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Deliverable 4.1 Homogeneous LCA methodology agreed by NEPTUNE and INNOWATECH

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Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

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NEPTUNE

New sustainable concepts and processes for optimization and upgrading municipal wastewater and sludge treatment

Work Package 4: Assessment of environmental sustainability and best practice

Deliverable D4.1: Homogeneous LCA methodology agreed by NEPTUNE and INNOWATECH

Contents

1   Objectives of NEPTUNE WP4

The main objectives of NEPTUNE WP4 include:

- Complementation of state-of-the-art life cycle assessment (LCA) to cover specific biological effects (e.g. endocrine disruption) of micropollutants and pathogens.
- Applying the LCA methodology on a variety of wastewater and sludge technologies in order to assess the environmental sustainability and best practices ranking list of
  - o   advanced wastewater treatment for micropollutants and pathogens removal,
  - o   advanced nutrient removal control methods and processes and
  - o   options for sludge handling and treatment
- Formulate decision support guidelines based on LCA, cost/efficiency assessment and local constraints.

These objectives are sought fulfilled by performing the following tasks:

1. Development of "new" methodology
   a. Defining overall methodological LCA framework in agreement with INNOWATECH
   b. Developing methodology for including potential impacts of micropollutants and pathogens in the life cycle impact assessment (LCIA) of waste water treatment technologies. Results from whole effluent testing (WET) will be included.
2. Application of the LCA methodology including the "new" LCIA methodology suited for waste water treatment technologies
   a. Providing and generating inventory data for the included waste water treatment technologies and sludge handling techniques
   b. Estimating characterization factors (to be used for (eco)toxic impact potentials) for included emissions (e.g. of micropollutants and pathogens) on the basis of gathered effect and fate data, and the developed extended LCIA methodology
   c. Modeling, running and interpreting the results of the LCAs on the included waste water treatments and sludge handling methods
3. Creation of a decision supporting guideline
   a. Describing pros and cons for the different included waste water treatment and sludge handling techniques based on the results from the LCAs and cost/efficiency analysis

The present deliverable (D4.1) only reports the results of task 1a (see Section 2 "Common LCA methodology"). The other tasks are included in future milestones and deliverables, i.e. task 1b is included in Milestone M4.1 (month 18) and deliverable D4.2 (month 28), and task 2 and task 3 are included in Milestone M4.2 (month 28) and deliverable D4.3 (month 35).

2   Common LCA methodology

In order to do a life cycle assessment (LCA) of a waste water treatment technique, a system to handle the mapped inventory data and a life cycle impact assessment (LCIA) method/model is needed. Besides NEPTUNE, another EU-funded project has the same methodology need namely INNOWATECH (contract No. 036882) running in parallel with NEPTUNE but focusing on industrial waste water. With the aim of facilitating cooperation between the two projects a common LCA methodology framework has been worked out and is described in the following. This methodology work has been done as a joint effort between NEPTUNE WP4 and INNOWATECH WP4 represented by the WP4 lead partner IVL. The aim of the co-operation is to establish common methodologies and/or LCA models and/or tools in order to achieve a homogenous approach in INNOWATECH and NEPTUNE. Further, the aim is to facilitate possibilities of data exchange between the two projects and eventually normalise the final output.

A coordination/working group with representatives from INNOWATECH (WP4) and NEPTUNE (WP4) has been set up. It consists of the following representatives from the two projects:

NEPTUNE: Henrik Fred Larsen (DTU/IPU), Michael Hauschild (DTU), Henrik
                        Wenzel (SDU).
INNOWATECH: Mats Almemark (IVL), Christian Junestedt (IVL).

In support of this work and as a starting point for especially NEPTUNE WP4, a review of existing LCA studies on waste water treatment technologies has been done by DTU and is included as an Appendix.

2.1 Goal and scope of LCA

The goal of the LCAs in both NEPTUNE and INNOWATECH is holistic environmental performance ranking (optimisation) of different wastewater treatment technologies. In NEPTUNE the objective is to assess post-treatment of municipal waste waters to remove focus micropollutants (and pathogens) and further to assess advanced nutrient removal control methods and sludge inertisation processes. In INNOWATECH the objective is to assess and to find sustainable treatment technologies for a variety of widely different industrial effluents.

Both projects have one common scope of their LCAs, namely to assess new or optimized treatment technologies in comparison to existing ones. In NEPTUNE the main existing treatment technology (i.e. the reference scenario) is a municipal wastewater treatment plant with best-available technology today but without any post-treatment, i.e. primary and secondary treatment only, and for sludge treatment the main reference scenario is incineration. In INNOWATECH the base-line cases will be models of existing treatment systems, which treat the industrial waste waters under study according to best-available technologies today. In both projects induced impacts will be compared to avoided impacts as illustrated in Figure 1 for end-of-line technologies included in NEPTUNE. In INNOWATECH the LCA models of the newly developed treatment systems will also be used to detect, as early as possible, environmentally weak points ("hot spots") of the new treatment designs.

The functional unit (fu) is 1 m^3 of "standard" wastewater, i.e. effluent water (one or a few types) from municipal wastewater treatment plants (NEPTUNE) or directly from industries (INNOWATECH) with characterized content of micropollutants, (pathogens) etc., for (further) treatment. The upstream system boundary is thus the influent to the post treatment (NEPTUNE) and the influent to the wastewater treatment plant (INNOWATECH), respectively. The downstream

system boundary is the receiving water, to which the effluent from the treatment is assessed as an emission.

LCA approach for:
End-of-line waste water treatment technologies (WWTT)
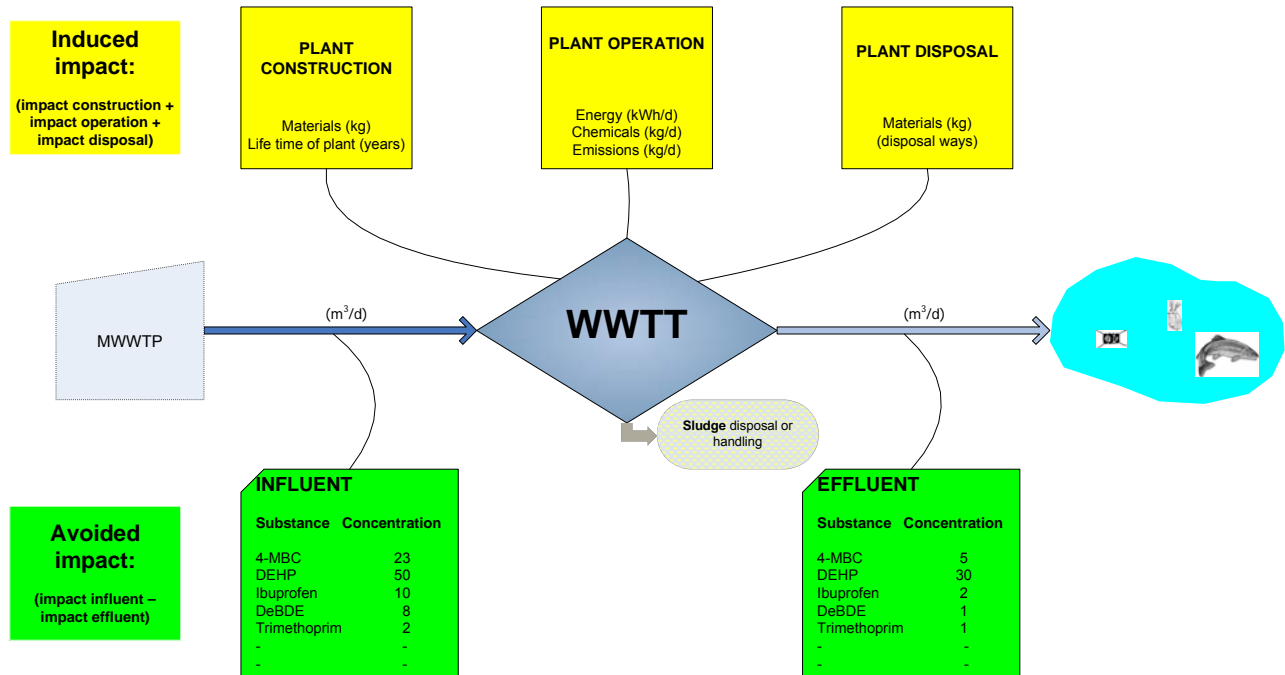
Figure 1. Illustration of the principle of induced impact and avoided impact. MWWTP: Municipal Waste Water Treatment Plant. The Waste Water Treatment Technology (WWTT) could for example be ozonation.

2.2 Inventory modeling tools

In both NEPTUNE and INNOWATECH GaBi (2006) will be used for generation of LCA inventories (i.e. LCA-system modeling). Further, INNOWATECH will use MatLab (2007) (Mathworks, Inc., version '7.4.0-287 (R2007a), 2007) for modeling the core waste water treatment processes (e.g. importance of variation in parameters like temperature and pH for the performance of the process), resulting in "dynamic" inventory data. Upstream and downstream processes will be described by life cycle inventories directly in GaBi. WP4 of NEPTUNE will not model wastewater treatment processes but will receive inventory data on the included processes from other WPs (i.e. WP1 and WP2) to be used for modeling the LCA unit processes in GaBi.

