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Research Article

Defining Best Available Technique Performances for Urban Wastewater Plants: A French Application

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Abstract: The treatment of wastewater (WW) and the resulting sludge in urban WW treatment plants (UWWTPs) is accompanied by a significant consumption of resources as well as the concomitant emission of pollutants into the environment. One of the objectives of the NEXT (next generation of wastewater treatment plants) project is to identify sufficiently long-term optimization opportunities for processes to be selected as best available techniques (BATs) within the meaning of the industrial emissions directive (IED). The methodological framework used in this article is based on multi-criteria statistical tools, processing data from industrial plants to classify the sites studied and identify the reference plants in order to propose BAT references and associated emission levels that are reachable. Two public databases available on the internet were used, and 1,010 plants served as samples. The application and results demonstrated the applicability of the methodology and validated the mathematical approach used, as the thresholds comply with current French and European regulations. In the framework of the analysis conducted, five techniques (membrane bioreactor, bacterial bed, sand filter, and high-load or medium-load activated sludge) were identified as BAT according to the range of regulatory classification requirements for WW treatment plants (WWTPs). In addition, an example of reference values that may constitute a possible basis for the regulatory thresholds has been proposed. In parallel, a few discussion points were identified, including the choice of the metric for the reference values, the lack of data for the sludge line limiting identification of the BATs to the water line alone, the approximate characterization in the databases of certain parameters, as well as the problem of technique coupling due to the identification of one main technique.

***Keywords*:** UWWTPs, BAT, performance assessment, reference value

Nomenclature

BAT	Best available technique
BATAEL	BAT-associated emission level
BREF	BAT reference document
ICPE	Installations classified for protection of the environment
IED	Industrial emission directive
PE	Population equivalent

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UWWTP	Urban wastewater treatment plant
WW	Wastewater

1. Introduction

In 2020, France had 22,002 WW treatment plants (WWTP) for the treatment of domestic WW, with a cumulative total capacity of 79.6 million PE. These WWTPs are intended to clean up the WW before discharging it into the natural environment. WWTPs can be classified into four categories:

- WWTPs of an "urban" nature, treating only effluents collected by an urban public WW collection network.
- WWTPs of an "industrial" nature, treating effluents directly from one or more sites classified as ICPEs (French ICPE) and capable of handling domestic and industrial effluents from an urban sanitation area.
- WWTPs of a "private" nature, not dependent on a public contracting authority, and treating domestic and industrial effluents from non-ICPE sites.
- WWTPs of a "mixed" nature, under a public contracting authority, and treating urban and industrial site effluents falling under the ICPE and originating from an urban sanitation area.

Whatever the type of WWTP, many methods of treatment can be used but the configuration remains the same. The treatment of WW and the resulting sludge within a WWTP is accompanied by a significant consumption of resources (chemical products, energy, etc.) and the concomitant emission of pollutants into the environment.

The French public water information service demonstrated through several analyses that the chemical and ecological condition of watercourses is critical in some places. In 2015, of the 10,706 watercourses in France, only 8.5% had a very good ecological status and 36.3% had a good ecological status. In terms of the chemical status, 62.0% had a good chemical status, 16.2% did not achieve a good chemical status, and 21.8% were of an undetermined status (insufficient information to assign a status).

Given the potential environmental impacts of WWTP, regulations have been established. In particular, the European directive 91/271/EEC on urban WW treatment, the Water Framework Directive 2000/60/EC to preserve and restore the status of surface waters (freshwater and coastal waters), the European IED 2010/75/EU and others like the Marine Strategy Framework Directive, the Bathing Water Quality Management Directive, and the Shellfish Water Quality Directive.

Whatever the directive, the classical WWTP thresholds for at-plant regulations are fixed either in terms of maximum concentrations, which are calculated at the plant outlet, or in terms of minimum efficiency, which is calculated as the ratio between the outgoing pollution and the incoming pollution. However, the IED regulatory framework is currently only applied to mixed WWTPs, as indicated in the French Decree of 2nd February 1998. This European directive focuses on the performance assessment of industrial installations according to the BATs as defined in Article 3 of the IED. WWTPs for WW of an "urban" nature are not subject to the French Decree of 2nd February 1998 but to a series of other regulations, which are the result of the transcription into French law (French Decree of 21st July 2015) of the European directive 91/271/EEC on UWWTPs.

Moreover, the French Decree of 17th December 2019 on BAT is applicable to certain WW treatment facilities subject to the permit system and the IED mentioned sets the applicable requirements. The operator must implement the BATs and ensure that the plant complies with the emission limit values set out in the appendices of this French Decree of 17th December 2019.

These regulation texts give frameworks and values for performance criteria regarding emissions or consumption based on BAT performances. However, these texts do not refer to methodologies for the environmental performance assessment of techniques regarding BAT performance. We therefore need to be able to support WWTP operators in their compliance efforts.

The literature review on the application of IED and BAT performances is considered exclusively the industrial sector. Most articles deal with a quantitative method except for [1-4], all of which are from the same Flemish institute. Moreover, two articles [5, 6] concern the comparison of candidate BATs for an industrial sector by applying a life cycle analysis (LCA) method to model processes and assess emission and impact reduction thanks to the application of BATs and by applying an adaptation of the Quality Function Deployment principles to emission reduction.

At the installation level, performance assessments with local concerns [7, 8], comparisons with references [9, 10], or selection of BATs [11-17] were considered. It is useful to mention that specific ad-hoc methodologies were developed by each author. However, no common methodology exists. A regional method was also considered for its insights on the relations between environmental and economic performances [18]. Most of these articles deal with quantitative assessment except for [10], which also proposes a qualitative approach.

As mentioned above, LCA is sometimes used in the literature to assess techniques in the context of the IED. [5, 15] propose the use of LCA to compare BATs and determine the most sustainable one among several BATs taken from the BREFs. However, as the choice of a BAT to be implemented at the local level has to be made on the basis of local indicators (sensitivity of the local environment, economic and technical means of the company), LCA cannot be a good and fully replicable decision support tool. Moreover, in the case of the comparison of BATs from BREFs, all of the techniques compared are already considered BATs at the sector level, and the choice of a BAT to be implemented at the local level shall be based on local indicators [19].

This literature review shows that (1) in terms of legislation, it is necessary to support the implementation of river requalification in order to achieve chemically and ecologically high-quality watercourses in compliance with the Water Framework Directive; and (2) this can only be possible by setting up the IED and the BAT implementation. As a consequence, it is essential to offer a method to define a BAT reference framework and associated techniques with regard to the state of the art in the water treatment sector and specifically UWWTPs, which guarantees, in addition to the achievement of environmental objectives, technical feasibility, and operational viability.

