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An innovative implementation of LCA within the EIA procedure: *lessons learned from two wastewater treatment plant case studies*

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Highlights

An innovative methodology for a first-stage implementation of LCA in EIA is proposed.

Its applicability is demonstrated on two wastewater treatment plant case studies.

The conclusions for the four EIA steps investigated differ with or without LCA.

LCA provides valuable additional information on 1) global and 2) off-site impacts.

LCA identifies pollution transfers towards a life cycle perspective.

Abstract

Life Cycle Assessment (LCA) has been identified in the literature as a promising tool to increase the performance of environmental assessments at different steps in the Environmental Impact Assessment (EIA) procedure. However, few publications have proposed a methodology for an extensive integration, and none have compared the results with existing EIA conclusions without LCA. This paper proposes a comprehensive operational methodology for implementing an LCA within an EIA. Based on a literature review, we identified four EIA steps that could theoretically benefit from LCA implementation, i.e., (a) the environmental comparison of alternatives, (b) the identification of key impacts, (c) the impact assessment, and (d) the impact of mitigation measures. For each of these steps, an LCA was implemented with specific goal and scope definitions that resulted in a specific set of indicators. This approach has been implemented in two contrasting Wastewater Treatment Plant (WWTP) projects and compared to existing EIA studies. The results showed that the two procedures, i.e., EIAs with or without inputs from LCA, led to

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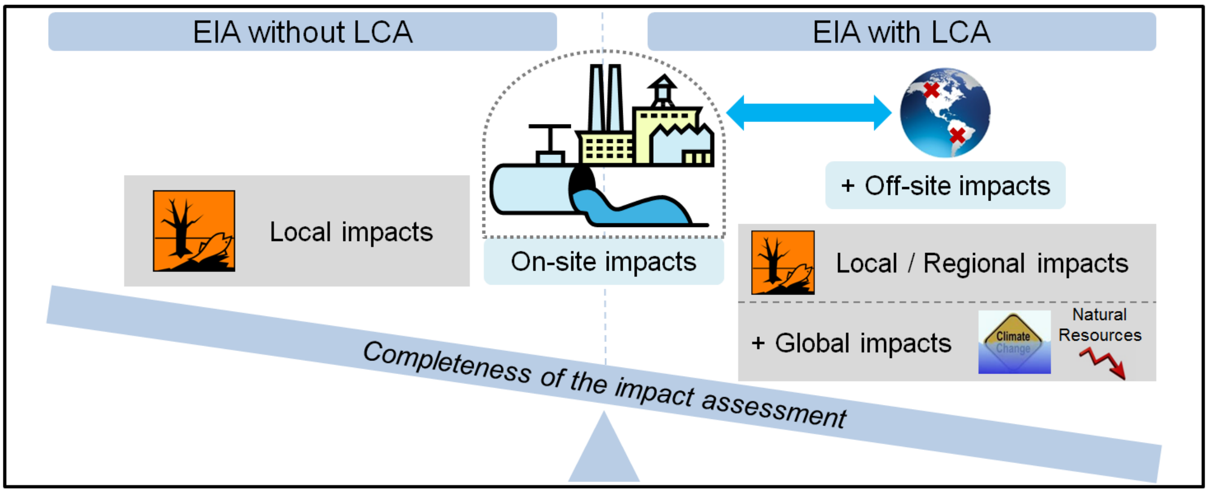
different conclusions. The environmental assessments of alternatives and mitigation measures were not carried out in the original studies and showed that other less polluting technologies could have been chosen. Regarding the scoping step, the selected environmental concerns were essentially different. Global impacts such as climate change or natural resource depletion were not taken into account in the original EIA studies. Impacts other than those occurring on the project site (off-site impacts) were not assessed, either. All these impacts can be significant compared to those initially considered. On the other hand, unlike current LCA applications, EIAs usually address natural and technological risks and neighbourhood disturbances such as noises or odours, which are very important for the public acceptability of projects. Regarding the impact assessment, even if the conclusions of the EIAs with or without LCA were partially common for local on-site impacts, LCA gives crucial additional information on global and off-site impacts and highlights the processes responsible for them. Finally, for all EIA steps investigated, interest in LCA was demonstrated for both WWTP case studies. The feasibility in terms of skills, time and cost of such implementation has also been assessed.

Graphical abstract



Keywords

Life Cycle Assessment (LCA); Integrated procedure; Wastewater Treatment Plant (WWTP); On-/Off-site impacts; Local/Global impacts

1 Introduction

1.1 Background

Environmental Impact Assessment (EIA) is a widespread and legally required procedure used to support local decision-making. According to data collected by the European Commission, approximately 16,000 EIAs are conducted each year across the EU-27 for different types of projects, including infrastructure (i.e., energy, transport, waste and wastewater treatment) and industrial and urban development (GHK, 2010). EIA procedures vary in their details, but the practical stages in most systems are generally those illustrated in Figure 1. First, screening (step 1 in Figure 1) determines whether a proposal should be subject to an EIA. For example, European EIA directives apply to a wide range of defined public and private projects; some of them are always mandatory (e.g., long-distance railway lines or installations for the disposal of hazardous waste), whereas others are at the discretion of the member states based on a case-by-case examination or on thresholds set by the member state. Second, scoping (step 2-a in Figure 1) examines the project characteristics and establishes the preferred option for achieving the project’s objectives (European Commission, 2001), for example, by choosing an alternative location or adopting a different technology or design for the project (Guidance on EIA - Scoping, 2001). The issues likely to be significant are then identified (step 2-b in Figure 1). In addition, scoping sets the scope and the temporal and geographical boundaries of the assessment. Third, the impact assessment phase, which is the core of the procedure, is generally divided into establishing an environmental baseline description before the project (current state) (step 3-a in Figure 1) and identifying, quantifying and evaluating the main environmental, social, and human health impacts (step 3-b in Figure 1) (IAIA and IEA, 1999). Fourth, mitigation measures are proposed to avoid, reduce, or offset the identified impacts (step 4 in Figure 1). Finally, a report is prepared, and after a review involving public opinion, the decision is made to approve or reject the project.

The EIA procedure relies on tools either for impact identification (scoping) or impact prediction (impact assessment). On the first point, different tools such as checklists, matrices, networks, consultations with local stakeholders (Ogola, 2007), map overlays, geographic information systems, expert systems, and professional judgement (UNEP, 2002) are usually used to ensure that all potential impacts are detected. For impact assessment, methods for predicting the characteristics of impacts include “best estimate” professional judgement, quantitative mathematical models, experiments, physical models, and case studies as analogues or points of references (UNEP, 2002). Therefore, EIA practitioners are free to use the best available methods or models and their own expertise to estimate project environmental impacts (Ogola, 2007). Among these tools, several authors have suggested the use of analytical tools such as Life Cycle Assessment (LCA) (Bidstrup, 2015; Finnveden and Moberg, 2005; Jeswani et al., 2010; Manuilova et al., 2009; Potting et al., 2012; Tukker, 2000; Židonienė and Kruopienė, 2014). LCA is a standardised tool designed to assess environmental impacts throughout a product's life cycle, i.e., from raw material acquisition to waste management, via production and use phases (ISO, 2006a, 2006b). Although originally focused on products and services, its application domain has recently expanded to LCAs of organisations, including specific sites (ISO, 2014). LCA assesses impacts with regard to functional units which reflect the quantified function(s) provided by the studied system. LCA has the double benefit of quantifying environmental impacts according to a life cycle perspective and a multicriteria approach. These key characteristics allow the identification of hotspots and shifting burdens between impact categories and life cycle stages (Finnveden et al., 2009).

1.2 Potential contributions of LCA to the EIA procedure: state of the art

Based on a review presented hereafter, Figure 1 shows where LCA could bring valuable contributions to some steps of the EIA procedure, i.e., during scoping (box-a and box-b), impact assessment (box-c) and mitigation measures (box-d).

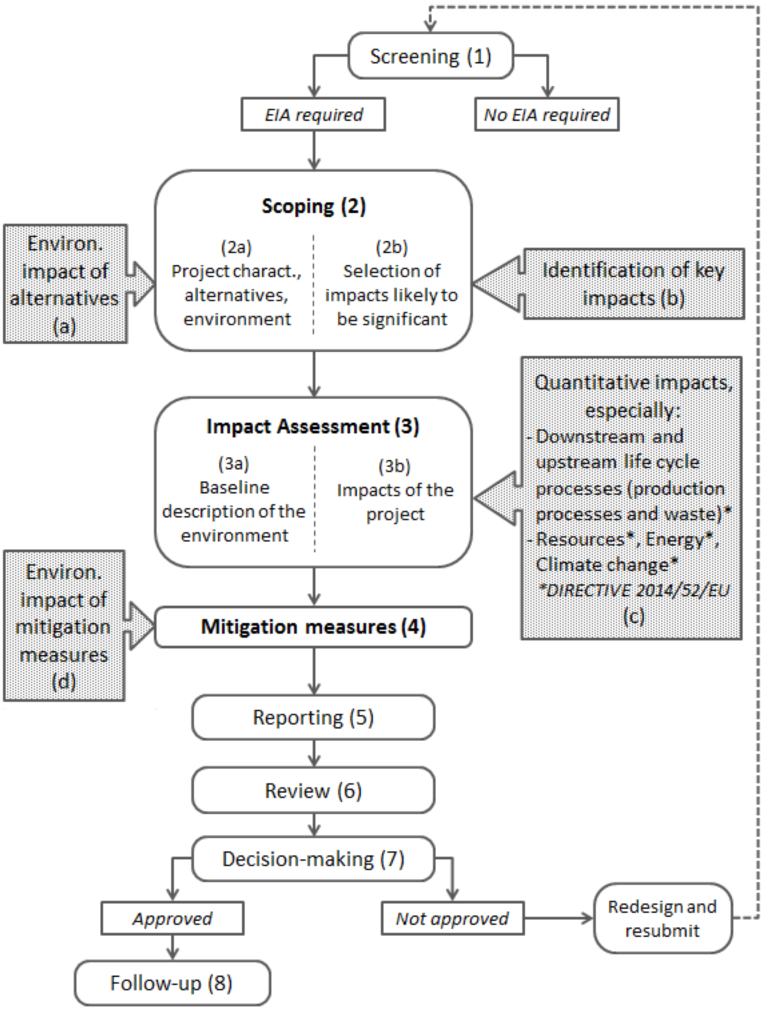


Figure 1: Potential contributions of the LCA approach (shown with arrows) to the EIA procedure

For the first scoping stage, Steinemann (2001) emphasised that the comparison of alternatives should be based on explicit environmental factors. In this sense, Manuilova et al. (2009) argued that LCA can be used to test all alternatives in depth (see box-a). Bidstrup (2015) also stressed that the standardised LCA method can help EIAs be more explicit on their embedded functions and provide a framework for the quantitative comparison of alternatives. At a higher level than projects (i.e., plans, programmes and policies), a methodological framework for Strategic Environmental Assessment (SEA) developed by Finnveden et al. (2003) also suggested that LCA can be useful to support choices between different alternatives. Moreover, Manuilova et al. (2009) suggested that LCA can be used to validate system boundaries by considering both global and regional impacts throughout lifecycles. LCA could add value to the scoping step when determining major issues that should be addressed as priorities (arrowed box-b in Figure 1).

For the impact assessment stage, as no specific or consensual analytical tool is imposed in EIA, Life Cycle Impact Assessment (LCIA) methodologies could usefully provide complementary information (arrowed box-c in Figure 1). LCIA provides a life cycle impact-oriented and quantitative assessment. In addition, with the development of site-dependent LCIA methodologies, there is a high potential to apply these models to EIA to increase the level of detail and accuracy of environmental assessment (Manuilova et al., 2009). Tukker (2000) and Manuilova et al. (2009) put forward that LCA permits the inclusion of emissions and effects related to upstream and downstream activities in the supply chain and not only at the location of the process itself. The indirect impacts of projects can be extremely relevant, as they can be higher than the direct ones (Lenzen et al., 2003; Potting et al., 2012). This inclusion is strongly encouraged by recent European legislation (Official Journal of the European Union, 2014). Regarding the nature of the impacts, Directive 2014/52/EU emphasises the need to consider a wide range of impact categories that include “resource depletion”, “energy”, “climate change” and “human health”. The multicriteria approach adopted by LCIA methods such as ReCiPe (Goedkoop et al., 2013) or ILCD (European Commission et al., 2010a) is particularly adapted to this requirement.

Finally, LCA could have real added value for assessing the impacts of abatement alternatives (Tukker, 2000) (arrowed box-d in Figure 1). So far, the impacts of mitigation measures and their implementation have been rarely considered.