2.3 Life cycle impact assessment (LCIA)

The following existing impact categories are to be included in both NEPTUNE and INNOWATECH:

- Global warming

- Acidification
- Nutrient enrichment/eutrophication
- Photochemical ozone formation
- Ecotoxicity (aquatic and terrestrial; via soil, water and air)
- Human toxicity (via soil, water and air)
- Resource consumption
- Waste generation
- (Stratospheric ozone depletion)

Stratospheric ozone depletion may or may not be relevant but it is a well implemented impact category and easy to include.

All these impact categories are included according to the EDIP97 methodology (Wenzel et al. 1997, Hauschild and Wenzel 1998). Both projects will use this methodology in its existing form and in a form where the principles of the OMNIITOX model GM-troph (Larsen and Hauschild 2007) and the UNEP/SETAC consensus model USEtox (Rosenbaum et al., 2007) will be integrated as related to ecotoxicity. INNOWATECH will perform a comparison of this approach with the characterisation factors prescribed for EPDs by the Swedish Environmental Management council. Any major discrepancies will be clarified by INNOWATECH.

The impact category "land use" is not well developed but may be relevant in cases including wet lands, and powdered activated carbon (PAC) needing additional space for clarifier, contact and flocculation reactor. Both of these waste water treatment processes are included in NEPTUNE. Therefore, NEPTUNE will look into the relevance and possibilities for including this impact category while INNOWATECH does not find it relevant.

Related to the impact category of ecotoxicity NEPTUNE is going to develop a methodology for including micropollutants (e.g. endocrine disruptors, pharmaceuticals), Whole Effluent Test (WET) results and site dependent assessment. The results of the methodology development on micropollutants and WET will be used by INNOWATECH whenever relevant. Site dependency is not assessed to be of relevance by INNOWATECH.

As a novel approach NEPTUNE is also going to develop an impact category for pathogens. INNOWATECH will look into the importance of this impact category for industrial wastewater (e.g. waste water from slaughter houses) and include it if relevant.

2.3.1 Impact assessment models for toxicity

When doing LCA studies on waste water treatment processes, and focusing on emission of micropollutants, the impact category covering aquatic ecotoxicity becomes very important. State-of-the-art and best practice methodology for LCA aquatic ecotoxicity impact assessment have recently been investigated and principles developed within OMNIITOX (Molander et al. 2004, Larsen and Hauschild 2007a, 2007b) and UNEP/SETAC (Rosenbaum et al., 2007), but only on chronic aquatic ecotoxicity and (yet) no normalisation references exists. A certain degree of consensus about using average toxicity (HC50) has been reached. However, the principles of "most sensitive species" (PNEC) are well known and typically used when assessing potential impact of emissions of micropollutants from WWTPs. Further, this is also the existing principle in the readily available EDIP97 methodology, including also terrestrial ecotoxicity, normalisation references and weighting factors. So, both principles will be used, starting with the existing EDIP97 (i.e. PNEC) and when the new best practice methodology (i.e. HC50) is implemented as part of the method development in NEPTUNE this alternative will be included.

The impact category "human toxicity" will be characterised with factors based on the human reference dose (HRD) approach of EDIP97.

2.4 Normalisation of the final output

The aim will be to present the main results of each project (WP4) according to a mutual framework (e.g. results normalised with identical normalisation references according to an agreed upon procedure) perhaps in a separate chapter in the final reports. Forcing all (detailed) results into a common framework will most probably not make sense due to the different approaches of NEPTUNE and INNOWATECH.

2.5 Data exchange between NEPTUNE and INNOWATECH

The following possible areas of data exchange have been identified:

- From NEPTUNE to INNOWATECH
    - o Life cycle impact assessment (LCIA) methodology and characterization factors on mutual substances, special focus micropollutants (and maybe pathogens if relevant)
    - o LCIA methodology and characterization factors on WET

- From INNOWATECH to NEPTUNE
    - o Inventory data on mutual wastewater treatment processes, e.g. ozonation, to the extent possible considering the intellectual property rights of the INNOWATECH partners.
    - o Cost estimates of mutual resources to be used in the cost/efficiency analysis

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Appendix

Existing LCA studies on waste water treatment technologies

A review of 22 existing studies on waste water treatment technologies involving life cycle assessment has been done. A schematic representation of the result is shown in Table 1. The different studies are shortly described below in Section A1 with focus on treatment technologies included, the degree of involvement of toxicity-related impact categories, the degree of inclusion of potential impact from effluent and sludge (especially as regards micropollutants) and main results. In Section A2 a summing up/discussion divided into LCA-relevant issues is included.

A1.   Short description of each reviewed study

The study by Vlasopoulos and colleagues on oil process water includes 20 different waste water treatment technologies and are therefore quite comprehensive on this issue (Vlasopoulos et al. 2006, Vlasopoulos 2004). However, the LCA study does not take into account the avoided impact from treated effluent in the impact assessment. To assess the (environmental) quality of the effluent cut-off values for boron, sodium, TDS and oil defined by end-use categories for agricultural irrigation or industrial use is used. Impact categories on ecotoxicity and human toxicity are not included at all. Main results of the LCA study shows that the impacts from the use stage, i.e. energy-related impacts (production of electricity), dominate the overall results for all but two technologies. These two technologies are wetlands and sand filtrations for which the impact during the material and construction stage is dominating. A decision supporting tool suitable for identifying and prioritising technologies for treating oil contaminated waste water aiming at nine end-use categories for water quality is described. This system, i.e. Integrated Assessment of Treatment technologies Model (IATM), is integrating technical evaluation (removal efficiency, end use criteria) and economic assessment with environmental performance in one tool.

A Danish study on municipal waste water focusing on priority substances as defined by the EU Water Framework Directive (EC 2000, 2001) and endocrine disrupters has recently been carried out by Clauson-Kaas et al. (2006). The LCA part of this study only includes three treatment technologies, i.e. sand filtration, MembranBioReactor (MBR) and ozonation. However, avoided impact from treated effluent is included in the impact assessment part for the impact categories on chronic ecotoxicity in both fresh water and salt water. The involved substance groups and substances comprises Cd, Pb, Ni, nonyl phenol ethoxylate (NPE), linear alkyl benzene sulphonate (LAS), DEHP, 17α-ethynylestradiol (EE2), 17β-estradiol (E2), Poly Aromatic Hydrocarbons (PAH) and further Zn, Cu, Hg and Cr. The induced impact from constructing and running the treatment techniques is compared to the avoided impact from the effluent due to the reduction in the content of these substances (cleaning). After sensitivity analysis (including variation in treatment efficiency, variation in ecotoxicity impact potential and more) it is concluded that for sand filtration the avoided impact is significantly higher than the induced impacts from building and running the sand filter. For ozonation and MBR the results are ambiguous, especially due to higher energy consumption (electricity) during the use stage. This study includes a description of the removal efficiency (including pathogens), resource consumption and costs for the following five tertiary treatment technologies: sand filtration, MBR, ozonation, UV treatment and UV treatment in combination with oxidation (i.e. ozonation or hydrogen peroxide).

The study by Mũnoz et al. (2005) is focusing on advanced oxidation processes (AOPs) and the use of solar energy instead of mainly fossil fuel generated electricity for reducing the DOC content of

kraft mill bleaching waste water. Four different AOPs are tested at laboratory scale. Impact categories on human toxicity and fresh water ecotoxicity are included but the avoided impact from the 'cleaned' effluent is not taken into account, i.e. assumed to be identical as long as 15% reduction in DOC is achieved. Not surprising, the results show that for all included impact categories and all included treatment technologies the solar driven alternative has a lower potential impact than the corresponding electricity (primarily based on fossil fuels) driven one. Further, the potential impact from producing and transporting reagents and catalyst (TiO_2, H_2O_2, $FeCl_3$) is one to two orders of magnitude below that of producing the needed electricity. For the solar driven alternatives lowest potential impact is achieved in heterogenous photocatalysis (PhC) using only TiO_2, and photo-Fenton (PhF) using H_2O_2 and $FeCl_3$.

In a second study by Mũnoz (Mũnoz et al. 2006) the performance of two solar driven advanced oxidation processes (AOPs), i.e. heterogeneous photocatalysis (PhC) and Photo-Fenton (PhF) on synthetic waste water (solution of pharmaceutical precursor, i.e. MPG) are compared by use of LCA. Human toxicity and freshwater aquatic toxicity are included among the impact categories. However, besides COD, DOC, N-ammonia and N-nitrate no other parameters/substances are included in the assessment of the (avoided) impact from the 'cleaned' effluent, and micropollutants are not included at all. As cut-off quality indicator for the AOP treated waste water, achievement of inherent biodegradability, i.e. 70% or more DOC disappeared in an adapted Zahn-Wellens biodegradability test (in this case corresponding with disappearance of MPG) is used. The results show that the environmental impact from the PhF process as compared to the PhC process is 80-90% lower for all impact categories except eutrophication (only 30% lower). The main reason for this difference is that the PhC process needs a 21 times larger area of the compound parabolic solar collector than the PhF process for treating the same amount of waste water at a given time. A larger amount of materials and energy with resulting potential environmental impact is therefore needed for the PhC process.