With this in mind, the NEXT (next generation of wastewater treatment plants) project aims to understand the behavior of WWTPs, including the sludge line, in order to develop quick in-situ analysis methods and to assess, from a technical, environmental, and economic point of view, optimization possibilities for the processes identified. The issues of the research work presented in this article concern the evaluation of the performance of techniques in order to contribute to the requirements of the IED and BAT.

2. WWTPs and BAT in the literature

Bibliographical references to BAT and their application to WWTPs remain fragmentary in the literature. As mentioned before, the regulatory framework of the IED applies only to mixed (industrial and urban) WWTPs and not to UWWTPs. Since 2010, industrial emissions have been covered by the IED, which has been transposed in each European member state. The IED lies on the concept of BAT which corresponds, as mentioned in Article 3, to technologies and organizational measures with minimum environmental impact and acceptable cost.

The performance associated with BATs in the BREFs is defined by a BATAEL. It is the range of emission levels obtained under normal operating conditions using a BAT or a combination of BATs, as described in the BAT conclusions, expressed as a mean over a given period of time, under specified reference conditions. When applied to WWTPs, BATs and performance assessments have to be investigated while taking into account three BREFs (Table 1).

Table 1. Summary of BREFs and BATs for water and sludge lines in the framework of the IED

Name of BREF	Water line BAT: Biological treatment (secondary treatment)	Sludge line BAT
BAT Conclusions CWW: Common Waste Water (CWW) and Waste Gas Treatment OJEU 30 May 2016	• Activated sludge • Membrane bioreactor	• Conditioning • Thickening/dewatering • Stabilization • Drying
BAT Conclusions WT: Waste Treatment (WT) OJEU 10 August 2018	(Non-exhaustive list) • Activated sludge • Membrane bioreactor	Sludge included in liquid biodegradable waste: sludge not specifically mentioned in BAT techniques but in anaerobic or aerobic techniques are BATs
BREF (WI): Waste Incineration (WI) August 2006	Not applicable	• Fluidized bed • Sludge drying using the heat recovered from the incineration process

Table 1 presents a synthesis of BATs for the two major WWTP lines: the water line and the sludge line. The detailed analysis of these documents highlights several important elements.

- First, the BAT requirements for sludge treatment are limited to the implementation of conditioning, thickening, dewatering, stabilization, and drying techniques with regard to their consumption of polymers, lime, and electricity. The information provided is essentially of a descriptive nature and concerns technical applicability. No data is provided on the expected emission level for these techniques or the characteristics of the sludge according to their recovery or disposal processes.
- Secondly, for the water line, the two applicable BREFs propose the same BAT as a reference: activated sludge and membrane bioreactor.
- Thirdly, only the water line is subject to regulatory requirements for nitrogen and phosphorus emissions. However, no associated BATAEL is mentioned. For France, the discharge limit values are set in Article 32 of the Decree of 2nd February 1998. This article mainly concerns WW discharged into the natural environment, which must comply with the concentration limit values according to the maximum allowable daily flow. The decree of 21st July 2015 states that the WWTPs must be able to prove that they are in good working order. For this, they suggest self-monitoring of water and sludge.
- Fourthly, the regulatory measures to be carried out on sludge only relate to the quantity of dry matter produced and the dry matter content (percentage of dry matter in the sludge).
- Finally, only the plants subject to authorization are subjected to the regulation by reporting the pollutant emissions to water and land (for those with more than 100,000 PE) and through the implementation of BATs.

Over and above the regulatory aspects, an analysis of the scientific literature shows that the content is limited. The bibliographic search focused on the keywords “best available techniques,” “wastewater,” and “sludge.” The scientific articles corresponding to our research deal with issues relating to the industrial sectors (textile, agri-food, leather tanning, etc.). [20, 21] focus mainly on the management and treatment of WW; the extent of the sludge line is not taken into consideration. [21] proposes the selection of BATs for treating WW from leather tanning and the finishing industry through an analysis combining quantitative and qualitative approaches based on expert opinions. The proposed implementation applies to 19 plants with six different options, which allows for a simple analysis that does not require statistical analysis methods. If we consider “urban wastewater” and “best available technique,” only one article was identified. [22] worked on BATs for urban WW reuse for irrigation. This review paper discusses the efficiency of the BATs for treatment to abate most contaminants of emerging concern, including antibiotics, antibiotic-resistant bacteria (ARB), and antibiotic resistance genes (ARGs); in particular, ozonation, activated carbon adsorption, chemical disinfectants, UV radiation, advanced oxidation processes (AOPs), and membrane filtration, as well as their advantages and drawbacks.

With the aim of assessing the performance of techniques, [23-25] focus on the Life Cycle Assessment method to identify technologies that have the potential to be BATs by comparing different possible, representative, and realistic treatment scenarios. In the same way, [26] proposes completing the technical feasibility analysis with a life cycle cost analysis in order to be able to ensure the right characteristics for water and sludge produced for potable water or recovery.

However, these studies do not provide information on the real performance decisions that make it possible to associate the techniques with reference values usable from a regulatory point of view.

In conclusion, the concept of BATs remains fragmented in regulatory texts and also in the scientific literature. Moreover, few articles exist on BATs for WWTPs or UWWTPs. Thus, in order to be able to identify which water or sludge treatment techniques can claim to be BATs in UWWTPs, a more detailed analysis is required with regard to the emission and consumption levels of the treatment techniques that go beyond the current regulatory level. Since comparison with reference techniques is essential, it is important to define references and associated techniques in relation to the sector of activities, ensuring operational feasibility and viability. In consequence, a methodology developed for the IED application and applied to the non-IED nuclear plant is proposed to be used [27].

As mixed WWTPs are already concerned by the IED, and given that their structure and objectives are quite similar to those of UWWTPs, we assume that these two types of WWTPs are quite close and therefore that the transfer of the method can be foreseen.

3. Material and methods

The methodological framework used in this article is based on the use of data to assess the techniques through the prism of BATs. This methodology was developed as part of a joint research program between Mines Saint-Etienne, the French National Institute for Industrial Environment and Risks (INERIS), and Electricité de France (EDF) [27].

The methodology is structured into five steps and relies mainly on the use of multi-criteria statistical tools. By using data from industrial plants, in particular consumption and emission values, it is possible to classify the sites studied and identify the reference plants. This classification allows determining, on the one hand, reference installations that serve to define the Best Available Technique Associated Emission Level (BATAEPL) consumption and emission values and, on the other hand, the BATs. The proposed methodology is therefore positioned as a decision-making aid for experts involved in the process of identifying and assessing BAT performance.

