Chapter 34
LCA of Wastewater Treatment

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Abstract The main purpose of wastewater treatment is to protect humans against waterborne diseases and to safeguard aquatic bio-resources like fish. The dominating environmental concerns within this domain are indeed still potential aquatic eutrophication/oxygen depletion due to nutrient/organic matter emissions and potential health impacts due to spreading of pathogens. Anyway, the use of treatment for micro-pollutants is increasing and a paradigm shift is ongoing—wastewater is more and more considered as a resource of, e.g. energy, nutrients and even polymers, in the innovations going on. The focus of LCA studies addressing wastewater treatment have from the very first published cases, been on energy and resource consumption. In recent time, the use of characterisation has increased and besides global warming potential, especially eutrophication is in focus. Even the toxicity-related impact categories are nowadays included more often. Application of LCA for comparing avoided against induced impacts, and hereby identifying trade-offs when introducing new technology, is increasingly used. A typical functional unit is the treatment of one cubic metre of wastewater which should be well defined regarding composition. Depending on the goal and scope of the study, all life cycle stages have the potential of being significant, though disposal of infrastructure seems to be the least important for the impact profile in many cases. No inventory data and none of the conventional impact categories (except stratospheric ozone depletion if emission of N_2O is excluded) should be ruled out; but eutrophication and ecotoxicity are in many cases among the dominating ones.

34.1 Introduction

The history and the present status of wastewater treatment including the overall use of LCA within this technology domain are briefly described below.

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34.1.1   History

For thousands of years water has been used for sanitary purposes with the resulting wastewater (WW) being emitted to the environment. However, due to an accelerating global population with increased sanitary demands combined with the industrial revolution, the pollution potential has reached a severe level in modern time. In order to protect the aquatic bio-resources (e.g. fish and crustaceans), human health and the aquatic ecosystems, wastewater treatment (WWT) is now widespread and becomes more and more advanced. Starting with simple systems for sedimentation (mechanical or primary treatment), more advanced processes for removing organic matter and nutrients (ammonia/nitrate), like activated sludge treatment (secondary treatment), have now been used for some decades in industrialised and densely populated countries. In recent years, the focus is more on tertiary treatment (removing phosphorus) and processes for removing micro-pollutants including ozonation and activated carbon treatment. A paradigm shift is ongoing—wastewater is more and more considered as a resource of, e.g. energy (biogas from anaerobic digestion of sludge), nutrients (especially phosphorus) and polymers (sludge). Innovations addressing these issues are ongoing these years.

The focus of LCA case studies within this area has consistently been on energy and in some cases combined with resource consumption. More recently, characterisation has increasingly been included and besides global warming potential (including direct emissions of CH_4 and N_2O from WWT) especially eutrophication is in focus. With the enhanced awareness of micro-pollutants in effluent and sludge also the toxicity-related impact categories are nowadays included more often. Using LCA for identifying trade-offs and comparing the relative sustainability of alternative treatment systems has also become widespread.

34.1.2   Present Status

Today, the number of wastewater treatment technologies is quite large with optimization and new technologies currently being introduced. This process is mainly driven by legislation like the EU Water Framework Directive for Europe (EC 2000) or the Australian Guidelines for Water Recycling being part of the National Water Quality Management Strategy for Australia (Australian Government 2015). The wastewater treatment technologies or systems may be divided into at least three main groups with some overlap:

- Treatment systems for removal of organic matter (e.g. sedimentation, activated sludge).
- Treatment systems for removal of nutrients (e.g. nitrification/denitrification, P-precipitation).
- Treatment systems for removal of micro-pollutants (e.g. ozonation, activated carbon).
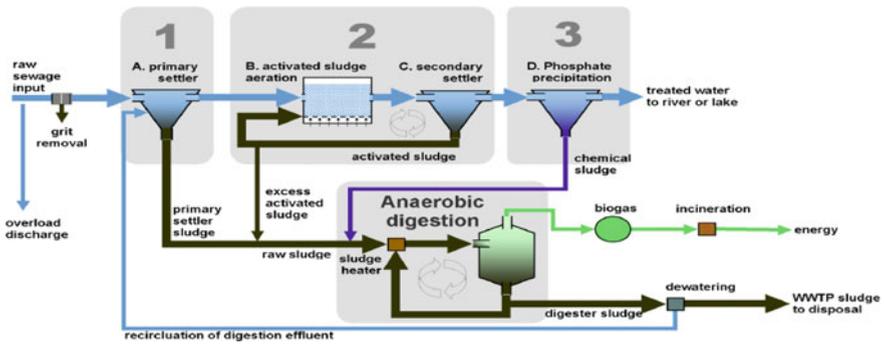
Fig. 34.1 Conventional wastewater treatment plant (Doka 2007, with permission)

Among new technologies that presently have only reached lab or pilot scale are, e.g.
microbial fuel cells and advanced oxidation processes like manganese oxidation.
Less advanced technologies/systems like source separation (e.g. separating toilet
water containing faeces from urine containing water and bathing water) are also part
of the innovation going on.

The traditional aim of sludge treatment is to reduce volume and mass in order to
save disposal costs. However, as sludge has been and still is used as fertiliser on
agricultural land (or, e.g. woods), removing pathogens is also a focus. Therefore,
different physical, mechanical and biological technologies like dewatering, diges-
tion, incineration and, e.g. heating for hygienic treatment are widespread. The
increased focus on resource recovery/recycling in recent years has led to enhanced
use of, e.g. anaerobic digestion for energy recovery (biogas/CH_4). Furthermore,
new technologies like sludge inertisation (wet oxidation, pyrolysis) and sludge
triage (separating primary and secondary sludge before treatment) for improved
exploitation/recovery of, e.g. phosphorus, are part of the innovation going on.