In a third study on AOPs, three processes are compared by use of LCA, i.e. artificial light Photo-Fenton (PhF) process, solar driven PhF process and artificial light PhF process coupled with biological treatment (García-Montaño et al. 2006). The waste water tested is a synthetic solution of a reactive azodye (Reactive Red 238) used for textile dying. No micropollutants are included in the assessment for potential impact from treated effluent, only the parametres DOC, COD, N-ammonia and N-nitrate. Both human toxicity, and aquatic toxicity in fresh water and salt water are included as impact categories. As cut-off quality indicator for the AOP treated waste water removal of 80% DOC is used. The results of this study show that artificial light PhF has the highest score (i.e. highest potential impact) in all impact categories. This is mainly due to a high consumption of H_2O_2 combined with high energy consumption for running the UVA lamps. The result of comparing the solar PhF process (no energy for UV lamps, high consumption of H_2O_2) with the artificial light PhF process coupled with biological treatment (moderate H_2O_2 consumption and moderate energy consumption for running the UVA lamps) is ambiguous. For half of the included impact categories (e.g. human toxicity and fresh water toxicity) solar PhF process gets the highest score and for the other half (e.g. terrestrial ecotoxicity and photochemical ozone formation) the artificial light PhF process coupled with biological treatment gets the highest score. An economic study covering chemical and energy costs during operation of the processes is included (costs in € per functional unit). The result of the economic assessment points at the artificial light PhF process coupled with biological treatment as most benign and the artificial light PhF (alone) as least benign. As a final conclusion it is predicted that the most advantageous process from both an environmental and an economic point of view for treating Reactive Red 238 contaminated textile waste water will be a solar driven PhF process coupled with biological treatment.

Sustainability of Dutch municipal waste water treatment, as compared to the total environmental impact of all Dutch societal activities, is assessment by Roeleveld et al. (1997) by use of LCA. In

total five scenarios are included, i.e. no treatment (raw sewage water), activated sludge (no denitrification), activated sludge (including denitrification), activated sludge + phosphor removal (FeCl$_3$), activated sludge + phosphor removal + activated carbon. Impact categories on human toxicity and fresh water ecotoxicity are included. Organic micropollutants of which only "phosphorus containing compounds" are mentioned, and metals specified as Hg, Cu, Cd, and Zn are included in the assessment for potential impact from treated effluent. The main results are all expressed as the percentage potential impact of the total emitted Dutch waste water as compared to the total potential impact of all Dutch societal activities. For the impact category "nutrient enrichment" the impact share of 39% (no treatment) is reduced to 9.3% if activated sludge with denitrification is included and further to 4.4% if also phosphorus removal is added. For "aquatic ecotoxicity" the impact share is 8.9% (no treatment) and treatment by activated sludge + denitrification + phosphorus removal results in a reduction to 2.4%. Including activated carbon results in a further reduction to 1%. Main contributing substances to the potential ecotoxicity impact from the waste water (no treatment) are heavy metals accounting for 87% (Hg overall dominating with 60%), whereas organic micropollutants only accounts for 13%. For the impact categories related to energy consumption (e.g. global warming, acidification etc.) the impact share are all less than 1%. If the (present) scenario, i.e. activated sludge + phosphor removal, is taken as reference the impact share of 4.4% for the category "nutrient enrichment" is the highest followed by 2.4% for "aquatic ecotoxicity" dominated by Hg and Cd. Energy consumption is contributing relatively little only accounting for 0.6% of the Dutch total. It is concluded that most attention should be paid to reduce the impact from the effluent and the sludge production whereas energy consumption should pay less attention. Further, the construction of WWTPs and the use of chemicals are not determining for the insustainability of Dutch WWTPs.

Beavis and Lundie (2003) have performed an LCA study on techniques for disinfection and digestion of sludge based on municipal Australian waste water. In the first case study on disinfection treatment of tertiary treated waste water UV treatment is compared to chlorination/dechlorination by chlorine or hypochlorite. In the second case study focusing on nutrients anaerobic digestion is compared to aerobic digestion. Human toxicity, terrestrial ecotoxicity and aquatic ecotoxicity in fresh water and salt water are included as impact categories. In the case study on disinfection the pathogen load before an after disinfection treatment is measured by the number of Colony Forming Units (CFU). In the second case study micropollutants in the effluent and the sludge are only included as assumed "common concentrations" of metals, pesticides and chlordane (no further specification). The results of case study one shows that UV treatment as compared to chlorination/dechlorination has the highest potential impact per f.u. in most impact categories, mainly due to a 6-7 times higher energy demand. Comparing the chlorine system with the hypochlorite system including dosing efficiency indicate that the latter may perform environmentally better by achieving a lower impact score in most impact categories – again the main reason is a higher energy demand (related to the production of bisulphite for dechlorination). Concerning the second case study, aerobic digestion (as compared to anaerobic) is scoring highest in all impact categories except for Photochemical Ozone Formation (insignificant) and Freshwater Aquatic Ecotoxicity (23 times lower). The main reason is a higher energy demand for aerobic digestion (use of aerators). The reason for the significantly lower potential impact for Freshwater Aquatic Ecotoxicity is that for anaerobic digestion a high share of the waste water/sludge content of biocides and chlordane ends up in the effluent (from sludge treatment) rather than in the biosolids as is the case for aerobic digestion.

An LCA study on municipal waste water recycling techniques/systems for irrigation on agricultural land in Australia is performed by Tangsubkul et al. (2005). Three treatment trains are compared, i.e. ozonation + continuous microfiltration (CMF), membrane bioreactor (MBR) + reverse osmosis (RO), and waste water stabilisation pond (WSP). The two first are either preceded by or embedded in a conventional treatment system including a tertiary level (sand filtration). Both effluent

(irrigation water) and sludge (biosolids) are used for land application. Human toxicity, terrestrial ecotoxicity and aquatic ecotoxicity in fresh water and salt water are included as impact categories. Besides mentioning unspecified metals there is no specification of the degree of inclusion of micropollutants in the study. To assess the potential impact from the construction stage (only flows where LCA data are missing) the Missing Inventory Estimation Tool (MIET) is used. By Input - Output analysis MIET estimates the environmental impact potentials from economic costs. The results show that the potential toxicity impact (all toxicity related impact categories, i.e. HT, CETS, CETF, CETSW) for all three treatment trains studied is mainly related to the application of biosolids (sludge) on land (87%-98%). For global warming the energy consumption in the use stage is dominating for the CMF (68%) and MBR (69%) treatment trains whereas the dominating contribution for WSP (65%) is related to methane emissions from the pond. The construction stage is also contributing significantly to global warming (17-35%) in each of the three treatment trains. For eutrophication the energy consumption in the use stage is dominating for the CMF (89%) and MBR (90%) treatment trains, whereas the construction stage dominates in the case of WSP (94%). For the special impact category on salinisation the CMF treatment train performs best. After normalisation of the impacts (region of Sydney) the contribution to the impact category on terrestrial ecotoxicity is dominating for all three treatment trains (38%-74%) mainly due to the biosolids land application. Overall the WSP option performs best except for the salinisation potential impact category.

Hospido et al. (2004) have done an LCA study on a Spanish municipal waste water treatment plant focusing on hot spots, variation in seasonal environmental performance, removal of organic matter and metals in sludge. No tertiary treatment technologies are included only primary and secondary treatment with nitrification-denitrification as an option. Sludge is treated by anaerobic digestion (partly biogas utilisation) and after dewatering used as fertiliser on agricultural land. The study includes human toxicity and terrestrial ecotoxicity but impact categories for ecotoxicity in water are not included. Besides metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn) in sludge, micropollutants are apparently not included. The results of the study show that seasonal variability is not important (variability of data higher than variability due to season) and that especially two impact categories turn out to be dominating for the normalised impact potentials of the WWTP, i.e. eutrophication (about 65%) as related to the effluent and terrestrial ecotoxicity (about 32%) as related to application of sludge on agricultural land. Ammonium, phosphate and organic matter (COD) is contributing with more than 95% to the impact category on eutrophication. Including a nitrification-denitrification step in the treatment results in a 54%-58% reduction in the potential eutrophication impact which is not significantly counteracted by associated increases in the other impact categories, i.e. global warming, acidification and photochemical ozone formation (normalised figures). As regards terrestrial ecotoxicity only metals contribute with Cr, Hg and Zn as the dominating ones.

Hans Brix (1999) is discussing the use of LCA on defining the term "green" as related to waste water treatment systems, i.e. aquaculture, constructed wetlands and conventional treatment. In aquaculture one of the main ideas is that biological production (e.g. crustaceans and fish) produced on basis of the nutrient content of settled and aerated waste water is harvested and nutrients are hereby recycled. Two types of aquaculture systems are included, i.e. a Nordic system (long retention time, artificial lighting included (greenhouse) and the Advanced Ecologically Engineered System (AEES) or "living machine" (short retention time, outdoor or greenhouse depending on climate). For constructed wetlands the plant uptake of nutrients can be significant in low loaded systems. However, according to Brix (1999) the plants are generally not harvested resulting in a release of the major part of the nutrients after decomposition. Three types of conventional waste water treatment systems are included, i.e. an "extension aeration plant" with anoxic filter for denitrification and UV for disinfection, a sequencing batch reactor (SBR) also including UV, and finally a "carousel oxidation ditch" including polishing filter and UV. Toxicity related impact categories and micropollutants are not include as no characterisation is done at all and he ends up

with a (semi)quantitative comparison based only on removal efficiency (BOD, Tot-N and Tot-P), degree of nutrient recycling and energy consumption in the use stage (kWh/m^3). The results show that the energy consumption in the use stage is higher for the aquaculture systems (especially if a greenhouse is included) then for the conventional ones, e.g. 0.51 kWh/m^3 as compared to 1.51 kWh/m^3. Constructed wetlands have very low energy consumption in the use stage, i.e. < 0.1 kWh/m^3. Removal efficiency for COD and nutrients are almost at the same level for all three systems, except for N-removal being lower for wetlands (and one aquaculture facility), i.e. ca. 50%, as compared to > 80% for all others. For nutrient recycling only aquaculture with long retention time (30 days) have a recycling percentage above 1, i.e. 10%.