This five-step methodology was applied to UWWTPs to identify techniques that could be qualified as BATs for the water and sludge treatment processes. The methodology will not be described in detail in this article but can be found in [27].

As part of their work, [27, p.1038] proposes two approaches for site (UWWTP) classification: the first, called *representative*, defines the reference installations as "installations having the main characteristics close to the mean of the set to which they belong, and may, as such, represent it." The second, called *high-performance*, defines reference plants as those with the best characteristics to achieve a high level of protection for the environment as a whole. Thus, through the high-performance approach, the reference sites are defined as the sites presenting the best performance by simultaneously considering all the quantitative environmental variables analyzed. Because the IED is founded on the performance of industrial installations, the approach applied for UWWTP is the latter, high-performance approach.

The five steps are:

- Step 1: Definition of scope and variables. Data collection.
- Step 2: Data analysis: In the case of missing data, a bias and classifications created from incomplete datasets are irrelevant for interpretation with regard to environmental performances. The objective is to operate a method of statistical imputation in order to reconstruct missing data from known information.
- Step 3: Classification of the plant: Performant installations are defined as installations with the best performances while simultaneously considering all the analysis variables. Therefore, a multicriteria optimization approach has been necessary; the Pareto front has been chosen [28].
- Step 4: Selection of reference sites: The list of classified installations obtained in the previous step is then used to prioritize the installations according to their performance. All sites on the Pareto front are optima, and they cannot be discriminated against.
- Step 5: Determination of reference performance level (BATAEPLs and BATs): This step aims to provide synthetic information about the classifications and selections obtained in the previous steps in order to propose BATAELs and potential BATs. Two tools are proposed: (1) a support for the determination of reference values through the assessment of an "effort rate" that estimates the impact of reference values on the population of installations; and (2) an aid for the identification of potential candidate BATs through a study of the relations among classes, techniques operating with the installations, and reference values.

4. Application and results

For the results to be robust, the data required to carry out the study were extracted from two open databases accessible via the internet:

- The ERU database with national coverage
- The PerfoSTEP database covering the Rhône-Mediterranean-Corsica (RMC) basin

Thus, in this study, each of the steps of the methodology was applied to the consolidated public data. Details concerning the choice of the scope of the study and the variables used, as well as the different analyses performed (Step 1), are described in Section 5.1. In the second part, which corresponds to Step 2 of the methodology, the study of the reconstructions of the missing data and their quality are discussed. In the third part, the analysis scenario, the high-performance classification, and its interpretation are described. The fourth step is then applied in order to propose reference plants and define reference values. These reference values will make it possible to analyze the techniques used and to propose candidate techniques as BATs.

4.1 *Step 1: Definition of the study scope and variables*

4.1.1 *Available data*

Two public databases available on the internet were used: the first contains data compliant with Directive No. 91/271/EU on Urban Waste Water Treatment (ERU in French) of French WWTPs; the second, PerfoSTEP, gathers data collected on plants in the RMC basin and contains data on incoming and outgoing loads, as well as the tonnage of sludge produced and its use (spreading, incineration, etc.). Although some data is common to both databases, the data complement each other on issues regarding compliance and environmental data of incoming and outgoing loads.

As a result, these two databases were merged based on the national WWTP identifier common to both databases and the most recent year available at the time of the study. Subsequently, and first of all, the redundant or empty variables were removed. In the second step, subsampling was applied to exclude:

- WWTPs of a mixed nature are therefore already covered by the IED and the BAT concept
- The WWTPs are not compliant with the regulations in force
- The variables considered aberrant

Thus, a total of 1,010 plants and 33 variables were retained and constituted the consolidated final database.

4.1.2 *Variables studied*

The identification of variables to be used for the study is a very important step because they are used in regulation decrees to determine the emission limit values. The variables studied were classified and grouped into three categories: analysis variables, normalization variables, and descriptive variables. For each one, the name, the unit of measurement, and the percentage of missing data have to be presented.

The analysis variables are generally the variables related to the operation of the processes. They combine the quantitative consumption and emission data of the industrial sites studied, in this case, UWWTPs. In the database selected for the study, 10 quantitative variables were available and potentially useful as analysis variables:

- Flow at the plant inlet - biochemical oxygen demand (BOD_5) (kg/d) – 0.5% of missing data
- Flow at the plant inlet – chemical oxygen demand (COD) (kg/d) – 0.5% of missing data
- Flow at the plant inlet – suspended solid (SS) (kg/d) – 0.5% of missing data
- Flow at the plant inlet – nitrogen global (NGL) (kg/d) – 36.8% of missing data
- Flow at the plant outlet – BOD_5 (kg/d) – 5.6% of missing data
- Flow at the plant outlet – COD (kg/d) – 3.6% of missing data
- Flow at the plant outlet – SS (kg/d) – 3.3% of missing data
- Flux at the plant outlet – NGL (kg/d) – 33.7% of missing data
- Sludge production without reagent (kg/d) – 0.0% of missing data
- Flow (m^3/d) – 0.0% of missing data

The normalization variables make it possible to adjust the series of values according to a transformation function in order to make them comparable with each other and consequently to limit the effects of scale and distortion between the sampled sites.

In order to make all the WWTPs comparable, four variables were identified: the rated capacity in PE, the rated capacity in kg of BOD_5, the reference flow in m^3/d, and the sum of the rated capacities (PE). Given that the ranges of statutory requirements are expressed in PE, it is the sum of the rated capacities expressed in PE that will be used as a normalization variable in this study.

The descriptive variables include all the available data that is not in the first two categories. Thus, of all the other data that may constitute descriptive variables, only those that correspond to technical or contextual information have been retained, excluding location information (Table 2). The apparently high percentages of missing data for the levels of treatment can be explained by the fact that only the sites in sensitive areas are covered.

