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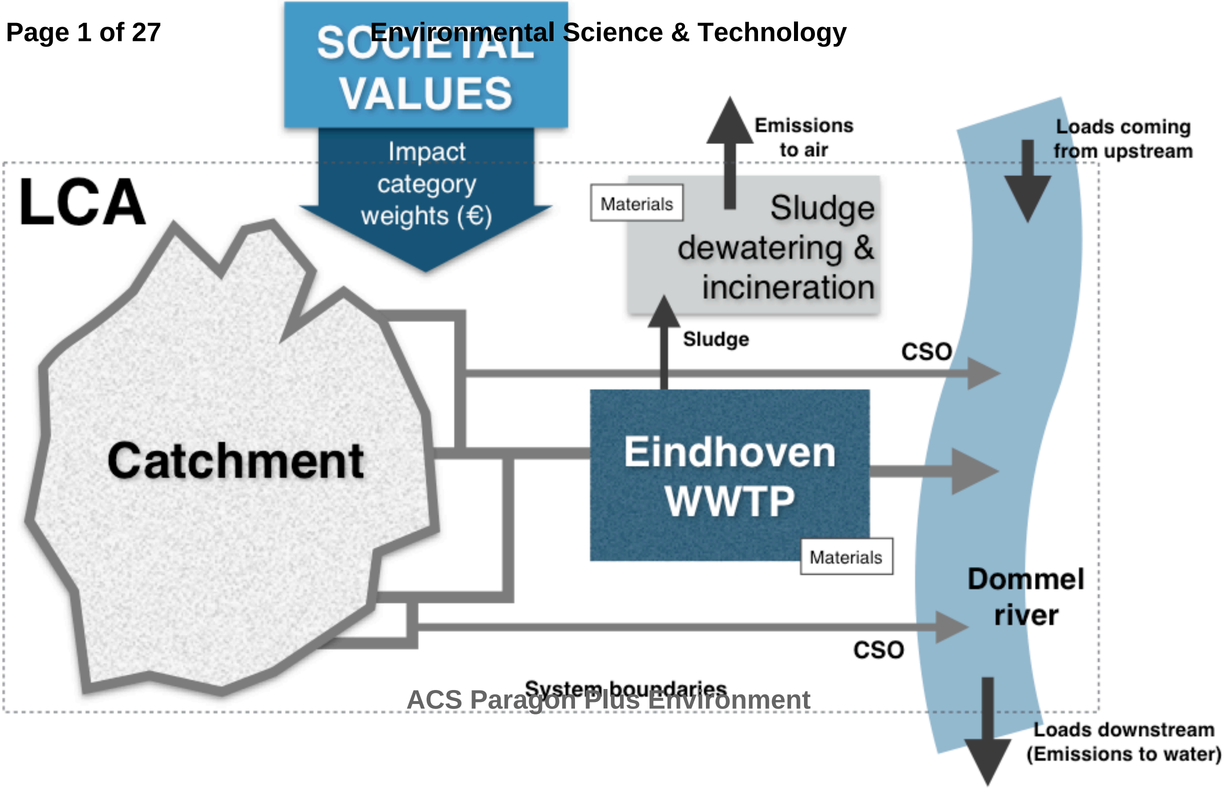
SOCIETAL VALUES
Impact category weights (€)
LCA
Materials
Emissions to air
Sludge dewatering & incineration
Loads coming from upstream
Sludge
CSO
Catchment
Eindhoven WWTP
Materials
Dommel river
CSO
System boundaries
Loads downstream (Emissions to water)

Assessing urban wastewater system upgrades using integrated modeling, life cycle analysis and shadow pricing

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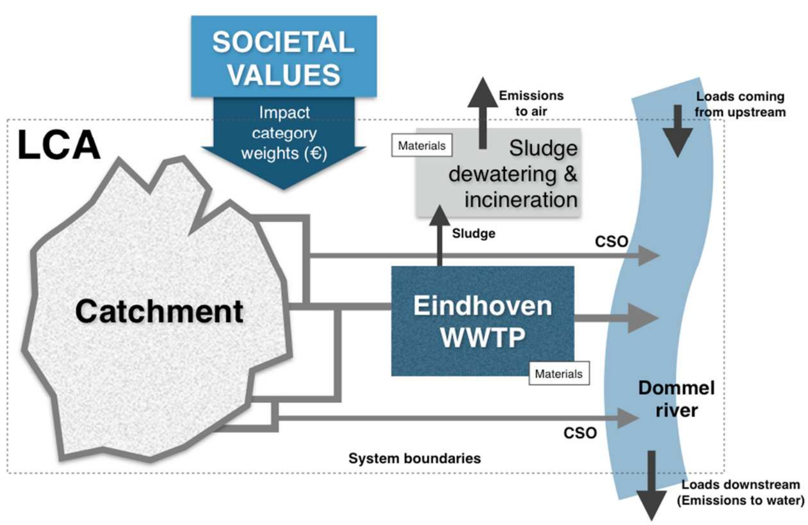
Keywords: weighting, integrated urban wastewater system, abatement, damage, uncertainty