A study involving LCA on hypothetical small scale waste water treatment systems has been done by Dixon et al. (2003). A constructed wetland (i.e. reedbed, RB) is compared to a conventional system (i.e. an aerated filter treatment unit, AF) on treating municipal waste water to an "acceptable discharge standard" (10 mg/L BOD, 25 mg/L SS, 5 mg/L ammonia). Impact categories are only included as occupied land by the plant (land use, footprint), CO_2 emission, energy consumption and solid emission (waste), so (eco)toxicity and micropollutants are not included at all. The comparison is done on three scales, i.e. 12 p.e., 60 p.e. and 200 p.e. The reedbed is considered as a carbon sink in the CO_2 balance (no harvesting). The overall result shows that the two systems are fairly similar regarding total embodied energy, e.g. for 200 p.e.: ca. 367,000 MJ (RB) and ca. 332,000 MJ (AF), with AF benefiting most from up scaling. Due to the carbon sink effect of the RB its CO_2 emission is significant lower than the AF, e.g. – 9,794 kg CO_2 as compared to +25,718 kg CO_2 for the largest scale. On solid emission RB is highest, mainly due to excavated soil. Not surprisingly the results for land use shows that the RB occupies significantly more land than the AF, i.e. 40 times more for the largest scale (1002 m^2 as compared to 24.9 m^2 for 200 p.e.). Transport is a very important contributor to the embodied energy and the CO_2 emission – especially for the reedbed. More than 30% of the energy consumption for the RB is related to transport and for the AF the corresponding figure is 9% (12 p.e.). However, for the AF the dominating contributor was pumping (blower, 84% contribution to energy utilisation). Also construction and materials like plastics and concrete contributes significantly to the total energy consumption and CO_2 emission. Sensitivity analysis shows that the model output is especially sensitive to the CO_2 uptake rate of the reedbed.

Gasafi et al. (2004) have done a study on the use of LCA in preliminary design. The LCA approach is here used for identification of hot spots by use of dominance analysis with the aim of environmentally optimizing the design process. The case study included is modelled supercritical water gasification (SCWG) of sewage sludge from a municipal waste water treatment plant. Only the typical energy-related impact categories (global warming, acidification, eutrophication and resource depletion) are included so no assessment of toxicity and micropollutants. Results of the case study shows that the energy supply for additional heat of the SCWG plant is the dominating contributor to global warming. On acidification the dewatering of sludge is dominating due to the production of the polymer used (polyacrylate). For eutrophication the largest contributor is also related to the dewatering of sludge, i.e. the emission of the dewatering waste water via treatment in a WWTP. The over all dominant resource depletion is in this case related to the consumption of fossil fuels and therefore closely related to the additional heat of the SCWG process.

Environmental performance of different operation conditions for membrane microfiltration (MF) by use of LCA have been investigated by Tangsubkul et al. (2006). To levels of maximum transmembrane pressures (TMP_{max}), i.e. 20 kPa and 50 kPa are compared in several scenarios with varying flux and varying chemical cleaning options. Human toxicity, terrestrial ecotoxicity and aquatic ecotoxicity in fresh water and salt water are included as impact categories. Potential impact of micropollutants in effluent is not included as effluent is assumed to be identical in all scenarios. The main results of the study shows that operating the MF at low flux (10(-30) L/m^2) at 50 kPa is best for all impact categories included. The drawback however is that at low flux more membrane

modules are needed and hence more cost. Electricity is contributing with 63%-99% of the total energy consumption and the majority of environmental impacts can be traced back to the electricity consumption in the operational stage. This is reflected by for example 79%-100% contribution to global warming from electricity usage and the corresponding figures for all the other included impact categories amounts to 56% - 100%, excluding photochemical ozone formation where membrane manufacturing contributes up to 70%. The results for transport show an insignificant contribution (e.g. max value 2%, photochemical ozone formation).

A Dutch study by Mels et al. (1999) on sustainability of sewage treatments includes LCA at the inventory level. A reference scenario is compared with two scenarios (A and B) including physical-chemical pre-treatment. The reference scenario comprises a low loaded activated sludge system including biological P and N removal followed by a post settler. The sludge is dewatered and incinerated in the reference scenario. In scenario A this system is supplemented by a preprecipitation step (Fe and PE) and a rapid sand filtration after the post settler. Scenario B is identical to scenario A except for the substitution of the preprecipitation by a flotation system. In both scenario A and B the sludge is thickened and digested resulting in biogas production. As the study doesn't include characterisation no toxicity impact categories are included as well as no assessment of micropollutants. Effluent is assumed to be identical in all scenarios. The results shows that the energy consumption (in the use stage) can be reduced significantly (90%-98%) by introducing physical-chemical pretreatment. This is due to the reduced need for aeration in the activated sludge tank and the production of biogas by the sludge digestion. However, the sludge amount for final disposal increases as compared to the reference scenario (about 33%) and a use of chemicals for precipitation/flocculation (especially $FeCl_3$) is introduced corresponding to about 300 ton per year (100,000 person equivalent plant).

Suh and Rousseaux (2002) have done a French study involving LCA on sludge treatment scenarios. The five scenarios compared all includes thickening and dewatering (except for anaerobic digestion) as first steps in the treatment train of the input mixed sludge. Two scenarios end up with land filling preceded by incineration and lime stabilisation, respectively. The last three end up with agricultural land application preceded by lime stabilisation, composting and anaerobic digestion, respectively. Human toxicity, terrestrial ecotoxicity and aquatic ecotoxicity in fresh water and salt water are included as impact categories. Micropollutants are only included in the sludge and only as non-specified metals and undefined substances related to the French regulation on threshold limits for landfill leachate and sludge for agricultural land application. The overall result including sensitivity analysis (variation in weighting factors) shows that anaerobic digestion combined with agricultural land application is preferable from an LCA point of view. This is mainly due to relatively low emissions from anaerobic digestion combined with a reduced amount of sludge for land application (avoided fertilizer not included in study). In general the main contributor to resource depletion is diesel oil consumption for transport of sludge and for global warning energy consumption (incineration) and methane emission from landfills. Metal emissions to air (incineration) have significant contributions to both human toxicity and ecotoxicity, however highest contribution to freshwater aquatic ecotoxicity is seen in the scenarios with agricultural application of the sludge.

LCA hot spots related to a plant performing supercritical water oxidation (SCWO) on sludge in Texas is studied by Svanström et al. (2004). Potential impacts from micropollutants in the effluent water and the wet solid residue after spreading on land is not included. Toxicity related impact categories are however apparently included for other emissions by the inclusion of the single point indicators EPS2000 and EcoIndicator99. The results show that gas-fired pre-heating is the main contributor to the overall environmental impact followed by electricity consumption (pumping and oxygen production). Recovery of heat (of which about 50% originates from the sludge) replacing gas heat production in a nearby textile plant more than make up the estimated impacts from all other

activities according to the results by EPS2000, EcoIndicator99 and for depletion-weighted resource consumption. The contribution from transport of oxygen is minor except for photochemical ozone formation. All tested indicators point at reduction of electricity consumption as a mean of substantial reduction in potential impact of the plant.

Six different sludge treatment technologies/processes are compared by use of LCA by Houillon and Jolliet (2005). The technologies include agricultural application, incineration, wet oxidation, pyrolysis, incineration in cement kilns and landfill. The study only comprises energy consumption and global warming so no toxicity related impact categories nor micropollutants are included. The authors however state that this will be done in a coming paper. The main results show that from an energy perspective incineration in fluidised bed and application on agricultural land is most attractive followed by landfill, incineration in cement kilns, pyrolysis and wet oxidation as the least attractive. However, if global warming potential is looked upon all the thermic oxidation processes (i.e. especially incineration in cement kilns, but also incineration, wet oxidation and pyrolysis) have a lower potential impact than application on agricultural land, and landfill has by far the highest potential impact (almost three times as high as application on agricultural land). This result on global warming is highly dependent on the reuse of the heat and "products" emerging from the treatment processes, e.g. methanol from wet oxidation and P and N in sludge, displacing (substituting) for example the use of externally supplied methanol in the nitrification/denitrification process and fertilizers on agricultural land, respectively. The high global warming potential for landfill is mainly due to methane emission from the landfill. The importance of transport for the energy consumption of application on agricultural land is shown by sensitivity analysis showing that doubling the distance results in a 23% increase in the overall energy consumption.