The main environmental concerns within the wastewater treatment domain are
still potential aquatic eutrophication/oxygen depletion due to nutrient/organic
matter emissions and potential health impacts due to spreading of pathogens.
Anyway, the focus on the potential ecotoxic effect of organic micro-pollutants (e.g.
pharmaceuticals) and metals (e.g. mercury) is increasing together with efforts to
improve the energy balance (e.g. optimise biogas production) and resource recovery
(e.g. phosphorus).

The process steps in a typical conventional wastewater treatment plant (WWTP)
are shown in Fig. 34.1.

34.2 Review of Existing LCA Case Studies on WWT

At least more than 60 LCA studies on wastewater treatment have been performed
since the mid 1990s, with the paper by Emmerson et al. (1995) being among the
first ones. Today, several review papers exist with Larsen et al. (2007), Corominas

et al. (2013) and Zang et al. (2015) being the most recent. The review by Larsen et al. (2007) includes 22 studies and focus on eco-toxicity-related impacts though conventional impact categories are also included. Corominas et al. (2013) reviewed 45 studies but excluded specific studies on sludge treatment. This is also the case for the review by Zang et al. (2015) that includes 53 studies (among these several Asian ones) on different technologies but focus on activated sludge plants. This chapter is mainly based on the review by Larsen et al. (2007) supplemented by the two other, more recent reviews (Corominas et al. 2013; Zang et al. 2015) together with some of the most comprehensive studies including Larsen et al. (2010). The results of the Larsen et al. (2007) review are briefly shown in Table 34.1 in Appendix. The reviewed studies include to varying degrees life cycle stages, LCA impact categories, micro-pollutants, and more, and present LCA profiles for wastewater treatment. The results are presented and discussed in the following sections on the importance of different life cycle stages for the impact profile, the relevance of different impact categories for this application domain, and the degree to which wastewater specific issues like micro-pollutants and pathogens are included. Finally, spatial differentiation, normalisation and weighting are addressed.

34.2.1 Importance of Life Cycle Stages

The life cycle of the service of wastewater treatment comprises different stages, i.e. material stage (production of raw materials, e.g. oil) including the construction of the plant, use stage (running the plant), transport "stage" (in some cases an integrated part of the other stages) and finally disposal, waste or reuse/recycling stage (e.g. landfill). These stages are dealt with in the subsections below.

Material and Construction Stage
Some of the LCA studies included in Table 34.1 in Appendix, like Emmerson et al. (1995) and Tillman et al. (1998), have included the construction of the wastewater treatment plant(s) in a detailed way. In the case Emmerson et al. (1995), the results show that although the energy consumption is overall dominated by the operation stage at one of the WWTPs analysed, it is of the same order of magnitude in both the construction and the operation stages at the two other WWTPs included. Also the studies by Tangsubkul et al. (2005), Vlasopoulos (2004) and Vlasopoulos et al. (2006) point at the possible importance of infrastructure for several different processes, e.g. constructed wet lands and sand filters. Newer studies, not included in Table 34.1 in Appendix, like Larsen et al. (2010) confirm that infrastructure/capital goods may play a significant role when dealing with newer and upcoming technologies like ozonation and sludge inertisation. That infrastructure needs to be addressed in all cases, either by including or arguing for excluding, is also stated in the review by Corominas et al. (2013).

Use Stage

The use stage (or plant operation stage) plays an often dominating role is documented in almost all studies. The main reason is the typical use of electricity, fuels and especially the emission of pollutants from the wastewater to air, with effluents and sludge.

Transport

Transport may or may not play a significant role (but typically not dominating) in the LCA profile of a Wast Water Treatment Technology (WWTT) depending on the created scenario and its scoping. An example of significant importance of transport is the Australian study by Beavis and Lundie (2003) focusing on energetically efficient distance to place of application of biosolids (based on sludge) used for fertilisation of agricultural land. In their specific cases threshold transport distance of 172 km (aerobic digested sludge) and 143 km (anaerobic digested sludge) could be estimated. Another example of the importance of distance to place of application is described in the paper by Houillon and Jolliet (2005) showing by sensitivity analysis that doubling the distance results in a 23% increase in the overall energy consumption. In the study by Dixon et al. (2003) on small-scale WWTPs, the transport in the case of reed bed contributed with 30% of the total energy consumption. Also, transportation of the wastewater may be important in scenarios where it is collected in tanks and transported to the treatment plant over long distances.

Disposal Stage

The importance of including the disposal of waste (in some cases as a resource for reuse or recycling) in LCA studies on wastewater is documented in several studies. One example is the disposal of sludge for agricultural application. Including the substitution of fertiliser production and the potential impact from especially the metal content of the sludge is very important (Beavis and Lundie 2003; Tangsubkul et al. 2005; Hospido et al. 2005), which has also been shown in more recent studies like Larsen et al. (2010) not included in Table 34.1 in Appendix. Another example is whether or not the methane production from anaerobic digestion is utilised (substituting fossil energy) or is emitted to air and hereby contributing significantly to the global warming potential (Tillman et al. 1998).

34.2.2 Relevance of Different Impact Categories

The environmental impact categories are here divided into the typical energy-related ones and typical toxicity (or chemical)-related ones. This is because a typical challenge in wastewater treatment is the achievement of higher effluent water quality at the expense of higher energy consumption. The energy-related categories comprise global warming, acidification and photochemical ozone formation, in a wastewater treatment system all primarily attributable to the combustion of fossil fuels in stationary or mobile processes. The toxicity-related impact categories include ecotoxicity and human toxicity. Eutrophication which in many other cases

is primarily energy related is here looked upon separately due to its high relevance for wastewater effluent. Resource consumption, stratospheric ozone depletion, land use, photochemical ozone formation, and waste generation are also treated separately.