Still, even if several authors have argued that LCA is an appropriate analytical tool for application in both EIA and SEA, little concrete application has yet been found in practice. A review of 85 Danish EIA or SEA reports showed that 22% were supported by LCA results, whereas only 7% really applied LCA as part of the methodology (Bidstrup, 2015). To address this issue, some recent publications have proposed formal yet partial procedures for such integration.

Regarding preliminary applications for EIA, Tukker (2000) gave some examples of an actual use of LCA in Dutch EIAs or SEAs and noted studies that could have benefited from LCA, essentially to provide a quantitative assessment of process alternatives but also to compare different abatement alternatives. Cornejo et al. (2002) proposed to use LCA in EIA and applied it to a major modernisation project of a newsprint mill. After assessing the environmental impacts of the project alternatives, they compared concentrations of significant air, water and solid waste emissions with environmental regulations. Židonienė and Kruopienė (2014) recently proposed an integrated LCA-EIA framework to compare several alternatives for a project. They compared different material insulation production scenarios with LCA to identify the one with the lowest environmental impacts. In line with Cornejo et al. (2002), they then proposed to assess the compatibility of the selected scenario with local conditions, i.e., air emissions, water pollution and site location with regard to biodiversity, protected areas and social environment. Morero et al. (2015) offered a comparison of the impact assessment of biogas upgrading processes, with LCA on one hand and with a specific cause and effect matrix used to comply with Argentinian EIA legislation on the other hand.

Regarding preliminary applications for SEA, Björklund (2012) used LCA in combination with other planning tools to design the scope of the environmental assessment and defining and assessing alternatives for municipal energy planning in Sweden. Bidstrup et al. (2015) proposed an LCA procedure for operationalising LCA in SEA. They defined several scenarios for Danish extraction planning and compared them on the basis of the two most significant impact categories of the baseline scenario.

1.3 Aim of the paper

First, this paper aims to propose an advanced integration of LCA within the EIA procedure. Many authors have discussed the analytical benefits of applying LCA in EIA in theory, and some of them already proposed preliminary procedures for a partial integration of LCA in some specific steps of the EIA procedure. Most mainly focused on assessing project alternatives with LCA and then discussing LCA results in the context of a specific location. The proposed procedure differs from prior studies by its effort in considering not only alternatives assessment but also other EIA steps. We offer to put all potential LCA analytical gains noted in the literature into practice in a comprehensive procedure. Concretely, we first clarified which steps of the standardised EIA procedure could benefit from LCA and then provided a complete methodology for an exhaustive LCA integration in EIA.

Second, the purpose of this study is to test ex-post the implementation of this innovative procedure in real EIA case studies (first-stage implementation) to further investigate the interest and feasibility of using LCA in an EIA procedure. For this purpose, we compare the outputs from an existing EIA procedure without LCA with the outputs from an EIA procedure using LCA as an analytical tool. We want to see if the main conclusions differ, and if so, how and to what extent LCA could actually contribute to EIA. This comparison is conducted using two real case studies dealing with wastewater treatment plants. This first-stage implementation can be seen as a proof of concept for analysing the LCA inputs within the

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EIA procedure. Nevertheless, this first step does not substitute to an effective and practical implementation of the proposed approach in real time during an EIA process including interactions with regulation authorities as well as a feedback analysis on decision-making (which is out of the scope of this paper).

Thus, the two main original aspects of our work are a comprehensive integration of LCA in the EIA procedure and the demonstration of LCA benefits based on existing case studies.

2 Materials and methods

2.1 Integration of inputs from LCA into four EIA procedure steps

The proposed methodology consists of revisiting an existing EIA (conducted ex-ante) by introducing LCA at different steps (conducted ex-post). It aims to demonstrate the added value and feasibility of including LCA in the EIA procedure in future studies. The final objective of the methodology is to apply LCA throughout an actual EIA study, both conducted simultaneously.

For the sake of demonstration, the LCA was conducted at each step of the EIA procedure as if both studies were carried out at the same time. For example, during step (2-a), LCA was used to compare the alternative scenarios based on standard Wastewater Treatment Plant (WWTP) technologies because at that point the system to be chosen and the precise future design of the processes are unknown. However, during step (3-b), the actual data for the design were assumed to be available, and the impacts of the technologies were assessed with LCA based on the actual data. LCA was therefore implemented at each relevant EIA step with a specific goal and scope. In addition, different indicators are provided, as presented in Table 1. Endpoint indicators are used for comparison or for environmental issues identification. Midpoint indicators are used for eco-design and the identification of hotspots that need to be mitigated.

Table 1: Specific LCA analysis used at each of the four selected EIA steps

Step of the EIA procedure	**Aim of the LCA**	**Object of the LCA study**	**LCA analysis and associated indicators**
Step 2-a: Alternatives	Comparison of alternatives and identification of best option	LCA of all potential alternatives	Analysis at endpoint level

Step 2-b: Scoping	Identification of main environmental concerns (hotspots)	LCA of selected alternative	Analysis at endpoint level, including the contribution of each midpoint impact to each endpoint category. *Nota bene: The few midpoint indicators that are not developed at the endpoint level are considered by default as environmental concerns.*
Step 3-b: Impact Assessment	Identification of main contributing life-cycle stages with: - a differentiation between on-site and off-site impacts - a differentiation between local/regional and global impacts		Analysis at midpoint and endpoint levels
Step 4: Mitigation measures	Contribution of the impacts of the implementation of mitigation measures to the entire WWTP impacts	LCA of mitigation measures	Analysis at midpoint and endpoint levels

The results of the LCA approach are then compared with the conclusions of existing current analytical methods or expert judgement mobilised in the EIA for each of those steps. Finally, the possible contribution of LCA to EIA is assessed by analysing whether the LCA integration changes the overall conclusions of the EIA study. The practical feasibility of the methodology in terms of means, resources and costs is discussed.

2.2 Application to two case studies

2.2.1 Choice and description of the case studies

The choice of case studies is based on three criteria, i.e., i) availability of existing EIA reports, (ii) availability of emission and resource use data and iii) opportunities to identify different alternatives to the proposed project. In addition, infrastructure projects, including water management, represent a large part of European EIA studies (GHK, 2010), and WWTPs are great contributors of water management EIAs. We thus have decided to focus on the environmental impact assessment of WWTPs in France. This choice is appropriate given that many wastewater treatment projects have recently been conducted in Europe to meet the requirements of the EU Water Framework Directive. WWTPs generate impacts on local water quality, and two contrasting case studies are compared in terms of environmental constraints due to protected areas. Both case studies and the main results of the EIA procedures are summarised in Table S 1, Table S 2 and Table S 3 based on technical documents produced during the procedures. Only information regarding the four EIA steps where LCA could provide interesting information (Boxes a, b, c, and d in Figure 1) are described in these tables. Both case studies are located in small cities in eastern France and have similar characteristics, except for the presence of a Natura 2000 area (EU protected nature conservation areas, including terrestrial and marine sites).

In many cases, the impacts are not addressed in the same section of the report, either because they come from different sources or because they do not have the same targets. For example, EIA differentiates between the "receiving environment" (surface water) and the "site" (other targets) or sanitary impacts. Consequently, the comparison with LCA—which produces results by impact category (e.g., climate change or eutrophication)—is not straightforward. To allow an easier and consistent comparison with LCA, the raw data have been re-classified (see Table S 4 for details on the reorganisation) to gather the same issues and extract concise and relevant indications in the Results section.

As the report is mainly descriptive and qualitative, we also propose to weight the impacts from minor concern (0 - no potential impact identified in the EIA) to moderate concern (1 - impact, but no proposed mitigation measures) and major concern (2 - impact, with proposed mitigation measures) depending on the qualitative content of each paragraph and whether corrective or mitigation measures are planned.

2.2.2 LCA of the two case studies

This section presents the implemented assessments following the four stages of LCA methodology as defined by ISO 14044 (ISO, 2006b).

LCA goal and scope

For the two case studies, several WWTP alternatives are considered in the respective EIA studies (Table S 1). Infiltration-Percolation (IP) has not been assessed by LCA because vertical Reed Bed Filters (vRBF) are always preferable, as they have fewer operating constraints (M.A.G.E. 42, 2007). Regarding intensive technologies, even if Activated Sludge (AS) and Activated Sludge Sequencing Batch Reactors (AS-SBR) have significant differences regarding treatment chronology, they have been assimilated to similar technologies as a proxy (the infrastructure construction and energy consumption are quite alike). Finally, because no Life Cycle Inventory (LCI) data are available for Biological Disks (BD) and because this

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technology is not widespread in France—only 2.2% of the WWTP < 2000 population equivalent (p.e.) in 2008 (Golla et al., 2010)—BD have not been modelled in this study. The WWTPs alternatives assessed by LCA are summarised in Table 2.

Table 2: Description of the systems investigated with LCA

	Case study 1	**Case study 2**
Goal of the LCA study	Choice, design and impact assessment of a new WWTP for the municipality of Altwiller	Choice, design and impact assessment of a new WWTP for the municipalities of Niedersteinbach and Obersteinbach
LCA Functional unit (FU)	Treatment of wastewater load from one population-equivalent (p.e.) during one day (1 p.e. = 60 $gBOD_5$/day)	
System boundaries	From all WWTP life-cycle stages to freshwater ecosystem, including WWTP construction, operation and maintenance, final dismantling and sludge end-of-life (Risch et al., 2015). The sewer system is not modelled for both case studies because it is identical for all alternatives. The mitigation measures planned during the EIA are also considered.	
Population Equivalent (p.e.)	440	684
WWTP assessed by LCA	AS, AS-SBR, vRBF (respectively, denoted AS1, AS-SBR1, and vRBF1)	AL, NL, AS, AS-SBR, hRBF, vRBF (respectively, denoted AL2, NL2, AS2, AS-SBR2, hRBF2, and vRBF2)

AS = Activated Sludge and AS-SBR= Activated Sludge Sequencing Batch Reactor / vRBF = vertical Reed Bed Filters / hRBF = horizontal Reed Bed Filters / NL = Naturally Aerated Lagoons / AL = Artificially Aerated Lagoons

Life Cycle Inventory

Different WWTP models were used, and the data sources for the LCI of each technology are provided in Table S 5. For all the WWTP models, agricultural spreading was considered to be sludge end-of-life, which is the case in both case studies. Emissions to water and air were estimated for phosphorus, nitrogen, carbon compounds and micropollutants (Choubert et al., 2011). For all these substances, the influent composition is compared to emissions and sludge compositions to comply with the mass balance. A selected inventory for the modelled WWTPs is described in the supporting information (Table S 6). The data presented correspond to the major operational parameters of a WWTP, the main infrastructure information, and conventional emissions to air and water. A distinction was made in the LCIs between the foreground and background activities to enable comparison with the EIA results. Foreground activities refer to civil engineering works for the construction of the WWTP and to on-site discharge and land occupation during the operational phase of the WWTP, whereas background activities correspond to the off-site activities needed for the construction phase (production and transport of all materials and equipment), the off-site activities needed for the operational phase of the WWTP (e.g., electricity production) and the sludge end-of-life. The Ecoinvent database version 3.1 was used for all background data. Regarding the impacts of the implementation of mitigation measures, a description of the associated LCIs is provided in Table S 7. These inventories involve coarse assumptions about civil engineering works because the goal here is not to obtain accurate results but rather the orders of magnitude of the potential impacts associated with such measures.

Life Cycle Impact Assessment

For the impact calculation phase, both the ReCiPe Midpoint and ReCiPe Endpoint version 1.11 2010 methods (Goedkoop et al., 2013) are used. The ReCiPe method calculates eighteen midpoint indicators (i.e., between environmental interventions and damages in the cause and effect chain) and three endpoint indicators (i.e., at the end of the cause and effect chain, indicating damages to human health, ecosystems and resource availability). The motivation to use endpoint indicators is the large number of midpoint indicators and their partially abstract meaning. Thus, damage modelling aids in the understanding and interpretation of midpoint indicators by making results in different midpoint categories cross-comparable within Areas of Protection (European Commission et al., 2010b).

LCA interpretation

LCA is implemented at each relevant EIA step with a specific goal and scope and associated set of indicators (Table 1). To facilitate the interpretation of the scoping and mitigation measures (EIA – steps 2 and 4), all the results are presented as a whole, without distinguishing on-site/off-site impacts or local/global impacts. However, for the interpretation of the results relative to the impact assessment step (EIA - step 3-b), we propose a further refinement. We differentiate between on-site impacts (impacts due to emissions occurring on the site of the project) and off-site impacts (impacts due to emissions occurring outside of the site, e.g., manufacturing plants in other parts of the globe). Regarding the environmental mechanisms, in LCA they are usually classified—in a rather simplistic way—according to their "spatial scale". Global environmental mechanisms such as climate change, ozone depletion and fossil fuel/mineral resources depletion will have the same potential impact wherever the emissions/consumptions occur on the planet. This does not mean that the effects (i.e., the consequences of climate change on human health and ecosystems) will not vary locally. In contrast, for non-global mechanisms (referred to as local or regional), the geographical situation of an emission or resource consumption has an influence on the magnitude of its impact. Environmental mechanisms such as acidification, eutrophication, photochemical oxidant formation, (eco)toxicity, land use and water use depend on regional conditions (Goedkoop et al., 2013). Figure 2 illustrates the possible differentiations; some impacts can be local and on-site (e.g., eutrophication in the river next to the site), global and on-site (e.g., climate change due to WWTP discharges), local and off-site (e.g., ionizing radiations at nuclear power plant), global and off-site (e.g., resource depletion associated with energy production).