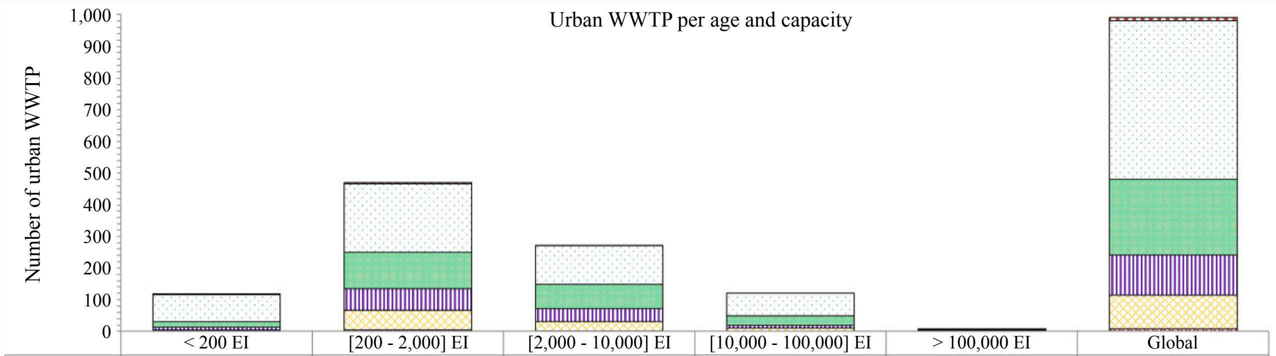
Table 2. List of descriptive variables

	Variable	Nature	Percentage of missing data
Technical variables (11)	Existence of discharge per second	Qualitative data	0% (0/1,010)
	Existence of a spreading plan		0% (0/1,010)
	Main sludge process		2.2% (22/1,010)
	Main water process		39.9% (404/1,010)
	Level of existing treatment: nitrogen		58.1% (587/1,010)
	Level of existing treatment: biological		8.6% (87/1,010)
	Level of existing treatment: disinfection		96.2% (973/1,010)
	Level of existing treatment: phosphorus		85.9% (869/1,010)
	Level of UWW treatment required: nitrogen		97.5% (986/1,010)
	Level of UWW treatment required: biological		0% (0/1,010)
	Level of UWW treatment required: phosphorus		95.5% (965/1,010)
Environmental variables (8)	Year of creation	Quantitative	0% (0/1,010)
	Maximum incoming load (PE)		0% (0/1,010)
	Size of the urban area (PE)		0% (0/1,010)
	Nitrogen sensitivity	Qualitative	0% (0/1,010)
	Phosphorus sensitivity		0% (0/1,010)
	Requirement range		0% (0/1,010)
	Type of discharge medium		0% (0/1,010)
	WWTP self-monitoring manual validation		0% (0/1,010)

4.2 *Step 2: Data processing*

This step is intended to consolidate the database from Step 1, in particular by reconstructing the missing data. The objective of this step is therefore to use a statistical imputation method that enables the “gaps to be filled” and thus reconstruct the missing data with the smallest possible error. The reconstruction of the missing data was done using the missForest tool. Several reconstructions were performed for our study. After an initial reconstruction, the estimated error with the 1,010 initial sites was 27%. In order to reduce this error, an analysis was carried out for each site, which led to the exclusion of 19 WWTPs (five sites for which the three key indicators BOD_5, COD, and SS were missing and 14 sites whose reconstructed reduction rates are negative). The new reconstruction, resulting in 991 sites, reduced the reconstruction error to 5%.

The remaining 991 sites include all types of WWTPs. Figure 1 shows the representativeness and proportions of the latter in terms of age and capacity (in PE). We note that almost half of the plants (47.5%, or 471 WWTPs) have a treatment capacity between [200 and 2,000] PE and that more than 50% of the plants have a creation date between [2000 and 2010]. Finally, it should be noted that plants with a capacity greater than 100,000 PE represent less than 1% of the sample analyzed (nine plants). Similarly, the sites built before 1970 and after 2010 account for 0.8% (eight sites) and 1% (10 sites) of the total number of plants analyzed, respectively.



	< 200 EI	[200 - 2,000] EI	[2,000 - 10,000] EI	[10,000 - 100,000] EI	> 100,000 EI	Global
> = 2010	4	5	1	0	0	10
[2000-2010]	84	217	122	72	4	499
[1990-2000]	18	115	77	29	2	241
[1980-1990]	9	68	40	10	0	127
[1970-1980]	3	61	29	10	3	106
[1960-1970]	1	5	2	0	0	8

Note: EI = Equivalent inhabitant

Figure 1. UWWTP per age and capacity (total sample)

4.3 *Steps 3 and 4: Classification of plants and selection of reference sites*

On the basis of standardized qualitative variables (inflow, reduction, and sludge production), the high-performance approach based on a classification using the Pareto front was tested. At the end of this method, 52 out of the 991 plants were identified and defined as the most high-performing. The sample analysis shows a strong representation in the selection of high-performance sites with a capacity between [200 and 2,000] PE (> 65%, 34 sites) followed by plants with a capacity of less than 200 PE (31%, 16 sites). Regarding the year of creation, the high-performance selection globally maintains the breakdown found in the reference sample. There are, however, two points to note: an under-representation of the WWTPs built between [1970 and 1980] (1.9% compared to 10.7% in the reference sample) and an over-representation of the WWTPs built after 2010 compared to the global sample (5.9% against 1% in the reference sample).

4.4 *Step 5: Determination of reference values and BATs*

4.4.1 *Reference values*

The reference plants selected in the previous step are used in this last step to determine reference values for the determination of emission levels associated with BATs. As underlined by [27], the reference values can be obtained via the use of several statistical/metric values: mean, median, mean +/– mean deviation, etc.

It is important to note at this stage that the choice of metric for the reference values is a central element that can strongly impact the final performance levels (BATAEL) established as well as the choice of the associated techniques (BAT references). Consequently, the final choice (mean, median, median + standard deviation, etc.) constitutes an important step, highlighting the individual expertise, experiences, or visions, but also the collective intelligence of the members of the sector studied and any possible bias due to lobbying, political aspects, or individual interests.

The objective of this article is therefore not to impose values on the UWWTPs but to demonstrate the interest of a common and structured methodology to identify reference plants and metric diversities and ultimately guide the decision process.

In the context of this work, and based on the results obtained from the data collected in the high-performance selection, we chose a reference value equal to the mean value plus the mean deviation as the metric. This choice is based on outcomes made by the WWTP experts in the NEXT project.

Table 3 shows the main statistical characteristics for the 52 reference sites as well as for the entire sample (991 sites). The data presented indicate the concentration at the outlet as well as the reduction observed for the following four constituents: BOD, COD, suspended solids, and total nitrogen. The reduction is obtained by calculating the difference between the concentration of a pollutant at an inlet and the concentration of the same pollutant at the outlet. In parallel, the tons of sludge produced are presented. We observe that the group of reference plants (high-performance) shows a lower mean and a lower median compared to the overall initial sample (base 100) and a lower standard deviation for the concentration indicators. On the other hand, in terms of reduction, the reference sample (high-performance) shows a lower performance with an observed reduction level for the overall sample that is higher by 0.1 to 9.4 points according to the indicators.