An LCA study on a specific Danish municipal waste water treatment plant is performed by Clauson-Kaas et al. (2001). The processes included are activated sludge (nitrification/denitrification), chemical phosphor removal (FeCl$_3$), and for sludge anaerobic digestion (biogas recovery) and incineration. Toxicity related impact categories, i.e. acute human toxicity (air), acute aquatic ecotoxicity and persistent toxicity (combination of chronic human toxicity and chronic ecotoxicity in soil and water) are included. Also micropollutants in the effluent is to some degree taken into account, i.e. Pb, Hg, Cu, Zn, Cr, Ni, Cd, Se, As and dioxine. The results are normalised by dividing the load for each included impact category with the number of persons connected to the WWTP. These figures are then compared with the corresponding average load from one person in Denmark in 1990 including all other sources (e.g. industry, agriculture etc.). The results shows that the highest contribution comes from the acute ecotoxicity of the waste water effluent (corresponding to about 5% of the load for that impact category from one average Danish person in 1990) followed by slag & ashes with a corresponding figure of about 4.5%. Nutrient enrichment amounts to about 2.5%, persistent toxicity about 2%, whereas global warming, acidification and acute human toxicity (air) all amounts to below 1% of the corresponding load for one average Danish person.

In an LCA study by Hospido et al. (2005), partly building on results and data from a former study (Hospido et al., 2004) also included in this appendix, anaerobic digestion of sludge is compared with different thermal alternatives. An existing (reference) scenario, i.e. anaerobic digestion + mechanical dewatering + agricultural land application, is compared with two thermal processes. The first thermal process (scenario 1) includes mechanical dewatering + incineration. The second (scenario 2) comprises mechanical dewatering + thermal drying + pyrolysis and is divided into two subscenarios, i.e. only pyrolysis gas (syngas) reused for energy recovery (subscenario 2a), and all fractions produced (syngas, char, tar) reused (subscenario 2b). Both human toxicity and terrestrial ecotoxicity are included as well as the inorganic micropollutants Cd, Cr, Cu, Hg, Ni, Pb and Zn. The normalised result of the assessment does not give a clear answer as to which scenario is the most attractive from an environmental point of view. The reference scenario performs best as

regards eutrofication (due to reuse of N and P as fertilizer) whereas the performance on human toxicity and terrestrial ecotoxicity is worst due to the metals emitted to the agricultural soil via the sludge application (assuming full bio-availability of total metal content in sludge). Another example is subscenario 2b performing overwhelming best for human toxicity and terrestrial ecotoxicity (due to avoided impact from syngas, char and tar substituting fossil fuel combustion and more) but performing second worse for acidification, global warming and eutrophication.

The LCA study by Bagley (2000) on municipal waste water treatment only includes the use stage. The three processes included are analyzed theoretically, primarily on basis of yield and decay constants for relevant microorganism. The processes include activated sludge with nitrification and separate denitrification (AS), integrated biological nutrient removal (BNR), and anaerobic treatment with separate biological nitrogen removal (AT). Only energy requirements (estimated as oxygen requirements) and process mass (estimated as sludge production and auxiliary requirements) is included and assumed to be correlated with environmental impact. Further, effluent criteria are fixed so neither toxicity-related impact categories nor micropollutants are included. The results shows that the anaerobic treatment (AT) has the lowest oxygen demand (less than half as compared to the activated sludge (AS) demand), produces methane (that could substitute fossil fuels) and results in the lowest amount of sludge (also less than half as compared to the activated sludge (AS) demand). However, the need for $FeCl_3$ is a bit higher for AT than AS, i.e. about 9%.

One of the earliest LCA studies on waste water treatment processes is done by Emmerson et al. (1995). Three (at that time existing) small waste water treatment plants each serving around 1000 people are included. One activated sludge plant (two aeration tanks and two secondary settlement tanks) and two biological filter plants (primary sedimentation tank, two circular biological filters with slag media and a secondary sedimentation tank) are included. The two biological filter plants differ by one having radial flow sedimentation tanks and the other having vertical flow sedimentation tanks. The study is relatively comprehensive on inventory data for materials used for construction. No characterisation is done and the quantitative assessment of impacts is mainly based on inventory data for energy consumption, air emissions (CO_2, SO_2, CO and more), material use and waste. Potential (eco)toxicity impacts and the importance of micropollutants are only commented qualitatively. The overall result shows that for the two "impact categories" focused upon, i.e. aggregate material use and CO_2 emission, the plants assessed account for less than 1% of the UK totals on a per capita basis. For energy use 95% of the consumption occurs in the operation stage for the activated sludge plant. However, for the biological filter plants the energy use is more or less equal in the construction and the operation stages. The share of the demolition stage as regards energy consumption is highest for the biological filter (vertical sedimentation tanks) and amounts to about 7%. For emission of CO_2 (non-renewable resources) the picture resembles the one for energy consumption to a high degree. However, for the biological filter plants the materials delivery, construction, maintenance and demolition are of equal significance as electricity generation on emissions of CO, NOx, hydrocarbons and particulates.

A comprehensive Swedish LCA study on one large (554,000 people) and one small (1,100 people) existing conventional central municipal waste water treatment plant as compared to two small fictitious local treatment systems is done by Tillman et al. (1998). The large conventional plant (reference scenario A) includes mechanically, biologically (+denitrification) and chemical treatment, sludge is digested (biogas utilized) and finally 70% is disposed for urban soil improvement (12% on agricultural land). The heat of the effluent is recovered for a district heating system by passing a heat pump. The small conventional plant (reference scenario B) also includes mechanically, biologically and chemical treatment, but the sludge is disposed in a land fill. The two local systems comprise a sand filter beds system (scenario 1) and a urine separation system (scenario 2), both in to variations (a+b) depending on the suggested placement on two existing locations in Sweden, i.e. reference scenario A, scenario 1a and 2a placed in Göteborg (Bergsjön),

and reference scenario B, scenario 1b and 2b placed in Hamburgsund. The sand filter beds system comprises a pre-treatment (separation of liquid and solids) followed by a filter bed before emission of the treated waste water (in scenario 1b the treated waste passes some pools and ditches before emission to a local stream). The sludge is in scenario 1a digested (biogas utilized) and finally disposed as fertilizer on agricultural land. In the scenario1b the sludge is dried on "sludge drying beds" and afterwards also applied on agricultural land. For the urine separation systems (scenario 2) a source separation of urine, faeces and grey water appears at the households. Urine is after seasonal storage applied to agricultural land. Faeces are treated the same way as sludge in scenario 1a and scenario 1b, respectively. Grey water is treated the same way as sewage water in scenario 1a and scenario 1b, except for land filling of sludge in scenario 2b. As presented in the paper the impact assessment is based on inventory data (no characterisation in impact categories is done) and therefore toxicity-related impact categories are not included as is also the case for micropollutants. However, the use of weighting methods and a few of the resulting outcomes are presented, so some kind of characterisation must have been done in the underlying work. The overall results for the comparison of the waste water treatment in the Hamburgsund case (ref. sc. A , sc, 1a and sc. 2a) shows that the urine separation system is in most respects preferable from an environmental point of view followed by the sand filter bed system and with the conventional system generally showing the highest potential impact per person equivalent. This result is confirmed by the result of the three applied weighting methods. The comparison in the Bergsjön case (ref. sc. B, sc, 1b and sc. 2b) was more ambiguous, probably due to a positive effect of scaling combined with coal as marginal for electricity production and gas as marginal for the district heat system.