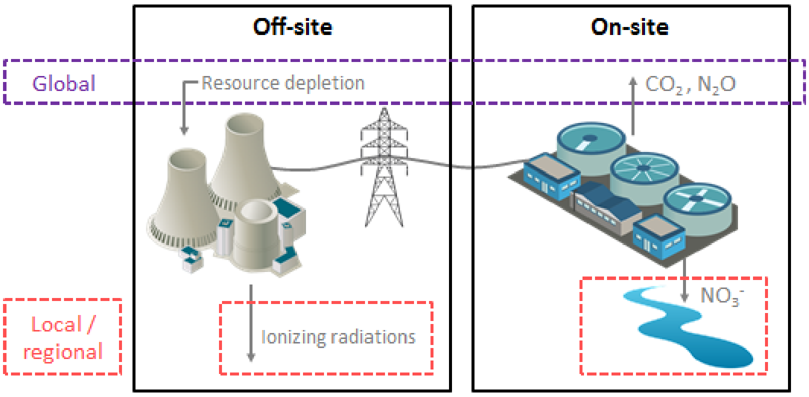

Figure 2: Differentiation between on/off-site activities and global/regional/local environmental mechanisms

The contributions of the different wastewater treatment life cycle stages are also examined in the EIA impact assessment step.

3 Results

3.1 Previous EIA conclusions (without inputs from LCA)

For step 2-a, the alternatives were chosen based on technical criteria and local pressures (see Table S 1). For case study 1, reed bed filters were selected, whereas the activated sludge process was preferred for case study 2. For step 2-b, EIA established spatial and temporal boundaries, but the selection of environmental concerns was mainly implicit and based on consultants' expertise and the regulatory constraints on this type of project. For step 3-b, Table S 8 qualifies the different issues according to the evaluation levels 0 (minor) to 2 (major) described previously. Impacts due to extreme climatic events were not considered.

The identified issues of major concern for both case studies are the impact of land transformation occurring during construction and water pollution during the operation of the

WWTP. Change in water flows is also a major issue for case study 1 and landscape alteration for case study 2. Other issues of less importance are noise during construction for both case studies and odours during the operation phase of the WWTP for case study 1. Finally, although mitigation measures were integrated in the project (step 4), their impacts were not considered in either EIA report.

3.2 LCA results (ex-post) for the four EIA steps

3.2.1 LCA results for EIA Step 2-a: Alternatives

Case study 1: Considering the endpoint indicators (Figure S 1), vertical reed bed filters are more efficient from an environmental perspective than the activated sludge process for all three areas of protection (human health, ecosystems and resources). This trend can be explained by the smaller impact of reed bed filters compared to activated sludge for all midpoint categories (Figure S 2), except for eutrophication (freshwater and marine) and occupation of urban area. This is due to (i) the less effective treatment of nitrogen and phosphorus by reed bed filters and (ii) their higher area requirements (extensive processes need more area per capita).

Case study 2: In view of the endpoint indicators (Figure 3), the naturally aerated lagoon system is clearly the worst performing alternative for human health and ecosystems and has the second greatest impact on resource depletion. This result is because the only midpoint indicators in which this lagoon system is the worst alternative are those that contribute most to the endpoint indicators (Figure S 3). The values of the potential impacts generated by the activated sludge process are intermediate, and the best apparent alternatives are vertical reed bed filters and artificially aerated lagoons.

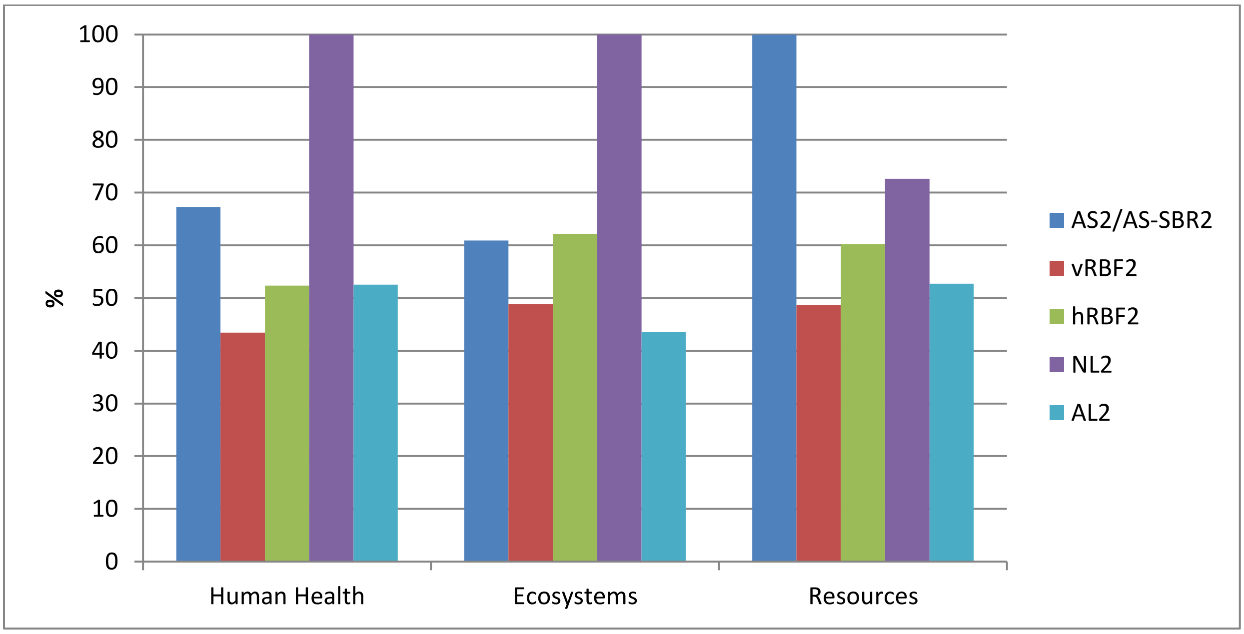

Figure 3: Endpoint impacts of the theoretical alternatives for case study 2

3.2.2 LCA results for EIA Step 2-b: Identification of key impacts

To judge the weight of the environmental concerns in the total impact of the WWTP, the contribution of each midpoint indicator to the three endpoint indicators (human health, ecosystems and resources) is considered. Table 3 summarises the main environmental concerns identified in the LCA results. The percentages indicate the contribution of the midpoint indicator to the endpoint indicator, respectively, for case studies 1 and 2. LCA expands the conventional EIA system boundaries to the entire Life Cycle of the WWTP. This allows for accounting and analysing a broader set of impacts (in particular global impacts), which is of great interest for the scoping step.

Table 3: Scoping with the LCA method (for both case studies)

	Human health (Figure S 4**Erreur ! Source du renvoi introuvable.**)	**Ecosystems** (Figure S 5)	**Resources** (Figure S 6)
Main contributor(s) to endpoint indicators	Climate change (86% and 82%)	Climate change (64% and 90%)	Fossil depletion (89% and 85%)
Secondary contributor(s) to endpoint indicators	Human toxicity (7% and 10%) Particulate matter formation (both 7%)	Urban land occupation (34% and 4%) Freshwater eutrophication (both 3%)	Metal depletion (11% and 15%)

Midpoint indicators not developed at the endpoint level	-	Marine eutrophication Water depletion	

However, one should be aware that data gaps influence the conclusions that can be drawn. For example, only 15 micropollutant substances could be assessed, either because they were not measured in the WWTP or because they were not characterised by the impact method used in the study. Therefore, the impacts on human toxicity and ecotoxicity may be underestimated and even eliminated during the scoping step (as for ecotoxicity), although they are relevant.

3.2.3 LCA results for EIA Step 3-b: Impact assessment

The aim of the impact assessment is to assess the contribution of the different WWTP life-cycle stages to highlight the sources of impacts previously identified during scoping. The contribution analysis was carried out on midpoint indicators. Based on the previous scoping phase, we restricted the scope of the study to the nine main contributing midpoint indicators.

Case study 1: Regarding the three global issues (climate change, fossil depletion and metal depletion), most of the climate change impact is due to the direct atmospheric emissions occurring during the operation step of the WWTP (operation on-site, mainly CO_2, N_2O and CH_4 emissions), whereas the depletion of fossil and metal resources is due to background activities (Figure 4). In particular, off-site construction (i.e., production and transport of all materials and equipment needed for the infrastructure) is the main contributor to metal and fossil depletion. The contribution to global impacts of off-site WWTP operation activities (e.g., energy production, production and transport of reagents, and transport operations for maintenance) is not negligible, whereas the sludge end-of-life has generally little impact (less than 5%).

For the six regional/local issues, four impacts are essentially due to foreground activities; eutrophication (freshwater and marine) and human toxicity are mainly dominated by the direct emissions of the WWTP (operation on-site), and urban land occupation is directly related to the area requirement of the WWTP (operation on-site). The remaining regional/local issues (particulate matter formation and water depletion) can essentially be associated with background activities. Sludge end-of-life still has a minor impact.

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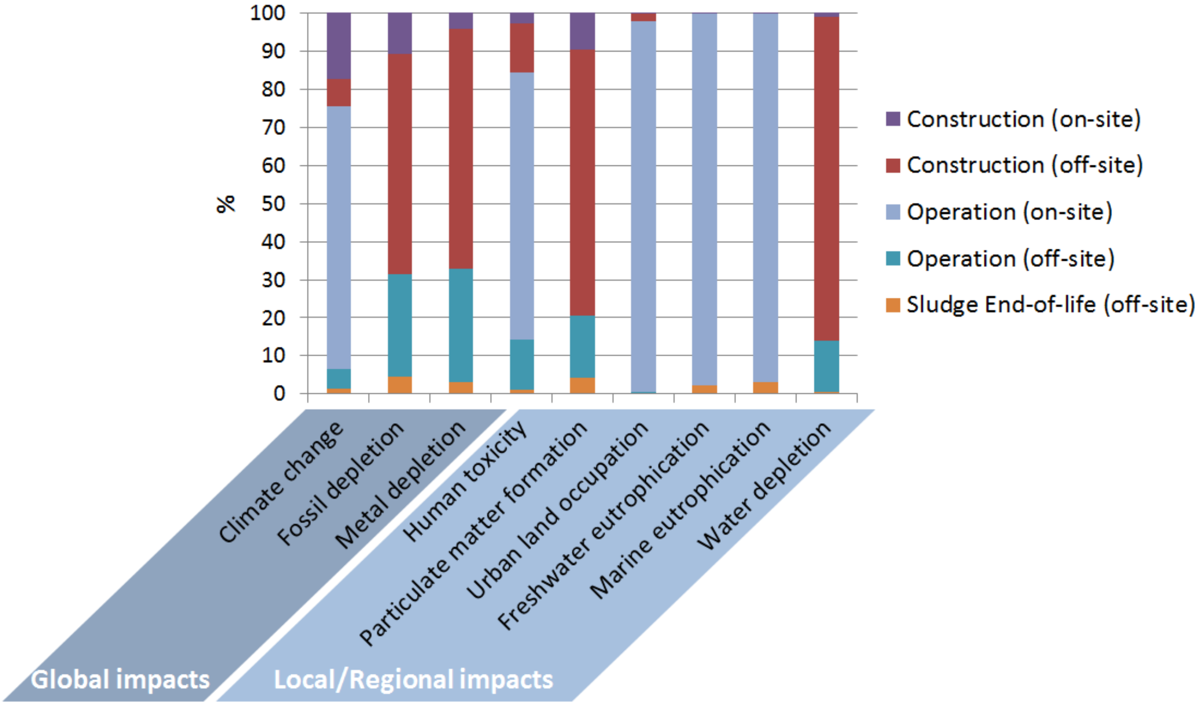

Figure 4: Selected midpoint impacts of real case study 1

Case study 2: Regarding global issues, most of the climate change impact is due to on-site activities (Figure 5). As in case study 1, this is due to the on-site atmospheric emissions of the WWTP, but in this case the contribution of emissions linked to diesel combustion during construction is higher. Here, too, fossil and metal depletions are due to background activities. The sludge end-of-life contributions are low but higher than in case study 1 (almost up to 10%).