Table 3. List of variables selected as performance indicators

		Outputs					Reductions			
		Sludge (no reagent)	BOD (mg/l)	COD (mg/l)	SS (mg/l)	NTK (mg/l)	BOD (%)	COD (%)	TSS (%)	NTK (%)
Global sample (992)	Minimum	0	0	0	0	0	14.3	22.9	12.2	0.0
	Maximum	7,422	1,370	6,677	1,339	5,765	100.0	100.0	100.0	100.0
	Mean	79	9.3	54.2	13.1	26.0	95.7	90.6	93.4	70.4
	Median	6	1.6	11.2	2.6	3.5	97.8	93.6	96.8	77.1
	Standard deviation	378.9	60.7	305.7	68.8	226.1	6.88	9.42	10.18	21.35
	Mean deviation	112.0	12.7	70.7	17.1	38.9	3.6	6.0	5.9	17.7
High performance sample (52)	Minimum	0	0	0	0	0	14.3	34.0	20.0	17.3
	Maximum	1,102	183.1	856.5	174.3	516.8	99.6	98.3	99.3	98.3
	Mean	70.2	7.5	43.4	9.5	19.0	93.5	88.4	91.9	66.6
	Median	1	1.0	7.0	1.3	2.6	96.7	92.4	96.7	69.8
	Standard deviation	190	26.0	131.6	27.0	71.9	12.3	11.2	14.3	22.5
	Mean deviation	101.9	10.2	58.5	12.7	26.0	5.9	7.4	7.5	18.7
Deviation (%): Global vs high-performance	Mean	-12.8	-24.1	-24.8	-38.2	-36.4	2.2	2.4	1.6	5.5
	Median	-500.0	-62.8	-58.7	-95.5	-35.8	1.1	1.3	0.1	9.4

In addition, in Table 4, an effort rate for the industrial sector (here the reference sample) is proposed for each variable. The "effort rate" corresponds to the percentage of plants that are not compliant with the proposed reference values (value greater than the reference value), and consequently, these plants are considered non-compliant.

Table 4. Reference values and effort rates used for the search of techniques

Variables	High-performance reference value	Effort rate
Sludge production (tDM/y)	172.1	8.3 %
Concentration of BOD (mg/l)	17.8	6.8 %
Concentration of COD (mg/l)	101.9	7.6 %
Concentration of SS (mg/l)	22.2	8.9 %
Concentration of NGL (mg/l)	45.1	5.6 %
Reduction of BOD (%)	87.7	6.8 %
Reduction of COD (%)	81.0	10.3 %
Reduction of SS (%)	84.4	10.4 %
Reduction of NGL (%)	47.8	16.6 %

Finally, a last aggregate effort/compliance indicator is proposed. It represents the plants from the initial sample that have at least one indicator that does not conform to one of the reference values. Out of all the plants, 61.9% of them comply with all the proposed reference values, 18% do not comply with one, and 20.1% have more than two non-compliances. The most interesting and non-compliant values are the performance levels targeted in terms of NGL reduction, followed by BOD and COD reduction.

In parallel, and in order to explain the reasons for this non-compliance, three analyses were carried out. The first focuses on the influence of the construction year of the WWTPs, the second on their treatment capacity, and the third on the treatment techniques used. Figure 2 shows the results of the first two analyses. The year of construction as well as the capacity in PE of the WWTPs show a limited influence in terms of the number of aggregated non-compliances. Between 34% and 40.2% of sites built between 1970 and 2010 are non-compliant (on at least one indicator). The sites built before 1970 and after 2010, respectively, see these values fall to less than 25%. At the same time, the low representation of these modalities (less than 2% of the total population studied) does not allow us to conclude that this parameter is significant. In the same way, the treatment capacity of the WWTPs shows limited variability between the modalities studied. Between 35.5% and 44.4%, the influence of capacity on the number of non-compliant sites is not proven. The third analysis shows more heterogeneous results and demonstrates a significant causality between emission levels and techniques. This point is developed in the next part.