Energy-Related Impact Categories

The typically high importance of the energy-related impact categories are documented in most of the studies reviewed. For example in the study by Clauson-Kaas et al. (2006), the induced potential impact (global warming, acidification, indirect eutrophication) related to the energy consumption from running two of the investigated treatment technologies (MBR and ozonation) is at least in the main scenario higher than the avoided potential impact (aquatic ecotoxicity) achieved by cleaning the water (normalised or weighted impact potentials). In the study by Beavis and Lundie (2003) focusing on disinfection technologies for effluents and digestion of sludge, the potential impacts related to energy consumption also plays a dominating role. In the review by Corominas et al. (2013), global warming, acidification and eutrophication is evaluated in 38, 27 and 28 of the 45 studies included, respectively. Newer impact categories like ionising radiation and particulate matter formation are also important as they are typically related to energy production.

Toxicity-Related Impact Categories

The importance of the toxicity-related impact categories, i.e. ecotoxicity and human toxicity, when doing LCA on wastewater treatment—especially if the chemical/toxic emission from the WWTP is actually included—is documented in several studies. In, for example, the Dutch study by Roeleveld et al. (1997) focusing on municipal wastewater treatment, the normalised results show aquatic ecotoxicity to be the second most important impact category only exceeded by eutrophication. Main contributors to the ecotoxicity of the effluent are metals (about 90%; Hg, Cd) whereas the included non-specified organic micro-pollutants account for the rest. That other micro-pollutants than just metals can play an important role for aquatic ecotoxicity in the LCA comparison of different wastewater treatment options is documented in the study by Clauson-Kaas et al. (2006) including endocrine disruptors and other organics. Terrestrial ecotoxicity may also in some cases play an important role. This is seen especially in cases involving agricultural application of sludge containing metals. One example is the study by Hospido et al. (2005) comparing anaerobic digestion of sludge with different thermal alternatives. In this case, the anaerobic digestion scenario includes agricultural application and gets the overall highest normalised impact score on terrestrial ecotoxicity due to the content of metals in the sludge. In the same study and same scenario, the impact category on human toxicity gets the second highest normalised impact score (human exposure to metals via food chains) showing that at least in a few cases human toxicity may play an important role in an LCA study of wastewater treatment technologies. That also human toxicity related to air emission from energy production may play an at least not negligible role in this context is shown in, for example, two Danish studies (Clauson-Kaas et al. 2001, 2006). More recent studies including pharmaceuticals and more, like Larsen et al. (2010), confirm the overall

results of this review. The importance of toxicity-related impact categories is also reflected in the reviews by Corominas et al. (2013) and Zang et al. (2015).

Eutrophication and Oxygen Depletion Due to Emission of Organic Matter

Reduction in emission of organic matter (COD, BOD) and nutrients (N, P) has always been a key challenge for municipal WWTPs. That it is also important in LCAs of wastewater treatment is documented in many studies. For example in the paper by Roeleveld et al. (1997) focusing on municipal wastewater treatment in The Netherlands, the impact share of eutrophication is clearly the highest with 4.4%, whereas the second highest, aquatic ecotoxicity, only amounts to 2.4% and energy consumption only 0.6% (normalised on basis of the total potential impact of all Dutch societal activities). Another example is the study by Hospido et al. (2004) on a Spanish municipal wastewater plant showing that eutrophication is the dominating impact category after normalisation with a share of about 65%. The typical dominance of eutrophication when wastewater effluent is included is confirmed by newer studies as described in the reviews by Corominas et al. (2013) and Zang et al. (2015). Distinguishing between emissions to freshwater (typically P-deficient) and marine water (in many cases N-deficient), and if possible include spatial (and temporal) differentiation is important for this impact category.

Stratospheric Ozone Depletion

The impact category stratospheric ozone depletion is included in 6 out of the 22 reviewed studies. It may play some (minor) role in ranking different alternative wastewater treatment technologies as shown for advanced oxidation processes by, e.g. Muñoz et al. (2005, 2006) and García-Montaño et al. (2006). However, after normalisation, the importance is typically negligible as regards WWTPs (Roeleveld et al. 1997; Hospido et al. 2004, 2005). This insignificant importance is confirmed by the Corominas et al. (2013) review but it should be noted that emission of N_2O, which is in focus regarding global warming potential related to WWTPs, is considered to be today's dominant ozone layer depleting emission (UNEP 2013).

Photochemical Ozone Formation

That the impact category on (tropospheric) photochemical ozone formation (POF) in some cases may play at least a minor role is shown in several studies. In the study by Vlasopoulos et al. (2006) comparing 20 different technologies for cleaning petroleum process waters, the POF is showing a normalised contribution, that is, at the same level as the one for eutrophication. Another example is the study by Tangsubkul et al. (2006) analysing microfiltration processes where the POF plays a relative important role (due to its relation to energy production, in this case electricity production) and is shown to be microfiltration flux dependent. That the emission of volatile organic compounds (VOC) from fossil fuel combustion (transport vehicles, machines etc.) can make the impact category for photochemical ozone formation significant in the comparison of different sludge treatment scenarios is shown by Suh and Rousseaux (2002). However, in the study on a municipal WWTP by Hospido et al. (2005) the normalised contribution from POF was found to be negligible.

Waste Generation

The disposal of "waste", for example, sludge produced during the wastewater treatment, is in a number of cases characterised by the use of the other impact categories. For example, the disposal of sludge on agricultural land is in some cases characterised by the use of the impact categories for terrestrial ecotoxicity, human toxicity and more (e.g. Hospido et al. 2005). The importance of addressing waste generation and its disposal is documented in several studies (e.g. Beavis and Lundie 2003; Tangsubkul et al. 2005). However, in many impact assessment cases and studies all or some of the waste is "only" included as, e.g. "hazardous waste", "slag and ashes", "solid waste" etc. (e.g. Clauson-Kaas et al. 2001; Tillman et al. 1998) or not at all (e.g. Dixon et al. 2003). One should always aim for characterising all waste disposals by the well-established impact categories including emissions to the biosphere (like freshwater ecotoxicity and human toxicity) and not just different waste categories.

