorbents selected on step 2, while enhancing degradation (for organic molecules) or trapping (for heavy metals) through bacterial consortia selected on step 3 .

From this research experience, I will only detail steps two to four, corresponding to my PhD work. I will emphasize on what it brought me methodologically or conceptually, rather than technically, as I presently do not use microbiology for my research.

Material selection for all-purpose low-cost sorption In [3], we reported the results of a batch[4] sorption experiment, performed on several chemicals used in vineyards. We used the most sold products in wine-growing activity at the time: two herbicides, diuron and glyphosate, one herbicide degradation product, 3,4-dichloroaniline (3,4-DCA) and one fungicide, copper. Pesticides are often combined during field application, and this combination may have an impact on chemical distribution and sorption behaviour. Additionally, the liquid phase encountered in the field is far from being pure as the water that is usually used in lab experiment. Its composition, with dissolved salts, complex organic matter and trace elements for instance, is very likely to alter the global physico-chemical behaviour of the system.

Thus for our experiment we dissolved the chemicals, alone and in combination, in liquid matrices of increasing chemical complexity (ultrapure water < runoff water < sediment extract[5]). The assumption behind sorption experiment is that using an intermediate material with higher (specific or) global affinity for target chemicals will increase their trapping rate in soil and thus decrease their bioavailability in both soil and water. Various materials can be used, from raw natural to processed natural up to highly-engineered ones. We chose several low-cost sorbing materials: corn cob, corn cob biochar[6], vermiculite, perlite, sugar beet pulp, sand and sediments. The concentration

[4] fixed volume experiment
[5] solution containing warm extract of filtered sediment
[6] homemade by burning corn cob in a lab backyard barbecue

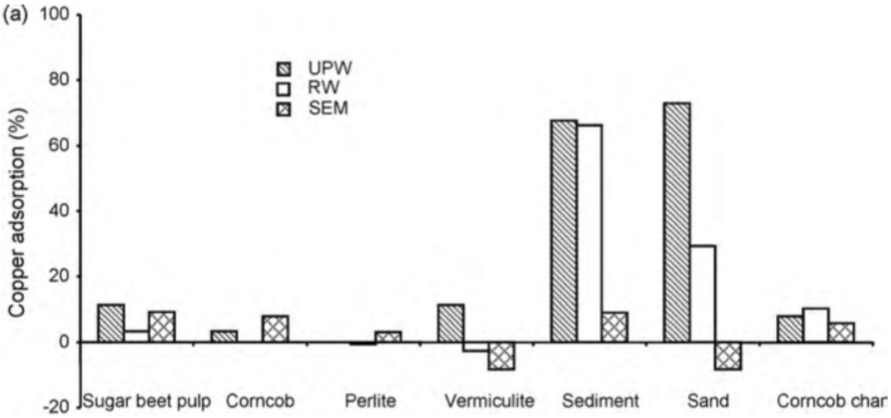


Figure 1: Impact of glyphosate on the sorption of copper in ultrapure water (UPW), runoff water (RW) and sediment extract medium (SEM). The data are presented by the difference in the maximum sorption percentage of copper between the single compound matrix and the mixture. From [3]

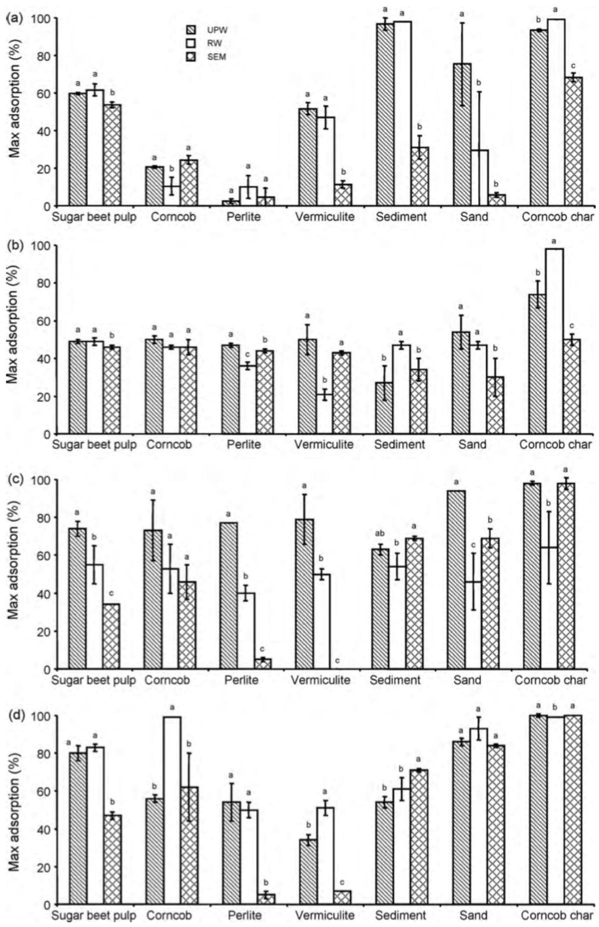


Fig. 1. Maximum sorption percentage of (a) copper, (b) glyphosate, (c) diuron and (d) 3,4-DCA on the selected sorbents in ultrapure water (UPW), runoff water (RW) and sediment extract medium (SEM). The error bars stand for mean standard errors. For each sorbent, mean values with different letters are significantly different (at P< 0.05).

Figure 2: Maximum sorption percentage of (a) copper, (b) glyphosate, (c) diuron and (d) 3,4-DCA on the selected sorbents in ultrapure water (UPW), runoff water (RW) and sediment extract medium (SEM). The error bars stand for mean standard errors. For each sorbent, mean values with different letters are significantly different (at $P < 0.05$). From [3]

of each compound was regularly measured to capture the moment when maximum chemicals' retention could be observed. Sampling volume was chosen small enough to allow analysis while remaining neglectible regarding batch volume; we computed retention efficiency directly from these concentration values. The results that struck me most in this experiment are:

i. The capacity of fairly simple media, far from highly engineered material, to sometimes provide efficient sorption for chemically diverse compounds after a few hours (Figure 1); a few configurations yielded more than 80% retention after a time range of 10 minutes to 48 hours. In this experiment, corncob char was the overall winner;

ii. The significant effect of increasing matrix complexity on sorption: overall sorption of target compounds decreases when complexity increases (Figure 1). Decreases can be sharp, from 100 to 40% for copper and sediment as a sorbent, or from 80 to 5% for diuron with perlite as a sorbent. This may be the result of an increase in potentially sorbing molecules, either natively present in the solution or spiked by us. Some of the 'native' compounds had better affinity with the sorbent, thus reducing the pesticide sorption;

iii. The significant effect of molecule number for sorption on substrates, with contrasting results. For instance copper sorption is strongly enhanced by the addition of glyphosate in runoff water (Figure 2), when sand and sediment are used as sorbents. This may be due to the glyphosate easily bonding on sand and sediment and creating bridges for copper to bond on. On the contrary, the moderate sorption observed with vermiculite became a release when adding glyphosate in sediment extract medium. To draw general conclusions is uneasy though, as almost no effect is observed when using corncob for instance.

When thinking about upscaling potential, this experiment departed from field systems because field concentrations are usually much smaller than what was used for the experiment [7], mainly for analytical reasons, stable physico-chemical conditions

[7] around 1 $ug \cdot L^{-1}$ [7] on the field vs. $\approx 0.1\ g \cdot L^{-1}$ in our experiment

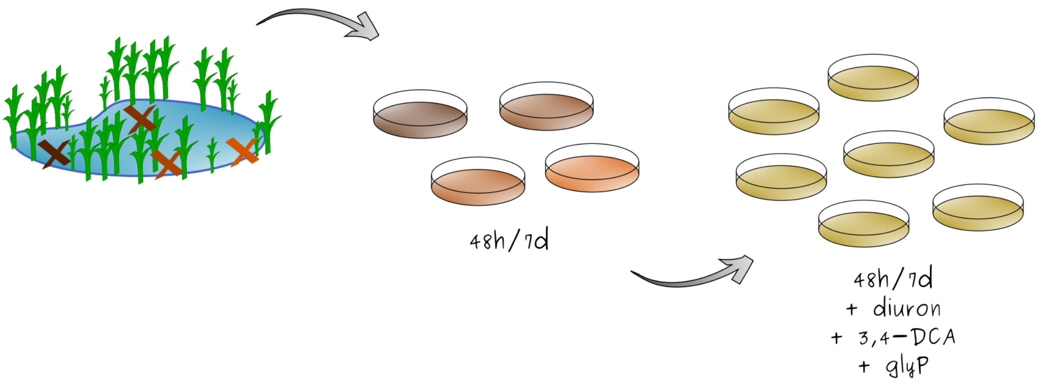


Figure 3: Sampling and enrichment methdology for the first degradation experiment. Cultures were made during 48 hours or 7 days.

were enforced during this lab experiment, contrary to environmental conditions, and solid matrices to exchange with will be numerous on the field. This discrepancy in concentrations may lead to several counteracting effects: for instance contaminants at environmental levels will be likely to sorb more due to lower concentration. Yet competition with 'native' solutes is very likely to increase, as environmental matrices contain a greater amount of the latter. Second, I would expect more variability in sorption and processing (degradation and/or trapping) due to changing environmental conditions (storm event related, seasonality) leading to pH and redox significant changes. Third, the diversity of substrates that could become sorbent will certainly increase in the field. Eventually, it seems pretty complicated to upscale these results to the field, even if we chose complex solid-liquid modalities and not trivial contaminant mixes.

Selection and first degradation experiment Due to the massive input of herbicides and fungicides in the vineyard we studied, some contaminants reached the downstream wetland with the runoff flow. The soil of this wetland, meant to be a stormwater basin, was consequently contaminated by both organic and non-organic compounds: between 5 and 40 $mg \cdot kg^{-1}$ copper, and 35 $ug \cdot kg^{-1}$ glyphosate among potential others. We supposed this contamination pressure would have generated adaptation of the indigenous micro-organisms; and that in return, these would have developed the metabolic ability to degrade diuron, 3,4-DCA and glyphosate and to sequester copper. In [4], we reported the isolation of field bacterial consortia[8] able to perform degradation of these organic compounds and complexation of copper in solution. We processed with a 3-step approach (Figure 3), that we detail below.

First, we planned sampling regarding location in the wetland: upper or lower soil layer, rhizospheric[9] or non-rhizospheric soil, as an indicator of mircoroganisms ability to survive in aerobic and anoxic conditions. We also discriminated samples near the wetland secondary inflow (subject to drying/rewetting cycles, and thus to periodic aerobic and anoxic conditions) from the ones in the quasi-stagnant part (always immersed, thus mostly anoxic if not anaerobic). This sorting within field oxygen content

[8] assemblage of bacterial strains
[9] the vicinity of plant roots

Table 2 Degradation efficiency of glyphosate, diuron or 3,4-DCA of bacterial cultures from this work. Corresponding values for selected isolates from the literature are provided for comparison

Isolate	Compound concentration (mg L^{-1})	Degradation (%) [a]	Degradation rate (mg L^{-1} h^{-1})	Additional source of nutrients	References
Glyphosate					
41	40	41	0.17	Yes	This work
106	40	57	0.24	Yes	This work
348	40	84	0.35	Yes	This work
Pseudomonas sp.	42	100	0.58	No	Dick and Quinn 1995
Streptomycetes	1700	60	2.35	No	Obojska et al. 1999
Diuron					
106	10	99	0.10	Yes	This work
348	10	40	0.04	Yes	This work
530	10	98	0.10	Yes	This work
Arthrobacter sp.	40	100	1.70	Yes	Tixier et al. 2002
Arthrobacter sp.	40	100	1.33	Yes	Widehem et al. 2002
Pseudomonas sp.	300	100	2.10	No	El-Deeb et al. 2000
Arthrobacter globiformis	20	100	0.17	Yes	Turnbull et al. 2001a
Rhizoctonia solani	20	97	0.01	No	Vroumsia et al. 1996
3,4-DCA					
2	10	100	0.10	Yes	This work
106	10	92	0.10	Yes	This work
154	10	100	0.10	Yes	This work
160	10	100	0.10	Yes	This work
174	10	100	0.10	Yes	This work
348	10	54	0.06	Yes	This work
Pseudomonas fluorescens	250	100	1.49	Yes	Travkin et al. 2003
Pseudomonas sp.	30	100	0.42	No	Dejonghe et al. 2003
Mortierella isabellina	40	90	0.33	No	Tixier et al. 2002

[a] For the bacteria investigated in this work, percentual degradation was determined in 200-µL LB cultures of the obtained colonies (containing 1 mg L^{-1} bacteria), after 96-h incubation at 28°C

Figure 4: Degradation efficiency of glyphosate, diuron or 3,4-DCA of bacterial cultures from this work. Corresponding values for selected isolates from the literature are provided for comparison.

is very important, as microbial metabolism depends strongly on it, and the mitigation result can be totally different, in terms of assimilation mechanism, magnitude and quickness. For instance, it could range between '1% of slight structural modifications in 2 weeks' and '100% total mineralisation in 24h'. Second, bacteria were extracted from the wetland soil samples and cultivated for 48h and 7 days on micro-plate culture to first retrieve cultivable microbes. This helped us selecting fast- and slow-growing microorganisms with the 48h and 7 days experiment, respectively. This is interesting because fast-growing microbes are generally able to adapt to rapidly changing conditions (e.g. a pulse in contaminant $\rightarrow$ fresh food arrival!), while slow-growing microbes are probably more adapted to, and thus more efficient to assimilate frequently encountered contaminants. Third, the most efficient assemblages were selected through a degradation study: micro-plate culture on a chemical-spiked solution (all compounds at $\approx 10\ \mathrm{mg \cdot L^{-1}}$) for 48 hours to 7 days. We would select only those with significant degradation results.

We finally retrieved 98 colonies able to survive the whole set-up, even if we applied high pesticide concentrations. Three, 35 and 7 were respectively able to degrade over 50% of the provided contaminant (Figure 4); 28 could complex copper. Additionally, 62% of them originated from the inflow of the stormwater basin, 77% were rhizospheric in character, and 65% were obtained after 7 culturing days. Most of them turned out to be bacterial consortia, a few were single strains. Samples encountering the contaminants most frequently provided slightly more efficient bacteria; these were mainly slow-growing and probably developed stronger metabolic adaptation. The majority of the selected bacteria grew in the rhizosphere, where plant-microbes symbiosis is likely to enhance degradation.

This study illustrates for me the ability to find within real ecosystems the ingredients for successful remediation: strategies, structures, processes and species that will help facing present environmental challenges generated by mankind. Although our experiment was somehow limited: a vast majority of field bacteria or assemblages are not cultivable in the lab. Thus we probably missed promising individuals. We only selected bacteria too, but fungi and mycorhiza have be shown to be potential good degraders.

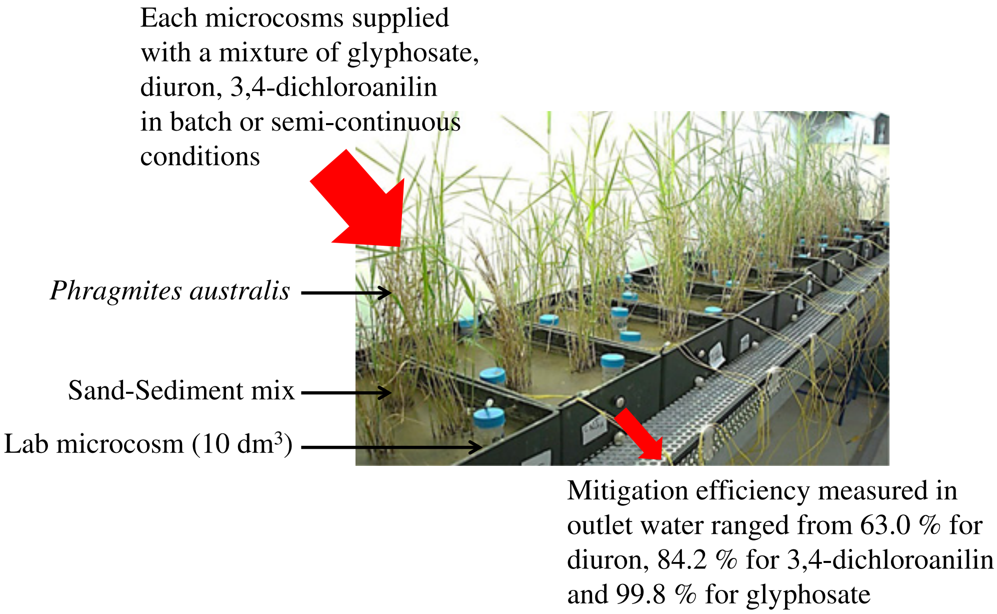


Figure 5: Microcosms experimental device

Table 1 – Detailed experimental design. I: inoculated microcosms with 1.1.10^{11} CFU kg^{-1}$_{sand-sediment}$ for all experiments (number of inoculations are indicated in parentheses); NI: non-inoculated microcosms. P: planted microcosms (number of plants are indicated in parentheses); NP: non-planted microcosms. In hydraulic regime column, all phases were consecutive. Cu: copper; gly: glyphosate; d34d: diuron and 3,4-DCA. Mentioned concentrations are initial ones. All simulated events were containing pollutants in experiments I and II. In experiment III, only the first simulated event was polluted.