Table 1. Existing LCA studies on waste water treatment technologies

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
Industrial waste water: Process water from extraction of oil and gas	Sand filtration Ozonation Dissolved air flotation Hydrocyclones Rotating biological contactors Absorbents Activated sludge Trickling filters Air stripping Aerated lagoons Wetlands Microfiltration Dual media filtration Granular activated carbon Organoclay Ultrafiltration Nanofiltration Reverse osmosis Electrodialysis Ion exchange (Macro porous polymer extraction) (Distillation) (10,000 m^3/d)	CML 2 baseline 2000, v.2.1 + normalisation (Western Europe 1995) SimaPro (v6) (consequential)	GW, DAR, AC, NE/ET, POF	+ material stage + construction + use stage ÷ transport ÷ waste treatment fu: Cleaning of 10,000 m^3 waste water to certain water quality levels [1] lt: 15 years	No quantification	Average (European mix)	None	Vlasopoulos et al. (2006) Vlasopoulos (2004)
Municipal waste water, related to the WFD	Sand filtration Membranbioreactor Ozonation (sludge incineration) (50,000 m^3/d)	EDIP97, supplemented with new development, i.e. CETSW, and CETS, CETF, AETF, and CETSW on endocrine disrupters + normalisation (Europe 1994) + weighting (distance to political reduction targets, Europe 2004) GaBi (v.4, 2003) (consequential)	GW, AC, NE/ET, POF, CHTS, CHTW, AHTA, CETS, CETF, AETF, CETSW	+ material stage + construction + use stage ÷ transport + waste treatment [2] fu: Further treatment of 1 m^3 waste water treated conventionally, i.e. MBNDK lt: 20 years	CETF, CETSW	Marginal (coal based)	Cd, Pb, Ni, NPE, LAS, DEHP, EE2, E2, PAH, (Zn, Cu, Hg, Cr)	Clauson-Kaas et al. (2006)
Industrial waste water:	Heterogeneous photocatalysis (PhC)	CML 2000 (not stated specifically in paper but	GW, DAR, AC, NE/ET, POF, HT,	+ material stage ÷ construction [4]	No quantification	Average (Spain mix)	None	Mũnoz et al. (2005)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
Kraft mill bleaching waste water	PhC combined with H₂O₂ Photo-Fenton (PhF) PhC combined with PhF (No capacity: lab scale: 100 ml)	included in reference list) BUWAL 250, IWAM LCA Data 2.0 and more (partly consequential)	CETF, OLD	+ use stage + transport ÷ waste treatment fu: Removal of 15% DOC from 1 m³ kraft pulp mill waste water lt: ? (laboratory experiment in Pyrex cells)				
Industrial waste water (synthetic) [3]	Heterogeneous photocatalysis (PhC) Photo-Fenton (PhF) (both solar-driven and coupled end of line to a MWWTP (MBNC)) Sludge incineration (after anaerobic digestion) (6,8 m³/d, batch mode, assumed on basis of pilot scale measurements)	CML 2000 SimaPro 6.0 Ecoinvent 2000 tool/data-base (partly consequential)	GW, AC, NE/ET, POF, HT, CETF, OLD, LU, EC	+ material stage + construction [4] + use stage + transport + waste treatment [5] fu: Treatment of 1 m³ synthetic α-methyl-phenylglycine (MPG) solution (500 mg/L) in order to obtain an inherent biodegrade-able effluent lt:: 15 years	Only for DOC, COD, N-ammonia and N-nitrate	Average (European, UCTE profile)	None	Mũnoz et al. (2006)
Industrial waste water (synthetic) [6]	Artificial light Photo-Fenton (PhF) process Solar driven PhF process Artificial light PhF process coupled with biological treatment (activated sludge; oxidation, nitrification) Sludge: Thickening (acrylonitrile), dewatering, stabilisation (lime) and finally landfill (No capacity: lab scale: 250 ml)	CML 2000 Ecoinvent database v. 1.1, BUWAL 250 ORWARE (Organic Waste Research) simulation model (consequential)	GW, DAR, AC, NE/ET, POF, HT, CETF, CETS, CETSW, OLD	+ material stage ÷ construction [4] + use stage + transport +waste treatment [7] fu: Removal of 80% DOC from 1,2 L of 250 mg/L Cibacron RED FN-R synthetic waste water from simulated batch dyeing lt: ? (laboratory experiment in Pyrex cells)	Only for DOC, COD, N-ammonia and N-nitrate	Average (European, UCTE grid)	None	García-Montaño et al. (2006)
Municipal	Activated sludge	CML 1992 (reference in	GW, DAR, AC,	+ material stage	COD, NE/ET,	Most	Heavy metals (Hg, Cu, Cd,	Roeleveld et al.