Land Use

Only three studies have included land use in the LCA and only as occupied square metres or square metres times years of occupation. In the case of Muñoz et al. (2006), the land use is associated with the construction of the plant and reflects the large area needed for the solar field. The results of Dixon et al. (2003) reflect the difference between the land use for small conventional plants and a constructed wetlands with the same capacity, i.e. the included wetlands require a factor of 17–40 times larger area than the corresponding conventional plants. Mels et al. (1999) analysed three different large (100,000 p.e.) wastewater treatment plants (one reference and two alternatives) and come up with an area need of 8000–10,000 m^2 depending on the plant. A general exclusion of land use can therefore not be recommended as it may play a role especially if the LCA includes constructed wetlands, high space demanding energy production or the like. That only a few studies have actually included land use until now is confirmed by the most recent review study by Zang et al. (2015).

Resource Consumption

8 out of the 22 LCA studies reviewed include an impact category for resource consumption/depletion. However, in more cases resource consumption data is included in the inventory data presented. That resource depletion may play an important role in the impact assessment of wastewater treatment and that, in many cases, it is associated with consumption of fossil fuels is shown by Roeleveld et al. (1997), Gasafi et al. (2004) and Suh and Rousseaux (2002). Later studies like Larsen et al. (2010) confirm this. Water consumption/use as a separate category has also been included in a few recent studies as described in Zang et al. (2015).

34.2.3 Micro-Pollutants and Pathogens in Effluent and Sludge

The reviewed papers (Table 34.1 in Appendix) only include micro-pollutants to a limited degree and pathogens are not included at all in an impact relevant manner.

Regarding inorganic micro-pollutants, the evaluation of potential toxic impact from metals in effluent or sludge is included in 8 out of the 22 studies reviewed. Two studies include metals only in the assessment of the wastewater effluent (Clauson-Kaas et al. 2001, 2006), three studies apparently include metals in both effluent and sludge (Roeleveld et al. 1997; Beavis and Lundie 2003; Tangsubkul et al. 2005), and the other three studies only include metals in sludge (Suh and Rousseaux 2002; Hospido et al. 2004, 2005).

Organic micro-pollutants in general are only dealt with in two studies and only specified as single substances (not groups) in one case (i.e. Clauson-Kaas et al. 2006). The Clauson-Kaas study includes linear alkyl benzene sulphonate (LAS), diethylhexyl phthalate (DEHP) and polycyclic aromatic hydrocarbons (PAHs), i.e. benzo(*a*)pyrene, benzo(*b*)fluoranthene, benzo(*g*,*h*,*i*)perylene, benzo(*k*)fluoranthene and indeno(1,2,3-*cd*)pyrene for effluent emissions. A newer study by Larsen et al. (2010), not included in Table 34.1 in Appendix, is one of the most comprehensive ones regarding organic micro-pollutants and includes 22 pharmaceuticals/ metabolites for effluent emissions, and LAS, nonylphenol, DEHP and benzo(*a*) pyrene for sludge applied on agricultural land.

Potential impacts of pathogens are not included in any of the 22 LCA studies. Reduction of pathogens by WWT is, however, included in two studies (Clauson-Kaas et al. 2006; Beavis and Lundie 2003) and pointed out as an important issue for sludge used for agricultural application (Hospido et al. 2004). Further, the lack of including human health risk caused by the presence of pathogens in wastewater is pointed out as a limitation "that can affect the use of LCA in decision support in water recycling planning" (Tangsubkul et al. 2005). A preliminary method on how to include pathogens in LCA has been developed by Larsen et al. (2009) and most recently this issue has been addressed regarding sewage sludge management (Harder et al. 2016).

34.2.4 Spatial Differentiation

Site dependency with regard to aquatic ecotoxicity is only included on a general level as a differentiation between fresh water aquatic environment and marine (saltwater) aquatic environment and only in six of the reviewed studies. However, several studies include site-dependent inventory data when specific existing wastewater treatment works are looked upon (e.g. Tillman et al. 1998; Emmerson et al. 1995; Muñoz et al. 2006). For WWT spatial differentiation seems especially relevant for impacts related to aquatic ecotoxicity and eutrophication.

34.2.5 Normalisation and Weighting

Twelve of the reviewed studies use normalisation with five of them supplementing with a weighting based on value choices. The normalisation is typically done on

basis of the total societal (land, region or global) potential impact per citizen within a reference year and the normalised results, for example, expressed in percentages of the total societal impact in each impact category (see also Sect. 10.3 on normalisation). By introducing value choices weighting factors may be estimated for each impact category or anticipated weighting factors (e.g. 0.5 and 1) may be used in sensitivity analysis as in the study by Suh and Rousseaux (2002). In the study by Clauson-Kaas et al. (2006), weighting factors (1.0–1.7) based on distance to political reduction targets, i.e. governmental and international conventions on reduction targets (actually the same as a normalisation reference for a future scenario) are used. In the case of Tillman et al. (1998) and Svanström et al. (2004), the "monetary" principle "willingness to pay", i.e. the willingness of society to pay for restoration of impacts on "areas of protection" is used. In the recent review by Corominas et al. (2013), the use of the hierarchist perspective (archetypes) for weighting is found in WWT LCA cases. The strength of using normalisation and weighting is that it makes comparison between different WWT alternatives more simple and creates the opportunity to aggregate all the impact potentials into one common impact score. On the other hand, the weakness is that weighting is based on value choices and not natural science and therefore debatable. Probably due to this and a very stubborn (site-specific) risk-based approach on how to do environmental assessment within this applicationdomain, the LCA approach has had a hard time gaining a foothold. Using normalisation references at different scales (catchment, region, nation etc.) and different weighting principles may therefore be a good idea in trying to test the robustness of a result and gain acceptance.

34.3   Methodological Issues

When modelling LCA cases on wastewater the issue in focus is typically the service of treating one volume unit (i.e. m^3) of more or less contaminated water. The processes leading to the contamination (e.g. sanitation and consumption) are only included in a limited way and in most cases not at all.