Experiment	Inoculation	Plants	Number of simulated events	Time offset between two consecutive events	Hydraulic regime		Concentrations in water
					Semi-continuous (SC)	Batch (B)	
I	Once at the beginning I (1)/NI	P (3)/NP	3 (every two weeks)	2 weeks	Phase 1: 1.6 L in 1.5 h; Phase 2: 4 h storage; Phase 3: 1.5 h emptying	–	Cu: 37.5 mg L^{-1} gly: 50 mg L^{-1} d34d: 10 mg L^{-1}
II	After each event I (3)/NI	P (4)	3 (every week)	1 week	Same as experiment I	1.6 L	Cu: 37.5 mg L^{-1} gly: 50 mg L^{-1} d34d: 10 mg L^{-1}
III	Once a week I (6)/NI	P (5)/NP	2 (every two weeks)	5 weeks	Phase 1: 1.6 L in 1.5 h; Phase 2: 6 h storage; Phase 3: 1.5 h emptying	–	Cu: 56.5 mg L^{-1} gly: 50 mg L^{-1} d34d: 10 mg L^{-1}

Figure 6: Detailed experimental design. I: inoculated microcosms with 1.1E+11 CFU kg$^{-1}_{\text{sand-sediment}}$ for all experiments (number of inoculations are indicated in parentheses); NI: non-inoculated microcosms. P: planted microcosms (number of plants are indicated in parentheses); NP: non-planted microcosms. In hydraulic regime column, all phases were consecutive. Cu: copper; gly: glyphosate; d34d: diuron and 3,4-DCA. Mentioned concentrations are initial ones. All simulated events were containing pollutants in experiments I and II. In experiment III, only the first simulated event was polluted.

Last, it might be that we were able to get significant mitigation efficiency because of we added contaminants by the truckload. It is unsure to me that we would get equivalent efficiency on the field with much lower amount. But at least the potential for success was demonstrated.

Microcosm biodegradation experiment The above experiments allowed us to isolate material and bacteria to achieve bioremediation in transient systems, although field conditions hardly compare to the ones we imposed in these lab experiments. Contaminants distribute between solid and liquid phase, mitigation must happen in a mixed solid-liquid material, competition for sorption occurs between these two phases and competition between microorganisms generates bacterial mortality.

Thus in [5] and [6], the most efficient bacterial consortium (selected at the former step) was used to study mitigation in lab microcosms , under soil and hydraulic conditions that were closer to real ones. We filled 1:150,000 scale boxes with soil, planted them with *Phragmites australis*[10] and submitted them to periodic feeding with polluted water, with or without emptying sequences (Figure 5). Concentrations used for the contaminants were again significantly higher than field values. We added bacteria at a concentration 100 fold the one in the soil. Experiment conditions are summarized in figure 6. We wished to observe possible differences due to plant presence, hydraulic regime and bacteria bioaugmentation.

The results showed that mitigation efficiency could be fairly high, especially in the set-up where 5 weeks rest were left to the system: concentration decreased from initial values to almost undetectable ones, for all contaminants ($\approx$ 90-100%). When less rest time was left, the results were not as satisfying: milder decrease could be observed ($\approx$ 60 - 70%), or even increase (up to 3 times the initial value!) along the experiment. Bioaugmentation had clearly no significant effect on the recorded mitigation, showing that indigenous bacteria – not the bioaugmented ones – were the ones playing the most significant part in what took place in the microcosm. Globally, neither bacterial bioaugmentation nor plant presence played a significant role in the measured mitiga-

[10]wetland plant commonly used in France for constructed treatment wetlands

tion. Moreover, cultivable bacterial population systematically decreased towards the system baseline value in a few days, which means bioaugmentation was not viable in these conditions. Redox potential was logically plummeting down around -200 mV when water was kept in the microcosm, while it oscillated between 0-150 mV (anoxic conditions) and 450-550 mV (aerobic) when water was emptied regularly. Logically, plants smoothed redox variations, due to oxygen release in the rhizosphere.

These results were interesting because a high mitigation efficiency was obtained, but somehow frustrating because our input was actually useless. Indigenous components of the ecosystem provided the expected service of soil and water quality regulation; and in this case, bioaugmentation was not a relevant option to increase mitigation. Eventually, transposing these systems and their results to field conditions could not be straightforward as i) weather conditions would be changing on the field, with effect on organisms' metabolism and thus mitigation magnitude, ii) given the bacterial surplus concentration we added, upscaling this amount to a real-scale system would mean filling it with barrels full of bacteria, and iii) going down from our $mg \cdot L^{1}$ concentrations to environmental ones could mean that mitigation would not be so efficient, when harmful compounds are not so overwhelmingly present. A reduced mitigation could not be excluded, with a concentration baseline remaining at levels of environmental concern.

Synthesis of PhD research activity

From a methodological point of view, these experiments resulted in significant effects only when large disturbances were used (high contaminant load or amount of bacteria). I have thus a nagging doubt that the results we obtained in the lab would have been difficult to transpose to the field. Indeed, I expect less competition and less perceivable effects on the field due to lower environmental concentration of chemicals, stronger competition for food with other soil organisms, while observing more variability in biophysical processes due to changing environmental conditions (e.g. storm events related hydraulic and chemical conditions, climatic parameter changes due to seasonality). Subsequently, the relevance of sole lab studies to explore field processes, draw conclusions and upscale treatment systems is part of the answer, but makes the upscaling unsure.

From a conceptual point of view, these studies illustrate the ability to find within natural ecosystems the structures, processes, species or strategies that will help facing present environmental challenges generated by mankind (notwithstanding behaviour changes, I will come back to this later). In our case, indigenous bacteria of the ecosystem provided the expected service of soil and water quality regulation, being adapted to pollution and having developed metabolic ability towards mitigation – organic compound degradation and heavy metal complexation –. Could the solution be to couple input reduction and ecological functions, to reach ecosystem self-processing threshold?

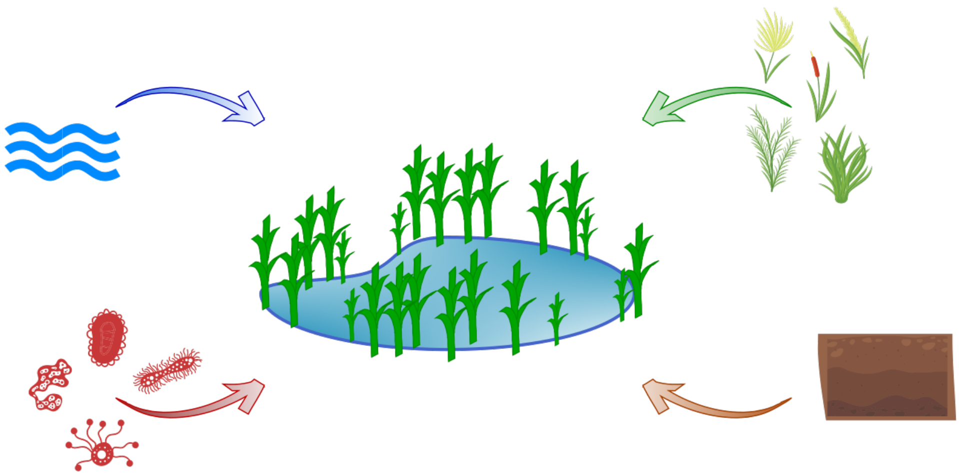


Figure 7: Elementary components of a wetland

1.2 Current research activity

In brief I will now present my research activity since I joined ENGEES and ICube laboratory as an Assistant Professor in 2012. Globally, it has mainly dealt with the management of urban water through constructed treatment wetlands (CTW). Through the manuscript, whenever used the notion of 'urban water' means for me 'urban wastewater and urban stormwater'; and the notion of 'management' means the handling of both quality and quantity.

Cities are hotspots for human water-related issues, as more than half of the world population will probably be urban dwellers by 2050 [8]. In addition to the number and density issue, urbanization impacts the availability of water as a resource. As many cities are entangled in streams (for instance, Strasbourg Metropolis is crossed by 500km of streams, for a 385km^2 total urban area), their early development, present situation and future trajectories are closely linked with water management. A crucial question that subsequently arises is how to get enough of sanitary acceptable water for urban citizens, without impairing the natural water cycle? Nature-Based Solutions (NBS) can help handling this delicate issue. Globally, they can be seen as systems using natural features and ecological functioning to achieve a specific goal. Compared to conventional techniques, lower financial costs and higher social acceptability – among other features – advocate for their increased use, in urban areas as well [9].

Constructed treatment wetlands (CTW) are one of these NBS. Set up anew by Kate Seidel in 1969 [10], they use wetland biophysical features (temporary or permanent presence of water, association of microfauna, soil and plants, figure 7) to generate wetland-associated ecological processes, eventually regulating water quality and quantity. This is an ecological engineering approach, *sensu* Mitsch et al. [11], as it uses natural processes to achieve a precise goal, while limiting heavy engineering infrastructures. As they are systems with less resource and energy requirements, CTW are increasingly used for urban water management.

Partly resulting from this increased use, they face numerous challenges: i) long-term operation generates concerns about their maintenance and the behaviour of

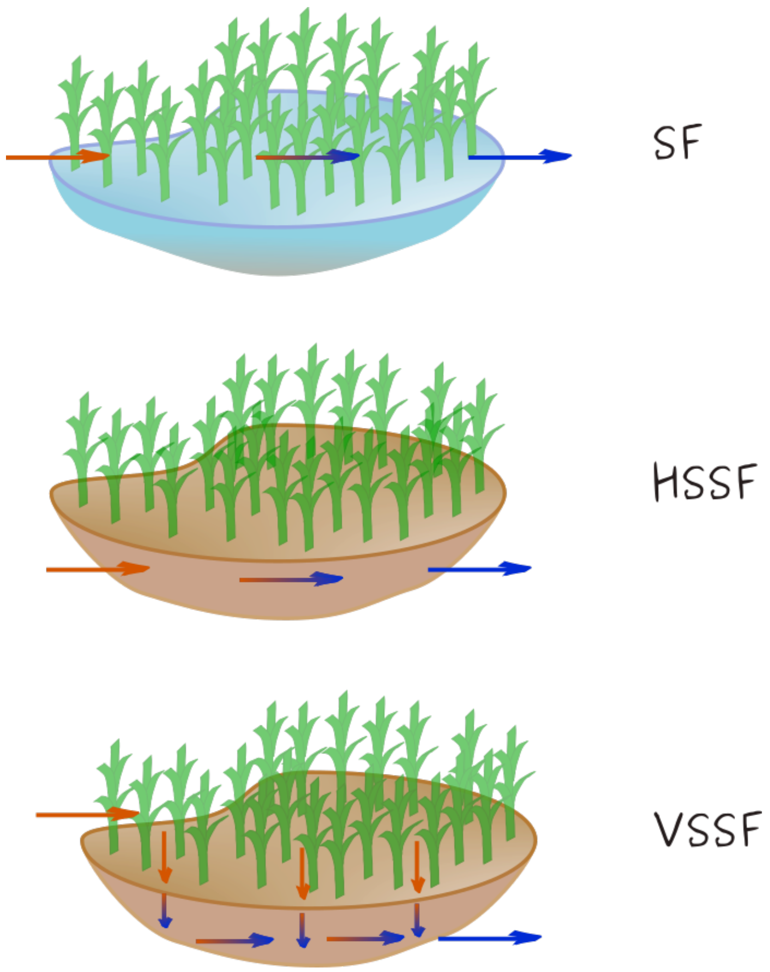


Figure 8: Hydraulic behaviours in wetland. SF: Surface Flow; HSSF: Horizontal SubSurface Flow; VSSF: Vertical SubSurface Flow

lasting contaminants[11], ii) accounting for more contaminants – the infamous micropollutants – questions their capacity to mitigate them, iii) freshly unveiled or formerly neglected mechanisms require optimization scenarios, and iv) better integration in urban landscapes could lead to greater benefits for the urban ecosystem. Our research work aims at bridging these gaps, through an approach combining hydrology, physicochemistry and urban ecology. We will detail in the following paragraphs a few results obtained since 2012 with this approach. For any further detail needed, the related publications are added in the Appendix part of the manuscript.

1.2.1 Hydrology

Hydrology is a fundamental feature of CTWs that significantly contributes to understanding their functioning: it gives access to the time that water, and subsequently dissolved compounds, spend in the wetland and how this time is spent. We study these features with lab experiments, field experiments and numerical modelling. These approaches are combined to avoid as much as possible the pitfalls of systems/mechanisms too complex to be satisfactorily analyzed, awkward lab-to-field results upscaling, and fuzzy predictions. Studies carried out on field hydraulic survey, dye tracer experiment and hydrodynamic modeling will be now detailed.

CTW hydraulic evolution First, I would like to detail a study designed to provide mid-term feedback on the hydraulic behaviour of wastewater CTWs [12]. The involved CTWs are subsurface flow systems, where inflowing water vertically infiltrates through the system before draining out at the bottom (Figure 8). Three layers help optimizing filtration, residence time and draining. The usual configuration is made of two stages: the first one meant to filter suspended matter and oxidize organic matter, the second one to nitrify reduced nitrogen. Hydraulic behaviour thus significantly influences this functioning. It has a direct impact on the flow regulation capacity through infiltration rate: the higher the infiltration rate, the less time water will send in the system. This parameter will help calculating the system volume to handle a given flow. There is an

[11] the most famous are maybe heavy metals

	Wastewater Concentration ($mg \cdot L^{-1}$)	Freshwater Concentration ($mg \cdot L^{-1}$)	Surface Load ($g \cdot m^{-2} \cdot j^{-1}$)
TSS	100 - 400	< 25	50
COD	300 - 1,000	< 20	100
BOD	150 - 500	< 3	50
NTK	30 - 100	1	10
NH_4^+	20 - 80	0.1	8
TP	10 - 25	0.05	5

Figure 9: Typical concentration and surface load of wastewater feeding constructed treatment wetland. Freshwater typical values are added for easier comparison.

V_{inf}/V_{inf-15}	*First stage*		*Second stage*	
	Cured	**Washed**	**Cured**	**Washed**
Site A	2E+1	4E+2	2E-1	5E+2
Site B	7E-1	6E+1	5E-1	1E+1
Site C	3E+0	7E+2	1E+0	4E+2
Site D	4E+1	7E+1	2E+0	6E+1

Figure 10: Comparison of infiltration speed after 15 years operation with i) renovation by superficial deposition layer removal (Cured) and ii) washed new medium (Washed)

indirect impact on biochemical processes as well: the longer water remains in the system, the more time will be available for compounds processing by organisms. Highly loaded water flows through these systems everyday (Figure 9); a mostly organic layer forms every time the system gets fed due to physical filtration at the surface of the system. This could lead to a severe decrease of infiltration rate as time goes by, especially if the size distribution of the material is wrongly chosen. The oldest CTW in Alsace were approaching 15 years in 2012, which seemed the right time to carry out a field survey on infiltration properties.

In collaboration with the local water agency[12], we subsequently carried out a study on 4 systems operated for 15 years at the time of the study; we especially investigated infiltration rate and its link with the deposit layer and the porous medium. We used a double-ring infiltrometer to measure field infiltration rates, and lab columns to measure it on fresh material. We chose sampling points based on the distance to the feeding pipe. As the objective was also to characterise the global strata within the system, we dug through the layers of the system to analyse the degree of mixing with organic matter. For the sake of comparison between maintenance strategies, we also scraped the organic deposit and performed the same measurements.

We globally observed a larger decrease of the infiltration rate on the first stage than on the second, which seems logical as more mater deposits on the first stage by sheer physical filtration. In some cases (i.e. when $V_{inf}/V_{inf\text{-}15} < 1$), the infiltration rate was actually enhanced by the deposit layer, probably because it was quite sandy on the corresponding sites. The most extreme example was met on a site where true clogging was almost reached; in this case, curing helped increasing the infiltration rate 40 fold. The infiltration capacity was on average fairly sustained over time. Yet hydraulic conductivity was most of the time enhanced by scraping the accumulated matter ($\approx$ 60%, figure 10). With a perspective on maintenance strategies, the comparison between the infiltration rate when scraping the old deposit or when simply using new medium was made; the infiltration rate was more increased by using new medium than by removing deposit layer. If cost sparing is needed, scraping should be favoured, as it nevertheless

[12] Agence de l'Eau Rhin-Meuse

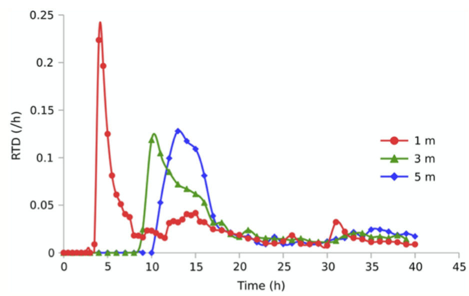


Fig. 6. Fluorescence curves for Experiment 2. Red circles (curve "1 m"), green triangles (curve "3 m"), and blue diamonds (curve "5 m"), respectively, represent the fluorescence at 1, 3, and 5 m from the injection point.