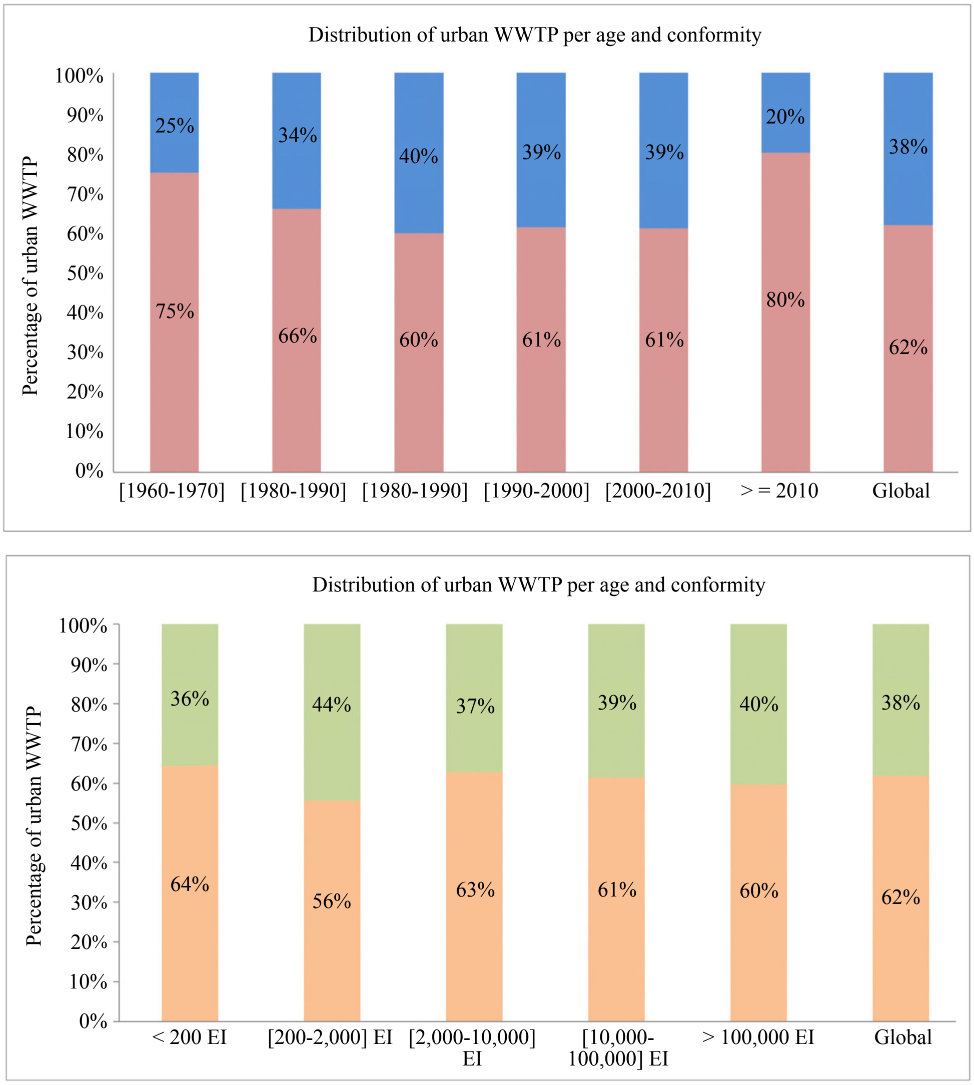


Figure 2. Influence of the year of construction and the capacity of the WWTPs on compliance with the proposed reference values

4.4.2 *Assisting in the identification of candidate techniques for BAT status*

The link between techniques and non-compliance makes it possible to understand the notion of "candidate BATs." As such, four techniques can initially be discarded: biofilters, natural lagoons, planted filters, and biological disks (Figure 3). For the first two, only 48.1% and 49.0% of plants, respectively, meet all of the proposed values. For planted filters and biological disks, this rate increases to 57.7% and 54.5%, respectively.

On the other hand, three techniques have probabilities of obtaining values greater than 75%. High-load activated sludge (88.9%), medium-load activated sludge (78.6%), and sand filters (75%). The mixed cultures, finishing filters, and primary physicochemical treatment are excluded from the analysis due to their low representation in the site sample analyzed (fewer than two sites).

Two techniques show high performance with a compliance rate close to 70%: the bacteria bed and the membrane bioreactor.

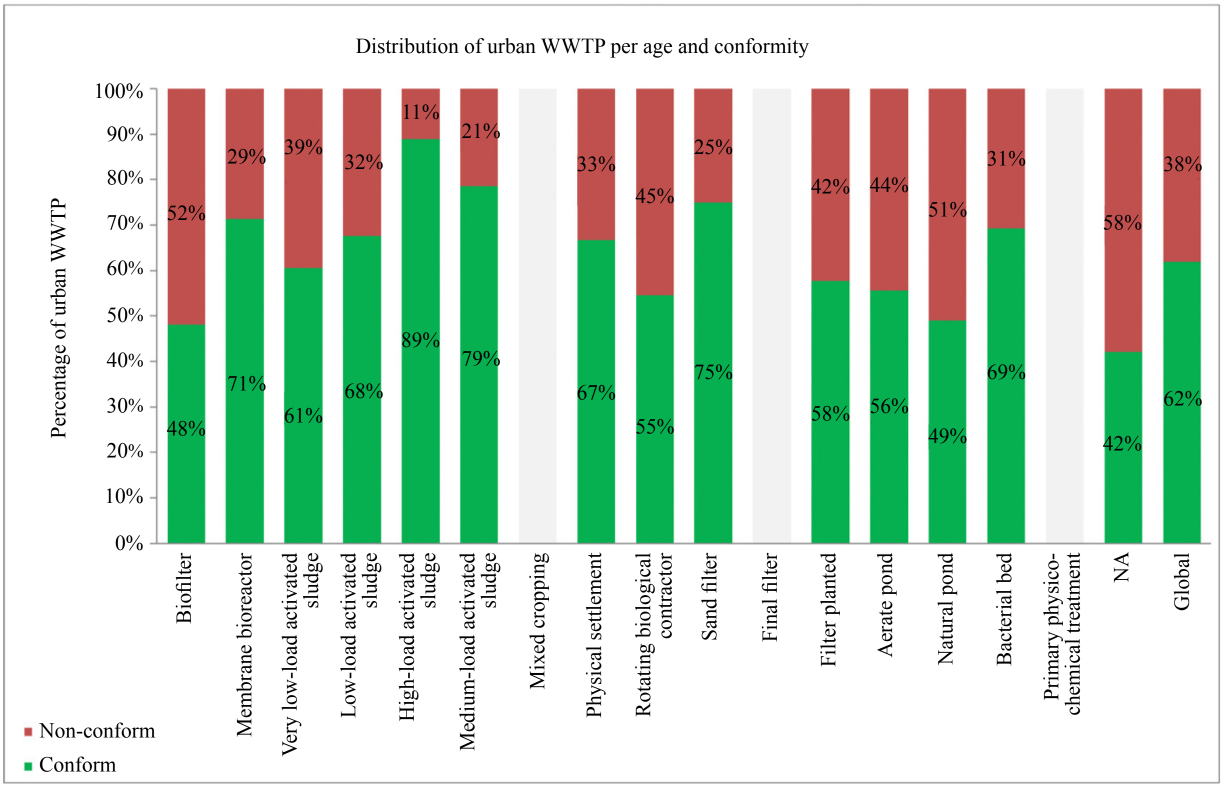


Figure 3. Distribution of the compliance of sites based on the type of techniques used

The coupling of these results with the breakdown of these techniques within the WWTPs grouped by treatment capacity (in PE) makes it possible to propose two types of BAT: common BATs not limited to the size of the installation and specific BATs whose deployment remains constrained by the size of the WWTP. In fact, the analysis shows that the activated sludge systems are represented in all capacity ranges of the studied WWTPs. To a lesser extent, and with the exception of sites with more than 100,000 inhabitants, this assertion is true for the bacteria bed technique. In contrast, sand filters and planted filters are used exclusively for sites with fewer than 2,000 PE. In the same way, membrane bioreactors and biofilters are only deployed in WWTPs with more than 2,000 PE.

In conclusion, five techniques are defined here as candidate BATs for the water line of UWWTPs. Three of them are common, and two of them are specific. The following Table 5 presents these results.

Table 5. Techniques identified as candidate BATs for the WWTP water line depending on the size of the plants

Techniques as BAT candidates for UWWTP	BAT typologies	Installation size
High-load activated sludge	Common	< 100,000 PE (99% of WWTP)
Medium-load activated sludge		All
Bacteria bed		< 100,000 PE (99% of WWTP)
Membrane bioreactor	Specific	> 2,000 PE
Sand filter		< 2,000 PE

5. Discussion

The study presented in this article was intended, on the one hand, to apply the methodology developed by [27] and, on the other hand, to analyze UWWTPs with regard to the performance of the best available techniques. This is in order to determine:

- The associated emission levels that may form the basis of regulatory limit values.
- The techniques that can be determined as the best available techniques for the water and sludge lines of WWTPs treating only urban WW.