Goal and Scope
The most commonly used functional unit (see Sect. 8.4.2) is one cubic metre of (ingoing) wastewater. If comparison among technologies is the aim, it is highly important to define the wastewater composition strictly (P content, COD content, etc.) in order to avoid introducing a bias in the comparison. Depending on the goal and scope "population equivalents" (e.g. based on BOD5) or nutrient content (kg phosphorus content) may also be used as functional unit. Defining the life time of the technologies in question is also important and may play a significant role. Scoping according to the goal is essential and may include the whole water cycle if the goal is mapping hot spots in a region's sanitary system or only specific process parameters if the aim is assessing the environmental performance of different technical process optimisations. It may, for example, be of high importance for the

impact contribution from infrastructure whether or not the sewer system is included. Including all (relevant) emissions and resource consumption/recovery like the handling/treatment and final disposal of sludge are very important as this emission route in many cases contains the major part of the pollutants (heavy metals, eutrophying substances). The direct emission of greenhouse gases (CO_2, CH_4 and N_2O) from the sewer system and/or from processes like activated sludge treatment (including nitrification/denitrification), sludge processing (e.g. anaerobic digestion), special treatments like ANaerobic AMMonium OXidation (ANAMMOX) and even emissions after disposal of sludge to agricultural land or landfill, may be important depending on the goal of the study. In this context, one should be aware of the content of fossil-based carbon in the sewage water, which may be at a level of up to 25% according to the review by Zang et al. (2015). For more information on the definition of goal and scope, see Chaps. 7 and 8, respectively.

Inventory

Foreground data is typically based on real plant measurement, laboratory/pilot tests or a combination with literature values and estimates. Background data (both upstream and downstream) are in most cases based on LCI databases like ecoinvent and GaBi. Transparency is always important in order to secure the possibility of a third part reproducing the study. For more detailed information on inventory in LCA, see Chap. 9.

Impact Assessment

In order to achieve as robust an impact assessment as possible, the use of more than one impact assessment method is recommended (see Chap. 10 on life cycle impact assessment). Depending on the goal and scope, presentation of results at all relevant levels, i.e. inventory, impact potentials, normalised and weighted (single score) results should be done. Both midpoint and endpoint (damage) results should be included (see Chap. 10). This may be achieved using, for example, the ILCD recommended methods (EU 2013) and the ReCiPe method (Goedkoop et al. 2013). As described above, the typically important impact categories for LCIA on wastewater include the toxicity related ones (human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and particulate matter formation), eutrophication (marine and freshwater), global warming, acidification, ionising radiation and (in some cases) water use, land use and stratospheric ozone depletion. Attempts to include special impact categories like pathogens and acute toxicity (due to, e.g. water emission of ammonia), and spatial and temporal differentiation (e.g. regarding eutrophication) when doing site-specific assessments may be relevant depending on the goal and scope of the study.

Interpretation

With the aim of optimising the reliability and robustness of the result the use of sensitivity analysis but also uncertainty estimations if possible is highly recommended (see Chap. 12 on interpretation).

An Alternative Approach on How to Do LCA on Wastewater Treatment

The approach used to reach the goal of an LCA on wastewater treatment is typically based on the general approaches like hot spot identification in the life cycle of a specific

technology or comparing the impact profile of different technologies performing the same service, e.g. phosphorus removal down to a specific level. An alternative is the "avoided against induced impacts" approach, where the impacts avoided by, e.g. introducing a new technology are compared to the impacts induced by this technology. This approach is illustrated in Figs. 34.2 and 34.3 and reflects a typical challenge in wastewater treatment, i.e. the achievement of higher effluent water quality at the expense of higher energy consumption or higher consumption of, e.g. precipitation chemicals.

This approach has now been used in several studies and was introduced by Wenzel et al. (2008) and in a more comprehensive way by Larsen et al. (2007, 2010). The approach puts special demands on the toxicity related impact categories and the eutrophication potential.

34.4 Concluding Remarks

When performing LCA on wastewater treatment, one should be aware of the following more or less domain specific issues:

- A typical functional unit is the treatment of one cubic metre of wastewater. Defining its composition/characteristics and/or using limit values for effluent is crucial for the reliability of the study in case of comparative studies
- All life cycle stages have the potential of being significant, and therefore need to be considered even though decommissioning and disposal of infrastructure in many cases seems to be the least important for the impact profile
- It is not generally possible in advance to consider some inventory data as unnecessary, but depending on the goal and scope large parts of the product system may be omitted (e.g. parts equal among alternatives)
- None of the conventional impact categories (except stratospheric ozone depletion if emission of N_2O is not included) should be excluded but eutrophication and ecotoxicity are in many cases among the dominating ones
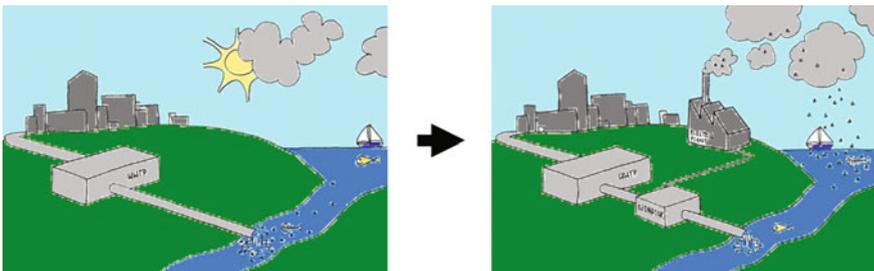
Fig. 34.2 By avoiding an obvious problem in one place we may induce a bigger problem somewhere else (sub-optimisation) (Larsen et al. 2010)
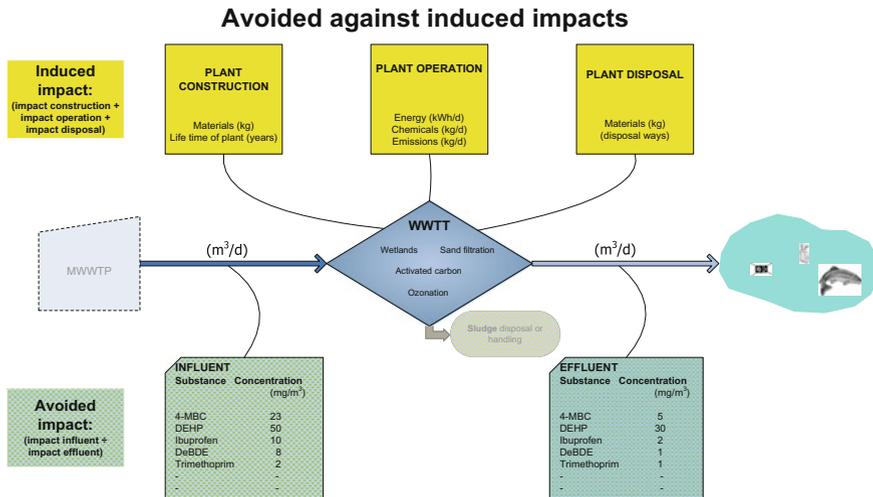
Fig. 34.3 The principle of avoided against induced impact illustrated for micro-pollutant polishing, by different wastewater treatment technologies (WWTT), e.g. ozonation of wastewater from a municipal wastewater treatment plant (MWWTP) (Larsen et al. 2007)