Figure 11: Residence Time Distribution curves in Tres Rios wetland ([13]

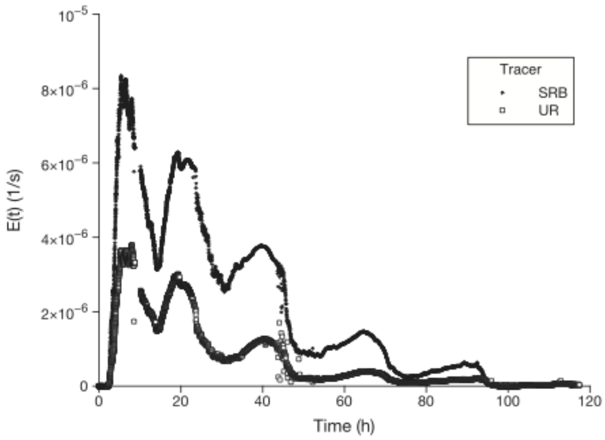


Figure 12: Residence Time Distribution curves measured in Lutter wetland ([14])

Eq. no.	Parameter	Symbol	Unit	Formula
(1)	Residence time distribution	$E(t)$	h^{-1}	$E(t) = \frac{C(t)}{\int_{t_0}^{t_f} C(t)\times dt} \left(\int_{t_0}^{t_f} E(t) \times dt = 1\right)$
(2)	Mean residence time	$\bar{t}$	h	$\bar{t} = \int_{t_0}^{t_f} E(t) \times t \times dt$
(3)	Standard deviation	σ	h	$\sigma = \sqrt{\int_{t_0}^{t_f} E(t) \times (t-\bar{t})^2 \times dt}$
(4)	Local mean velocity	$\bar{V}$	cm/h	$\bar{V} = \frac{\Delta X}{t}$
(5)	Peclet number	Pe	–	$\frac{\sigma^2}{\bar{t}^2} = \frac{2}{Pe} + \frac{8}{Pe^2}$
(6)	Transpiration flow	Q_{ET}	m^3/h	$Q_{ET} = V_{ET}/t_{transpiration}$
(7)	"Biological Tide" velocity	$v_{Biological\ Tide}$	cm/h	$v_{Biological\ Tide} = Q_{ET}/S_{flow-through}$

Notes: t_0, starting time of the experiment. t_f, ending time of the experiment.

Figure 13: Hydrodynamic parameters assessed with dye tracer experiment

increases infiltration rate; if maximum infiltration is needed, gravel renewing should be preferred.

Assessing this type of feature seems thus positive for efficient operation on the long term, as trajectories of these systems are influenced by multiple factors: size distribution of the gravels, sewage network characteristics (with / without additional suspended solids) and day-to-day operation, to name a few. These systems eventually worked pretty well hydraulically speaking after 15 years of operation. This study brought me a first experience of field hydrology work. Additionally, it gave me a more operational view on these systems, with perspectives on mid- to long-term operational issues.

Dye tracer experiments A study like the one we described in the former paragraph gives a global view of CTWs hydrology. To obtain more detailed hydrological features, tracer experiments can be used. We regularly used this approach to determine the actual flowpath (and hence the hydrodynamic type of reactor equivalent to the system and the related equations [14]), to compute a hydraulic residence time globally and analytically [15] or to measure water velocity at very small magnitudes [13]. A tracer is a non-reactive substance that perfectly mixes with water; dye tracer experiments rely on the use of a fluorescent dye tracer injected into the system. Injection is followed by fluorescence measurements on strategic locations to detect dye particles and thus assess the time they need to flow towards that specific spot. As tracer particles are perfectly soluble in water, the time recorded is also the one that water molecules need to flow through the system. Time distribution curves (percentage of particles having flown through in a given time) of dye particles / water are subsequently determined (Figures 11, 12). They are used to compute various synthetic parameters (Figure 13): residence time distribution, mean residence time, dispersion, velocity, recovery rate giving a more detailed image of the system's hydrological behaviour. To illustrate this kind of study, we will detail below the experiment and results from [13].

As part of a collaboration with Daniel Childers and his research team from the Central Arizona Phoenix Long-Term Ecological Research (LTER), we participated to an ecological study of a constructed treatment wetland.

Figure 14: Aerial image of the 42-ha Tres Rios constructed treatment wetland. White lines are the locations of the 10 marsh transects (each 50–60 m long), and blue arrows show the water inflow and outflow points. The star indicates where the July 2015 controlled-flow dye study was conducted

Before developing this study, let us quickly introduce the LTER initiative and its french equivalent: the first has been going on since 1980 [16], the second since 2000. The idea is to carry out research on perennial sites (the so-called 'zones ateliers' in France) in specific biomes to study ecological processes whose time scale is belongs to long-term. Most of the time, the complexity of the studied ecosystems justifies inter-disciplinarity, bringing together human and natural sciences. Human sciences became then fully integrated in what will become long-term social-ecological research (LTSER, [17] and [18]) network. Moreover, the targeted application level often justifies trans-disciplinarity, which requires to gather stakeholders (local administrative institutions, citizens) around the issue that is studied.

Tres Rios CTW (Figure 14) is located in the arid and hot Sonoran desert (AZ, USA). Monthly average temperatures range from 11.2℃ in December to 33.5℃ in July. Annual precipitation averages 231 $mm \cdot yr^{-1}$ with most rainfall from December to March and from July to September. It is fed by treated water from one of Phoenix WWTP; incoming flow ranges between 95,000 and 270,000 $m^3 \cdot d^{-1}$ of effluent depending on the time of year, for a total volume of the system of approximately 357,500 m^3. The purpose of this wetland is to enhance nitrogen and phosphorus uptake before water discharge into the Salt River. Due to the xeric environment, a large volume of water is transpired daily; up to 150,000 m^3 per day during the hot summer days [19]. For compounds that are not volatile (and among them nitrates) significant evapoconcentration is expected, although not observed [20]. This field observation, combined with global water budget considerations (see 'Urban Ecology' part), led to the hypothesis of a preferential flow inside the wetland. Plant transpiration is responsible for a massive water loss, so the direction of this flow was supposed to be towards the marsh zone of the wetland. This water movement would be biologically driven, so it was tentatively called the "Biological Tide".

Given the configuration of the system, the velocity of this flow was expected to be very low, and was undetectable with devices like doppler velocimeters after failed attempts. The objective of the experiment was thus to determine the velocity of this water flow, which would at the same time prove its very existence. We assumed the use of

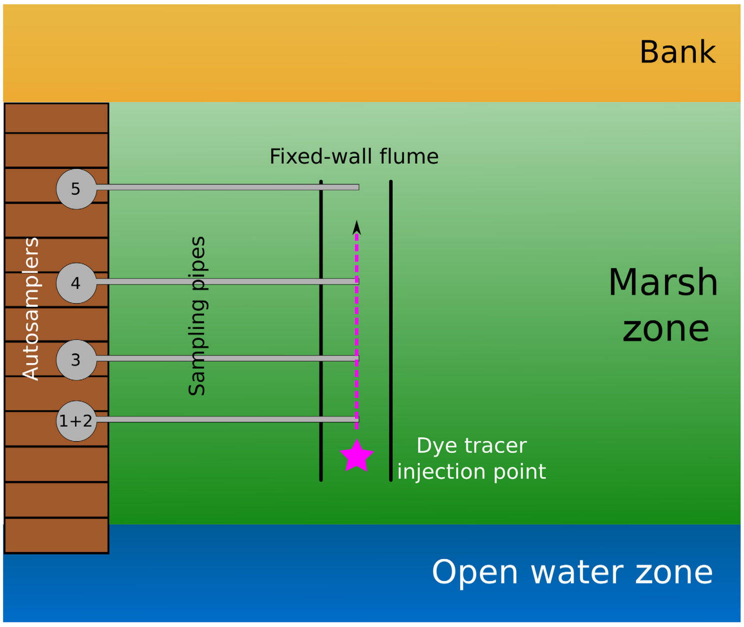


Figure 15: Experimental design, including the approximate location of the 2 9 16 m flume (shown as “fixed-wall flume”) adjacent to a boardwalk (left) and within the 50 m wide marsh. Sampling pipes allowed the autosamplers to collect water from within the flume without any disturbance of the marsh or soils during the experiment. The purple star indicates the dye tracer injection point.

dye tracer on a long enough measurement period would allow to measure this. To minimize blurring effect from lateral dispersion, a flume was installed within the marsh zone. Autosamplers were installed at defined intervals to retrieve water, analyse the fluorescence of the samples and determine water velocity (Figure 15). The dye tracer was chosen to remain stable under solar radiation and allow multi-days experiment. We poured it at the border between open water and marsh zone, and launched the experiment over 2 days. Due to the presence of organic matter in the water, there is a baseline fluorescence, that was accounted for to determine the samples true fluorescence. We withdrew samples at the end of the experiment and brought them to the lab to determine tracer concentration, by measuring fluorescence against a calibration curve.

We observed increased dispersion with distance to the injection point, due to the multiple flowpaths created by the plants present in the marsh zone. We determined an average velocity of 16 $cm \cdot h^{-1}$ i.e. 3.8 $m \cdot d^{-1}$, a very small velocity indeed. This flow was largely dispersive, which is logical given the multiple paths available. With this velocity, water would cover the marsh in around 4 to 13 days, compared to the 4 days residence time by design of the system. No night/day effect were observed so far, but we performed a limited number of experiments. The values we obtained correlated with other measurement methods that we will detail in the 'Urban Ecology' paragraph.

This experiment was a great opportunity to couple ecological and physical point of views in both field and lab work and to generate novel knowledge with potential consequences on a lot of existing CTWs. On the top of it, it was refreshing and exciting to provide evidence for new properties of an ecosystem, without talking of pollution or disturbance as too often these days.

Hydrodynamic modeling The evidence of novel functioning in wetland ecosystems can lead to promising new ways of managing their CTW counterpart. It is however physically difficult to explore all scenarios on the field, as it would require a lot of space, time and money. This can be compensated by using a numerical modelling approach: design scenarios and their hydrological and biogeochemical consequences can be ex-

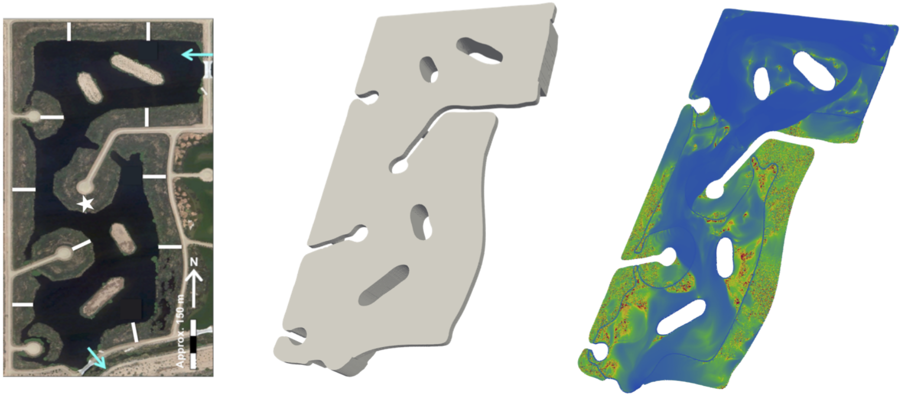


Figure 16: From aerial photography to numerical model of Tres Rios wetland

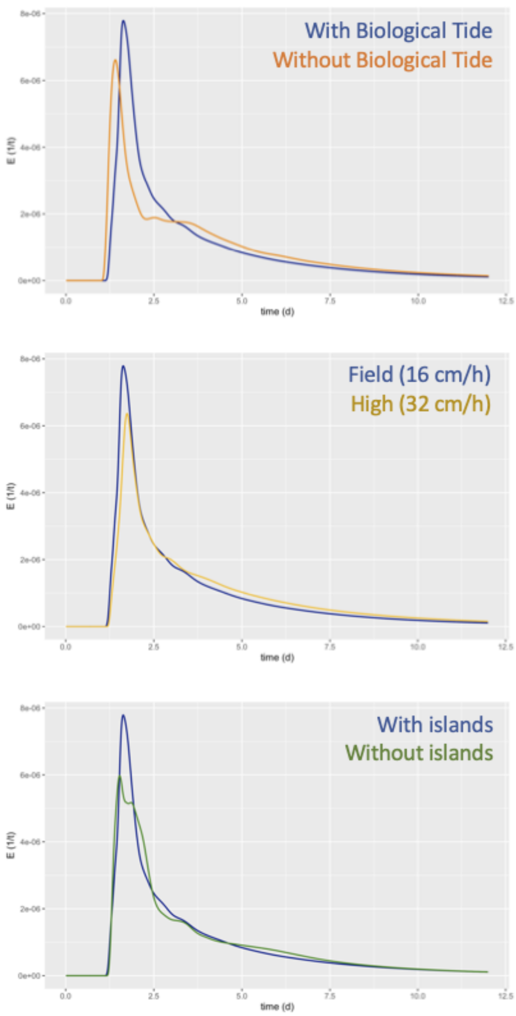


Figure 17: Modelled breakthrough curves for Tres Rios wetland

plored numerically. The most relevant configurations can be determined and applied on the field. To do so, a good understanding of the way the system works is required. As the Biological Tide had been previously demonstrated, we had a reasonable view of this point. Following this experiment, values for the Biological tide were available. We went on with a preliminary study carried out in 2019 [21], in which we used modelling to gain access to velocity fields across the whole wetland, otherwise difficult to measure. Actually, more than the velocity field itself, we were interested in its evolution with different configurations. The final objective is to increase the residence time without enlarging the wetland, to allow better biogeochemical processing of nutrients with a limited space requirement.

We tested the following hypotheses:

1. Is there a significant effect of BT: simulation with BT (and marsh water velocity at 16 $cm \cdot h^{-1}$) or without BT;

2. Is there a significant effect of plant community composition and plant density: with moderately transpiring and highly transpiring plants, leading to a 16 and 32 $cm \cdot h^{-1}$ marsh water velocity, respectively;

3. Is there a significant effect of the spatial configuration created by the presence of islands: with 16 $cm \cdot h^{-1}$ marsh water velocity, with and without islands.

We used an open-source software (OpenFOAM) and modelled the system with a hexahedral mesh (Figure 16), a steady-state, laminar solver (simpleFoam) for hydrodynamics and a simple diffusion model solver (scalarTransportFoam) for particle transport model, which allows to model tracer experiments. On this preliminary study, neither turbulence (because of the low velocity within the system), nor plant volume (as it was $\approx 2\%$ of the marsh volume) were accounted for. Preliminary calculations (mesh definition, preliminary runs to ensure parameters acceptability, etc.) were made on an office computer; real calculations were performed on the University computation center.

We obtained modelled RTD curves (Figure 17): no striking differences were obtained on the mean hydraulic residence time (HRT) between all configurations, but

qualitative differences of water distribution within the system were observed. The Biological Tide represented around 8% of incoming flow, and accounted for a 10% variation of hydrodynamic parameters when taken into account. To go further and make this work sounder, the following steps may need to be followed:

- The aforementioned approximations need to be taken back and modelled, at least to see if the hypothesis of neglect is verified;
- Model calibration and validation need to be done on the field;
- The mesh needs to be refined at the in- and outflow of the system.

This ongoing work aims at using the prediction capacity of modelling to propose design scenarios to stakeholders, informing better tools for constructed treatment wetland design using ecological knowledge. This will eventually produce systems with better processing rates, not because of heavier engineering but because of better knowledge of the system ecology. To quantify this last point, the hydrological characterization needs to be coupled with biogeochemical models, which helps assessing chemical compounds' behaviour and finally processing efficiency of CTWs.

Intermediate synthesis - hydrology In short, this work in hydrology and hydrodynamics were a good chance to discover and enjoy field work and to enhance my skills in hydrology. At the same time it allowed me to gain perspective on operational issues, as well as to enjoy the work to establish fresh new findings. Eventually, I had a first approach to how interesting and relevant modelling can be, both for fundamental or applied objectives.

1.2.2 Physico-chemistry

Physico-chemistry is another fundamental feature of CTWs, as it also contributes to the understanding of their functioning, when one is interested in the behaviour of chemical compounds inside these systems. The related ecological functions are important to determine the corresponding downstream ecosystem services. So far, we studied these physico-chemical features with lab and field experiments. These approaches are combined to deal with systems/mechanisms too complex to be satisfactorily analyzed on the field, but also to study them when lab studies would too simplified to satisfyingly explore field phenomena. Studies carried out on micropollutants, soil/contaminant interaction and temporal dynamics will be now detailed.

Micropollutants The European wastewater Directive (1991) established mandatory wastewater management for all cities above 2,000 inhabitants in Europe since 2006. Since that day, major[13] harmful compounds (suspended solids, organic matter, nitrogen and phosphorus) in wastewater have been satisfactorily handled in most cases. As major pollution is now mitigated, concerns turn towards a so-called new issue, contamination by micropollutants. The notion of micropollutants stems from the concentration of the compound at stake, from $ng \cdot L^{-1}$ to $ug \cdot L^{-1}$. This definition is mainly regulatory and very wide – some might say vague –, as it encompasses all chemical types (from organic to organo-metallic molecules, to heavy metals) and all uses (from pesticides to drugs to detergents). Their environmental effect has been documented since many years [22, 23, 24], and the research on their mitigation is a hot research topic [25, 26, 27]. For the compounds that are discharged with wastewater, there is hope that management systems would handle them as well as they can handle major compounds. The same concern exists for stormwater, and the same question about the mitigation capacity of CTWs arises. Thus we carried out studies to help determining the capacity of CTWs to mitigate this pollution in urban water.