ABSTRACT

This study assesses the environmental impacts of four measures proposed for upgrading of the urban wastewater system of Eindhoven and the Dommel River in the Netherlands, against the base-case "do-nothing" option. The measures aim to reduce the overall environmental impact of the Eindhoven urban wastewater system (UWS) by targeting river dissolved oxygen depletion and ammonia peaks, reducing combined sewer overflows and enhancing nutrient removal. The measures are evaluated using a life cycle analysis with the boundaries including the receiving river section by means of an integrated model of the UWS. An uncertainty analysis of the estimated impacts has been performed to support the outcomes. The study also uses the economic concept of shadow prices to assign relative weights of socio-economic importance to the estimated life cycle impacts. This novel integration of tools complements the assessments of this UWS with the inclusion of long-term global environmental impacts and the investigation of trade-offs between different environmental impacts through a single monetary unit. The results support the selection of deeper clarifiers as the most environmentally beneficial measure for upgrade.



Abstract art

INTRODUCTION

Sustainable development has now been adopted as an overarching goal of all economic and social development by multiple United Nations agencies, individual nations, local governments and corporations[1]. Prerequisites for this are decisions encompassing technical economic, social and environmental considerations[2]. For urban wastewater systems (UWSs) management this integration can only be achieved through the integration of state-of-the-art tools that support decision making.

Water management agencies are already conducting several studies to ensure the operation of the UWS adheres to these principles (for example the KALLISTO project[3–6] by the Waterschap de Dommel (WdD)). These studies have evaluated the cost-effectiveness and the technical performance of various proposed UWS upgrades, often looking at the ecological improvement of the receiving water body. An important tool in these analyses has been integrated modeling, encompassing the whole UWS and receiving medium and enabling dynamic assessments of the systems at hand[3–8]. Despite the great strides made during these assessments, some aspects often remain unaddressed – primarily global and long-term environmental impacts.

Life Cycle Analysis (LCA) is a technique to quantify the impacts associated with all the stages of a product, service or process from cradle-to-grave, in order to evaluate the environmental impact of its entire life cycle[9]. The application of LCA allows for the assessment of secondary, global impacts brought about by the proposed measures for UWS upgrading. There have been multiple examples of the LCA method being applied to UWSs, several of which have expanded on the conventional wastewater treatment plant (WWTP) boundaries to include other parts of the UWS[10,11] (for example, [12–14]). To the best knowledge of the authors, no LCA on the UWS has yet employed a deterministic integrated model taking into account hydraulics as well as biochemical processes of the whole system (sewer system, WWTP and receiving water body). For this purpose we employ an integrated model of the UWS - already used in previous studies[3–6] - which has shown to be a powerful tool to analyse and evaluate the proposed measures. This allows for a more integrative analysis as well as climatic and seasonal variations in the influent composition. The river model allows for the consideration of its functions and its capacity to dilute and uptake the discharged loads. Integrated modeling also provides the ability to investigate the dynamic effect of operational changes and upgrades on the assessment of the LCA impact categories.