The application and results demonstrated the applicability of the methodology used. However, a few points of discussion can be identified.

5.1 *The consequences of the metrics/reference values*

As mentioned previously, the choice of the metric used to establish the reference values is a crucial step that can have a strong impact on the final results. The choice of metric must therefore be the result of a collective process aimed at minimizing the possible influences stemming from individual interests. The developed methodology therefore proposes to identify the possibilities and, therefore, provide the opportunity to analyze the consequences of the choices made. However, in terms of future work, a parametric analysis to test all the combinations of the proposed metrics (reference values) could be considered in order to allow an analysis of field possibilities and therefore better support decision-making.

5.2 *The importance of the data and deficiencies in the sludge line*

The databases used in this study have gaps. Not only was there a lack of data on the parameters identified, but the analysis also highlighted the critical lack of data on the sludge line. In fact, only the sludge tonnage is mentioned. This limits the scope of the results in terms of a global and integrated analysis of all the plants (lines) as suggested in the different regulations. Because sludge is not yet considered a product despite existing recovery processes [29], the sludge line remains perceived as a non-impacting element to manage treatment waste. As a matter of fact, until now, the sludge line was regarded as a black box that did not contribute to the environmental challenges of WWTPs.

However, the status of waste is now called into question by the European regulations for certain activities. WW sludge is being researched with the aim of developing processes to transform it into high-value products (bioplastics, mineral fertilizers, ceramics, biomethane, etc.). In this context, sludge could therefore go from the status of a waste to that of an expected by-product at the end of the water purification process [29]. This paradigm shift has consequences for the positioning of the sludge line, which would in fact become a production unit. Thus, these steps of the water treatment process would appear as a unit in their own right and would therefore be identified as a contributor to the environmental impact.

It is with this in mind that the NEXT project is focusing on the problem of sludge from WW treatment in WWTPs. The characteristics of sewage sludge are rarely used for the purpose of treatment line optimization or for the purpose of regulatory compliance directly applied to WWTPs. This is the main reason why the identification of BATs with regard to the performance of existing techniques and the determination of BATAELs could not be achieved. As a result, the associated issues concern determining the parameters to be monitored, which may make it possible to draw conclusions on the best available techniques.

Process monitoring generally takes place according to the sludge disposal processes and the conformity of the sludge characteristics to the specifications of the disposal process. Thus, these characteristics may be useful for assessing process performance in the sludge value chain. Experts provide a list of agronomic properties of sludge that includes dry matter content parameters (percentage of dry matter), percentage of organic matter, Kjeldahl nitrogen (N-NTK), ammonia nitrogen/Kjeldahl nitrogen ratio (N-NH_4/N-NTK), nitrogen/phosphorus ratio (N/P_2O_5), phosphorus (P_2O_5), potassium (K_2O), calcium (Ca), magnesium (Mg), and pH. In addition, indicators of energy consumption, duration of stay, pH, and associated odor nuisances may also be important.

In conclusion, an organization of the feedback of field data in the same way as the water line for all UWWTPs is needed in order to be able to apply the methodology to the sludge lines and to propose standards to ensure compliance with the regulatory requirements.

5.3 *Isolated technique vs coupling of techniques*

The analyses proposed with regard to the age of the plants show that the year of creation of a WWTP has a limited influence in terms of the number of non-compliances. The breakdown of the plants shows a strong representation over the period 1990-2010 compared to the entire 1960-2010 period, with 70% of the plants in the [200-2,000] requirement range and 73% in the [2,000-10,000] requirement range. In addition, 44% of the plants stated as being created between 2000 and 2010 come from the [200-2,000] range and 25% from the [2,000-10,000] range.

A question is raised about the name of the "creation" parameter because a large number of plants may have been created over the period 1990-2010, according to the databases. This period coincides with the deadlines for bringing plants into compliance with the Urban Waste Water Treatment (ERU in French) Directive No. 91/271/EEC of 21 May 1991 whose objective is to protect the environment against deterioration due to the discharge of this WW. The requirements of this directive were transcribed into French law by Law No. 92-3 of 3 January 1992 on water, Decree No. 94-469 of 3 June 1994 relating to the collection and treatment of WW, and the decree of 22 June 2007 on the collection, transport and treatment of WW from sanitation areas. These regulatory texts provide chronologically defined timelines for compliance, starting with the largest municipalities discharging into the most sensitive environments and ending with the smallest communities. The compliance schedule was defined according to the norms in the following:

- More than 10,000 PE → No later than 31/12/1998
- More than 15,000 PE → No later than 31/12/2000
- Between 2,000 and 15,000 PE → No later than 31/12/2005
- Less than 2,000 PE → No later than 31/12/2005

The parameter "age range" of the installation could therefore bring together new plants and plants that were brought into compliance between 1990 and 2010 with regard to the aforementioned schedule. The fact that plants were massively brought into compliance during the 1990-2010 period would explain the lack of impact of "plant age" on performance.

5.4 *Influence of the age of the WW treatment plants*

From a regulatory point of view, the concept of technique incorporates a wide range of possibilities, covering production processes, WWTP, substitution of chemical products, or organizational arrangements. The elements studied in this research project are based primarily on WWTP for the secondary treatment of urban WW. Although a WW treatment plant is composed of a sequence of unit processes, only information on the main treatment is provided. Thus, the conclusions made regarding candidate BATs include only one element of the treatment, as if they were used alone. The assumption is therefore made that only the secondary treatment technique has an influence on plant performance, despite the measures taken upstream and downstream of the entire water line, which comprise a coupling that may be different from unit processes on the one hand and organizational arrangements on the other [27].

Nevertheless, the BREFs for mixed WWTPs also provide unique BATs for each treatment phase. The comparison of our results with those of the BREFs shows that the techniques used in our study are in line with those of the BREFs for mixed, industrial, and biological WWTPs (Table 6).