Before switching to the chosen methodology, I will describe in a few words this stormwater management site, as it focuses a lot of my research work. In the early

[13] compounds whose concentration ranges between 1 and 100 $mg \cdot L^{-1}$

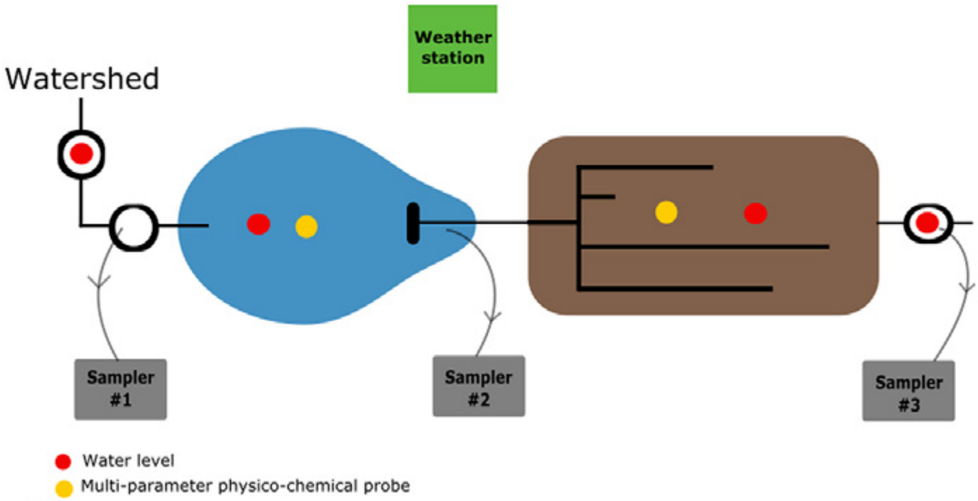


Figure 18: Sampling set-up for Ostwald's stormwater constructed wetlands

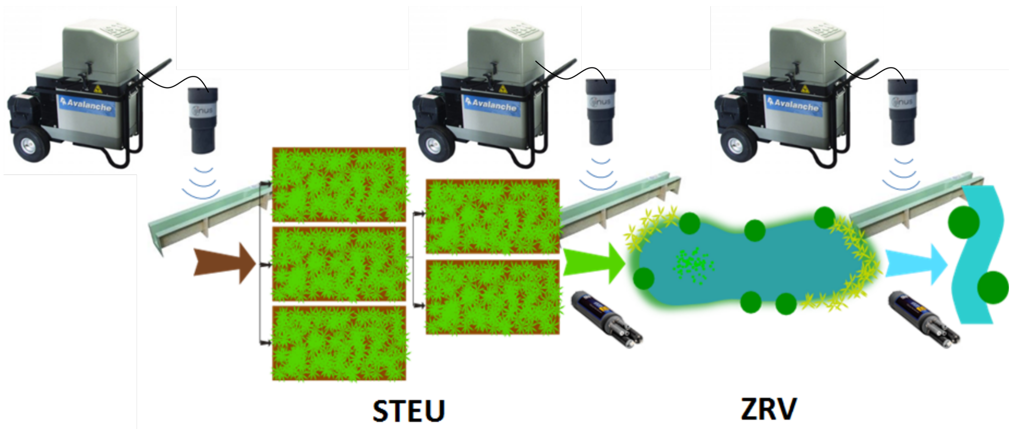


Figure 19: Sampling set-up for wastewater constructed wetlands. STEU: wastewater treatment plant; ZRV: constructed wetland

days was a strong link between ENGEES school, ICube laboratory (then IMFS) and Strasbourg metropolis; there was also a strong link between University of Strasbourg researchers and Strasbourg metropolis. In short, there was a strong transdisciplinarian link. Within EMS boundaries, are a lot of streams. One of them was recognized to be in a mediocre state. To abide by the law, it should be brought back to an adequate state. A restoration project was initiated, to reshape the stream, its adjacent surrounding and prevent future disturbance. It could be seen as the conjugation if three main works:

1. Physical reshaping of the stream bed;
2. Remodeling of the riparian corridor;
3. Installation of a stormwater management system.

The program was redefined by handling and financial issues due the massive pollution of stream sediment. The stormwater management system was eventually built before stream reshaping and riparian corridor remodeling. Three extensive stormwater management systems were built to collect their corresponding stormwater runoff from one of the three upstream residential urban watershed. To manage quality and quantity management, each system is constructed similarly: a pond followed by a constructed treatment wetland, discharging in re-created ponds. The connection with the stream was restored as the re-created ponds have groundwater links with the stream. A sampling equipment was set up to collect water samples and analyze their content; the difficulty was to trigger it automatically on the basis of stochastic events (rainfall). The stormwater management has been operating since 2012.

The approach we use is a global quantitative field approach to avoid pertaining lab work question (cf. PhD work synthesis), in which we measure contaminant concentrations and water flow at the inlet and at the outlet of the CTW we study ([28, 29, 30]). This allows to calculate fluxes, multiplying concentrations by flow. Most of the experimental configuration and field work was quite similar across sites (Figures 18 and 19): we used refrigerated autosamplers to capture daily flow-indexed samples, physico-chemical probes for onsite continuous measurements (temperature, redox potential,

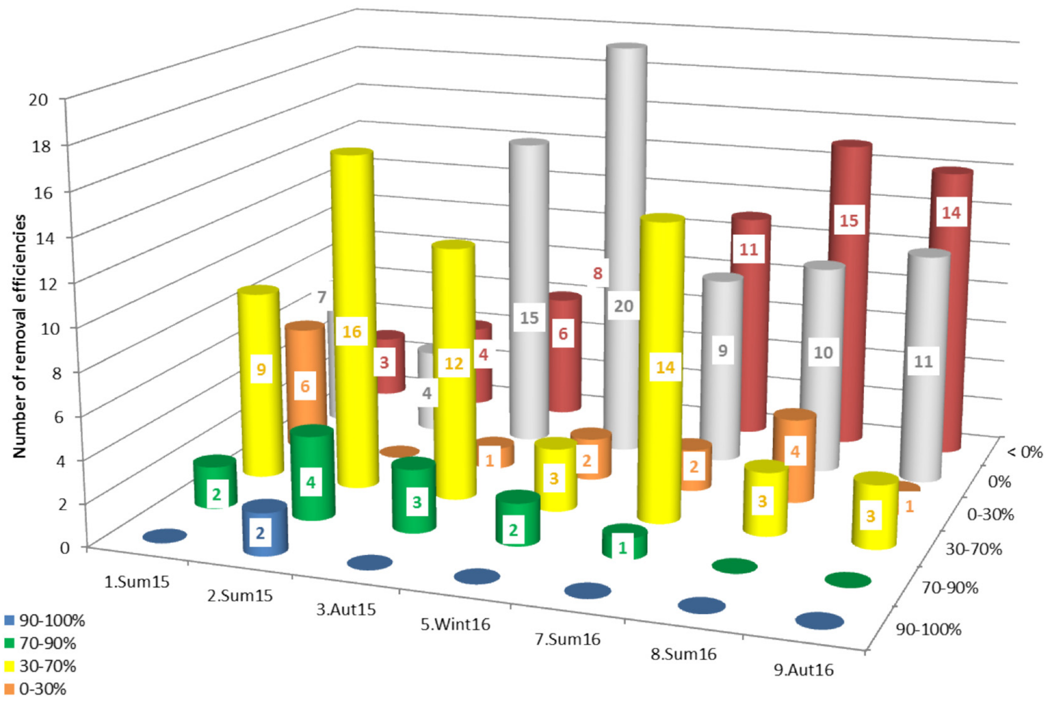


Fig. 5. SFTW drug removal gathered by class efficiency.

Figure 20: SFTW drug removal sorted by class efficiency

Table 3
Removal efficiency (RE) of the SCW, the pond and the filter to remove dissolved (D), particulate (P) heavy metals and PAHs (minimum – maximum [average]) (—: below limit of detection; ND: number of detection; *: RE not calculable because of a null output volume).

Micropollutants	Pond RE (%)		Filter RE (%)		SCW RE (%)		ND
	Conc.	Mass	Conc.	Mass	Conc.	Mass	
Chromium-D	–	87	96	100	96	100	1
Chromium-P	0–54 [27]	−67-100 [44]	0–76 [38]	97	0–54 [27]	94–100 [97]	3
Cobalt-D	–	100	–	*	–	100	2
Cobalt-P	−77	58–100 [86]	21	93	−41	97–100 [98]	3
Copper-D	–	59	–	99	–	100	1
Copper-P	19–56 [6]	48–100[83]	49–91 [70]	99	47–96 [70]	100	3
Lead-D	0	75–100 [90]	96	94–100 [99]	96	100	11
Lead-P	−74-10 [−38]	63–100 [88]	86–95 [91]	91–100 [98]	87–94 [90]	100	12
Zinc-D	−20-67 [37]	100	94–98 [97]	*	96–99 [98]	100	1
Zinc-P	−200-57 [−6]	100	75–99 [93]	*	88–99 [93]	100	1
Acenaphtene	50	84–100 [97]	–	88–100 [94]	50	98–100 [99]	5
Benzo(a)pyrene	91	59–100 [86]	–	30–100[44]	91	93–100 [99]	11
Fluorene	0–50 [38]	100	50–75 [56]	*	50–75 [56]	100	1
Phenanthrene	−100-75 [2]	38–100 [82]	50–92 [74]	97–100 [98]	50–92 [68]	98–100 [100]	9
Anthracene	–	59–100 [84]	90	94–100 [97]	–	98–100 [99]	6
Fluoranthene	−100-76 [8]	100	50–88 [71]	*	50–88 [71]	100	1
Pyrene	0–75 [11]	100	67–75 [74]	*	75–92 [77]	100	1
Benzo(a)anthracene	92	100	–	*	92	98-100 [100]	2
Chrysene	90	100	–	*	90	100	1
Benzo(b)fluoranthene	0–92 [46]	−25-100 [80]	50	16–100 [76]	50–92 [71]	66–100 [94]	10

Figure 21: Removal efficiency (RE) of the stormwater CTW, the pond and the filter to remove dissolved (D), particulate (P) heavy metals and PAHs (minimum - maximum [average]) (-: below detection limit; ND: number of detection; *: not calculable RE because of a null output volume)

pH, conductivity, dissolved oxygen) and weather station to monitor related parameters. Flows and contaminant concentrations were assessed differently:

- For wastewater, the study sites are equipped with venturi gauges for regulatory flow measurements. We installed height-measuring loggers to monitor the water height, and calculate flow, during the experiment. This work was co-supervised by Dimitri Heintz from the IBMP[14], all drug analyses were made at his lab;
- For stormwater, an automated system was installed to capture significant level increase in the CTW. As the bathymetry of the pond was known, the actual flow was computed with these measurements. Significant level increase would also trigger sampling. All analyses were made by an external laboratory.

Regardless of the season, a moderate to null mitigation efficiency was observed for most of the 86 drugs that were followed in wastewater [29] (Figure 20). Even more striking, for approximately 10% of them, an increase was observed between the inlet and the outlet of the system. No clear mitigation pattern emerged from the seasonal survey, even when considering single molecules. The complexity of the ecosystem and of its interactions made these results hard to understand. We made an attempt to sort between chemical properties of study molecules, but nothing significant came out of this. The increase at the outflow of the system is chemically impossible, but can be explained by the release of molecules from the system i) either from a conjugated form that was not detected at the inlet, ii) or from already-stored molecules. Conversely, a high mitigation efficiency was obtained for the compounds (5 heavy metals and 10 polycyclic aromatic hydrocarbons) followed in stormwater [30] (Figure 21). Here again, it was difficult to relate these results to environmental parameters, such as rainfall or dry weather period. Interestingly, the distribution of compounds between solid and liquid phase had an impact on the mitigation recorded through both CTWs. No release was observed in this study.

Globally, it appears that the mitigation efficiency of CTWs towards micropollutants is uncertain, but reassuringly (or not) higly-engineered wastewater management systems

[14] Plant Molecular Biology Institute in Strasbourg

do no better, not to talk about conventional ways of managing stormwater in concrete tanks and pipes. The chemical diversity of the study molecules, coupled with the complexity of the ecosystems we looked at, resulted in patterns that were very obscure to interpretate. As of today, we have not been able to delineate the drivers of the observed concentration and load decreases. This work showed that normalized mitigation was simply impossible to expect from these systems, and that hopes for dealing with this issue on the sole basis of treatment seems irrelevant.

Soil-contaminant interaction In the wake of the previous study on stormwater contaminants, questions arose about the sustainability of heavy metals retention in CTWs. Indeed, a heavy metal that is withdrawn from water will stay in the solid phase (e.g. soil or plants), unless it transfers back to the liquid phase. The confinement of these contaminants is always temporary, and raises concerns about their release if environmental conditions change beyond a given threshold. Additionally, the use of CTW for stormwater management remains quite recent, so maintenance questions after 10 years operation are just being asked; the handling of sediments where stormwater contaminants accumulated remains free of regulatory framework so far. To try and answer these questions, we led a study to determine i) the mechanisms responsible for this confinement, ii) the impact of physico-chemical variations on storage and iii) the impact of molecule competition on storage. We worked with Mireille Del Nero and his team from the IPHC[15] to share perspectives and have access to some specific equipment. A lab-scale study was carried out [31] on a few model metals to make mechanisms more understandable.

Copper (Cu), zinc (Zn) and lead (Pb) were used as model metals because they were prevailing from the former field surveys. Soil sampled from the actual stormwater field site were used for lab batch experiments. Their mineral composition was determined to assess the accumulation of the studied metals and its evolution with depth. Water sampled on the site was also analyzed for heavy metals. Several values of pH, metal-sand contact time and initial metal concentration were tested to study metal sorption

[15] Hubert Curien Pluridisciplinarian Institute in Strasbourg

dynamics in batch experiments.

The mass balance calculations suggest retention and remobilization along the CTW sequence for Zn, unlike Pb and Cu. The main confinement mechanisms were identified: according to the sequential extractions results, Pb and Zn are both mainly associated to residual fractions (surface of primary clays, in heavy minerals, into Fe/Mn oxihydroxyde). Cu is potentially associated to carbonates minerals in the CTW. In CTW field conditions (i.e. metals at trace concentrations and pH lower than 7.5), the batch experiment results suggest that the global affinity of the CTW substrate for metals ranks as follows: Pb=Cu > Zn. Pb and Cu form surface complexes on sites of the substrate, as hydroxyl groups of iron oxides. Zn is involved in ion exchange and/or compensation of negative charges at the surface of CTW substrate (pH < 5). The metals sorption capacities of the substrate reveal that Zn is potentially desorbable from the substrate under the field conditions. Conversely, Cu and Pb removal efficiencies are above 90%. No competition effect was observed, and saturation risk was deemed low. Although changing physico-chemical conditions can have a strong impact on zinc storage, the required magnitude makes it unlikely to be met on the field. The question of long-term behaviour of these compounds in the solid phase is nevertheless asked. This question would have never been raised without the long-term place-based research going on this site.

Intermediate synthesis - physico-chemistry Contaminants do not seem to be globally well mitigated by constructed treatment wetlands, although some particular compounds can be. Even for well-mitigated contaminants, release potential with changing conditions was significant, and was observed on the field especially in wastewater studies. This work about the physico-chemistry of CTWs allowed me to deal with the complexity of this field and the conclusions that can be drawn operationally speaking.

1.2.3 Urban ecology

Ecology is the science of the interactions between organisms and the place they live in. As we are studying systems in urban environments, such type of study belongs to the field of urban ecology. In these studies, the explicit accounting of the biological contingent[16] allows to complete the understanding of CTW functioning and the subsequent diagnosis regarding the issues we study. Field studies about the ecology of CTWs regarding plant transpiration in mesic climate and citizen perceptions will be now exposed.

Plant transpiration in CTWs under mesic climate Prolonging the collaboration with CAP-LTER, we carried out a study on plant transpiration in urban water management CTWs under a more temperate climate than the Sonoran desert (Bois et al. in preparation). The objective study was to assess plant transpiration in mesic climate, in CTWs managing urban water, and to determine their significance regarding the global water balance of the system. Transpiration was proven to be a deeply significant driver in Phoenix, and we wanted to know if this was as important under Alsace french climate. Plant transpiration is mainly driven by solar radiation, temperature and relative humidity; extreme values are reached in the sonoran desert, leading to strong transpiration. As these values are much softer around Strasbourg, one can wonder how the resulting transpiration will be. And as strong conclusions and significant management recommendations were formulated for Tres Rios, the applied question was to know whether similar advices could be given in our research sites to improve benefits retrieved from CTWs.