Furthermore, if the aim is to perform an environmental product declaration (EPD), one should consult the already existing product category rules (PCR) for "Wastewater collection and treatment services" (Environdec 2014).

It should be noted that a future change in the relative importance of the different impact categories is likely due to coming improved inventory data and enhanced LCIA methodology including an increase in the number of characterisation factors or the use of, e.g. whole effluent toxicity (Larsen et al. 2009) regarding aquatic ecotoxicity. As discussed by Larsen et al. (2010), existing methodologies only cover a minor part of the possible toxicity impact of pollutants in wastewater due to lack of (good) characterisation factors. Including the specific toxic modes of action of, e.g. endocrine disrupters in a proper way, have the potential of increasing the importance of aquatic ecotoxicity significantly as shown in Larsen et al. (2009, 2010). Another example is the achievement of better inventory data on N_2O and CH_4 emissions from WWT which might change the importance of global warming drastically (Zang et al. 2015).

Appendix

See Table 34.1.

Table 34.1 Results of review on 22 LCA WWT cases (Larsen et al. 2007)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Industrial wastewater: process water from extraction of oil and gas Sand filtration, ozonation and 20 other technologies	GW, DAR, AC, NE/ET, POF	+ Material stage + Construction + Use stage ÷ Transport ÷ Waste treatment FU: Cleaning of 10,000 m³ wastewater to certain water quality levels[a] Life time: 15 years	No quantification [none]	Vlasopoulos et al. (2006) Vlasopoulos (2004)
Municipal wastewater, related to the WFD Sand filtration Membranbioreactor Ozonation	GW, AC, NE/ET, POF, CHTS, CHTW, AHTA, CETS, CETF, AETF, CETSW	+ Material stage + Construction + Use stage ÷ Transport + Waste treatment[b] FU: Further treatment of 1 m³ wastewater treated conventionally, i.e. MBNC Life time: 20 years	CETF, CETSW [Cd, Pb, Ni, NPE, LAS, DEHP, EE2, E2, PAH, (Zn, Cu, Hg, Cr)]	Clauson-Kaas et al. (2006)
Industrial wastewater: kraft mill bleaching wastewater Heterogeneous photocatalysis (PhC)	GW, DAR, AC, NE/ET, POF, HT, CETF, OLD	+ Material stage ÷ Construction[d] + Use stage + transport ÷ Waste treatment FU: Removal of 15% DOC from 1 m³ kraft pulp mill wastewater Life time: ? (laboratory experiment in Pyrex cells)	No quantification [none]	Muñoz et al. (2005)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Industrial wastewater (synthetic)[c] Heterogeneous photocatalysis (PhC)	GW, AC, NE/ET, POF, HT, CETF, OLD, LU, EC	+ Material stage + Construction[d] + Use stage + Transport + Waste treatment[e] FU: Treatment of 1 m³ synthetic α-methyl-phenyl-glycine (MPG) solution (500 mg/L) in order to obtain an inherent biodegradable effluent Life time: 15 years	Only for DOC, COD, N-ammonia and N-nitrate [none]	Muñoz et al. (2006)
Industrial wastewater (synthetic)[f] Photo-Fenton (PhF) process	GW, DAR, AC, NE/ET, POF, HT, CETF, CETS, CETSW, OLD	+ Material stage ÷ Construction[d] + Use stage + Transport + Waste treatment[g] FU: Removal of 80% DOC from 1.2 L of 250 mg/L Cibacron RED FN-R synthetic wastewater from simulated batch dyeing Life time: ? (laboratory experiment in Pyrex cells)	Only for DOC, COD, N-ammonia and N-nitrate [none]	García-Montaño et al. (2006)
Municipal wastewater in the Netherlands (total sustainability in society)	GW, DAR, AC, NE/ET, POF, HT, CETF, CETS, OLD, (discharge of	+ Material stage + Construction + Use stage	COD, NE/ET, CETF	Roeleveld et al. (1997)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Activated sludge FeCl$_3$ (phosphor removal) Activated carbon	COD), (production of normal, toxic and nuclear waste)	+ Transport (÷ Waste treatment) FU: 24,000,000 p.e. (not defined) Life time: Not defined	[Hg, Cu, Cd, Zn, organic phosphorus containing compounds]	
Municipal wastewater in Australia (focus on disinfection and nutrients) UV Chlorination/dechlorination by chlorine or hypochlorite Dissolved air flotation	GW, AC, NE/ET (freshwater and marine), POF, HT, CETS, CETF, CETSW	+ Material stage ÷ Construction + Use stage + Transport (÷ Waste treatment) Case study I: FU: Disinfection (measured by CFU) of 1000 m^3 tertiary treated wastewater (chlorine residual less than 0.01 mg/L) Case study II: fu: 1000 m^3 wastewater yielding 714 kg biosolids (25% solids, anaerobic digestion) or 1250 kg biosolids (18% solids, aerobic digestion) Life time: Not defined	Case study I: CFU-measurements Case study II: At least CETF Sludge: (At least CETS, but not specified) [common concentrations of metals, pesticides and chlordane assumed]	Beavis and Lundie (2003)