For regional/local issues, the conclusions are also similar to case study 1; the same four impacts are essentially due to the same foreground activities: eutrophication (freshwater and marine), human toxicity and urban land occupation. However, marine eutrophication is almost equally distributed between the foreground and background activities. Particulate matter formation and water depletion are also mainly associated with background activities. Here, too, the sludge end-of-life has generally little impact, except for marine eutrophication (responsible for 40% of the impacts).

As for case study 1, half of the impacts are associated with foreground activities (construction or on-site operation activities), whereas the others represent mainly off-site impacts due to background activities of the WWTP (Figure 5). However, contrary to case study 1, for case study 2, the off-site impacts are mainly due to background operation activities and, to a lesser extent, infrastructure. Indeed, off-site construction is the main contributor for 1 indicator only (metal depletion), versus 4 for case study 1, and off-site impacts of the WWTP operation are the largest contributors to 3 indicators, versus none for case study 1.

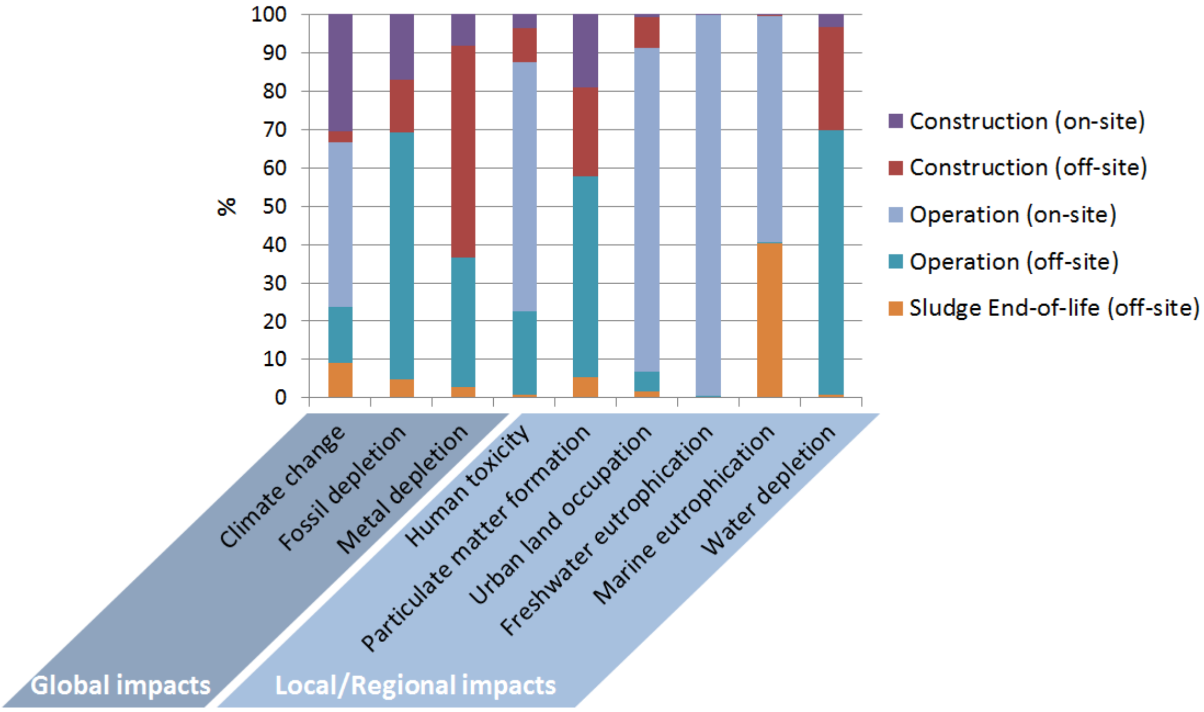

Figure 5: Selected midpoint impacts of real case study 2

The contribution analysis also allows an explanation of the observed differences in Figure S 5; compared to case study 1, the contribution of climate change to ecosystem damage is higher in case study 2, essentially because of electricity consumption during the operation phase of the WWTP but also because of the use of polymers. On the other hand, the contribution of urban land occupation is lower because of the compactness of the activated sludge process compared to reed bed filters, which require larger land areas.

From the scoping, we learned that for both case studies the main contributor to both human health and ecosystems endpoint indicators is climate change. This is essentially due to foreground activities, mainly to on-site atmospheric emissions during WWTP operation (69%) for case study 1 and construction (30%) and on-site atmospheric emissions during WWTP operation (43%) for case study 2 (first bars in Figure 4 and Figure 5). Background processes via off-site construction, off-site operation and sludge end-of-life for case study 1, and mainly off-site operation for case study 2 also have a significant role in climate change. Note that for other business sectors such as tertiary activities requiring electricity generated from fossil fuels, background activities can be responsible for a large part of the climate change impact.

The impacts of case study 1 (Figure 6) are mainly global, and they are more likely to occur on-site. The case study 2 results are similar to the case study 1 results (Figure S 7), except that the off-site impacts are slightly more important for human health and ecosystems and damages to resources tend to more frequently occur on-site than for case study 1. The local/regional impacts on ecosystems are higher for case study 1 than for case study 2; in this case, they are essentially global (climate change).

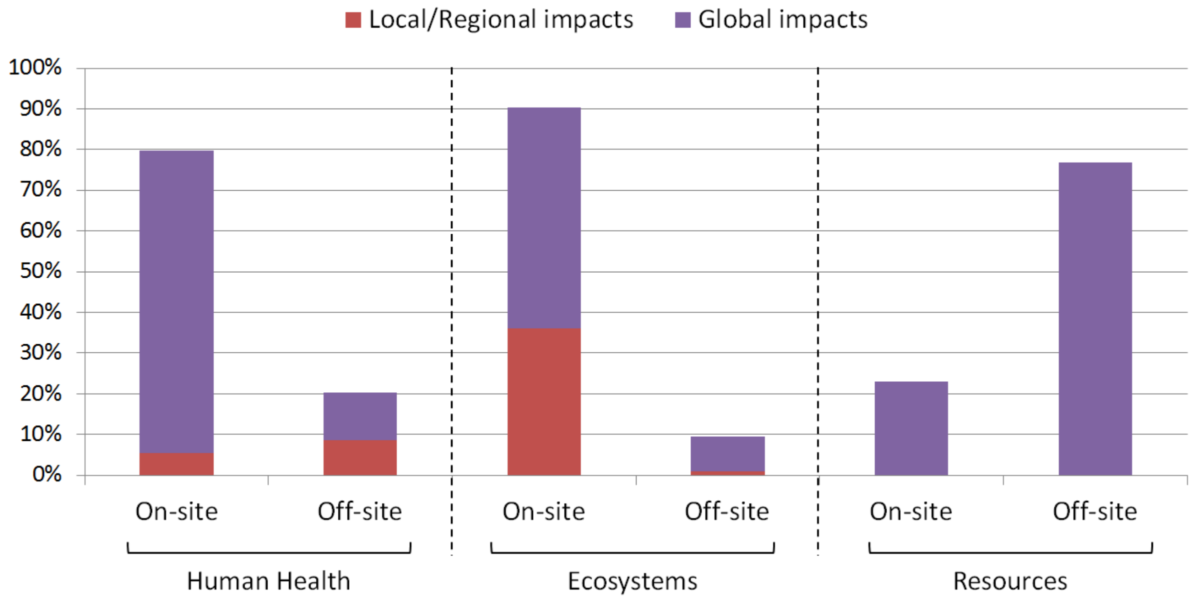

Figure 6: Main concerns exposed based on LCA endpoint indicators for case study 1

Based on these conclusions, other mitigation measures than those implemented in EIA case studies without LCA could have been proposed. To decrease global impacts, the focus should be on monitoring on-site atmospheric emissions and optimising water flows for case study 1 (vRBF) or basin aeration conditions for case study 2 (AS) to avoid emissions of nitrification/denitrification by-products (e.g., N_2O). A system for collecting greenhouse gases could also be implemented. Other materials for infrastructure could be preferred when possible. Locally produced, renewable energy may be a good option to reduce impacts due to electricity consumption. Transport itineraries for materials, maintenance or sludge end-of-life could perhaps be optimised, and diesel vehicles could be replaced by less polluting vehicles. To decrease local/regional impacts, the possible mitigation measures would mainly be on-site; there must be additional efforts to decrease local discharges, even if they already are in line with regulations. Land occupation should also be mitigated.

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3.2.4 LCA results for EIA Step 4: Mitigation measures

The impacts of the implementation of the mitigation measures have been assessed for case study 1, and their contribution to the entire WWTP impacts has been calculated (Figure S 8 and Figure S 9). For case study 2, fewer mitigation measures were set up, and they were not significant enough to modify the inventory, e.g., the required amounts of materials and the transport distances (see Table S 7). In the case of a very extensive technology with few civil engineering works such as reed bed filters, the impacts of the implementation of the mitigation measures turn out to be significant. They range from less than 1% (e.g., eutrophication) to 58.2% (terrestrial ecotoxicity) for midpoint indicators and from 14.4% (resources) to 20.4% (human health) for endpoints indicators. The same implementation of mitigation measures on activated sludge would be smaller; for example, for terrestrial ecotoxicity, the impacts of implementation of mitigation measures would only represent 6.8% of the WWTP impacts.

Note that if LCA can be used to assess the impacts of the implementation of the mitigation measures, the final effectiveness of the mitigation measures was not evaluated by LCA because it only assesses potential impacts, not predictions.

4 Discussion

4.1 Do the EIAs conclusions with or without LCA differ?

The possible contribution of LCA to EIA is assessed by analysing whether or not the LCA implementation changed the overall conclusions of the EIA study (Table 4). The results show that the EIAs conclusions with or without inputs from LCA strongly differ.

Table 4: Difference for the EIAs conclusions with or without LCA implementation

	Case study 1: EIA conclusions		**Case study 2: EIA conclusions**	
	Without LCA	**With LCA**	**Without LCA**	**With LCA**
Step 2-a: Alternatives and choice of a solution	Same preferred option: reed bed filters		Different conclusions	
	Conclusion driven by technical criteria	Conclusion driven by environmental profile	Preferred option = activated sludge (based only on local pressure on land)	Preferred options = reed bed filters and aerated lagoons (environmental profiles)
Step 2-b:	Different scope and hotspot analysis		Different scope and hotspot analysis	

Identification of key impacts	Water body quality Impacts on fauna, flora, landscape	Climate change Fossil, metal, water depletion Human toxicity Particulate matter formation Land Occupation Eutrophication	Water body quality Impacts on fauna, flora, landscape	Climate change Fossil, metal, water depl. Human toxicity Particulate matter form. Land Occupation Eutrophication
Step 3-b: Impact Assessment	Partially common concerns (water pollution/ecotoxicity and land transformation impacts) LCA gives crucial additional information to current EIA: 1) Highlights more impacts, especially global ones (e.g., climate change) 2) Adds information on the processes responsible for the impacts 3) Assesses off-site impacts due to background activities			
	Identification of main local **pressures/ concerns** (qualitative): (i) Major concern: water pollution and flows, land transformation (ii) Mean concern: noise and odour	1-Quantification of the **impacts** (local and global): climate change, urban land occupation, fossil depletion 2-Contribution analysis (background /foreground activities), e.g., climate change essentially due to the on-site discharges of the WWTP	Identification of main local **pressures/ concerns** (qualitative) (i) Major concern: water pollution, land transformation, landscape (ii) Mean concern: noise	1-Quantification of the **impacts** (local and global): climate change, fossil depletion 2-Contribution analysis (background /foreground activities), e.g., climate change essentially due to the on-site discharges of the WWTP
Step 4: Mitigation measures	Different		Different	
	Impacts of measures not analysed	Impacts assessed	Impacts of measures not analysed	Impacts assessed

In our case studies, the choice of alternatives is based on either technical conditions or land pressure, and the EIA does not report the environmental impacts of all technologies. For case study 1, the preferred technology turns out to be the same with or without LCA inputs, even if one conclusion is based on environmental profiles and the other one on technical constraints. For case study 2, the conclusions differ because of the environmental pressure on protected areas specific to the case study 2 location. In this case, a different technology would have been chosen when only looking at the LCA profile. Thus, to provide a complete picture of the actual environmental impacts, environmental profiles should be interpreted in the light of specific local conditions.

For step 2-b, the selected environmental concerns are essentially different. Furthermore, the scoping method without LCA is mainly implicit and based on the expertise of the EIA practitioners, whereas it is based on the LCA results for the EIA with LCA. In the EIA Directive 2014/52/EU (Official Journal of the European Union, 2014), the panorama of impacts is wide: population, human health, biodiversity (e.g., fauna and flora), land, soil (e.g., organic matter, erosion, compaction, sealing), water (e.g., hydromorphological changes, quantity and quality), air, climate (e.g., greenhouse gas emissions and impacts relevant to adaptation), material assets, cultural heritage, including architectural and archaeological aspects, and landscape. Nevertheless, in the case studies considered, the impact of the project on climate change (e.g., the nature and magnitude of greenhouse gas emissions) is not assessed, despite the fact that this aspect is becoming increasingly important in recent legislation and in societal concerns. In contrast, regarding the nature of the impacts, unlike current LCA methodologies, EIA usually addresses natural and technological risks and neighbourhood disturbances such as noise or odour, which are very important for the public acceptability of projects.