We used the same measurement as in [13] to quantify this phenomenon: water transpired by plants photosynthesis artificially provoked by carbon dioxide flow is measured by a portable infra-red gas analyzer (IRGA). An amount of transpired water per leaf area and per time unit is measured and subsequently converted into a transpired water volume per biomass unit and per time unit. This requires the live biomass within the CTW to be measured. We went on field sessions at the key moments of the veg-

[16] in the broad sense, as it includes Human

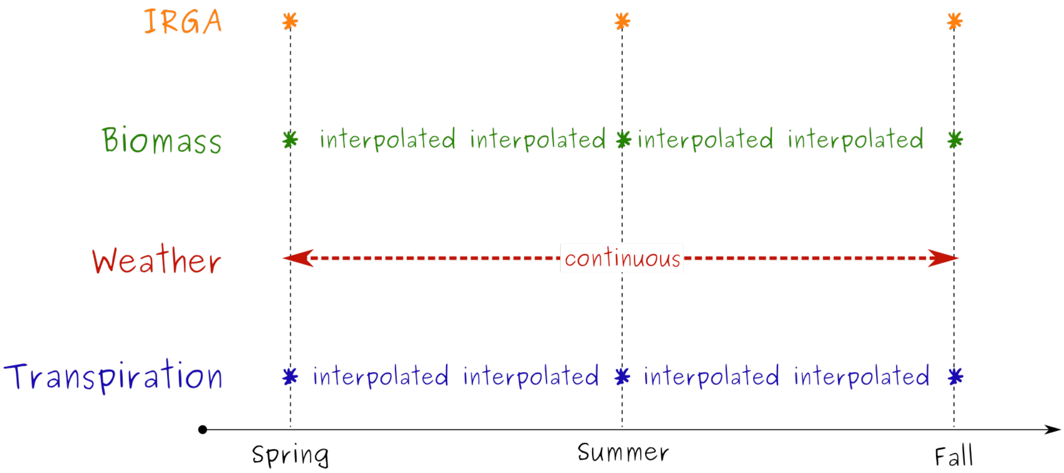
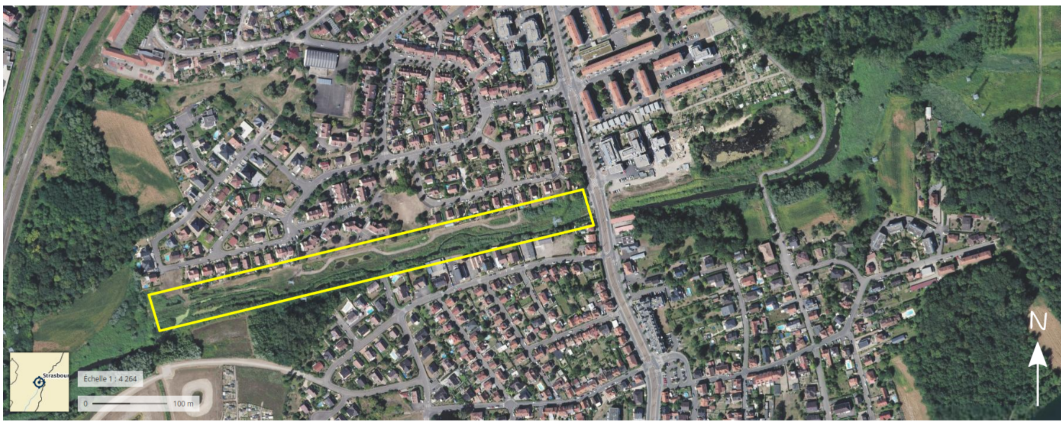


Figure 22: Transpiration computation and interpolation method



Données cartographiques : © FEDER, Région Grand-Est, Préfecture de la région Grand-Est, Conseil départemental du Bas-Rhin

Figure 23: Surroundings of Ostwaldergraben study site. The research site is framed in yellow

etative season: spring, summer and fall, and coupled this measurement with biomass sampling and weather monitoring, to link biological and physical parameters. Thanks to the biological measurements at these key moments and continuous weather monitoring, we were able to scale transpiration at a yearly time span to provide larger insight into the effect of transpiration under mesic climate (Figure 22).

For wastewater CTW, hourly transpiration could reach 25% of the incoming flow at the hottest time of the year. Biomass in the systems was logically influenced by the load of inflowing water: it developed more in systems handling wastewater than in systems handling stormwater. The contribution of transpiration to the global water balance dropped down to 2% of the total when considering water balance on an annual scale, though, as there is no transpiration at night but water continues to flow, nor during winter when biomass is dead. For stormwater managing CTWs, strong transpiration during the summer coupled with stochastic feeding might lead to plant water stress. These findings show that depending on the objective of the CTW (flow reduction, pollution handling), sizing may be adjusted according to transpiration magnitude and the type of handled water.

Blue and green corridor restoration Woven into an urban landscape and in a stream restoration project, three mitigation systems made of a pond followed by a CTW (cf. description in § 1.2.2. - Micropollutants) have been operating since 2012. As discussed in the previous parts, we strongly focused on hydrological and physico-chemical functioning of these studies, and then evolved towards more integrative studies, as illustrated by the aforementioned transpiration survey. To go one step ahead, we wanted to expand spatially: we would investigate the social side of this study site and question the perceptions that local communities have from it, and come back to the global purpose of the restoration project and the larger part of the landscape that belong to the project [32] (Figure 23). To gain social insight, tested hypotheses were i) The distance to the Ostwaldergraben site influences the residents' representation of the Ostwaldergraben; (ii) the knowledge of the functionality of the site (mitigation) modifies the inhabitants' behaviors linked to their own pollution in the rainwater network

collection; and (iii) there is a typical profile of inhabitants who show a stronger awareness of the link between pollution in the stormwater network collection and the pollution of the Ostwaldergraben stream. The ecological issue was the disconnection between two natural wetlands generated by urban infrastructures, and the mediocre state of the stream due to chemical and morphological features. This mediocre state prevented fish species from moving across the stream in low-water periods. Thus we could include the management systems into their close environment, gain knowledge on the issues at stake beyond treatment efficiency, and see how they interact with this primary purpose of stormwater regulation and blue and green corridor restoration. We worked with Carine Heitz, a geographer from the GESTE[17] laboratory, and Jean-Nicolas Beisel, an ecologist from the LIVE[18] laboratory.

We coupled field sociological inquiries with ecological feedback and physico-chemical results. A field social survey was carried out: first, semi-structured interviews were held with a few residents to have a first approach to their perceptions and prepare the following step. Second, questionnaires were set with refined questions from the interviews. They were mailed to every neighbouring resident. The ecological feedback was obtained first by digging into the archives of the stream restoration project, and then by thorough discussion with city officers that work(ed) on the project. Finally, we used the results we already obtained on CTW physico-chemical and hydrological characterisation to complete the study.

On the 147 households of the neighbourhood, 45% answered the mailed questionnaire, without any reminder. The distance seems to play a role on the relation with the site: residents with a direct view on the site think the stream is polluted and wish the site would remain close to the public. The reintroduction function linked with the corridors is correctly understood and the aesthetics aspects positively viewed, but misunderstanding on the exact mitigating role of the CTWs persists. The information provided at the entrance gates of the site was seldom read (55% of the respondents) or misunderstood, so communication can be improved. Especially since 91% percent of the

[17] Gestion Environnementale des Services de l'Eau
[18] Image, City and Environment Laboratory

respondents did not attend the public meetings, and 82% did not visit the restored site: city efforts to communicate were not necessarily successful, without responsibility on its side, as public inquiries and charrettes were held. Globally, replication of this type of system is encouraged by local communities. Related with the last social hypothesis, no significant link was established between inhabitant profile and environmental awareness. Considering the ecological aspect of the project, restructuring of the stream and its banks were successful: amphibian species could transfer from the upstream to downstream natural wetland, terrestrial species could cross under the bridge and fish species were swimming in a stream with more water depth all-year long. As the stream was re-meandered, lotic and lentic profiles were set anew, which re-created a diversity of habitats. This diversity could benefit the lifelong settling of aquatic species. As we discussed earlier, mitigation objectives for stormwater were reached, which makes the stream much less impacted by stormwater physical and chemical pollution. Still new questions arise: the extensive stormwater management system provided new habitats for amphibians, that were not initially thought as such. As heavy metal contamination accumulates in the system, these habitats could prove harmful for the local fauna.

Intermediate synthesis - urban ecology The urban ecology approach allows us to explicitly add biological and social considerations to the sole physico-chemical ones that were our main work since then. Thanks to this we showed that plants have a significant impact on the system functioning; this could give way to management evolution and system modification, even thinking of enhanced sizing in the future. This urban ecological approach blending biophysical and social templates seems to be for me the most relevant one to study constructed treatment wetlands in urban landscape as complex systems working on the long term.

Synthesis of current research activity and perspectives To study CTWs handling urban water, we started our ecological engineering approach with mainly hydrological and physico-chemistry work. We included ecological and sociological approaches as ways to answers questions emerging on the way of this work and to participate in an assessment of CTWs long-term behaviour. Yet given the random mitigation observed for some compounds, it seems that they can hardly be the linchpin of a reduction strategy, at least for micropollutants issues. One can then ask if the most relevant long-term strategy would preferably be source reduction, with subsequent shrinkage of mitigation systems – if not withdrawal –, resulting in an overall lower treatment cost. To sum it up, these first research years convinced me of how valuable CTW can be in the field of urban water management. To go further and to make up for limits shown in previous work, I think it is important to add new horizons to these CTWs, though.

First, to consider CTWs as the only systems to manage urban water makes limited sense, for many other components of nature in cities can act similarly. To enlarge this perspective, we will thus introduce the concept of Urban Ecological Infrastructures. Focusing on the efficiency of treatment seems logical, yet this point of view is narrow and hardly allows to understand the mechanisms leading to the provided service. We propose to come back to a more phenomenological approach, studying the ecological functions ahead of their human-centered counterpart, the ecosystem services. As we saw earlier, water management service results from intertwined biophysical and social phenomena. The latter will ultimately decide if these systems are set up, and how they will be managed once installed. Therefore I think it is crucial to see these systems in a broader framework than the usual "treatment system" one: I will enlarge it to the notion of social-ecosystem (SES). The objective of all these systems is to help reaching sustainability for our society: to better understand this objective, we will develop this notion. Finally, needed transformations to reach sustainability also happen with specific time dynamics; in the age of immediacy and urgency, I feel it necessary to have a reflection on long-term aspects. This notion of time scale is especially important since our capacity to change (or not) and to maintain this change on the short- and long-term will strongly influence on the trajectory the SES will transform to.

2 Research project

I will start presenting the work hypotheses that support the project, before asking the research questions that form the project outline. I will then strive to develop relevant parts of a few supporting concepts of these hypotheses and questions in the 'theoretical background' part. These developments will be preferentially kept centered on the research project to avoid long and pointless theoretical developments. As I am a user of these concepts and not an expert, this is a first approach I will gradually refine thanks to research work and discussions.

Following several authors, water management encompasses transport, quality and quantity management before use, transfer to users, and quality/quantity management before discharge in natural environment [33, 34, 35]. It has evolved over the course of history to presently end up as infrastructures mixing water pipes, sewers, water treatment works (drinking water) and sewage treatment works (wastewater); it handles thus the whole urban water cycle, from drinking to waste- and stormwater. Although this whole cycle could theoretically be handled differently through the use of alternative solutions I will define herafter, I will focus on waste- and stormwater cycles and their transport and quantity/quality management. My use of the "urban water management" notion covers these features only; I will not deal with the production of drinking water.

2.1 Definition

2.1.1 Work hypotheses

I propose to build this research project on the following work hypotheses:

1. Water in urban environments can be to a large extent managed by urban ecological infrastructures (UEI), i.e. natural or semi-natural ecosystems like constructed treatment wetlands, ponds, streams, green roofs and bioswales. They are expected to be understood and adopted by scientists and managers alike, to generate concrete applications;

2. UEI host a comprehensive set of ecological functions – e.g. water absorption, nu-

trient cycling, sediment retention, and transpiration – that result from interactions between its components and its external constraints. A whole range of ecosystem services (ES) derived from these functions benefit mankind; primarily here regulation of water quality and quantity, but other services can be provided as well. To name a few, habitat provision, aesthetic landscape creation, thermal energy regulation and biomass production;

3. Blatantly human-influenced, UEI can be conceptualized as social-ecological systems (SES), where the social template is fully integrated in the structure and function of the ecosystem, along with the biophysical template and the external constraints. UEI are embedded in a larger SES: the city. Accordingly, UEI functioning and trajectory are expected to depend on the three aforementioned components: for instance, climate change generated by mankind induces hydrological alterations that lead to water scarcity/profusion, pushing people to act against climate change in return;

4. Water management UEI features can help cities reaching sustainable trajectories, allowing the urban SES to live its full expected lifespan. Sustainability is weakly supported by development in its commercial meaning. Such kinds of trajectory are characterized by simplicity, using the least possible – material, space –, integrating natural cycles and bringing people together. UEI are not perfectly simple but they bring a whole lot of simplicity with them;

5. The social-ecological dynamics of water management UEI presents a broad time range, from minutes – storm event –, to years – contaminant accumulation – and decades – perception changes –. To understand the system at its full extent requires to account for this and to carry out studies at the appropriate time scale;

6. A growing body of evidence shows the relevance of UEI to manage water. It can help implementing more environmentally sensible water management to address concerns on this resource. Yet in many cases, a strong resist-stance in front of environmental degradation results in an absence of change. The study of the social template within the SES is mandatory to explore and trigger evolutions.

2.1.2 Research questions

As suggested above, the study of UEI for water management from a single scientific point of view – thus studying a thematically reduced number of functions and services – makes little sense. For this does not allow to accurately understand this social-ecological system, neither to characterize the interactions between the ecological functions and the trade-offs between services. Moreover, the various temporal dynamics of these SES and the resulting trajectories advocate for appropriate lengths of experiment to document this very evolution, as well as its sustainability. Eventually, the role of the social template in UEI trajectories is crucial as it will result in increasing or alleviating the disturbances that they are facing. In short, I am interested in the multi-functionality and long-term dynamics of water UEI. The resulting research questions cannot be as precise and specific as mono-disciplinarian research, but they serve another purpose: to contribute i) to the knowledge of these complex systems and ii) to the application of this understanding towards actual change. I would like to help answering to these questions:

1. **What are the interactions between ecological functions and subsequent trade-offs between ecosystem services supplied within a given water UEI?** Examples could be plant transpiration vs. water distribution (flow buffering vs. water provision), contaminant storage vs. biotope degradation (quality regulation vs. habitat), or source of ease vs. predation (aesthetics vs. mosquito predation);

2. **How does the long-term dynamics of water UEI affect both ecological functions and ecosystem services?** Examples could be the evolution of mitigation status with increased storage and release potential, air/water temperature increase and their effect on water budget, or the impact of system ageing on plant succession;

3. **How does stakeholders evolution alter UEI's functioning?** Examples could be the impact of local communities on stormwater pollution and resulting pollution pressure alleviation, managing flow impoundments on a stream and the result on

the thermal regime and biotic communities, or how changing the design of a given UEI will enhance water regulation service.

I hope that bringing pieces of evidence to answer these questions will help considering and valuing UEI in a more unabridged, relevant and sustainable way. I would be happy if it contributed to addressing the challenges urban SES face today.

2.2 Theoretical background

In this part, I will emphasize on the concepts that will be useful to implement my research project. I see them as having several statuses:

i- Currently developed with colleagues, tools I will use for my research: urban ecological infrastructures;

ii- Especially developed in networks I am involved in (LTSER), tools I will use for my research: social-ecological systems, long-term dynamics, human influence;

iii- Initially developed in other research areas, but I think they ought to be included in my research work: ecological functions, ecosystem services, sustainability.

While striving to integrate these concepts, I hope to show how they can serve the purpose of water management in urban context in a more nature-respecting way. I will articulate this part in three main sections. In the first I will define my main research object, urban ecological infrastructures, explain how it is relevant as a research object and how it departs from nature-base solutions. I will then turn to concepts that can help understanding the way these systems work, using the notions of ecological functions and ecosystem services, social-ecological systems, sustainability and simplicity. Eventually, concepts related to the temporal trajectory of these systems will be examined: time dynamics and human influence.