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
waste water in the Netherlands (total sustain-ability in society)	FeCl$_3$ (phosphor removal) Activated carbon Sludge: Thickening, dewatering (polymer) and finally (20% DM) incineration or landfill (100,000 p.e., not defined)	Dutch) + normalisation (the Netherlands 1990) (partly consequential)	NE/ET, POF, HT, CETF, CETS, OLD, (discharge of COD), (production of normal, toxic and nuclear waste)	+ construction + use stage + transport (÷ waste treatment) fu: 24,000,000 p.e. (not defined) lt: Not defined	CETF	probably average but not specified	Zn) Organic micropollutants (phosphorus containing compounds, otherwise not specified)	(1997)
Municipal waste water in Australia (focus on disinfection and nutrients)	Case study I: UV Chlorination/dechlorination by chlorine or hypochlorite Case study II: Sludge: Thickening (Dissolved Air Flotation, DAF), aerobic or anaerobic digestion, dewatering (polymer) and finally application on agricultural land (biosolids as fertiliser) (6,000 m^3/d, case study I))	USES-LCA (not stated specifically in paper but assumed on basis of description; characterisation factors for ecotoxicity modified for Australian conditions) (consequential)	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 1,000 m^3 tertiary treated waste water (chlorine residual less than 0.01 mg/L) Case study II: fu: 1,000 m^3 waste water yielding 714 kg biosolids (25% solids, anaerobic digestion) or 1250 kg biosolids (18% solids, aerobic digestion) lt: Not defined	Case study I: CFU-measurements Case study II: At least CETF Sludge: (At least CETS, but not specified)	Most probably (Australian) average but not specified (coal mentioned)	(common concentrations of metals, pesticides and chlordane assumed)	Beavis and Lundie (2003)
Municipal waste water in Australia (focus on recycling for irrigation application)	Ozonation + Continuous microfiltration (CMF) Membrane bioreactor (MBR) + reverse osmosis (RO) Waste water stabilisation pond (WSP) (All except WSP preceded or included in conventional treatment up to a tertiary level (sand filtration)) (5,000 m^3/d)	USES-LCA (not stated specifically in paper but assumed on basis of description; characterisation factors for ecotoxicity modified for Australian conditions) + normalisation (global data (2000?)) GaBi 3 v. 2 (2004)	GW, NE/ET, HT, CETS, CETF, CETSW, Salinisation	+ material stage + construction + use stage + transport (÷ waste treatment) fu: 1,000 m^3 recycled waste water meeting national threshold limits for irrigation of sensitive crops (incoming raw	Effluent as irrigation water (i.e. emission to soil): NE/ET, HT, CETS, CETF, CETSW, Salinisation Sludge as biosolids (i.e. emission to soil):	Most probably (Australian) average but not specified	(besides mentioning metals no specification)	Tangsubkul et al. (2005)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
		(consequential)		sewage of "medium" strength, i.e. 500 mg/L, 40 mg/L tot-N, etc.) lt: Not defined	NE/ET, HT, CETS, CETF, CETSW			
Municipal waste water in Spain (focus on en-vironmental performance, i.e. removal of organic matter)	Only primary and secondary treatment (option with nitrification-denitrification evaluated) Sludge: Anaerobic digestion (biogas used for heating or burned in a torch), dewatering (polymer) and finally application on agricultural land (about 60,000 m^3/d, 90,000 inhabitants, WWTP occupies 14,000 m^2)	CML (1992, 2001) USESLCA (1999, 2000) and more + normalisation (Western Europe (1995)) SimaPro 5.0 database (2001) Pre 4 database (1998) BUWAL 250 (1996) SPIN, RIVM (1992, 1995) IVAM LCA Data 2.0 (1998) Site-specific data (2001-2002) (focus on hot spots)	GW, DAR, AC, NE/ET, POF, HT, CETS, OLD	+ material stage ÷ construction + use stage + transport + waste treatment fu (1): 53,349 m^3/d (humid season) fu (2): 49,214 m^3/d (dry season) lt: Not defined	NE/ET, (HT) Sludge : CETS, HT (GW, DAR, AC, NE/ET, POF, OLD)	Average, Spain (impacts basd on BUWAL 250 (1996)	No evaluation (only consequences of adding nitrification-denitrification on eutrophication assessed) For sludge: Cd, Cr, Cu, Hg, Ni, Pb and Zn	Hospido et al. (2004)
Municipal waste water (focusing on energy consumption and reuse potential)	Aquaculture (Solar aquatic wastewater treatment) Constructed wetlands Conventional systems (1. Extension aeration + denitrification+UV. 2. Sequencing Batch Reactor (SBR) + UV. 3. Carousel oxidation ditch + UV)	No method No modeling tool	"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: 1m^3 lt: Not defined	No quantification	No approach – only quantity	None	Brix (1999)
Municipal waste water (focusing on small scale treatment)	Constructed wetland (reedbed, RB) Aerated filter treatment (AF) (12 p.e., 60, p.e. and 200	No "standard" method (principles used informed by ISO 14041) SimaPro software (2002)	Besides LU (included as m^2 occupied by plant) impact categories are only included as CO2 emitted, energy consumption and	+ material stage + construction + use stage + transport ÷ waste treatment fu: 1 p.e. (0.2 m^3/day)	No quantification	Average (UK energy mix) (232 g CO$_2$ per kWh)	None	Dixon et al. (2003)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
	p.e.)	(consequential)	solid emission (i.e. waste)	treated to acceptable discharge standards, i.e 10 mg/L BOD, 25 mg/L SS and 5 mg/L ammonia: Scales: 12 p.e., 60 p.e. and 200 p.e. lt: 10 years				
Sludge form municipal waste water plant (focus on hotspots and process design)	Supercritical water gasification (SCWG) (T > 274 grad C, P > 22.1 MPa) (capacity of SCWG plant not defined)	No "standard" method but determination of impact categories based on methodology by German Federal Environment Agency (1999) Umberto v. 4.0 (2001) (hot spots, dominance analysis)	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) lt: Not defined	Effluent from SCWG plant via WWTP: NE/ET	Average (Germany energy mix)	None	Gasafi et al. (2004)
Industrial waste water, brewery (focus on operation conditions for membrane filtration)	Membrane microfiltration, different operation conditions (secondary effluent filtration, nominal pore size 0.2 mym) (1,000 m³/d)	USES-LCA (not stated specifically in paper but assumed on basis of description; characterisation factors for ecotoxicity modified for Australian conditions, eutrophication expressed in O₂ equivalents) + normalisation (global data (2000?)) GaBi 3 v. 2 (2004) (consequential)	GW, NE/ET, HT, CETS, CETF, CETSW, POF	+ material stage + construction + use stage + transport (÷ waste treatment) fu: 1,000 m³/day (produced from incoming settled effluent water from a sequencing batch reactor (SBR), 40 mg/L TSS and permeate turbidities of < 1 NTU) lt: 20 years (membrane 5 years)	No quantification (assumed to be equal for all scenarios)	Most probably average but not specified (Australian) Sensitivity analysis on substitution by natural gas or hydropower or nuclear power	None	Tangsubkul et al. (2006)
Municipal waste water (focus on physical-	Reference scenario: Low load activated sludge system with biological P and N removal + dewatering and	No LCIA method, only inventory (environmental interventions)	No characterization only inventory (energy balance, final sludge production, effluent	÷ material stage ÷ construction + use stage (÷ transport)	No quantification (assumed to be equal for all scenarios)	Not defined	None	Mels et al. (1999)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
chemical pretreatment)	incineration of sludge Scenario A: *Preprecipitation* (Fe + PE) + low loaded activated sludge system + rapid sand filtration + sludge thickening and digestion Scenario B: *Flotation* (Fe + flocculant) + low loaded activated sludge system + rapid sand filtration + sludge thickening + digestion (100,000 p.e., p.e.= 150 L/d, imaginary plant)	(consequential)	quality, use of chemicals, space requirements, i.e. LU)	(÷ waste treatment) fu: 7,120,000 m^3/year (19,500 m^3/day) (treated to acceptable discharge standards, i.e <10 mg/L BOD, <50 mh/L COD, <10mg/L Tot-N, <1 mg/L Tot-P, <10 mg/L SS) lt: Not defined				
Sludge form municipal waste water plant (focus on final disposal)	Stabilization processes: Lime stabilization Composting Anaerobic digestion Disposal: Incineration Agricultural land application Landfill Five fictional combinations (scenarios) of stabilization and disposal (capacity not defined)	CML 2000 + normalisation (Western Europe, mid-'90s) + weighting (1 and 0.5 included in sensitivity analysis) BUWAL(1998) and more (consequential)	GW, NE/ET, HT, CETS, CETF, CETSW, POF, DAR	+ material stage ÷ construction + use stage + transport (+ waste treatment) fu: 1 ton DM mixed sewage sludge lt: Not specified but more than 30 years mentioned in argumentation for leaving out construction	No quantification For sludge: GW, NE/ET, HT, CETS, CETF, CETSW, POF, DAR	Not defined (but most probably average)	None For sludge: 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.	Suh and Rousseaux (2002)
Predominant-ly municipal waste water sludge (focusing on hot spots and energy consumption)	Supercritical water oxidation (SCWO) (T > 374 grad C, P > 22.1 MPa) (capacity: 9.2 ton sludge DM/day)	EDIP97 EPS2000 EcoIndicator99 + normalisation and weighting, only EPS2000 (willingness to pay) and EcoIndicator99 (distance to target) LCAit v. 4.0	GW, POF, DAR For EPS2000 : Human health, biological diversity, ecosystem production, resources and aesthetic values) For EcoIndicator99: Human health, ecosystem health and	+ material stage ÷ construction + use stage + transport (÷ waste treatment) fu: 1,000 kg wet sludge (7% TS) treated at specific plant. Water effluent and gases assumed to have no adverse	No quantification (assumed to have no adverse impact for both water effluent and wet solid effluent)	Average (Texas mix)	None	Svanström et al. (2004)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
		(hot spots)	resources	impacts lt: Not defined				
Sludge form municipal waste water plant (focus on energy and global warming)	Agricultural land application Incineration Wet oxidation (WETOX (T = 235 grad C, P = 4 MPa) Pyrolysis Incineration in cement kilns Landfill (300,000 p.e.; 90,000 m³/day)	No standard LCIA method, only energy consumption and GW (consequential)	GW	+ material stage ÷ construction + use stage + transport (+ waste treatment) fu: 1,000 kg DM sludge disposed (wet sludge: 0.3% dry solid content) lt: Not defined	No quantification	Average (European mix)	None	Houillon and Jolliet (2005)
Municipal waste water treatment plant in Denmark (focus on hot spots)	Activated sludge: nitrification/denitrification FeCl₃ (phosphor removal) Sludge: Dewatering (polymer), anaerobic digestion (biogas recovery), incineration (365,000 p.e., p.e.= 60 g BOD/day)	EDIP97 + normalisation (Denmark 1990) (hot spots)	GW, AC, NE/ET, Persistent toxicity ((CETS + CETF + CHTS + CHTW)/4), AHTA, AETF, slag & ashes	+ material stage ÷ construction + use stage ? transport (÷ waste treatment) fu: 29,800,000 m³ waste water treated (i.e. one year, 1998) lt: Not defined	NE/ET, Persistent toxicity, AETF	Not stated, but most probably average (Danish mix)	Pb, Hg, Cu, Zn, Cr, Ni, Cd, Se, As, dioxine	Clauson-Kaas et al. (2001)
Sludge form municipal waste water plant (focus on post-treatments)	Anaerobic digestion + agricultural land application Incineration Pyrolysis	CML (1992, 2001, 2002) USESLCA (1999, 2000) and more + normalisation (Western Europe (1995)) SimaPro 5.1 database BUWAL 250 (1996) IDEMAT 2001 APME (1999) ETH-ESU 96 (1996) Site-specific data (2001-2002) (consequential)	GW, DAR, AC, NE/ET, POF, HT, CETS, OLD	+ material stage ÷ construction + use stage + transport (+ waste treatment) fu: 1,000 kg DM sludge managed (thickened mixed: 1% dry matter) lt: Not defined	No quantification For sludge: GW, DAR, AC, NE/ET, POF, HT, CETS, OLD	Average (Spanish mix)	None For sludge: Cd, Cr, Cu, Hg, Ni, Pb and Zn	Hospido et al. (2005)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
Municipal waste water (focus on energy consumption and sludge production)	Activated sludge with nitrification and separate stage denitrifcation Integrated biological phosphorous and nitrogen removal Anaerobic treatment with separate stage biological nitrogen removal (2,750 m^3/d ; 10,000 people, theoretical plant)	No LCIA method, only inventory (consequential)	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: 2,750 m^3/day waste water treated (fixed discharge levels:: <15 mg/L BOD$_5$, <15 mg/L TSS, < 0.5 mg N/L ammonia, <10mg/L Tot-N, <1 mg/L Tot-P, lt: Not defined	No quantification (assumed to be equal for all scenarios)	Not defined	None	Bagley (2000)
Municipal waste water (focus on small-scale WWTPs)	Activated sludge Biological filter (radial-flow settlement tank) Biological filter (vertical- flow settlement tank) (200 m^3/d , dry weather; 1000 people, existing plants)	No LCIA method, only inventory (consequential)	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 m^3/ dry matter (compliance of effluent and sludge (agricultural application) with regulatory framework) lt: 15 years	No quantification (assumed to be equal for all scenarios	Average (hard coal)	None	Emmerson et al. (1995)
Municipal waste water (focus on change from central WWTPs to local systems)	Ref sc A: Conventional large centralized plant: mechanically, biologically(+denitrification) and chemically + heat recovery. Sludge digested (biogas recovery), final disposal primarily as soil improvement (70%). Ref sc B: Conventional small centralized plant: mechanically, biologically and	Impact assessment by three different methods mentioned but only EPS method stated in paper. Assessment almost entirely based on inventory, only a few overall impact assessment results mentioned Main result from the use of three weighting methods mentioned based on	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 waste water from 1 p.e. during one year. p.e. not defined in paper	No direct specification in paper of impact categories but at least assessed on basis of COD, BOD, N-tot and P-tot.i	Marginal ("average behavior", i.e. fossil fuels, mostly coal)	No specification in paper	Tillman et al. (1998)

Study on	WWT/ST technologies included in LCA (capacity of WWT)	LCIA method, LCA modelling tool/database (system modelling principle)	Impact categories included for LCIA	Scoping, functional unit (fu) and life time (lt)	Potential impact of effluent quantified by	Energy approach for electricity	Reduction of micro-pollutants in effluent due to treatment included, items	Reference
	chemically. Sludge disposed at landfill. Sc 1a+1b: Sand filter, two small local plants: pretreatment (separation of solids and liquid), filter bed, pools+ditches (b). Sludge: digestion(biogas recovery, a), sludge drying bed (b) and agricultural use Sc 2a+2b: Urine separation system, two small local plants: source separation in urine, faeces and grey water. Urine: Storage + agricultural use. Faeces: digestion (biogas recovery, a), sludge drying bed (b) and agricultural use. Grey water: pretreatment (separation of solids and liquid), filter bed, pools+ditches (b). Sludge: digestion (biogas recovery, a), landfill (b) or agricultural use (a). (Ref sc A: 554,000 people) (Sc 1a+2a: 12,600 people) (Ref sc B + Sc 1b+ Sc 2b: 1,100 people)	"willingness to pay" (EPS) and "Environmental themes and ecoscarcity (distance to politically set targets) Site-specific data (1993) Litterature data (consequential, prospective)		lt: Stated that this is taken into account (full technical life time for each component) but not specified in paper				

MWWTP: Municipal Waste Water Treatment Plant WWT: Waste Water Treatment   ST: Sludge treatment   WFD: Water Framework Directive (EC 2000, 2002)
MBNC: Mechanical (settlement)/Biological/Nitrification/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 Layer 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.: "Waste water" person equivalents   CFU:
Colony Forming Units

[1] Related to end-use categories (irrigation of wheat, cotton, barley, alfalfa, sorghum, rhodes, citrus, and for industrial use 'cooling system feed' and 'boiler feed')
[2] Treatment of waste from decommissioning of equipment included. For sludge only sludge incineration as disposal included
[3] Synthetic solution of α-methyl-phenylglycine (a pharmaceutical precursor)

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

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

[6] Synthetic solution of the reactive azodye Cibacron Red FN-R (C.I. Reactive Red 238)

[7] 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

A2.   Summing up and discussion

The reviewed studies include in varying degrees life cycle stages, LCA impact categories, micropollutants and more, and present LCA-profiles for waste water treatment. All these items are relevant as a starting point for doing new LCAs on waste water treatment technologies based on comparison between induced and avoided impacts and including micropollutants and pathogens as in NEPTUNE. Below is a summing up and discussion of the way and to which degree LCA relevant items are included in the reviewed papers.