For the impact assessment (step 3-b), the main difference between the EIAs with or without LCA lies in the calculation of the impacts itself. EIA mainly identifies local pollution sources or pressures (qualitative/quantitative assessment), whereas LCA always calculates the total potential impacts (quantitative assessment). In principle, EIA should cover the direct effects and any indirect, secondary, cumulative, transboundary, short-term, medium-term and long-term, permanent and temporary, and positive and negative effects of a project (Official Journal of the European Union, 2014). However, in the case studies (without LCA), only on-site impacts were identified, and all off-site (or indirect) impacts were missing. Adding LCA helps to highlight more impacts, especially global impacts and off-site impacts, and gives information on the processes responsible for them.

For step 4, the conclusions of the EIAs with or without LCA clearly differed due to the missing consideration of the impacts of the implementation of mitigation measures in the current EIA studies (without LCA).

The interest of LCA for EIA studies has been demonstrated on two case studies, but some methodological and practical bottlenecks remain.

4.2 Differences in scopes and impact assessment calculations between EIA and LCA

The main methodological issue for the implementation of LCA in EIA would be the difference in scopes and boundaries of the studied system between them. The EIA scope only includes on-site impacts but forecasts them under normal and degraded conditions (extreme climatic or water conditions in our case studies). Conversely, the LCA scope covers on-site and off-site impacts but only in a normal mode of operation. Note that sludge end-of-life is generally planned in the EIA (agricultural spreading in the case studies), but it falls outside the EIA scope because the associated impacts are not taken into account (Figure 7).

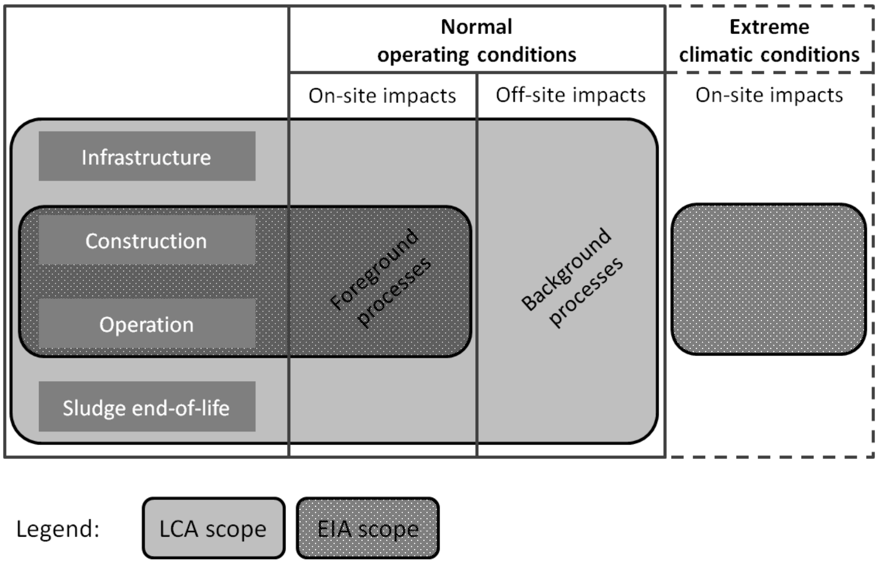

Figure 7: Scopes of the EIA and LCA approaches

Temporal boundaries also differ; for example, in the case studies, the impacts related to the WWTP construction site were identified as of a “temporary nature” because of the temporary nature of the construction, whereas the impacts occurring during normal operation of the WWTP were defined as “permanent or temporary”. However, in LCA, temporary phases of a process (e.g., civil engineering works) can prove to have longer term effects because impacts such as resource depletion or climate change are considered. Regarding their study object and focus, EIA evaluates the impact of concrete projects, whereas LCA is tailored to draw the performance of product and service systems for a large range of impacts (Potting et al., 2012). For EIA, importing impact characterisation techniques from LCA would imply that the study object and focus in EIA might encompass the study object and focus of LCA. EIA generally addresses local impacts (e.g., air and water pollution, landscape change, and noise) and is supposed to choose the most appropriate methods regarding the uniqueness of the site and the selected impacts. The EIA spatial boundaries stay generally within a regional area (“the site and its environment”). As a consequence, the choice of issues relevant for these restricted boundaries may lead to neglecting significant off-site impacts. In EIA case studies, global impacts (e.g., climate change, resource depletion, and ozone depletion) are poorly considered, even if they are due to on-site activities. A recent study analysed approximately 1700 Spanish environmental records of decision (RODs) for projects submitted for EIA and concluded that on average climate change is considered in only 14% of them, half of them only "citing" it (Enríquez-de-Salamanca et al., 2016). As displayed in Figure 6 and Figure S 7, among the impacts assessed with LCA, the assessment of current EIA studies only addresses the on-site and local/regional impacts (uniform light-grey for on-site impacts). However, as stressed in the last section (3.3), in regulatory decrees the scope of EIA tends to become wider (Official Journal of the European Union, 2014). As a consequence, current EIA boundaries usually considered by EIA practitioners should definitively be extended to allow the assessment of off-site impacts (with LCA).

In other words, EIA could, such as LCA, consider the whole planet as a place for potential impacts (no boundaries) and include (i) global impacts and (ii) off-site impacts. In this sense, some recent EIA projects with potential significant CO_2 emissions (in particular, energy and transportation projects) and for which energy efficiency is a key issue, such as building projects, tend to include energy and climate change indicators (European Commission, 2009). Specific analytical tools can assess greenhouse gas emissions (e.g., Bilan Carbone® from the French environment and energy management agency ADEME), but LCA goes further on climate change causality (damages to ecosystems and human health) and covers a more holistic range of environmental problems. However, although they generally provide a complete quantification of net environmental impacts from a regional (e.g., eutrophication, acidification, and ecotoxicity) or global perspective (e.g., climate change), standard LCIA methods do not address local concerns such as neighbourhood nuisances or landscape integration of projects. Moreover, the EIA framework, which is typically designed for a site-specific assessment, not only has to take into account the specific local geographic situation but should also evaluate the existing background pressure on the environment (Jeswani et al., 2010), whereas LCIA methods only assess additional impact contributions.

One should also be aware that the term "impact assessment" has different meanings in EIA and LCA. LCA always calculates a *potential impact* assuming the presence of a target. For EIA studies, there is more information on the presence or absence of a target; thus, the *estimated risk* in EIA is assessed by crossing the hazard identification with a real exposure quantification (Thabrew et al., 2009). Exposure is non-existent if there is no potentially affected target. Furthermore, mitigation measures can remove exposure and consequently remove risk (even if the hazard, pollution for example, is still there). Most of the time, current practice in EIA consists of identifying the risk but not in assessing quantitative consequences/impacts of that risk. Consequently, for more consistency between the methods, the definition of “impact” would have to be aligned.

4.3 Practical feasibility of combining EIA and LCA

A more practical bottleneck for the proposed methodology is that EIA and LCA are developed and used by two rather different communities of scientists and practitioners and are often used in different contexts (Tukker, 2000). A combined use of several tools would require a more comprehensive interdisciplinary approach to align the different tool characteristics and focuses (Buytaert et al., 2011). Even if researchers are open to building bridges between these two disciplines, in practice, an EIA practitioner has rarely both EIA expertise and LCA modelling skills. EIA consultancy firms could hire the services of LCA subcontractors, but the production cost of such an EIA study would increase and may not fit into the global budget. With a wider scope than current EIA studies, more quantitative data are needed for LCA, and data collection can prove to be both time-consuming and costly. The estimated cost ranges from 10 k€ to 100 k€ for products for which databases covering a large part of the life cycle already exist (Boeglin and Veuillet, 2005). If the emission and resource use data are particularly specific and not previously collected as inventory, the LCA cost can exceed a hundred thousand euros. On the other hand, according to a study conducted for the European Commission (GHK, 2010), the EIA cost to a developer in the EU is approximately 1% of the project cost, with an average cost of 53 k€. The French environmental institution CGEDD estimates that cost ranges from a few thousand euros for the simplest studies up to several million euros for impact assessments of major rail and highway infrastructures (Lavoux and Féménias, 2011). Thus, the orders of magnitude of EIA and LCA costs appear to be similar. Consequently, the extra cost for performing an LCA would be a significant additional cost for EIA consultants and could at least double the current price of EIA studies. This bottleneck could be approached with the use of simplified LCA softwares such as the ACV4E software (*http://acv4e.irstea.fr*) developed by the French research institute IRSTEA and designed for local WWTP actors. With that kind of simplified LCAs, the time and cost of an LCA implementation could be significantly reduced.

Moreover, the appropriation and the potential use of this procedure by the EIA practitioners would be a second-stage or practical implementation that needs to be studied in the future.

4.4 Towards a generic methodology

The objective of the paper was to test the applicability of the proposed methodology on a real case study. Although a high share of European EIA studies address infrastructure projects such as energy, transport, water management and waste management (GHK, 2010), one can still question if the selected case studies are representative of overall EIA practice, and thus if the proposed procedure can easily be applied to other types of projects. The general EIA process was designed to fit all types of public and private projects; thus our procedure could also be useful for installations and projects other than WWTPs. This is why we applied the framework to a project involving contrasted technical solutions (from extensive ones such as red bed filters to more intensive ones) and strong local pressures on the environment (freshwater in our case), which is common for many projects subject to EIA. Nevertheless, after this first step of implementation, the feasibility of and interest in the proposed procedure will need to be tested and validated on several other types of projects.

5 Conclusions and perspectives

A literature review demonstrated that many authors foresaw and discussed the theoretical benefits of LCA for EIA, but the review also revealed a lack of applied research on the subject. Thus, a methodology for implementing LCIA in four specific steps of the EIA procedure was proposed, i.e., the choice of alternatives, identification of key impacts, project impact assessment and mitigation measures. The use of LCA led to significant differences and justified the interest in combining both approaches. Even if the conclusions of EIAs with or without LCA were partially common, especially for local on-site impacts, LCA provided crucial additional information. The LCA approach allowed (i) a comparison of alternatives on environmental criteria, ii) the addition of information on the processes responsible for the impacts, (iii) a consideration of additional impacts, especially global impacts (e.g., climate change or resource depletion), and (iv) an assessment of off-site impacts due to background activities. The LCA-EIA results on the WWTP case studies showed that to improve the quality of local water bodies (e.g., eutrophication or ecotoxicity), significant impacts on other categories and in other places can be generated (e.g., climate change associated with energy production). LCA expanded the scope of the assessment and identified pollution transfers towards a life cycle perspective.

Nonetheless, the question arises as to whether local/regional or global impacts and on-site or off-site impacts are given the same weight in decision-making for project developers. Local impacts and neighbourhood disturbances occurring on-site are essential for project acceptability, but over the last decade, global environmental issues such as resource sustainability and climate change have also become more important in policy making (Official Journal of the European Union, 2014). However, more generally, the link between “provided information” and “decision-making” is not always straightforward, and more research, e.g., through the introduction of management sciences in the LCA field, should better study the use of LCA as an environmental assessment tool to support public decision-making.

In terms of applicability, potential bottlenecks for the widespread use of the methodology were identified, and recommendations to address such operational limitations were proposed.

Finally, there is room to improve the proposed methodological framework, especially by strengthening the relevance of LCIA methods for impact assessment in EIA. Given the very specific and local nature of industrial projects subject to EIA legislation, one important weakness of current LCIA methods is their limited consideration of local specificities. Another potential major lever is the improvement of various environmental pathways. For example, to date, LCIA methods have poor or no consideration of certain environmental issues such as natural and technological risks and neighbourhood nuisances. However, current LCIA research is working to improve this situation.

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9 Supplementary material

List of Tables

The EIA documents were available in French during the public consultation phase at *www.alsace.developpement-durable.gouv.fr*.