2.2.1 Nature in cities: the concept of Urban Ecological Infrastructures

Urban water management is necessary. The ecological functions that contribute to it, such as nutrient cycling that leads to organic matter return to soils, and the natural or

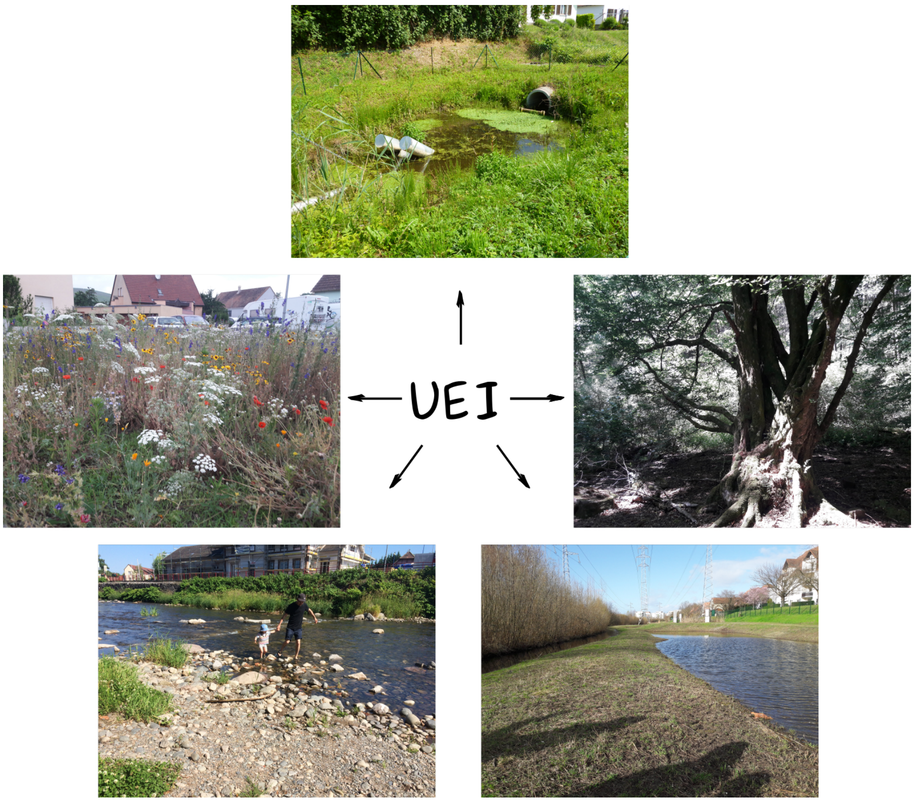


Figure 24: Examples of UEI

semi-natural systems that support these functions are increasingly used to answer part of today's environmental issues. We saw that constructed wetlands can help achieving this; they are not the only natural features of urban landscapes that can do this, though. Nature-Based Solutions (NBS) and the ecosystem services[19] (ES) they provide are broadly acknowledged ([36], [37], [9]). Yet the understanding of the NBS concept by some is not totally satisfying:

- it seems generally more turned towards the result obtained (enhanced water quality for instance), often a single result, than the process leading to this result (e.g. dissolved organic matter consumption by heterotrophic bacteria). It might be enough for end-users, but insufficient when trying to i) study all ecological functions and subsequent ES of a given system and ii) expand the use of theses systems in different social-ecological contexts;
- it concerns mostly ecologically engineered systems, does not include all types of ecosystems, and sometimes fails to be adopted by urban planners;
- wetlands do not necessarily appear as NBS, notably under the "Green Infrastructure" label. Actually they are a blend of green and blue ecosystems, and present unique features as ecotones.

We propose an extending concept to compensate for these limitations. It is named Urban Ecological Infrastructures (UEI), and was detailed in an article co-authored in 2019 [38]. We will extract the most relevant features for our work here, followed by the entire publication.

By definition located in cities, UEI can be (constructed) wetlands, urban streams, lakes, channels, lawns, forests, trees, flower pots, bare soils, to name a few (Figure 24). Actually "UEI comprises all parts of a city that support ecological structures and functions", which means that a swimming pool or a public concrete shade cannot be considered as UEI. This concept gives a clearer definition of what can be called 'ecological' and what cannot; it thus helps to discriminate which systems are truly environmentally-friendly and which are presented to be so, but are not really. Moreover, by using eco-

[19] a concept we will come back to in next section

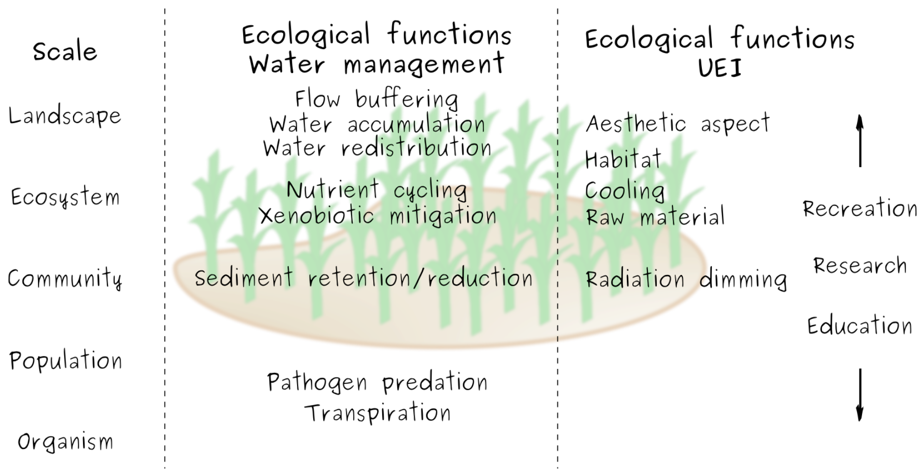


Figure 25: Ecological functions acting in a UEI

logical and infrastructure in the same locution, it conceptually bridges the gap between science – ecology, that study these systems from a fundamental point of view – and practice – urban planning, that eventually create these infrastructures –; this is meant to help transforming concepts into concrete actions.

Let us further apply this UEI concept on the example of constructed wetlands used for water management in urban contexts. Their ecological structure is the conjugation of (pseudo-)soil, vegetation, microfauna and either storm- or wastewater. Resulting from the interactions between these structural elements, ecological functions arise: physical processes such as filtration and retention, biogeochemical processes such as organic matter oxidation and reduced nitrogen nitrification, biological processes such as plant transpiration (Figure 25). All these functional items would obviously exist in the absence of people around; in a renewed manner since Käthe Seidel work in the early 60's, these systems have been specifically used and studied for what mankind benefit from them. Indeed the combination of these functions provide CTWs with the ability to increase water quality (by reducing pollutant loads) and regulate water quantity (by buffering stormwater peak flows). These features can become of great interest in an urban context, as i) cities are increasing, and 50% of the world population could be urban by 2050, which makes them responsible for at least half of the domestic water processing load, and almost more of the stormwater management load; ii) water access and sanitation is still a concern, as acknowledged by UN in the Sustainable Development Goal, and iii) energy requirements of these systems are much lower than conventional systems to reach the same efficiency. This contribution is however not perfect: for instance, these systems generally work efficiently with more space requirement, and consume a significant amount of natural resources.

2.2.2 What makes UEI fit for urban water management?

Ecological functions and ecosystem services Urban water management objectives can be achieved thanks to biological, chemical and physical interactions involving the biocenosis and its biotope within the studied ecosystem. These interactions are the ecological functions, present at all scales of the ecosystem: individual organisms,

Ecological function	Ecosystem Service
Flow buffering Water accumulation Water redistribution Transpiration	(Water quantity) Regulation
Nutrient cycling Xenobiotic mitigation Sediment retention/reduction Pathogen predation	(Water quality) Regulation
Transpiration Cooling Radiation dimming	(Climatic) Regulation
Raw material	Provision
Habitat	Support
Aesthetic aspect Recreation Research Education	Cultural

Figure 26: Ecological functions and ecosystem services in UEI for water management

population, communities, ecosystem. In UEI for water management, the functions we can primarily think of as relevant are nutrient cycling, xenobiotics mitigation, pathogens predation, sediment retention and reduction, water accumulation, water redistribution, transpiration and flow buffering [39, 38] (Figure 26). To study the relevance of UEI for water management, we would benefit from investigating these functions, because:

i - they will define the efficiency of these infrastructures in achieving the goal set, providing magnitude figures, variability assessment and a comparison basis;

ii - we can better benefit from the system features, as in the case of the biological Tide. Evapotranspiration could help reducing the system size while keeping water accumulation to an adequate level, and nitrogen processing acceptable;

iii - it allows to cleverly adapt UEI to other configurations. The strategy is to get the expected functions where the system will be located, which will not necessarily be the same type of location where initial studies were made. Typology here is taken in a wide acceptance, including biophysical and social features.

Moreover, ecological functions in a given ecosystem are numerous, and we could rely on them to yield more than just water quality and quantity regulation, with limited effort. For instance, UEI for water management can include other functions such as cooling, radiation dimming, habitats creation for amphibians, fishes and waterfowl, locations suited for educational, scientific and recreational purposes, spots offering aesthetic landscapes. In a time of climate change, biodiversity crisis and greying of the landscape, these functions can help alleviating environmental and social stress. Without proper study though, the magnitude of the function will remain elusive, and without joint studies, the feedbacks between functions would stay undetermined. For instance, when we look at CTWs in an urban setting we can choose to focus on functions related to water management. By doing so, we may be losing part of the picture [40], and we illustrated this with the case of the Ostwaldergraben [32]: to improve the state of the urban stream and restore blue and green connectivity, the course of the stream was remeandered and CTWs were created to cycle nutrient, mitigate xenobiotics, retain and reduce sediment, and buffer flows. Looking only at these functions, the system

would be deemed to achieve its purpose, as contaminant levels significantly decrease along the CTW and runoff flow seldom discharge into the stream. Yet when crossed with a population ecology analysis, the result might be more complex. Being wetlands, the CTWs also create habitats for (endangered) amphibian species. The result is a desirable habitat for amphibians, yet increasingly loaded with stormwater contaminants. It seems thus relevant to look out for multiple ecological functions, as i) this gives a more integrated view on UEI and lets envision more benefits from them, and ii) the co-existence of different ecological function necessarily goes along with feedbacks between them, that can alter the individually expected results.

Ecological functions are inherently part of ecosystems, and exist without Human to document it; when they can be used for Human benefits, their results are labelled as ecosystem services, and were aprticularly established as a framework in the Millenium Ecosystem Assessment [41]. Four types of ES were defined:

- Cultural services and amenities, such as the aesthetics provided by a nicely meandering urban stream, the recreation allowed by playing in a brook, the sense of place one can feel amidst an urban forest, the education that a constructed wetland can help to achieve or the joy to observe waterfowl in an aesthetic wetland landscape [42];

- Provisioning services, such as cereals grown in urban agricultural lots [43], fruits provided by urban help-yourself orchards [44], ready-for-irrigation water provided by constructed wetlands or mosquitos from still water that become food for bats;

- Regulating services, such as shade and subsequent refreshment provided by urban trees, refreshment provided by vegetated walls transpiration, denitrification provided by non-perennial urban wetlands [45], flow buffering or the global improvement of water quality after flowing through a constructed treatment wetland;

- Supporting services, such as the craft transport possibility provided by water channels, the ability for plants to grow in an urban vacant lot, or habitats provided for amphibians by wetlands.

This concept was first thought as a metaphor to try and bring people back to Nature [46]. Derived from economic and ecological theories and adopting economic vocabulary, the ES notion gives an explicit view of what ecosystems provide; it gives way to its financial assessment [47]. No technological artifacts could fully replicate the immense variety of structures and functions that make the Earth livable for Human, which make ecosystem services valuation relevant not in absolute value[20], but as the cost we should add to get similar services, should ecosystems functioning fail. It has become a very productive area of research, as shown by a search engine query[21] using the expressions "Ecosystem services" and "Ecological functions", between 1997 (year of the infamous Costanza's publication) and 2021, totalling 110,370 publications for 247,397 on the topic of ecological functions. As cities are specific types of ecosystems (see next section), they also display ecological functions that can be derived as ecosystem services as well [48, 49]. When focusing on UEIs, many examples show that a single UEI can actually provide an array of ES [50], which can be interesting in the prospect of urban limited space to obtain a number of services.

However, it seems that today this concept has led us astray from the original intents of its authors [46], notwithstanding conceptual limits that make it not so universal and fit to describe the reality of how ecosystems (human included) contribute to life on Earth, fraught with limits. Anyhow, this concept still generates debate more than twenty years after, and should be handled with care [51], [52]. Personally, I see this concept as maybe more pedagogical than operational, while giving sometimes way to finalist discourses among stakeholders (the so-called mitigation power, plants/bacteria/fungi will work specifically on contaminant mitigation, etc.). For purpose of knowledge production and sharing, it seems to me that ecological functions are the most appropriate entry point as they are more precise and quantifiable. On the other hand, for purposes of communication with stakeholders, local communities or public audience, the ecosystem services approach would seem more self-explaining. This approach can thus be a weapon of choice for transition towards more sustainable trajectories initiated in a

[20] $= \infty$

[21] ScienceDirect; query made on 2020/07/05

bottom-up manner. Now from a systemic perspective, it seems important to understand what the drivers in these systems are and how they provide feedbacks to each other. The concept of social-ecological system can help choosing the proper study scale, and determine the leverage points and locks within the system.

Social-Ecological Systems The term ecosystem was first proposed in 1935 by Sir Arthur Tansley, although many references linking organisms and their surroundings can be found earlier [53]. Within the ecology theory of organization levels, this organization level is above community and below landscape. This ecological system gathers all organisms (the biocenosis) interacting in a given location (the biotope) and leading to clearly defined biotic structures and energy/nutrient exchanges [53]. It is a functional unit with in- and outlets defined at its boundaries. Ecosystems are complex adaptive systems [54]: their components interact at various hierarchical scales, they have the ability to maintain in changing environments and respond to changes in other ecosystems. They also display properties unique to them, that emerge when forming the ecosystem, and cannot be expected when linearly summing the properties of their components.

Today, it seems that virtually all ecosystems on Earth are either directly or indirectly affected by Human actions [55], [56]. The question that arises then is "Is it still relevant to study ecosystems from a mere biophysical point of view?" The answer is, in many cases, "no". Thus, more than thinking in terms of ecosystems, it seems interesting - if not mandatory in the case of cities - to think in terms of ecosystems and its social template: this leads to the notion of socio-ecological system (SES) [57], well-suited to study human interactions with and within ecosystems [58], [59]. One can rather use the term soci**al**-ecological system to highlight the significance of social mechanisms on the functioning of these units.

A specific framework for the study of SES in long-term social-ecological research was developed in 2011 [17]. The systems that I study are clearly a part of larger urban SES, so the study of urban ecological infrastructures through the SES lens seems relevant to try and capture the multiple ecological functions and derived ecosystem

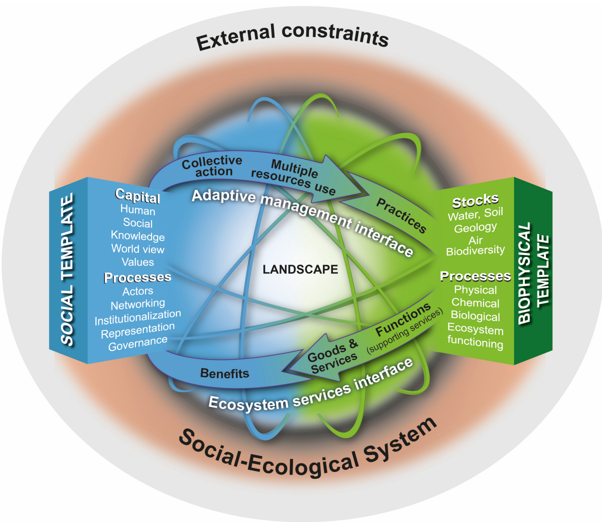


Figure 27: Social-EcoSystem conceptual framework of the French LTSER network. From [18]

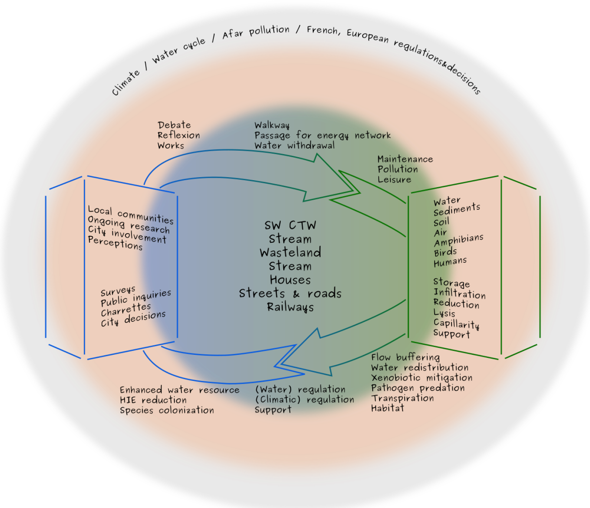


Figure 28: SES framework applied to OG's stormwater CTW

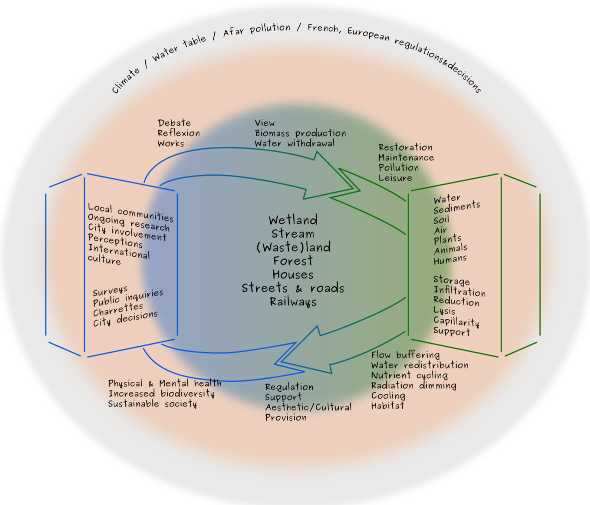


Figure 29: SES framework applied to UEI for water management

services. Usually, the study of the social template for such a system is the realm of Social Sciences and Humanities – e.g. Sociology, Economy, Philosophy, Anthropology –, while the study of the biophysical template is Natural Sciences' own – e.g. Biology, Ecology, Physics, Geology –. And these studies were not necessarily meeting and cross-fertilizing. The SES framework defined within the French LTSER network (Figure 27, [18]), adapted from the one defined in [17], helps conceptualising the Human interaction with the ecosystem. Briefly, a social-ecological system is made of two templates: the biophysical one corresponds to the classical ecological definition of ecosystem (a UEI in the case in point), the social one encompasses all immaterial structures and processes created by Human, as individual or groups of individuals (Society). A two-ways interaction is defined between these templates, from the benefits that Mankind gets from ecosystems functioning (ES derived from ecological functions) to the signals ecosystems get from Mankind (collective action, multiple resources use, practices). These interactions take place in the landscape defined by the conjunction of both biophysical and social templates, and potentially happen between every stages of the interactions. A complex chain of feedbacks is formed between these components and processes, which influences the way the system works. Overarching these templates and their interactions in the landscape, external constraints also play a significant and unavoidable role on the SES functioning. Recently, time influence was explicitly added to this framework [38], to emphasize on the temporally dynamic nature of this system. The drivers of the SES become thus more apparent, and can be more easily selected depending on the objective of the study. I tried and applied this framework to the stormwater CTW we study in Strasbourg (Figure 28), and more broadly to UEI for water management (Figure 29) to illustrate the global understanding it allows.