A2.1.   Importance of different life cycle stages

The life cycle of the service of waste water treatment (e.g. treatment of 1 m^3) 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 LCA studies like Emmerson et al. (1995) and Tillman et al. (1998) have included the construction of the waste water 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. One of the outcomes of the Tillman et al. (1998) study is that although the emissions to water and electricity consumption for the WWTPs included is higher in the operation stage than the investment (material/construction stage) there is no clear tendency for the other consumptions/emissions. Further, it is stated that "although environmental burdens from investing in the system are in no way negligible in comparison with those of their operation, they vary far less between alternatives from operation" (Tillman et al. 1998). Results from these two studies (Emmerson et al. (1995) and Tillman et al. 1998) are in some cases (e.g. Beavis and Lundie 2003, Svanström et al.) referred to and used as an argument for excluding the construction and material stage. That the material and construction stage in some cases play an even very important role is, however, documented. For example the results of the study by Tangsubkul et al. (2005) point at a relatively high importance of the construction stage, e.g. 17-35% of the total global warming potential for conventional treatment + microfiltration + ozonation, conventional treatment + membrane bioreactor + reverse osmosis, and stabilisation pond. For the latter the results show that concerning eutrophication (though low as absolute number) the share for construction may be as high as 94%. Also in the study on treatment of oil process water (Vlasopoulos 2004, Vlasopoulos et al. 2006) the results show that for wetlands and sandfiltration the material and construction stage is dominating with regard to potential environmental impacts.

Also when looking at the part of the material stage related to the production of chemicals used in the treatment of waste water (e.g. polymers for sludge thickening and precipitation chemicals for phosphor removal) these may be of minor or significant importance for the LCA depending on the types, the scenario and the scoping of the LCA. For example in the study by Roeleveld et al. (1997) focusing on the sustainability of Dutch municipal waste water treatment, the use of chemicals (polymers and FeCl$_3$) is not found to be determining for the sustainability. On the other hand the largest contribution to the dominating energy-related potential impacts in the study by Beavis and Lundie (2003) comes from the production of bisulphite a chemical used for dechlorination of the effluent after disinfection by chlorination.

Use stage
That the use stage often plays an important role is documented in almost all studies, due to the use of electricity, fuels and 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 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 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 reedbed contributed with 30% of the total energy consumption. Also transportation of the waste water 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 is documented in several studies. One example is the disposal of sludge for agricultural application. The importance of including the substitution of fertilizer 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). Another example is whether or not the methane production from anaerobic digestion is utilized (substituting fossil energy) or is emitted to air and hereby contributing significantly to global warming potential (Tillman et al. 1998).

A2.2.   Relevance of different impact categories
The environmental impact categories are here divided into the typical energy-related ones and typical chemical (or toxicity)-related ones. The energy-related categories comprise global warming, acidification and photochemical ozone formation, all primarily attributable to the combustion of fossil fuels in stationary or mobile processes. Eutrophication which in many other cases is primarily energy-related is here looked upon separately due to its high relevance for waste water effluent. The chemical-related impact categories include ecotoxicity and human toxicity. Resource consumption, stratospheric ozone depletion or ozone layer 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, nutrient enrichment (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). Another example is the study by Beavis and Lundie (2003) focusing on disinfection technologies for effluents and digestion of sludge where potential impacts related to energy consumption also play a dominating role.

Chemical-related impact categories
The importance of the chemical-related impact categories, i.e. ecotoxicity and human toxicity, when doing LCA on waste water 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 waste water treatment, aquatic ecotoxicity turns out to be the second most important impact category only exceeded by eutrophication (normalised figures). Main contributors to the ecotoxicity of the effluent are metals (about 90%; Hg, Cd) whereas the included non-specified organic micropollutants account for the rest. That other micropollutants than just metals can play an important role for aquatic ecotoxicity in the LCA comparison of different waste water treatment options (induced impacts as compared to avoided) 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 and ground water) showing that at least in a few cases human toxicity may play an important role in an LCA study of waste water treatment technologies. That human toxicity related to air emission from energy production in this context may play an at least not negligible role is shown in for example the two Danish studies (Clauson-Kaas et al. 2001, 2006).

Eutrophication
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 waste water treatment is documented in many studies. For example in the paper by Roeleveld et al. (1997) focusing on municipal waste water 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 waste water plant showing that eutrophication is the dominating impact category after normalisation with a share of about 65%.

Stratospheric ozone depletion
The impact category on stratospheric ozone depletion or ozone layer depletion (OLD) is included in six out of the twenty-two reviewed studies. It may play some (minor) role in ranking different alternative waste water 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 1997, Hospido et al. 2004, 2005).

Photochemical ozone formation
That the impact category on (tropospheric) photochemical ozone formation (POF) in some cases may play at least a minor important 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 eutrofication. Another example is the study by Tangsubkul et al. (2006) analysing microfiltration processes where the POF play 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 VOC emission 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 MWWTP by Hospido et al. (2005) the normalised contribution from POF was found to be negligible.

Waste generation
The disposal of "waste" for example produced during the waste water treatment is in a number of cases characterized by the use of the other impact categories. For example the disposal of sludge on agricultural land is in some cases characterized by use of the impact categories for terrestrial ecotoxicity, human toxicity and more (e.g. Hospido et al. 2005). That waste generation and its disposal are taken into account and analysed when doing an LCA on waste water treatment 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) and Tillman et al. 1998) or not at all (e.g. Dixon et al. 2003).

Resource consumption
Eight out of the twenty-two 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 waste water treatment and that it in many cases is associated with consumption of fossil fuels is shown by for example Roeleveld et al. (1997), Gasafi et al. (2004), and Suh and Rousseaux (2002) .

Land use
Only three studies have included land use in the LCA and only as occupied square meters or square meters times years of occupation. In the case of Munoz 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) reflects the difference between the land use for small conventional plants and a constructed wetlands with the same capacity, i.e. the included wetlands requires a factor 17-40 bigger area than the corresponding conventional plants. Mels et al. (1999) analyze three different large (100,000 p.e.) waste water treatment plants (one reference and two alternatives) and come up with an area need of 8,000 m^2 – 10,000 m^2 depending on the plant.

A2.3. Micropollutants and pathogens in effluent and sludge
As described in the following subsections , the reviewed papers only include micropollutants to a limited degree and pathogens not at all in an impact relevant manner.

Micropollutants including metals
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 waste water 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 three studies only include metals in sludge (Suh and Rousseaux 2002, Hospido et al. 2004, 2005). Only five studies (Clauson-Kaas et al. 2001, 2006, Roeleveld et al. 1997 and Hospido et al. 2004, 2005) specify the metals which are actually included, as total Hg, Cu, Cd, Zn, Cr, Ni, Pb, (As and Se in one case).

Organic micropollutants in general are only included in the assessment in two studies and only specified as single substances (not groups) in one case (Clauson-Kaas et al. 2006), i.e. linear alkyl benzene sulphonate (LAS), DEHP and Poly 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. Clauson-Kaas et al. (2001) states that dioxin is included.

Known endocrine disruptors are also only included in the study by Clauson-Kaaset al. (2006), i.e. 17α-ethynylestradiol (EE2), 17β-estradiol (E2) and nonyl phenol ethoxylate (NPE).

The special group of pharmaceuticals is not included at all in any of the reviewed papers except for MPG (a pharmaceutical precursor) being part of the synthetic waste water in the study by Muñoz et al. (2006).

Pesticides are only mentioned as an included group (no specification) in one study (Beavis and Lundie 2003). Roeleveld et al. (1997) mentions the inclusions of phosphorous containing substances – presumably including pesticides.

Pathogens

Potential impact of pathogens is not included in any of the LCAs in the reviewed papers. Reduction of pathogens by WWT is however included in 2 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 waste water is pointed out as a limitation "that can affect the use of LCA in decision support in water recycling planning" (Tangsubkul et al. 2005).

A2.4.   Whole effluent toxicity

None of the reviewed papers include whole effluent toxicity in the impact assessment.

A2.5.   Site dependency

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 waste water treatment works are looked upon (e.g. Tillman et al. 1998, Emmerson et al. 1995, Muñoz et al. 2006).

A2.6.   Normalisation and weighting

Eleven of the reviewed studies use normalisation but only four supplement 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. This potential impact is estimated for each impact category giving rise to a normalisation reference for each impact category. By dividing the actual impact potentials in a given LCA study with the corresponding normalisation references it becomes possible to express the results in percentages of the total societal impact in each impact category. In this way it is possible to get an impression of the relative magnitude of the impacts included in the study. 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. The strength of using normalisation and weighting is that it makes comparison between different WWTT alternatives a lot 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. Using different weighting principles may therefore be a good idea in trying to test the solidity of a result.

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