Table S 1: Brief description of the case studies and main information on the first three steps of the EIA procedure

	Case study 1 (CS 1)	**Case study 2 (CS 2)**
City	Altwiller	Obersteinbach / Niedersteinbach
Region	Alsace	Alsace
Project	To collect and treat wastewater	
Goal and scope of the EIA	Upgrading or rebuilding WWTP to fulfill Water Framework Directive and population growth.	
Main dates	EIA report: 17/11/2011 Put into use: 25/07/2013	EIA report: 20/01/2011 Put into use: 30/07/2013
Technical constraints	DBO_5: 26.4 kg/day	DBO_5: 41 kg/day
Environmental constraints	Phosphorus and nitrogen sensitivity	Natura 2000 Phosphorus and nitrogen sensitivity
Main documents (see supporting information)	EIA report, prefectural order, soil and water expertise	EIA report, prefectural order, Natura 2000 impact report
Screening (EIA - step 1)	All wastewater treatment plants of local municipalities of a capacity inferior to 10 000 population equivalents have to provide an environmental impact statement (a final report summarising the EIA) according to French regulation (see Articles R.122-5 and R.122-6 of environmental code)	
Alternatives identified during scoping (EIA - step 2-a)	Centralised WWTP with different technological processes, i.e., i) vertical Reed Bed Filters (vRBF), ii) Activated Sludge (AS) and iii) Infiltration-Percolation (IP)	Centralised WWTP with different technological processes, i.e., i) vertical or horizontal Reed Bed Filters (respectively vRBF and hRBF), ii) Activated Sludge or Activated Sludge Sequencing Batch Reactor (AS and AS-

		SBR), iii) Naturally Aerated Lagoons (NL) iv) Artificially Aerated Lagoons (AL), v) Biological Disks (BD), and vi) Infiltration-Percolation (IP)
Justification of the chosen system	Reed bed filters were chosen because of the effluent volume to be treated, the required treatment levels especially for N, the low operation costs, the integration into the landscape, the easiness to operate, and the low sub-product production.	Activated sludge process was selected because of the effluent volume to be treated, its high treatment efficiency and its reduced area requirement that minimises its impacts on the Natura 2000 area.
Scoping – identification of key impacts (EIA - step 2-b)	The spatial boundaries are those of the projects and the downstream watershed. Temporal boundaries are defined in two phases, i.e., the civil engineering works and the period of operation. Two main environmental issues implicitly emerged, i.e., water body quality and the impacts due to civil engineering works on fauna, flora, landscape…	

Table S 2: Initial state of the environment for the two case studies

		Case study 1	**Case study 2**
	Issues	**State**	**State**
Baseline description of the initial environmental state (EIA – step 3-a)	Location / Weather / Geology / Hydrogeology	Description	Description
	Receiving environment: Water quality	Fair to poor quality (for nitrogen and phosphor parameters) identified	Good ecological status identified
	Earthquake risks	No risk identified	No risk identified
	Flood risks	No risk identified	No risk identified
	Fauna and flora	Potential wetland of low interest (0,4 ha)	Natura 2000 area with species of community interest
	Abstraction of drinking water	None	None
	Human environment	First residences at 300 m	First residence at 150 m

Table S 3: Impact assessment and proposed mitigation measures for the two case studies

		Case study 1		**Case study 2**	
	Issues	**Impacts**	**Corrective/ Mitigation measures**	**Impacts**	**Corrective/ Mitigation measures**
Impacts on the receiving environment (EIA – step 3-b1)	Water flows	Low stream flow: stagnation of plant flow	Reshaping the ditch to improve water flow + maintenance	None	No measure
	Dry weather	Decreasing of self-purification Class of state “Mean”	Plant sizing to perform a more rigorous water treatment for COD, BOD_5 and NH_4^+	Issues with phosphor and suspended matter	Activated sludge allows better performance than required and setup of a sludge blanket detector
	Wet weather	Insufficient	Corrective	Identical to	No measure

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		dilution capacity of the environment	measure: Plant sizing to strengthen rainwater treatment (a fraction of rainwater)	dry weather (separate sewer system)	
	Civil engineering works	Risks for suspended matter	Excavated area reconditioning	Risks for suspended matter	Civil engineering works during summer + operation from river banks
	Incident / Accident	Low risk of accidental release	Isolation valves	Low risk of accidental release	Isolation valves
Impacts on the site during civil engineering works (EIA -step 3-b2)	Human environment	Noise	No measure	None	No measure
	Natural environment	Indirect impacts on downstream wetland of high interest due to sewage pipe laying	Clay plugs	Natura 2000 perimeter but outside of habitats of community interest	Limited land transformation
		Positive impact due to reshaping and replanting works on discharge location	No measure		
		0,4 ha of potential wetland of low interest will be transformed	0,85 ha of area maintained as wild land (rehabilitation)		
Impacts on the site during operation (EIA - step 3-b3)	Odor, noise, landscape, land occupation, service road & traffic, natural environment, and groundwater pollution	No significant impacts, except odor near stormwater overflows	No measure	Impact on wetland landscape	Chalet type buried construction work
Impacts due to extreme climatic or water events	Frost/Storm/ Flood	Storm: Direct release in the natural environment in case of power cut	Remote management system	Direct release in the natural environment in case of power cut	Remote management system
Sanitary impacts	Microbial, chemical and physical impacts via Surface water/Air/ Groundwater	Air: no propagation of aerosols (except for personnel) due to quantities and distances Water: Low microbial risks	Prevent water stagnation with the reshaping	None	No measure

Table S 4: Reorganisation of the issues and associated impacts

General issues	**Detailed issues**	**Impacts**	**Paragraph dealing with this aspect in the EIA report**
WATER-USE	Change on water flows – Operation	Impact on Human Health and Ecosystems	Impact on the receiving environment > Impact on flows
	Water pollution – Operation	Impact on Human Health (Toxicity)	Health section > Microbial and chemical impacts
		Impact on Ecosystems (Ecotoxicity)	Impact on the receiving environment > Impacts in dry weather + Impacts in wet weather + Impacts during civil works
			Impact on the implantation site > Impacts of operation (groundwater)
LAND-USE	Land transformation – Construction	Impact on Ecosystems	Impact on the implantation site > Impacts of construction
	Land occupation – Operation	Impact on Ecosystems	Impact on the implantation site > Impacts of operation > Soil occupation + Impact on the natural environment (fauna & flora)
AIR	Air pollution – Operation	Impact on Human Health	Health section > Microbial impacts
NUISANCES	Noise – Construction	Impact on Human Health and Social Impact	Impact on the implantation site > Impacts of operation
	Noise – Operation	Impact on Human Health	Impact on the implantation site > Impacts of operation
			Health section > Physical impacts
	Service road & traffic – Operation	Social Impact	Impact on the implantation site > Impacts of operation
	Odor – Operation	Social Impact	Impact on the implantation site > Impacts of operation
	Light pollution – Operation	Impact on Human Health	Health section > Physical impacts
	Landscape – Operation	Social Impact	Impact on the implantation site > Impacts of operation

Table S 5: Description of WWTPs Life Cycle Inventories (LCI)

	WWTP model	**Population Equivalent**	**LCI sources**	**Comments**
Case study 1	AS1 / AS-SBR1	440	(1) (2)	LCI model adapted and extrapolated from a 5200 p.e. AS*.
	vRBF1	440	(1) (3) (4) (5) (6) (7)	For the impact assessment (step 4), the LCI model was adapted using data available in the EIA study 1.
Case study 2	AL2	684	(10) (11)	
	AS2 / AS-SBR2	684	(1) (2) (12)	LCI model adapted and extrapolated from a 5200 p.e. AS*. For the impact assessment (step 4), the model was adapted using data available in the EIA study 2.
	hRBF2	684	(1) (3) (4) (5) (6) (7) (8)	
	vRBF2	684	(1) (3) (4) (5) (6) (7)	
	NL2	684	(3) (6) (9) (10) (11)	

(1) (Risch et al., 2014)*; (2)* (Risch et al., 2015)*; (3)* (Boutin et al., 2007)*; (4)* (EPNAC, 2015)*; (5)* (Macrophytes et Traitement des Eaux, 2005)*; (6)* (Liénard et al., 2004)*; (7)* (M.A.G.E. 42, 2007)*; (8)* (Molle et al., 2008)*; (9)* (Racault et al., 1997)*; (10)* (Alexandre et al., 1998)*; (11)* (von Sperling, 2007)*; (12)* (SDEA, 2013)

**For the same capacity range of WWTP the chosen FU allows a consistent extrapolation of the results for other capacity. The following adaptations were made: no chemical treatment to remove phosphate, all sludge considered to be used in agriculture.*

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Table S 6: Selected inventory data for the WWTP model

	Functional Unit: Treatment of wastewater load from 1 p.e./day (1 p.e. = 60 gBOD5/day)	**WWTP model**							
		AS1/AS-SBR1 AS2/AS-SBR2	**AS2/AS-SBR2 (EIA data)**	**vRBF1**	**vRBF1 (EIA data)**	**vRBF2**	**hRBF2**	**AL2**	**NL2**
WWTP LCI	Electricity consumption (kJ)	462	717	6	166	6	6	360	6
	Building materials (kg)								
	Concrete	2,01E-02	2,40E-02	9,76E-03	6,96E-03	6,28E-03	6,28E-03	5,71E-03	5,10E-03
	Gravel	5,83E-02	6,00E-02	2,97E-01	3,57E-01	2,81E-01	4,54E-01	4,95E-02	1,63E-01
	Sand	3,79E-03	3,79E-03	4,21E-02	4,78E-02	4,21E-02	0,00E+00	0,00E+00	0,00E+00
	Plastics	1,20E-04	1,15E-04	1,17E-03	1,56E-03	1,10E-03	1,41E-03	5,94E-04	3,15E-03
	Steel	2,06E-04	2,51E-04	2,24E-04	9,40E-05	2,04E-04	2,04E-04	5,27E-05	3,87E-05
	Land occupation (m^2)	7,59E-05	8,33E-05	5,48E-04	1,35E-03	5,48E-04	8,77E-04	4,11E-04	3,01E-03
	Sludge production (kg dry matter)	1,06E-01	6,84E-02	1,64E-02	1,64E-02	1,64E-02	1,64E-02	3,29E-02	3,29E-02
	Chemicals consumption (g)								
	Conditioning agent (lime, hydrated)	31,20	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Precipitating agent (iron chloride (III))	19,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Flocculant (polymer)	0,87	1,67	0,00	0,00	0,00	0,00	0,00	0,00
	Number of round trips	2,74E-05	2,74E-05	7,25E-04	7,32E-04	4,79E-04	4,87E-04	2,30E-04	2,78E-04
Foreground emissions	Air emissions (g)								
	CO2	68,41	68,41	109,41	109,41	109,41	109,41	100,47	94,16
	CH4	0,12	0,12	0,21	0,21	0,21	0,21	0,19	0,18
	N2O	0,05	0,05	0,08	0,08	0,08	0,16	0,00	0,04
	NH3	0,00	0,00	0,00	0,00	0,00	0,00	0,91	3,64
	Water emissions (g)								
	P (particulate)	0,06	0,06	0,00	0,00	0,00	0,00	0,08	0,04
	PO43-	3,44	3,44	4,60	4,60	4,60	4,50	4,66	2,04
	N (organic)	0,25	0,25	1,80	1,80	1,80	1,80	2,43	1,08
	NH4+	0,32	0,32	0,32	0,32	0,32	2,22	5,55	2,47
	NO3-	3,10	3,10	27,90	27,90	27,90	5,31	3,32	0,00
	NO2-	0,17	0,17	0,00	0,00	0,00	0,00	0,00	0,00

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Table S 7: Description of the implementation of mitigation measures modelled (LCI)

	Mitigated impacts	**Mitigation measures**	**Hypotheses for the LCI of the implementation of the measures**
Case study 1	Change in water flows and pollution	a) Reshaping the ditch to improve water flow: on 100m b) Maintenance/ditch cleaning	**a) Civil engineering works : 2 days (16h) of excavator and dump truck** **b) Civil engineering works : 4h of excavator and dump truck once a year (WWTP lifetime= 30 years)**
		Plant sizing (no details)	No change in WWTP operation modelling
		Operation from river banks and excavated area reconditioning	Already modelled in LCI (generic modelling of construction)
	Land transformation	a) Clay plugs within unsorted material layer b-1) Riverbank reprofiling and revegetation (100m) b-2) Return to the natural state of 0.85ha of land*	a) Unsorted material layer was not modelled; thus nor is clay b-1) Benefit not quantifiable in LCIA b-2) Supposed ecological equilibrium with destroyed wetland – Poor consideration of land transformation impacts in LCIA
	Odour	Canal cleaning	**Civil engineering works : 1 week (40h) of excavator and dump truck**
Case study 2	Change in water flows and pollution	Sludge blanket detector	WWTP small electronic equipment not modelled; thus nor is this detector
		Operation from river banks and excavated area reconditioning	Already modelled in LCI (generic modelling of construction)
	Land transformation	Positioning installation in less sensitive areas (location)	Already modelled in LCI (generic modelling of construction)
	Landscape	Landscape integration via chalet type buried construction work	Already modelled in LCI (generic modelling of construction)

**The destruction of ordinary wetland area has a mitigation ratio of 2 (Inter-Services Water Mission MISE report). The proposed mitigation measure for the destruction of 0.4ha of ordinary wetland is to leave fallow 0.85ha of land to allow the recolonisation of land by characteristic species of wetland.*