Sustainability Sustainability can be primarily seen as a property of a system that lasts; more specifically, it is a feature of a system that reaches its full expected life span [60]. The key statement of sustainability, under the label of sustainable development, is the capacity of a social-ecological system to meet present human needs while keeping the ability to meet them in the future, as phrased in the Brundtland report more than 30

Institutional version				Ideologistic version				Academic version			
Institution	*WCED*	*IIED*	*WBCSD*	*Ideology*	*Eco-theology*	*Eco-Feminism*	*Eco-socialism*	*Academic Discipline*	*Environmental economics*	*Deep ecology*	*Social ecology*
Drivers	Political consensus	Rural development	Business interest	Liberation theory	Liberation theology	Radical feminism	Marxism	Drivers (Epistemological Orientation)	Economic reductionism	Ecological reductionism	Reductionist-holistic
Solution epicenter	Sustainable growth	Primary Environmental Care	Eco-efficiency	Source of the Environmental Crisis	Disrespect to divine providence	Male-centered epistemology	Capitalism	Source of Environmental Crisis	Undervaluing of ecological goods	Human domination over nature	Domination of people and nature
Solution platform	Nation-state	Communities	Business and industry	Solution Epicenter	Spiritual revival	Gynocentric value hierarchy	Social egalitarianism	Solutions epicenter	Internalization of externalities	Reverence and respect for nature	Co-evolution of nature and humanity
Instruments (leadership)	Governments, international organizations	National, international NGOs	Corporate leadership	Leadership Center	Churches and congregations	Women's movement	Labor movement	Instruments (Mechanism of Solutions)	Market instrument	Biocentric egalitarianism	Rethinking of the social hierarchy

Figure 30: Underlying values for sustainability pursuit. From [62]

years ago [61]. The origin of this common sense concept is traced back to traditional beliefs ("living in harmony with nature and in society" [62]), malthusian economics, and contemporary thoughts such as Schumacher's Small Is Beautiful in 1979. Its vague meaning may be the reason for its worldwide acceptance [62], although it is leading to largely diverging interpretations of sustainable development today. The very concept of sustainability can be interpreted in different ways: notably, it can be seen as a process, not an endpoint [63], [64], as such constantly evolving as a SES trajectory changes, or as a normative framework to discuss environmental issues and objectives for the future [65]. In the modern era, this concept was explicitly developed in response to the environmental crisis, although many environmental crises were faced in the course of human history; three main versions can be delineated (Figure 30, [62]) :

1. The institutional version, where sustainable development is defined by the Brundtland report, with an emphasis on the needs and institutional instruments to generate solutions (e.g. WCED, IIED, WBCSD);

2. The ideological version, that describes a source of environmental oppression and proposes a change of ideology to overcome that oppression (e.g. Eco-theology, Eco-feminism, Eco-socialism);

3. The academic version, where the reasons for the crisis are identified and conceptual modifications proposed to solve the problem (e.g. Environmental economics, Deep ecology, Social ecology).

I will make use of the academic version, trying to stay aware of the major pitfalls pointed out in [62]:

- SES are complex systems, made of several templates overarched by external constraints. To consider separately these templates and then their linear sum to get the whole picture, to consider only the whole system while ignoring the interactions between the templates or to ignore external constraints may lead to erroneous conclusions. Ideally, all interactions should be accounted for, at least conceptually;

- To think sustainability as the encounter between three separate "parts" – ecological, social and economic – comes from the underlying assumption that they are separated in essence. Yet they are only facets of a same object, fundamentally interacting with each others;

- The environmental and the ecological crises are something different, as ecosystems are part of the environment, but the environment includes more than ecosystems. There are economic, social, political and cultural interactions too. Moreover, the "environment" should not be something distant and abstract, but the network of relations and meanings around us;

- Vision is the way to escape from present situation to think about more desirable futures. Yet vision without ethics – understood as a quality of a means, not a means in itself – could be more destructive than constructive. And as behaviour change may not entirely result from self-made decision, the understanding of the constraints that drive this change is important. Actions towards a desirable future should be based on a vision, guided by a concrete body of theory and made possible by unlocking drivers of change.

The term sustainability has generated a lot of debate, and it is probably not over [66]. Whether it is a framework or a process is not necessarily crucial to me, but what must remain is the fact that we need to head towards a trajectory that will make future life possible, and that the way to get there is as important as the goal we set. In this respect, high technology will probably solve endpoint problems, but it will not deal with the roots of it, and sometimes at the expense of other important features that support sustainability. For instance, production of drinking water from seawater through reverse-osmotic desalination is surely efficient, but has a high energetic and environmental cost that can be detrimental to surrounding ecosystems [67], [68]. This makes me think that sustainability cannot be about sustainable development as it is understood today, because development would trespass the "limits to growth", a biophysical boundary that was recalled 45 years ago [69]. In a finite system like Earth, a sustainable SES i) uses renewable resources, ii) preserves the balance between the resource

utilization rate and its renewal rate, iii) generates by-products that can be further used and iv) optimizes its energetic consumption. I would rather propose that 'sustainable evolution' is a more objective notion that does not exclude de-growth if it is the way to reach sustainability.

Finally, the concept of sustainability can apply to any SES, and it has been refined to suit the urban context and address the challenge of world urbanization; indeed, by 2050, it is estimated that 80% of the world population will be living in cities [8]. At first glance, cities are highly not sustainable [64], but definitions for a sustainable city have been formulated [70], [71] and a lot of work has been done to study the way to reach sustainable trajectories. Urban ecology, the study of interactions between urban species – birds, mammals, plants, ... and Human – with their environment, can help reaching this goal [72], [73]. The features of the urban SES call for adaption of sustainability principles, identifying reasons for lock-ins, potential requirements and evolution for cities [63].

2.2.3 Evolution of UEI

Across all the studies presented in section 'Current research activity' and their respective scientific fields, time keeps appearing under various forms [22] and extended scales [23]. I will now detail why using this integrative parameter seems meaningful to me: first to study the system temporal evolution, second to study how the social template acts on UEI evolution.

Temporal evolution In SESs, a large variety of processes and interactions take place (cf. Figure 27). There is no such thing as a typical associated time-scale here because of the system inherently broad time span [74]. A relevant experiment time-scale should then include the slowest phenomena one wishes to study. I will illustrate this with the example of stormwater management, before moving on to further analysis.

About the study of stormwater management carried out in Ostwald, it seems now

[22] residence time, rainfall duration, water budget when including transpiration, evolution of perceptions
[23] from minutes to hours (rainfall and sorption equilibrium), to years (local communities appropriating a stormwater management site or metals accumulating in stormwater sediment)

logical but looking back in 2012, my first thought was that such tiny concentrations in stormwater [28] were hardly worth building such management systems (apart from my additional ignorance of physical disturbances created by stormwater run-off directly discharging in a small stream). The study of individual storm events was enough to quantify the efficiency of the system from a WFD perspective, i.e. the question of water quality after management by the system. And indeed the mitigation efficiency was significant, as we discussed earlier in the manuscript [30]. Yet when looking at contaminant loads in stormwater on a yearly basis, significant variation across the seasons was shown; for the issue of mitigation behaviour of the system to be significantly addressed, the study would have to expand on the four seasons. And surprizingly enough, despite climatic and biological seasonal evolution ([75], Bois et al. submitted), mitigation remained stable [75], probably because of buffering behaviour of the system. As efficiency survey kept going on for several years, we grew aware of the ever-increasing metal load in deposited sediments (once again this restrospectively looks obvious), and the dynamic behaviour of these persistant compounds created the need to document the long-term contaminant behaviour in this UEI [31]. Overall, these nested time scales were relevant to study the issue; the short-term study gave initial answers, and raised questions the long-term study still helps answering to, while bringing useful feedback for managers.

Mechanisms with long time span can be seen as creating the context in which a SES is embedded, and a given function within it can be seen as deriving from shorter time span mechanisms [74]. In the above example, context includes climatic parameters and political decisions; short time span mechanisms include unintended paint discharges and maintenance operations, and the mechanism studied is the sorption of contaminants within a UEI. As all variables are likely to evolve, the context of the system will probably change over time, although more slowly than the functions studied. Consequences of slowly evolving parameters (such as greenhouse gases emissions generating climate change and subsequent hydrological cycle modifications) may thus be significantly delayed, which in turn make them delicate to study and manage [58]. Thus long-term studies are relevant to try and capture this slow-paced evolution, as

a significant driver of SES evolution [76]. Moreover, long-term studies enable to delineate natural long-term changes (endogenous changes from slow-varying variables) from human-induced or other exogenous perturbations [54]. As such, advices on UEI management informed by long-term studies should aim at preserving the course of a (sustainable) trajectory, rather than a snapshot state from a single study.

In the case of water management UEI, long-term issues related to the research questions may be formulated as [77]: investigating i) slow processes[24], ii) rare events and episodic phenomena[25], and iii) complex interactions[26]. These processes are typically happening at the scale of SES or larger, because of their complex structure, their multiple spatial scales involved, the variety of existing functions and feedbacks, and the range of disturbances (from stormwater flush to climate change), whose small magnitude make undetectable on the short-term but significant driver on the long-term (our aforementioned example) or on the contrary whose large magnitude creates long-term consequences [77], [78]. Long-term evolution obviously characterizes mechanisms of social interactions, as part of the social template of SES, in a way that a fixed spatial or temporal scale is not suitable to analyse such complex systems, and that long-term consequences of management need to be studied on an accordingly long-term range [79].

UEI and Human influence By definition, social-ecosytems are partly driven by human action, as reminded in the aforementioned framework. The fact that the social and biophysical templates are intertwined is no more a discovery, and has been fruitfully implemented and used for research purpose in various cases, from land use as a SES feature depending on natural, socio-economic and governance drivers [80], to human infrastructure significantly altering matter and energy flows along a river [81] and to the role of technology in artificially overcoming systemic environmental limitations [82] to name a few. One particularly obvious yet striking example is the case of cities, urban SESs where human-induced presses and pulses disturbances are strong drivers of the

[24]modifications of species areas, ecochemical degradation processes, ecotoxicological effects, chronic effects, consequences of global climate change / land use change / restoration measures
[25]consequences of extreme weather conditions
[26]behavioural changes of organisms, studies across organizational levels

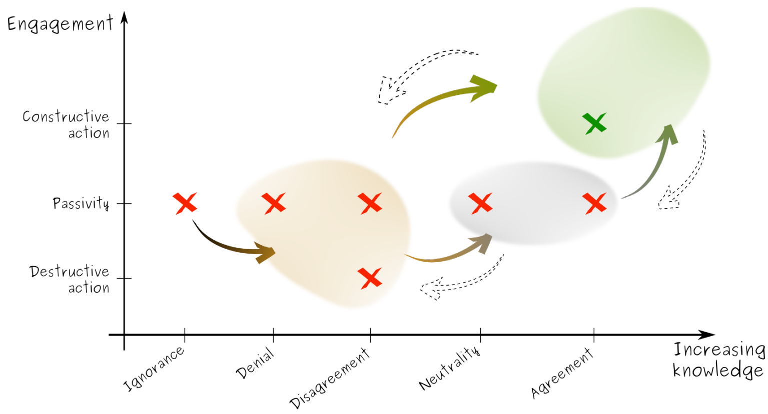


Figure 31: Outline of action taken vs. knowledge status. Only the green zone corresponds to constructive action

SES trajectory [83]. As small-scale social-ecosystems, UEI functioning and dynamics are logically under Human influence as well.

The social template is crucial to the SES study, not only because of disturbance, but also because as from it will ultimately come the deliberate decision to transform to more sustainable trajectories for the system [84]. Nevertheless, scientific evidence of various disturbances generated by Human and their tremendous environmental consequences has been piling up for many decades not only from scientific sources ([85] with a first edition in 1961, [86], [87],[88]); yet so far we did not really change the way we live according to these challenges ([89], [90] [91]), exemplified by a 6% pesticide use increase in France between 2011 and 2014, despite a national plan[27] aimed at a two-fold decrease of their use between 2008 and 2018. This is even more striking as literature about change abounds (from Gandhi's philosophical statement on the inner change reflected in the world, to Kurt Lewin's theory of change in 1947 [92] or [93] in the field of energy consumption behaviour and [94] on the psychological reasons for the absence of change, to name a few). Beyond the study of ecological functions at stake in a specific situation, I feel that a research work aiming at societal evolution (research-action) and SES transformation can benefit from studying the issue of change; its motivations, triggers, temporal dynamics and stability. A related scientific question would be how will the social template and subsequently the whole SES evolve after a specific type of social disturbance, e.g. presentation of (new) knowledge or discussion about new piece of evidence. The fundamental objective is to understand the drivers of change; the applied objective is to guide and facilitate change towards sustainable trajectories.

First, we need to define the starting point regarding knowledge level of a given fact: there can be ignorance or knowledge. What comes next is the opinion about this knowledge: when aware of the facts, there can be denial, disagreement, neutrality or agreement. Eventually, two attitudes can be adopted: action or passivity. Finally, drivers of change act across a complex evolution landscape, summarized in figure 31. Evolution is a neutral concept, which means it can shift towards more knowledge, agreement and action or from action to passivity, and from agreement to disagreement.

[27] Ecophyto

Second, change can happen on nested social scales: individual, collective (e.g. local community) or institutional. On each of these scales, reasons for change are numerous:

- individual action: physiological, psychological and neurological reasons can be responsible for the lack of change [94] and can be related to personal or social factors, some of them being not related with environmental concerns but with ego-centric ones [95]. It is also worth noting that activism may be counter-productive for other people [96]. The reasons for change conversely need to rely on continuous pedagogy, fact-based discourse, equity insurance, reduced costs, and risk reduction among others;
- collective action: readiness for change can be primarily seen as fueled by common thoughts that not only change is required, but that it is achievable and desirable, and by the positive vision induced by this change [97]. Moreover, what would not trigger change at an individual level can trigger change when considering the common good, as illustrated by the commons dilemma, but faces the dilution of responsibility or benefit[28] [98];
- institutional change: if change is physically hindered by inertia of heavily concrete-based infrastructures in the case of cities, there is a need to bring together officers from different areas of expertise to avoid heavily siloed governance hampering change [63]. While this is surely a complex question [99], integrating different fields of expertise is positive [100] and can provide successful examples [101].

Third, once these reasons for a change are identified, one can ask how to drive and guide change on the three levels – individual, collective and institutional – so that it happens. Individually speaking, it seems more fruitful to present a vision and a comprehensive view of change rather than providing detailed to-do list; interestingly, altruistic values would be more change-inducing than biospheric values [102]. On a collective level, the rise of convinced and convincing leaders seems to be a condition to collective change, along with realizing one is not alone to have views about the need

[28] "change is good as long as it happens to somebody else" mentality [63]

for change [103]; capacity building, project co-construction and collective reflection also seem relevant to drive and sustain collective change. On an institutional level, maybe more than on the two others, the situation is fairly complex [104] and requires establishing an operational yet accurate framework [105]: it is likely that many attempts are needed before reaching something workable at a local scale. Interviews about blue-green infrastructures in Swedish cities showed that beyond individual change, education, legal evolution and economic incentives are needed to actually change the way stormwater is managed [106]. In a gleam of hope, other examples show that the transition is ongoing, even if not fulfilled at the time of publication [107].

2.3 About the supervision of young researchers

It might seem unusual to write about supervision in a HDR[29] manuscript , as this moment is often seen as a way to prove one's worth in a given scientific field. Yet the truth is that not only you do research, but you also interact with people: fellow researchers, technicians, stakeholders, postdocs, and young researchers – Ph.D and Master students –. For the latter, the interaction actually means supervision; as supervision is partly made of teaching, it is important to understand how teaching and research enrich each other to make the most out of it [108]. The final objective is obviously to be a "good" supervisor, although this mantra does not mean much at this point of the discussion. Therefore I think it is important to define this supervisor role with minimal andragogical[30] considerations to better know what fruitful supervision can be. Yet without the consciousness of knowing where I stand, it is impossible to know how to act and how to evolve to achieve the sometimes overlooked objectives of supervision. With this first milestone of a reflexive stance, I hope to switch from intuition to (good) intentions and gradually improve in this role, as highlighted in [109], aligning teaching objectives, supervision methodology and work assessment. My first assumption is that PhD and Master are not only research occasions, but also teaching occasions. I will first define teaching objectives for PhD and master work, then develop the values in which they are embedded; I will eventually explain the supervisor stance that would result from these values to reach teaching objectives.