Table 6. Comparison of BATs from the analysis and BATs from CWW and WT BREFs

		Our results					
		< 100,000 PE (99% of WWT	All	< 100,000 PE (99% of WWT)	> 2,000 PE	< 2,000 PE	BAT from BREFs CWW or WT
Activated sludge	High-load	X					X*
	Medium load		X				
Membrane bioreactor					X		X
Bacteria bed				X			
Sand filter						X	

*Activated sludge (no precision on the load)

Concerning the reference values that result from the processing of the data in our study, we can note that they corroborate with the BATAELs proposed in the two BREFs concerned, as well as the regulatory values stemming from the decree of 21 July 2015 relating to the collective sanitation systems (Table 7). In addition, the validity of the reference values proposed in our study can be reinforced by the observed proximity to the expert values of the assessment of new sanitation processes for small- and medium-sized communities (EPNAC) working group (water agencies, Direction Départementale des Térritoires (DDT), Service d'Assistance Technique à l'exploitation des Stations d'Epuration (SATESE), Institut national de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture (IRSTEA), Office National de l'Eau et des Milieux Aquatiques (ONEMA), Ministère de l'Ecologie, du Développement Durable et de l'Energie (MEDDE), Ministry of Health) organized by the Ministry of Environment in 2015.

These elements validate, on the one hand, the scientific approach developed and, on the other hand, the robustness of the methodology.

Table 7. Comparison between BATAELs for CWW and WT BREFs and the ones proposed by our studies

Variables	High-performance reference value	BATAEL (annual mean) BREF CWW	BATAEL (annual mean) BREF WT	Regulation threshold (French Decree 21/07/2015)
Sludge production (tDM/y)	172.1	NA	NA	NA
Concentration of BOD (mg/l)	17.8	No BATAEL applies to the BOD. As an indication, the mean annual BOD5 of effluents from a biological WW treatment plant is generally ≤ 20 mg/l	NA	25 or 35 according to the requirement range
Concentration of COD (mg/l)	101.9	30-100	30-300	125 or 200 according to the requirement range
Concentration of SS (mg/l)	22.2	5.0-35	5-60	35
Concentration of NGL (mg/l)	45.1	5-25 mg/L	10-60	NA except for sensitive area 10 or 15 mg/L
BOD reduction (%)	87.7	NA	NA	60% or 80% according to the requirement range
COD reduction (%)	81.0	NA	NA	60 or 75% according to the requirement range
SS reduction (%)	84.4	NA	NA	50 or 90% according to the requirement range
NGL reduction (%)	47.8	NA	NA	70%

Note: NA = Not available

5.5 *Contribution of the methodology*

The methodology used for the identification of the reference BATs, and the associated performances (BATAEL) is the result of research work carried out in collaboration with INERIS and EDF, which had as a preliminary application two sectors, namely the food industry and nuclear installations [27]. This new application makes it possible to confirm the orientations that have been taken and validate the process and the robustness of the methodology.

Thus, this methodology contributes to the establishment of a reference system of techniques for the water treatment sector (mixed WWTP) by using the state-of-the art, databases of technique performances and descriptions of WWTP. In addition, this process allows the data to be reconstructed with sufficient accuracy.

Compared to other methods (e.g., LCA), it makes use of real data and a data management model that provides performance values to guarantee feasibility and operational validity.

Moreover, the identification of BAT reference and the choice of a BAT to be implemented at the local level have to be made on the basis of real data and local indicators (sensitivity of the local environment and economic and technical means of the company), respectively. In this case, the LCA is not adapted as mentioned by [27] and [19]. Nevertheless, LCA can be used to compare BATs with one another and determine the most sustainable one amongst several BATs taken from the BREFs [5, 15].

Finally, as this method was developed as a contribution to the application of the European directive on industrial emissions, it aims to allow the identification of benchmarks in terms of techniques and performance and is thus part of the tools for identifying and updating the regulatory thresholds of industrial installations (mixed WWTP).

The methodology has not yet been tested at the local level, which would consist of testing it on a single installation. It is presumed that such an application would require some changes to the methodology. Moreover, its local context should be considered to adapt the conclusions from national or international levels, and then it should be discussed whether it is an exception or not.

5.6 *Limits of the methodology*

The methodology is based on several mathematical methods to collect, treat, and analyze data from databases. One requirement was the robustness of the methodology. The imputation of missing data in Step 2 seems to be the only internal source of variations. Other tools could be used instead of those presented in this paper. In the case of a large number of facilities, kriging techniques for data reconstruction could be more efficient than MissForest. Moreover, regarding facility classifications (Step 3), other multi-objective optimization methods could be used instead of the Pareto front for performance classification, such as scalar or non-scalar approaches or indicator-based approaches [30].

In order to be sure that the methodology is robust, experts are involved at every step. They define and select the key elements and make key decisions. For example, they choose the variables for Steps 1 and 2, define the course of classifications in Step 3, select reference values for Step 4, and validate the proposed potential BAT candidates in Step 5.

6. Conclusion

The regulatory framework of the IED and its BAT principle do not currently apply to UWWTPs that only treat effluents from "urban" sanitation areas. Only the mixed plants are concerned. However, in a context of decision support based on performance comparison, the BAT concept can be disseminated and represents an opportunity to improve water and sludge treatment systems. Moreover, it could contribute to improving surface water quality by preventing the discharge of pollution. The process associated with the implementation of BATs provides benchmarks in terms of performance. In this context, the use of the methodological approach developed for IED and the validation of the application thereof to these non-IED plants, UWWTPs, have been carried out.

The results obtained demonstrate the transferability of the methodological approach to a sector not covered by the IED. This has resulted in particular in the validation of the technical results selected as BATs as well as the associated reference values by comparison with existing French and European regulation frameworks. Five techniques (membrane bioreactor, bacteria bed, sand filter, and high-load or medium-load activated sludge) were identified as BATs (common or specific) according to the range of regulatory classification requirements for WWTPs.

Moreover, the fact that UWWTP was massively brought into compliance during the 1990-2010 period would explain the lack of impact of "plant age" on performance.

In addition, reference values that may constitute the basis of regulatory thresholds were proposed. The methodological choices for determining the standard were also focused on taking into consideration the entire sector studied in order to derive a rate of effort that represents the challenge of bringing plants into compliance within the study scope. In addition, a comparison of the results with expert statements and similar references has validated the scientific approach of the methodology. However, a few discussion points have been identified, including the impact of the metric to define reference values, a crucial lack of data from the sludge line limiting the identification of BATs to the water line alone, the approximate baselining of certain parameters in the databases, as well as the problem of the coupling of techniques because of the identification of one main technique.

The purpose of this proposal is to obtain benchmarks for UWWTPs, both from a technical point of view and in terms of performance. The aim is to make this information more accessible to operators and help them make the right choices when it comes to improving their facilities.

Finally, the study contributes to the application of the strong concept of BATs for WW treatment in a European context. It also makes it possible to link two major European directives, the IED and the Urban Waste Water Treatment (ERU in French), and to contribute to the Water Framework Directive.

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Declaration of interest

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

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