Table S 8: Issues considered within the existing EIA and proposed rating for the two case studies

Issues(1) considered in existing EIA	**Case Study 1 (CS1) - Qualification / Rating in EIA**		**Case Study 2 (CS2) - Qualification / Rating in EIA**	
Change in water flows – Operation – HH & E	Low waterflow, Mitigation measure to improve waterflow	**2**	WWTP flow insignificant, No measure	0
Water pollution – Operation – HH	Microbial: No recreational use of the receiving environment, negligible risk Chemical: no use of chemical products for the treatment, zero risk	0	Microbial: No recreational use of the receiving environment, negligible risk Chemical: no use of chemical products for the treatment, zero risk	0
Water pollution – Operation – E	Dry weather: Stream downgrading, Measure (plant sizing): 2 Wet weather: Non negligible impact, Measure (plant sizing): 2 Civil engineering works: No major impact but risks of suspended matter, Measure (excavated area reconditioning): 2	**2**	Dry/Wet weather: Stream downgrading, Measure (sludge blanket detector): 2 Civil engineering works: Risk of suspended matter, Measure (operation from river banks): 2	**2**
	Infiltration risk negligible: no groundwater pollution	0	No groundwater pollution	0
Air pollution – Operation – HH	Risk negligible due to (i) low aerosol quantities (ii) large distances with surrounding habitations	0	Risk negligible due to (i) low aerosol quantities (ii) large distances with surrounding habitations	0
Land transformation – Construction – E	1) Indirect impact on a remarkable(2) wetland + Measure to avoid drainage 2) Destruction of ordinary(2) wetland area (0.4ha) – Mitigation measure (rehabilitation)	**2**	Irremediable effect (zone Natura 2000), but non-significant (<0.01% of the Natura 2000 site) and no habitats of community interest, Measure (positioning installation in less sensitive areas)	**2**
Land occupation – Operation –E	Insignificant ground footprint on agricultural area	0	Insignificant ground footprint on pasture area	0
Noise – Construction – HH & S	Noise, No measure	**1**	Noise, No measure	**1**
Noise – Operation – HH	No disturbing noise / Few health risks from noise	0	Limited noise nuisance / Few health risks from noise	0
Traffic – Operation – S	No impact	0	Impact negligible	0
Odor – Operation –S	One of the most sensitive aspects: 1) Stormwater overflows: odor risk, 2) Pumping station/Plant: limited risk, Measure (cleaning work on the canal, but no measure on the plant site)	**1**	Limited odor nuisance	0
Light pollution – Operation – HH	No impact mentioned	0	No impact mentioned	0
Landscape – Operation – S	Impact very limited, No measure	0	1) Landscape disturbance (near Natura 2000, discontinuity with the urbanised area), Measure (landscape integration via chalet type buried construction work)	**2**

(1) Impacts on Human Health (HH), Ecosystems (E) and Societal issues (S)

(2) Remarkable wetlands host exceptional biodiversity. Ordinary wetlands correspond to all other wetlands [Schémas Directeurs d'Aménagement et de Gestion des Eaux (SDAGE)]

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List of Figures

Legend for Figure S 1, Figure S 2 and Figure S 3:

AS = Activated Sludge and AS-SBR= Activated Sludge Sequencing Batch Reactor / vRBF = vertical Reed Bed Filters / hRBF = horizontal Reed Bed Filters / NL = Naturally Aerated Lagoons / AL = Artificially Aerated Lagoons

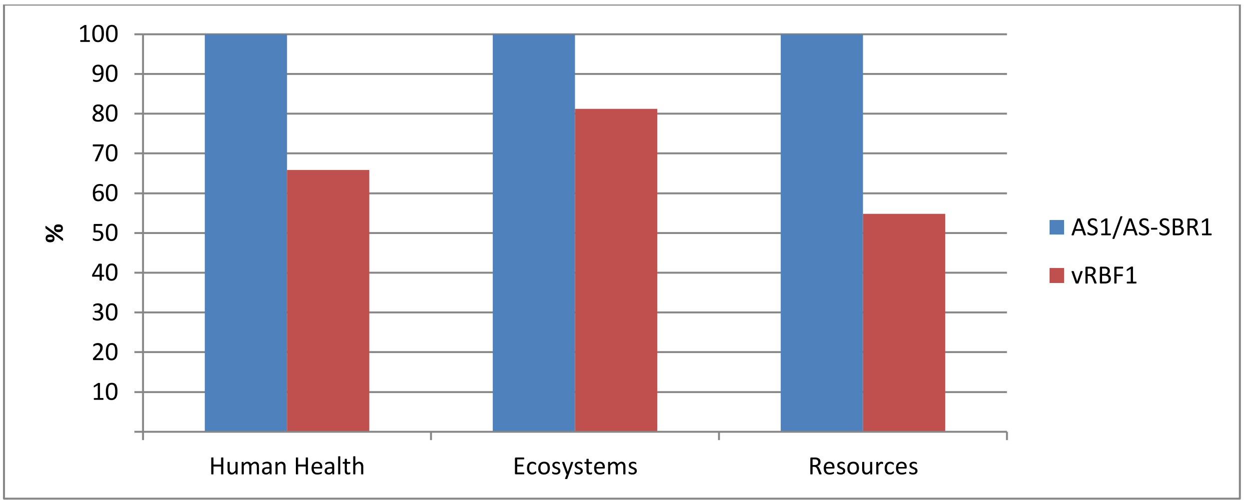

Figure S 1: Endpoint impacts of the theoretical alternatives for case study 1

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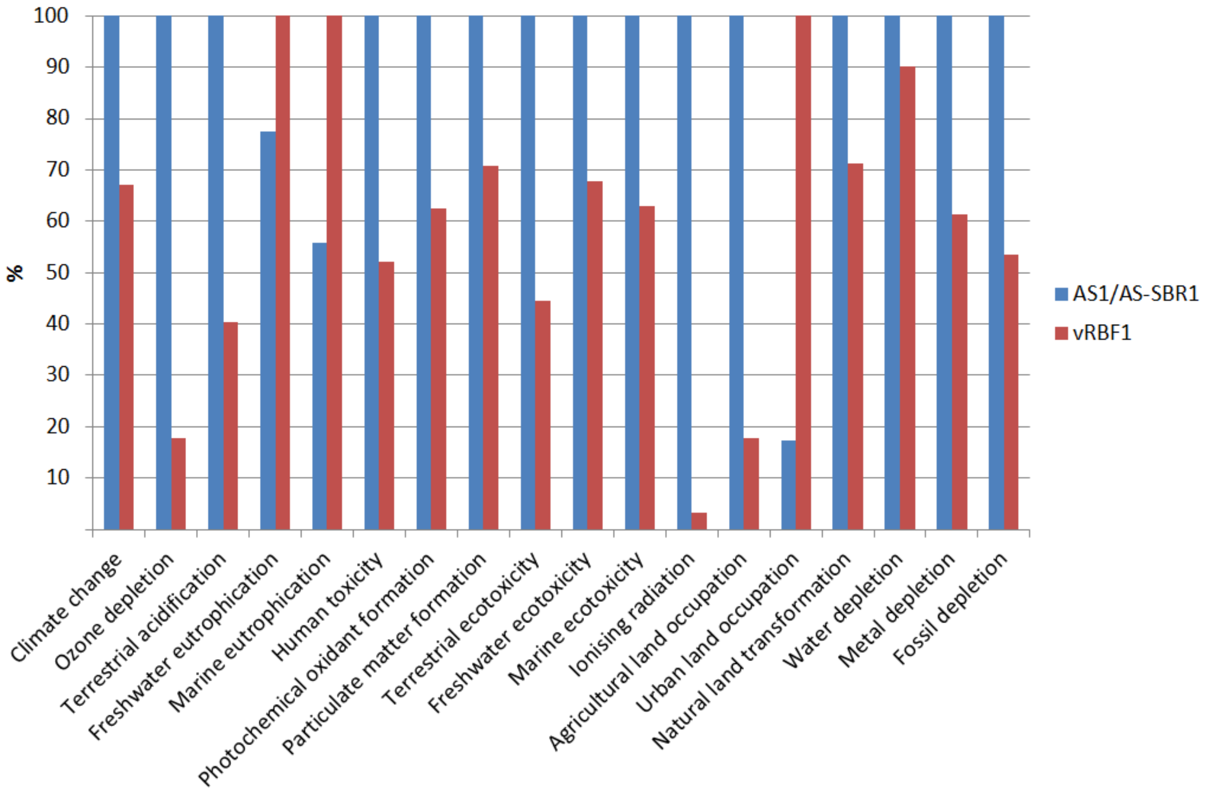

Figure S 2: Midpoint impacts of the theoretical alternatives for case study 1

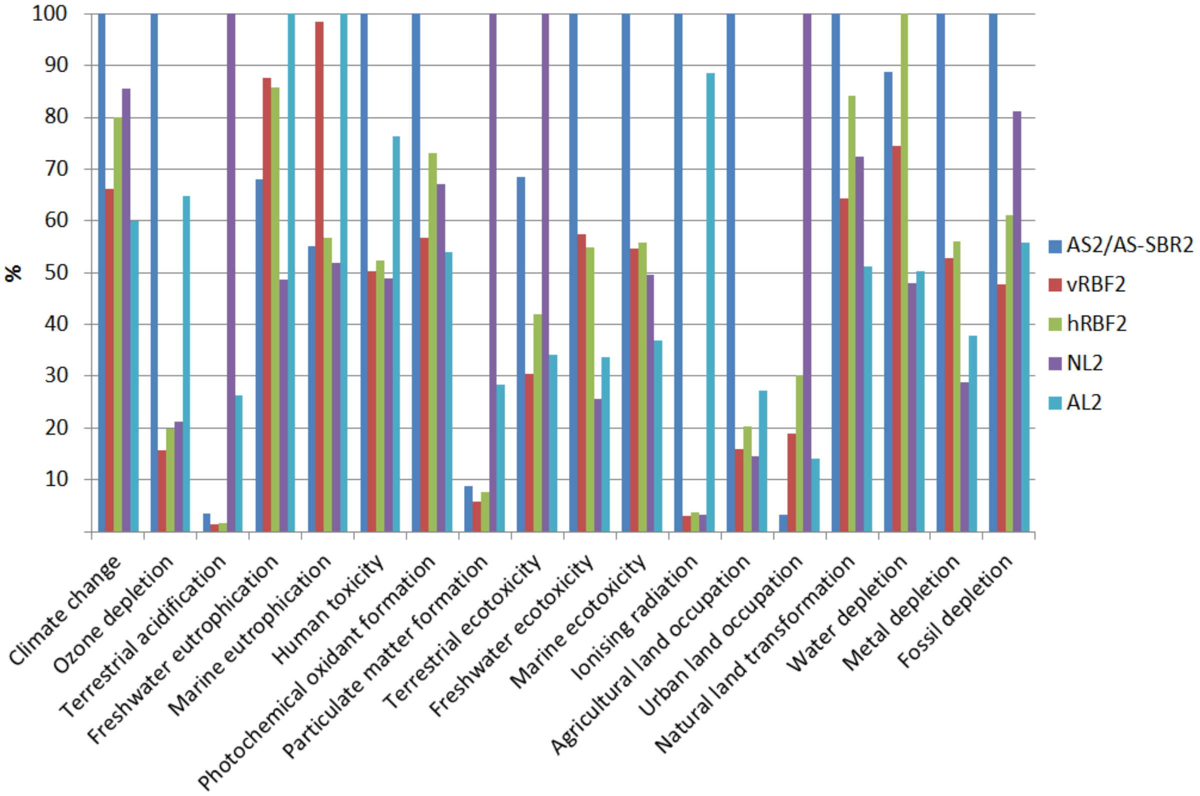

Figure S 3: Midpoint impacts of the theoretical alternatives for case study 2

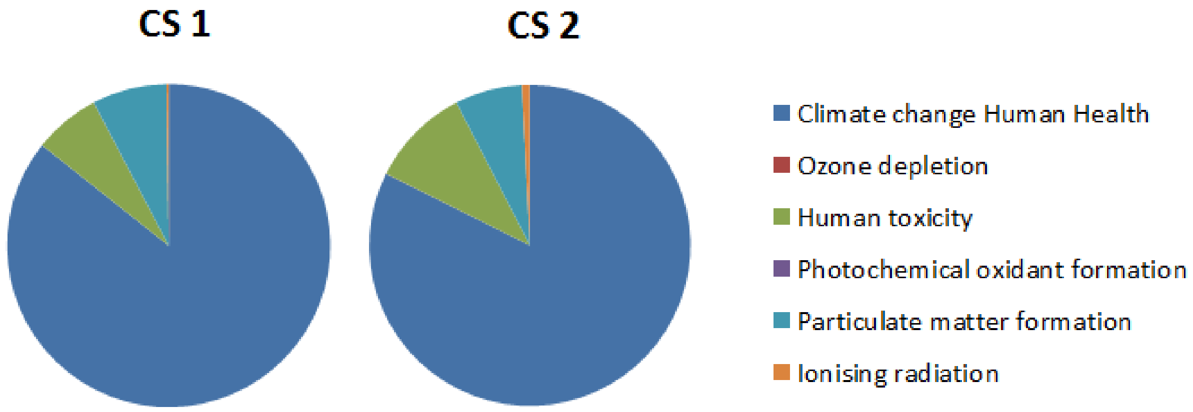

Figure S 4: Contributions to the endpoint Human Health for case study 1 (left) and case study 2 (right)