2.3.1 Teaching objectives

An important aspect of a Master or a PhD is the results[31] the young researcher obtains: it should result from carefully prepared literature review, generating precise research questions based on relevant subsequent work hypotheses, crafty experiment set-ups, rigorous data collection and acute data analysis. This forms the backbone of the methodological objectives, that may actually be the most important ones for a

[29] 'habilitation to supervise research' when translated straight from French
[30] pedagogy for adults
[31] whether the results are "positive" or "negative" is not the point here; the aim is to get sound results and be able to discuss them

Master and PhD work, when looking at what the student yields from these moments. Indeed, from Master to PhD work, or from PhD to post-doc work, one seldom studies the same object and even sometimes shifts from one scientific field to another. Thus the only way to still do research while discovering a new field seems to apply a known methodology. It is important that the student actively participates in this; adopting the Healey model about research and teaching [110], this would be a research-based approach. More precisely, at the end of his/her Master or PhD, a student should be able to:

1. Write a literature review in which enough context is provided to get the big picture, and enough specific facts are synthesized to define accurate knowledge gaps (Master/PhD);

2. Formulate scientific issues and research questions, inspired by the former literature review step. They should be also realistic for the time span available (PhD);

3. Plan his/her work, defining the steps and the chosen methodology. This will provide a framework to come back to when starting to get lost (Master/PhD);

4. Apply an existing methodology, consciously yet critically (Master) / go beyond[32] what exists to bring his/her scientific contribution to the studied issues (PhD);

5. Achieve his/her work, autonomously carrying out the experiment, collecting data and analyzing them (Master/PhD), drawing conclusions (PhD). This step can include adaptation of initial objectives (Master/PhD);

6. Present his/her work in a way that highlights what is brought, while progressively leading the reader into understanding (Master/PhD);

7. Put his/her work into perspective and presents the associated next steps and potential improvement (Master/PhD).

Yet a Master or a PhD work is not only learning about methodology, but also – mostly? – applying it to reach technical objectives. Then again, teaching only about a specific

[32]and sometimes going beyond means going back

scientific field does not make the student an autonomous researcher. In the theory of knowledge transfer [111], the steps towards knowledge[33] transfer are 1) to apply it to a concrete situation (contextualization) to favor its acquisition, 2) to apply it again in different concrete situations (re-contextualization) to reinforce its acquisition and highlight the similarities between situations, and 3) to extract the invariant elements from the two first steps (de-contextualization), to gain perspective and make it usable in different situations. When the essence of the knowledge is perceived and understood, it becomes transferable. During a Master, if the supervisor insists on step #1 and 3#, there might be a chance that the student starts learning the methodology and will be able to apply it afterwards. During a PhD, the three steps are likely to be completed, which means the PhD will master the methodology, and become an accomplished and autonomous researcher afterwards.

As written above, along these cross-cutting objectives come technical objectives: to master a specific conceptual and theoretical background (e.g. hydrodynamics and the use of dye tracing experiments to document it in a wetland), to carry out the specific experiment and subsequent analyses (e.g. dye tracer experiment and water fluorescence analyses), and to process data and yield results (e.g. with residence time distribution curves and mean residence time computation). They are specific to each scientific field and will be of course part of the teaching objectives. Within the model of Healey, this would correspond to a research tutored approach [110]. Eventually, the approach I would use is a two-fold approach, combining research tutored and research based approaches. Technical objectives have been developed in former parts of the manuscript, so I will focus on cross-cutting objectives here, especially in the next section on the role of the supervisor in creating proper work conditions to allow the young student to reach these objectives.

2.3.2 Underlying values

The first role of the supervisor is to create a frame for the student to evolve in, as it gives the student something to lean on. It is made of a few educational hypotheses,

[33] knowledge of the methodology here

briefly exposed and then developed hereafter:

- The greater good that can done to the other is not to transfer him/her our richness but to reveal them their own;
- Benevolence is a powerful attitude to foster learning ;
- Mutual acknowledgment is the first step towards unbiased and productive relationship;
- My aim is not to answer the student questions, but to make sure he/she can answer the questions he/she is asking;
- Hot water was only invented once, and Nature did it;
- The student owns its research work, the supervisor only drives it.

Greater good: The idea is that to acquire something, one must have practiced it, not just seen it. Moreover, repeating things reinforces their acquisition, which is a source of self-efficacy feeling;

Benevolence: This attitude was shown in several studies to improve engagement in work, creativity and well-being at work [112], [113], [114], which are desirable skills for a young researcher;

Acknowledgement: Knowing where each one stands – the student is here to achieve the work, the supervisor is here to help achieving the work – is the first step to a situation where everyone knows what he has to do, and what he can ask the other to do. In any case, if the student learns to do research, the supervisor learns to supervise;

Questions: the aim is that the student spontaneous attitude in front of questions is "I can handle it myself" rather than "I will ask my supervisor for the answer, he must know this". This is a marker of self-efficacy [115], [116] and autonomy; this feeling grows with time if the scheme is repeated;

Hot water: we may be extraordinarily clever scientists, but in the end we are just trying to understand what happens in our environment, and sometimes clumsily try to reproduce it;

Owner: whatever the quality of the work, it should be the result of the student's actions. Said differently, the supervisor should not be the main actor here; it is thus pointless for the supervisor to take credit for this work [117]. He is expected to play a significant part in orientation and choices to be made along the student's work, though.

On another topic, funding can sometimes be a source of biases in the way research is considered and done, particularly for the student. As money gets more and more scarce, it is a great temptation to use the supervisor greater experience to define a subject that has the best chances to be selected. Yet doing this greatly reduces the student autonomy and creativity, reducing him/her to a mere workforce, while standing the aforementioned teaching objectives. On the contrary, if the student defines his/her research subject alone or in collaperation – a blend of collaboration and cooperation [118] – with his/her supervisor, it is a great way to improve his/her capacity as well as a first sign of engagement. To be honest, in France this does not happen so often, only the universities "merit grants" would allow students to mature their subject independently from imposed orientations before grant submission. If we follow this point of view, it also solves the problem of how the subject is chosen. Sometimes, if the supervisor defines the subject, it may lead to situations where the supervisor actually seeks to advance his/her personal research through the student work; once again, this does not foster the student autonomy and prevents him/her from finding his/her own centers of interest. The most altruistic thing to do would be to let the student choose the subject and accept to supervise him/her, provided the supervisor is legitimate to do so, especially in terms of academic skills. In this case, supervision would start with help on refining the subject before submission for grants.

2.3.3 Pedagogical stance and everyday application

Once supervision underlying values are clarified, suitable behaviours can be defined among the many possible stances when supervising research work. the question is how to let live the above stated values through a pedagogical stance that helps reaching the teaching objectives? If we admit that carrying a research work is both a question of technical and human aspects, supervision should apply to both. Four typical stances can be outlined [117]:

i - Laissez-faire, where both aspects are loosely managed by the supervisor;

ii - Pastoral, where human aspects are the only ones to be significantly managed and technical aspects are poorly supervised → the well-being of the student is the most important;

iii - Directive, where technical aspects are the only ones to be significantly supervised and human aspects are loosely managed → the work of the student is the most important;

iv - Contractual, where both aspects are significantly managed.

To manage the human aspect does not mean being a friend or a confident to the student, for this could lead to misplaced behaviour from one side or the other, or being charged with social or emotional concerns that are way beyond the supervisor's responsibility and capacity. In the range of acceptable behaviour, one can choose the casual or formal way to interact; I prefer the casual way, as I think it is better for creativity to work in a relaxed than in a formal atmosphere. I also think that relaxed atmosphere does not prevent from achieving technical objectives, as defined in the previous section. To end up with this outline, loose does not mean wrong, it should just mean less intensive. The choice of stance to adopt is inherently dynamical: it depends on the needs of the student, but also on the situation. For instance, a student that is already mastering the scientific method but endures stress will require only slight technical but developed human supervision. On the contrary, a student at ease with interactions but lacking rigor will require significant technical supervision. And of course, an adequate

supervision should adapt to the student evolution. Similarly, technical supervision will probably be intensive at the beginning of the work while setting the first milestones, or during crucial experiment or writing phases. Globally, my aim is to reach the contractual stance as often as I can.

I would like to develop further the type of supervision that can be achieved regarding the technical aspect, as several kinds of supervision can be distinguished: formative evaluator (critical friend) [119], educator (partner) [120], expert (mentor) [121] and peer (cognitive companion) [122]. These styles are complementary and present benefits that can be used depending on the situation. More precisely:

Critical friend: a critical friend is not complacent, yet he strives to be objective and constructive. On a daily basis, he rises when feedback must be provided. It is important to say when the work done is good and more important why it is good; it is also important to say when the work done needs improvements, and what they can be ;

Partner: a partner strives to help the other improve, and that includes providing precise and benevolent feedback. For instance, when reviewing a production, commenting with "no" or "to be rephrased" does not help at all. The supervisor needs to provide feedbacks such as "this sentence is too vague: what did you mean by that? I think it would be preferable to shorten and precise it", both precise, benevolent[34] understandable and guiding without proposing something (it is the students work to do it);

Mentor: a mentor – sometimes called 'the expert' – is an experienced person, not the one who owns the truth. At some thresholds, decisions need to be made, and the mentor is the one with the most elements to propose the most suitable ones. As such, the supervisor needs to present his/her expectations to the student at the beginning of the supervision. Only negotiable issues will be discussed, the others will be simply stated by the supervisor;

[34] the unsaid statement is "you knew what you meant, I did not understand it" rather than "you are wrong"

Cognitive companion: following the cognitive apprenticeship framework, the supervisor should clarify how he proceeds to reach a given objective (for instance, achieving a meaningful literature review). This way the student can appropriate the methodology and apply it for the next round. In this process, rather than give the student answers, it seems better to help him finding his answers. This will foster independence and self-confidence of the student. To come back on the 'decision' topic, more than the decision itself, the reasoning leading to the decision is the most important for the student to understand and acquire.

Eventually, I think that the most important here is to become aware of his own beliefs on supervision and see how they fit with the objectives we set, consciously or not, for our research work. After this reflection I will update my supervising stance to try and reach teaching objectives while respecting the above described values.

2.4 Methodology

More than a detailed protocol, I would rather describe the points of attention during the construction of a research project. More specifically, in a chronological sorting:

- Start by tailoring specific research questions from the general ones defined earlier in the manuscript;
- Define the SES boundaries (e.g. UEI (WW + SW), UEI + surroundings). This also allows identifying external constraints;
- Define the spatial scale(s) for the study. It ranges from local (e.g. plant, soil, water) to the whole SES (e.g. to deal with perception and change);
- Define the temporal scale(s) for the study. It ranges from minutes (e.g. storm event) to decade (for perceptions) and also allows precising which phenomena will taken into account;
- Which stakeholders are part of the social template, and which/ would need to be involved in the project?
- Establish the protocol: what variables from the biophysical template, the social template and the external constraints should be monitored? Given this, should the project go for big money or keep on small budget;
- Involve collaborators, related to the research questions, that complete our own field of expertise to cover the scientific areas required to adequately handle the issues;
- Foresee results: what can we hypothesize will be the knowledge increase, related to the research questions
- Anticipate uncertainties and limits. Could stem from ill-defined system, maladjusted time scale or erroneous work hypotheses.

Furthermore I think that before actually starting to do work, research projects would benefit from co-construction between colleagues and stakeholders, as this will probably give i) a broader outreach to the work, ii) more scientific relevance to the study of complex systems such as SES and ii) more social relevance to the work conducted. This transdisciplinary aspect of research, as it involves non-academic participants, will contribute to the dissemination and operational implementation of the knowledge gathered during the project. Moreover, to investigate ecological functions interactions and subsequent ES trade-offs requires to conduct interdisciplinary research[35], as the relevant concepts and tools differ within a given function / service (e.g. water quality regulation calls for chemistry considerations, while water quantity regulation calls for physics considerations), not to mention from one service to another (e.g. water quality regulation is about chemistry, aesthetics aspects of a water management UEI is about arts and psychology). We need interdisciplinarity to inform the study system from different points of view and get a more accurate vision on it. For instance, we are currently implementing this methodology in the set-up of a research project about UEI implementation with colleagues in the Cat Ba touristic island, Vietnam. The study of long-term dynamics requires obviously to carry out experiments on a large time scale, but also calls for place-based research, to assess long-term evolution of a given UEI. This aspect will be dealt with through a PhD program about the precise assessment of the water balance of stormwater managing UEI in Strasbourg. Finally, the ability to investigate behaviours and management impacts calls for the use of modelling and subsequent scenarios; thus there might be a chance to anticipate and propose what would seem to be more sustainable trajectories. This is what I am currently doing for the Phoenix treatment wetland, investigating alternative set-ups in relation to treatment efficiency.

[35] interdisciplinarity is included in transdisciplinarity

3 Perspectives

The first thing I am sure of is that this manuscript represents a start rather than a final point. Until now, my research activity led me to be aware of the complexity that SES display, and of the necessity of behavioural change as science and technology only cannot compensate for all the degradation we presently create. I must also confess that it is both fun and interesting to combine scientific approaches.

I intentionally defined a broad scope for my research project; thus I hope to stay open to these big pictures aspects that help me both understanding better the situation and envision more relevant attitudes and transformations to address these challenges. It also keeps me free to move between wide-reach and focused projects. This work pushed me to clarify my thoughts and support them with literature arguments, although literature review remains a never-ending quest. Finally, by studying the multi-functionality and long-term dynamics of UEI, I wish to explore the urban SES and the interaction between social and biophysical variables.

Dedicating a part of the manuscript on supervision was important for me, as it will probably be a significant part of my near future. Starting reflections about it will hopefully help me to start on a good basis and avoid some basic pitfalls (before falling into more elaborated ones). At this point, I wish to match the underlying assumption that we **are** good supervisors anyway, as evidenced by our scientific discourse.

On the place of Science in Society, I think as [123] that Science is not here to make decisions; I rather see it as a way to unfold the complexity of Nature, even in urban context (e.g. UEI), to bring comprehensive understanding of a given system and allow decisions to be made in full conscience and responsibility by the ones responsible for making them.

Now what comes next? The outline of my research project actually engulfs the research projects I am currently involved in. I will thus keep on the teamwork on them: study of UEI for stormwater in Ostwald and improvement of our LTSER site research, design scenarios for Tres Rios CTW, study of UEI implementation in Cat Ba (VN) to avoid tourism-induced environmental degradation, but with a different perspective and

expanded scientific spectrum to answer a larger set of question. I will add to this set another type of research, the study and modeling of thermal regime from upstream forested streams. Being an average[36] scientist, I do not expect getting any award or medal soon[37], but hope that our contribution can result in individual or higher organizational level change, participating into the solution to present environmental challenges.

[36] if not less
[37] and I hope not to waste public money

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Summary - EN Environmental issues in urban areas are numerous and complex. Among them, handling the volume and quality of storm- and wastewater to avoid disturbances can be achieved with a gradient of approaches. Urban ecological infrastructures host a comprehensive set of ecological functions that can provide ecosystem services to alleviate these disturbances for Human and other species. These social-ecological systems, complex by essence, integrate biophysical and social templates under external constraints. Their associated time dynamics range from minutes to decades, and call for appropriate study time scale. Research questions about interactions between ecological functions, trade-offs between ecosystem services, long-term dynamics affecting both functions and services, and stakeholders evolution impact on their functioning seem relevant to help cities reach sustainable trajectories. In this process of building knowledge and applications, researchers work in a whole ecosystem, significantly structured by young researchers. Getting aware of one's own vision of supervision, of its numerous values and stances is a first step to guiding them to reach their full potential and bring the most to science - and eventually to Society, and Nature.

Keywords - EN social-ecosystem, ecological functions, ecosystem services, nature-based solutions, ecological engineering, stormwater, wastewater, cities

Résumé - FR Les questions environnementales se posant dans les zones urbaines sont nombreuses et complexes. L'une d'entre elles, la gestion de la qualité et de la quantité des eaux pluviales et résiduaires, peut être traitée par un gradient d'approches. Les infrastructures écologiques urbaines hébergent un ensemble de fonctions écologiques qui peuvent minimiser ces perturbations par le biais des services écosystémiques fournis aux Hommes et aux autres espèces. Ces sociaux-écosystèmes, complexes par essence, intègrent une composante biophysique et une composante sociale interagissant sous contraintes externes. Les dynamiques temporelles associées s'échelonnent de la minute à la décennie, nécessitant de définir une échelle temporelle d'étude idoine. Les questions de recherche sur les interactions entre fonctions écologiques, les équilibres entre services écosystémiques, la dynamique à long terme de ces fonctions et services et l'impact de l'évolution des acteurs sur leur fonctionnement peuvent aider les villes à se placer sur des trajectoires durables. Lors de ce processus de création du savoir et de ses applications, les chercheurs travaillent au sein d'un écosystème, structuré de façon significative par les jeunes chercheurs. La prise de conscience de sa propre vision de l'encadrement et des valeurs et positionnements qui y sont associés constituent une première étape en vue de leur faire atteindre leur richesse maximale et contribuer ainsi au mieux à la science - et à travers elle, à la Société et à la Nature.

Mots-clés - FR social-écosystème, fonctions écologiques, services écosystémiques, solutions fondées sur la nature, ingénierie écologique, eau de ruissellement, eau résiduaire, villes