Municipal wastewater in Australia (focus on recycling for irrigation application)	GW, NE/ET, HT, CETS, CETF, CETSW, salinisation	+ Material stage + Construction + Use stage + Transport	Effluent as irrigation water, i.e. emission to soil: NE/ET, HT, CETS, CETF, CETSW, salinisation	Tangsubkul et al. (2005)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Ozonation + continuous microfiltration (CMF) Membrane bioreactor (MBR) + reverse osmosis (RO)		(÷ Waste treatment) FU: 1000 m³ recycled wastewater meeting national threshold limits for irrigation of sensitive crops (incoming raw sewage of "medium" strength, i.e. 500 mg/L, 40 mg/L tot-N, etc.) Life time: Not defined	Sludge as biosolids, i.e. emission to soil: NE/ET, HT, CETS, CETF, CETSW [besides mentioning metals no specification]	
Municipal wastewater in Spain (focus on environmental performance, i.e. removal of organic matter and hotspots) Only primary and secondary treatment	GW, DAR, AC, NE/ET, POF, HT, CETS, OLD	+ Material stage ÷ Construction + Use stage + Transport + Waste treatment FU (1): 53,349 m³/day (humid season) FU (2): 49,214 m³/day (dry season) Life time: Not defined	NE/ET, (HT) Sludge: CETS, HT (GW, DAR, AC, NE/ET, POF, OLD) [Cd, Cr, Cu, Hg, Ni, Pb and Zn]	Hospido et al. (2004)
Municipal wastewater (focusing on energy consumption and reuse potential) Constructed wetlands, UV, Sequencing batch reactor	"No impact categories", i.e. only comparison of removal efficiency (BOD, Tot-N and Tot-P), nutrient recycling and energy consumption	÷ Material stage ÷ Construction + Use stage ÷ Transport (+ waste treatment) FU: 1 m³ Life time: Not defined	No quantification [none]	Brix (1999)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Municipal wastewater (focusing on small-scale treatment) Constructed wetland	Besides LU (included as m^2 occupied by plant) impact categories are only included as CO_2 emitted, energy consumption and solid emission (i.e. waste)	+ Material stage + Construction + Use stage + Transport ÷ Waste treatment FU: 1 p.e. (0.2 m^3/day) treated to acceptable discharge standards, i.e. 10 mg/L BOD, 25 mg/L SS and 5 mg/L ammonia: Scales: 12, 60 and 200 p.e. Life time: 10 years	No quantification [none]	Dixon et al. (2003)
Sludge form municipal wastewater plant (focus on hotspots and process design) Supercritical water gasification (SCWG)	GW, DAR, AC, NE/ET	+ Material stage ÷ Construction + Use stage + Transport (+ Waste treatment) FU: 1 ton DM undigested sewage sludge (3% DM equals 33 ton wet sludge) Life time: Not defined	Effluent from SCWG plant via WWTP: NE/ET [none]	Gasafi et al. (2004)
Industrial wastewater, brewery (focus on operation conditions for membrane filtration)	GW, NE/ET, HT, CETS, CETF, CETSW, POF	+ Material stage + Construction + Use stage + Transport (÷ Waste treatment)	No quantification (assumed to be equal for all scenarios) [none]	Tangsubkul et al. (2006)

(continued)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
		FU: 1000 m³/day (produced from incoming settled effluent water from a sequencing batch reactor (SBR), 40 mg/L TSS and permeate turbidity's of <1 NTU) Life time: 20 years (membrane 5 years)		
Municipal wastewater (focus on physical-chemical pre-treatment) activated sludge, *Pre-precipitation, Flotation*	No characterization only inventory (energy balance, final sludge production, effluent quality, use of chemicals, space requirements, i.e. LU)	÷ Material stage ÷ Construction + Use stage (÷ Transport) (÷ Waste treatment) FU: 7,120,000 m³/year (19,500 m³/day) (treated to acceptable discharge standards, i.e. <10 mg/L BOD, <50 mg/L COD, <10 mg/L Tot-N, <1 mg/L Tot-P, <10 mg/L SS) Life time: Not defined	No quantification (assumed to be equal for all scenarios) [none]	Mels et al. (1999)
Sludge form municipal wastewater plant (focus on final disposal), Incineration Agricultural land application	GW, NE/ET, HT, CETS, CETF, CETSW, POF, DAR	+ Material stage ÷ Construction + Use stage + Transport (+ Waste treatment)	No quantification For sludge: GW, NE/ET, HT, CETS, CETF, CETSW, POF, DAR, AC	Suh and Rousseaux (2002)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Landfill		FU: 1 ton DM mixed sewage sludge. Life time: Not specified but more than 30 years mentioned in argumentation for leaving out construction	[Substances and concentrations according to threshold limits in French regulation on leachate from landfills and content of sludge for agricultural land application. Only metals included for land application. No further specification]	
Predominantly municipal wastewater sludge (focusing on hot spots and energy consumption) Supercritical water oxidation	GW, POF, DAR For EPS2000: Human health, biological diversity, ecosystem production, resources and aesthetic values) For EcoIndicator99: Human health, ecosystem health and resources	+ Material stage ÷ Construction + Use stage + Transport (÷ Waste treatment) FU: 1000 kg wet sludge (7% TS) treated at specific plant. Water effluent and gases assumed to have no adverse impacts Life time: Not defined	No quantification (assumed to have no adverse impact for both water effluent and wet solid effluent) [none]	Svanström et al. (2004)
Sludge form municipal wastewater plant (focus on energy and global warming) Agricultural land application Incineration Wet oxidation	GW	+ Material stage ÷ Construction + Use stage + Transport (+ Waste treatment) FU: 1000 kg DM sludge disposed	No quantification [none]	Houillon and Jolliet (2005)