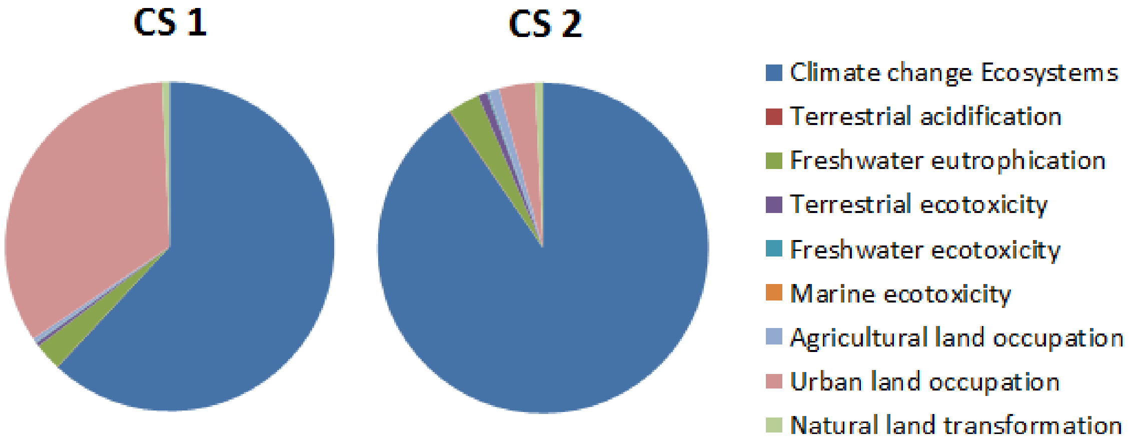

Figure S 5: Contributions to the endpoint Ecosystems for case study 1 (left) and case study 2 (right)

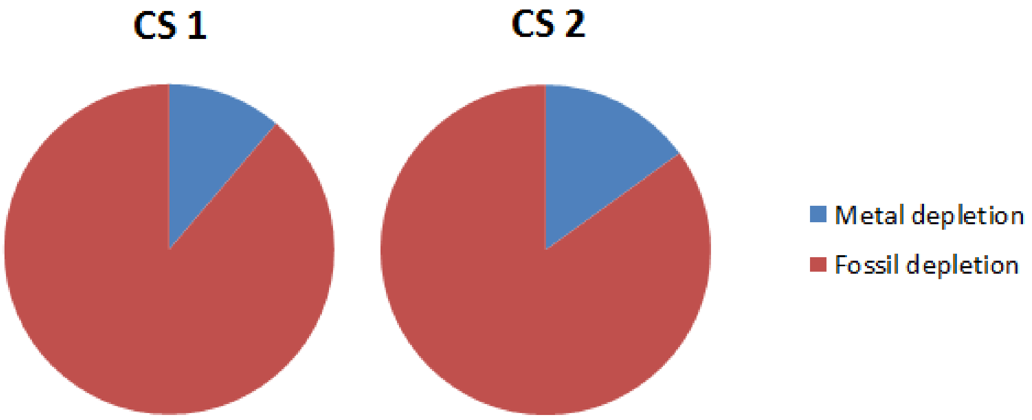

Figure S 6: Contributions to the endpoint Resources for case study 1 (left) and case study 2 (right)

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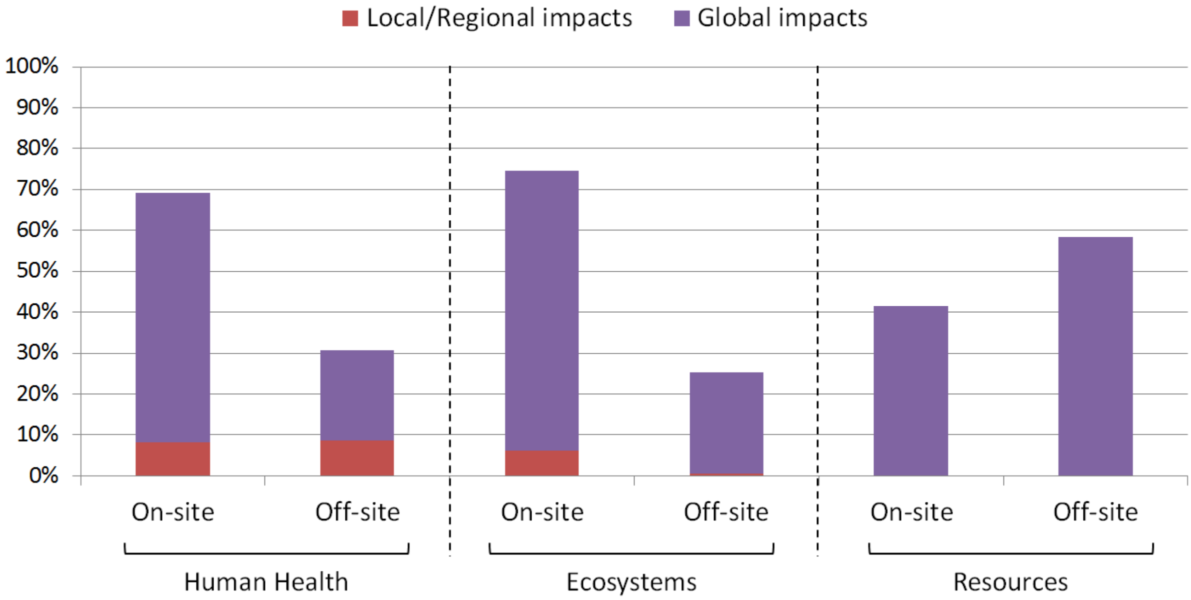

Figure S 7: Main concerns exposed based on LCA endpoint indicators for case study 2

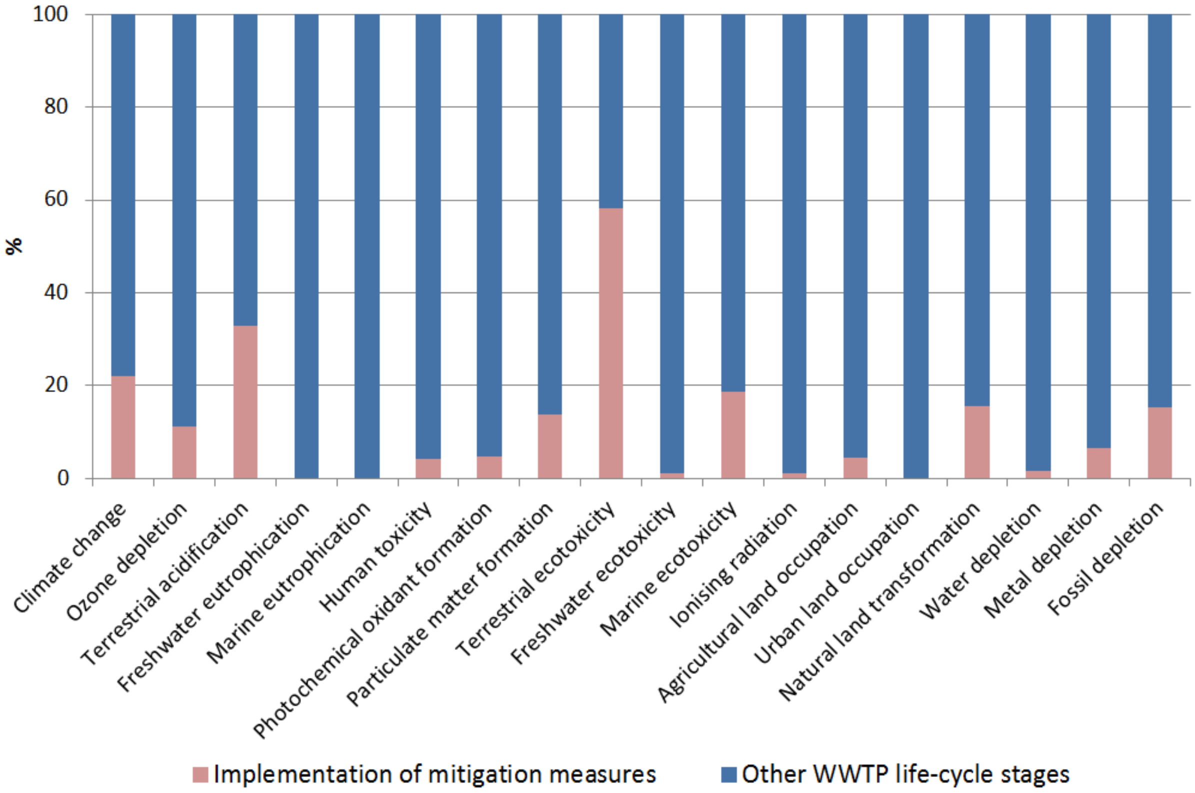

Figure S 8: Contribution of the impacts of the implementation of mitigation measures to the entire WWTP impacts for case study 1 (midpoint indicators)

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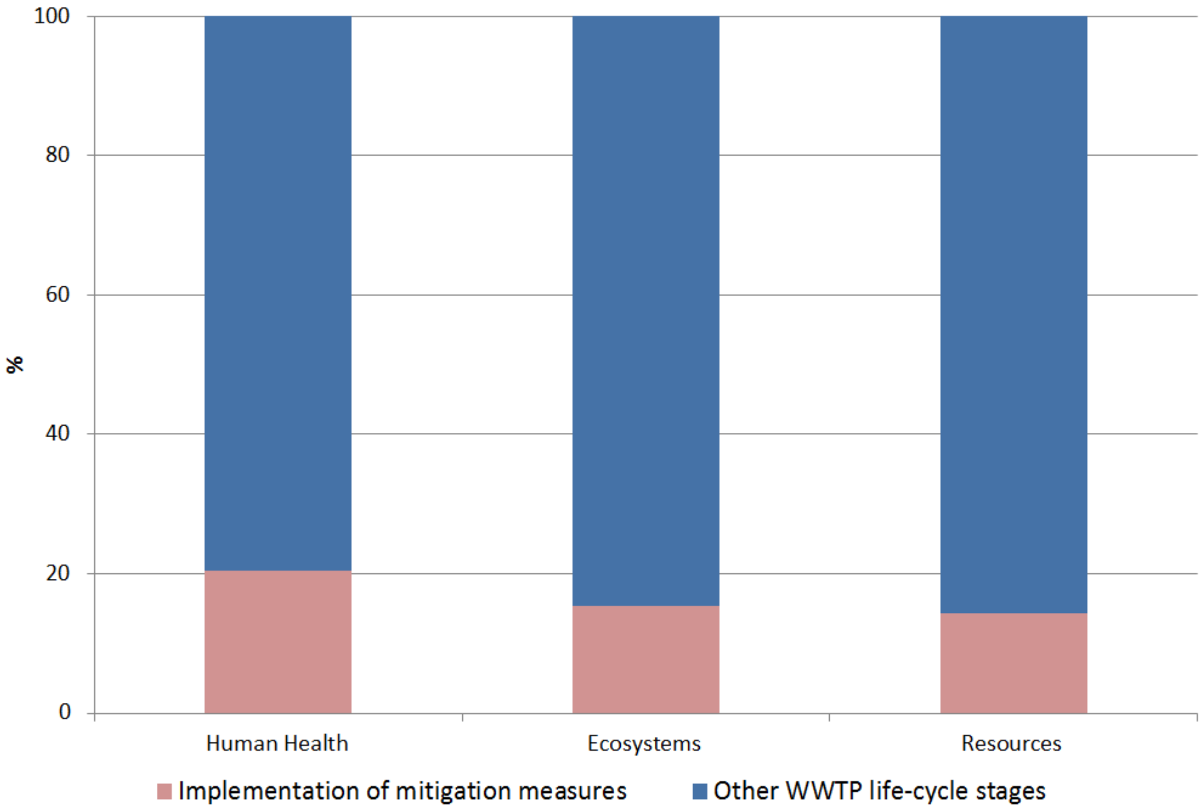

Figure S 9: Contribution of the impacts of the implementation of mitigation measures to the entire WWTP impacts for case study 1 (endpoint indicators)

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