(continued)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Pyrolysis Incineration in cement kilns Landfill		(wet sludge: 0.3% dry solid content) Life time: Not defined		
Municipal wastewater treatment plant in Denmark (focus on hot spots) Activated sludge: nitrification/denitrification, phosphor removal, sludge incineration	GW, AC, NE/ET, Persistent toxicity ((CETS + CETF + CHTS + CHTW)/ 4), AHTA, AETF, slag and ashes	+ Material stage ÷ Construction + Use stage ? Transport (÷ Waste treatment) FU: 29,800,000 m³ wastewater treated (i.e. 1 year, 1998) Life time: Not defined	NE/ET, Persistent toxicity, AETF [Pb, Hg, Cu, Zn, Cr, Ni, Cd, Se, As, dioxin]	Clauson-Kaas et al. (2001)
Sludge form municipal wastewater plant (focus on post-treatments) Anaerobic digestion + agricultural land application Incineration Pyrolysis	GW, DAR, AC, NE/ET, POF, HT, CETS, OLD	+ Material stage ÷ Construction + Use stage + Transport (+ Waste treatment) FU: 1000 kg DM sludge managed (thickened mixed: 1% dry matter) Life time: Not defined	No quantification For sludge: GW, DAR, AC, NE/ET, POF, HT, CETS, OLD [Cd, Cr, Cu, Hg, Ni, Pb and Zn]	Hospido et al. (2005)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Municipal wastewater (focus on energy consumption and sludge production) Activated sludge: nitrification/denitrification, biological P-removal	No characterization only inventory (oxygen requirements, sludge production and auxiliaries requirement/production (methanol, $FeCl_3$ and methane)	÷ Material stage ÷ Construction + Use stage ÷ Transport ÷ Waste treatment FU: 2750 m³/day wastewater treated (fixed discharge levels: <15 mg/L BOD_5, <15 mg/L TSS, <0.5 mg N/l ammonia, <10 mg/L Tot-N, <1 mg/L Tot-P Life time: Not defined	No quantification (assumed to be equal for all scenarios) [none]	Bagley (2000)
Municipal wastewater (focus on small-scale WWTPs) Activated sludge	No (quantitative) characterization only inventory (energy consumption, material use, waste, air emission from energy production—especially CO_2 (but also SO_2, CO and more)	+ Material stage + Construction + Use stage + Transport (+ Waste treatment) FU: 15 years of functioning, i.e. 1,095,000 m³ (compliance of effluent and sludge (agricultural application) with regulatory framework) Life time: 15 years	No quantification (assumed to be equal for all scenarios [none]	Emmerson et al. (1995)

Table 34.1 (continued)

Study on	Impact categories included for LCIA	Scoping, functional unit (FU) and life time	Potential impact of effluent quantified by [micro-pollutants]	References
Municipal wastewater (focus on change from conventional central WWTPs to local systems), sand filter, filter bed, urine separation	No specification, only inventory data used in detailed impact assessment, i.e. energy consumption; air emission of CO_2, methane, SO_2 etc.; water emission of N-tot, P-tot, BOD etc.; waste such as sludge, hazardous waste etc.	+ Material stage + Construction + Use stage + Transport (+ Waste treatment) FU: The treatment of wastewater from 1 p.e. during 1 year. p.e. not defined in paper Life time: Stated that this is taken into account (full technical life time for each component) but not specified in paper	No direct specification in paper of impact categories but at least assessed on basis of COD, BOD, N-tot and P-tot. [No specification]	Tillman et al. (1998)

MWWTP Municipal wastewater treatment plant; *WWT* Wastewater treatment; *ST* Sludge treatment; *WFD* Water framework directive (EC 2000, 2001); *MBNC* Mechanical (settlement)/biological/nitrification-denitrification/chemical phosphate removal; *GW* Global warming; *POF* Photochemical ozone formation; *AC* Acidification; *NE/ET* Nutrient enrichment/eutrophication; *DAR* Depletion of abiotic resources (sometimes divided into mineral resources and fossil energy resources); *OLD* Ozone depletion; *LU* Land use; *EC* (non-renewable) Energy consumption; *HT* Human toxicity; *CHTS* Chronic human toxicity soil; *CHTW* Chronic human toxicity water; *AHTA* Acute human toxicity air; *CETS* Chronic ecotoxicity soil; *CETF* Chronic ecotoxicity fresh water; *AETF* Acute ecotoxicity fresh water; *CETSW* Chronic ecotoxicity salt water; *DOC* Dissolved organic carbon p.e.: "wastewater" person equivalents; *CFU* Colony forming units; *NTU* Nephelometric turbidity units; + included; ÷ not included

[a]Related to end-use categories (irrigation of wheat, cotton, barley, alfalfa, sorghum, rhodes, citrus and for industrial use 'cooling system feed' and 'boiler feed')

[b]Treatment of waste from decommissioning of equipment included. For sludge only sludge incineration as disposal included

[c]Synthetic solution of α-methyl-phenyl-glycine (a pharmaceutical precursor)

[d]Same type of UVA lamp used in all cases —only differences in running time for achieving 15% reduction in DOC

[e]Transport and land filling of used catalyst included. For sludge only sludge incineration as disposal included

[f]Synthetic solution of the reactive azo dye Cibacron Red FN-R (C.I. Reactive Red 238)

[g]For sludge: dewatering, thickening and finally deposited at a landfill. Leachate (COD, BOD_7, NO_3^- and NH_4^+) and gas emission (CO_2, CH_4, NO_x and NH_3) estimated by ORWARE. 50% capture of gas (burned) and 90% capture of leachate (treated in WWTP) assumed

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