Weighting is an optional step during a LCA and it can be used to include a prioritisation of the various impact categories and convert and aggregate the results into a single indicator. It is thought to be subjective and has therefore always been a controversial step of the LCA technique as it reflects personal values in the social, ethical and political fields[15–17]. Despite their subjectivity, these value-choices may be more relevant to the decision-making process as they can simplify and aggregate impacts. Weighting can be either quantitative or qualitative[18,19] and authors have suggested that methods based on monetary values or the judgement of an expert panel are the most promising[20]. Currency appears to be a unit that can be easily integrated by decision-makers in the decision process and be contrasted against other indicators[19,21]. It is also a unit that is easily understandable and communicable by a wide range of decision-makers[22]. Valuation aims to express the value society puts on them in monetary terms for purposes of assessment and internalisation[23]. By attaching a value on an emission the estimated environmental damage (or ‘cost’) can be an indicator of the environmental losses for the society regarding its present and future emission goals[24,25]. This a largely vague undertaking, mainly hindered by the fact that in many cases no market exists for elements such as water quality or pollution[1]. Various methods for valuation of externalities have been developed in the field of economic theory[19] with the most common technique appearing in water resources literature being the Contingent Valuation Method (CVM). CVM is considered by many authors as a consolidated method, given its numerous practical applications[26–28]. Nonetheless, there is no unanimous consensus on the validity of this methodology in the scientific community as a tool for the valuation of environmental goods[29–32]. One of the most common criticisms of the CVM and other survey-based methods is that people are often responding to a survey and not a budget constraint, which tends to bias positively their support of abatement costs[33]. Shadow pricing offers an alternative approach to this for the valuation of environmental externalities (in this case pollution), among other purposes[32,34]. The “desktop” shadow price estimation has very low costs, compared to traditional surveying methods and, for applications in a policy context, decision makers have found approaches based on the premise that government represents society more promising[19]. Among various other uses, authors have proposed the use of shadow prices to assign relative weights to environmental impacts identified in environmental analyses such as LCAs[23]. The values used in this study were derived from abatement and damage costs related to each environmental impact for the country of the Netherlands.

The objective of this paper is to employ a novel approach to assess measures for UWS upgrading. The measures are evaluated by integrating a deterministic model with LCA and the application of weights of relative abatement prioritisation to the estimated impacts. The utility of this integrated approach is illustrated with the case study of the Eindhoven UWS. The boundary of the analysis is extended to include the adjacent river section of the Eindhoven UWS, i.e. the river Dommel, taking into account its dilution and purification capacity. With this new application of LCA and weighting through shadow prices, we present a novel integration of methods to account for sustainable development, compared to traditional approaches. The application presented in this paper aims to complement the other studies performed by the managing authority in Eindhoven (WdD) to decide on upgrades for the UWS while adhering to the principles of sustainable development.

CASE STUDY: EINDHOVEN URBAN WASTEWATER SYSTEM

The studied system is the Eindhoven WWTP and its collection system, located in the southeast of the Netherlands. The Eindhoven WWTP treats the wastewater of 750,000 inhabitant equivalents (IE) with a design load of 136 g COD/day/IE. The received wastewater is treated in three parallel lines, each consisting of a primary settler, a biological tank and four secondary settlers. The plant has a modified UCT (University Cape Town) configuration for biological chemical oxygen demand (COD), nitrogen (N) and phosphorous (P) removal. The proposed measures to be evaluated and their principal targets (enhance nutrient removal, reduce CSOs and reduce river DO depletion) are summarised in Table 1.

Measure A involves the deepening of the secondary clarifiers of the Eindhoven WWTP. This has significant improvements on smoothing ammonia peaks and the average nitrate removal, by increasing the biological capacity of the plant by allowing a higher sludge mass in the activated sludge system. For measure B, the installation of newly developed in-stream aeration systems is considered to aerate flowing surface water, increasing oxygen levels and thus improving river water quality[35]. By tackling dissolved oxygen (DO) depletion the protection of critical river fauna species is better ensured. For enhanced total nitrogen and phosphorus removal, Measure C is proposed – the installation of a sand filter for effluent polishing. Finally, with the aim of reducing the release of combined sewer overflows (CSOs) and prevent DO depletion, Measure D involves the construction of additional storage capacity in the Eindhoven collection system. A more detailed description of the studied system and the proposed measures can be found in the Supporting Information.

Symbol	Measure	Target
A	Improvement to the WWTP by deepening the secondary clarifiers	Enhanced ammonium removal
B	River quality improvement by installing in-stream aeration stations in the Dommel River	Reduce dissolved oxygen (DO) depletion in the river
C	Construction of a tertiary sand filter as an add-on to the WWTP	Enhanced nitrate and phosphorus removal
D	Construction of additional storage capacity as an add-on to the combined sewer system	Reduce combined sewer overflows (CSOs)

Table 1 - Measures to be evaluated for application to the UWS

METHODOLOGY FOR ASSESSING AND WEIGHTING LIFE CYCLE ENVIRONMENTAL IMPACTS

There are four main phases in an LCA analysis: *Goal & Scope Definition*, *Inventory Analysis*, *Impact Assessment* and *Interpretation*. Their application is described below, with the Interpretation in the Results section. Weighting is applied during the *Impact Assessment* phase. In this study we employ shadow prices to attach weights on the estimated impacts. Uncertainty analyses were also performed, first on four of the critical parameters of the LCA to assess the robustness of the impacts estimation, and secondly on the assumed shadow prices used as weights.

Goal & scope definition

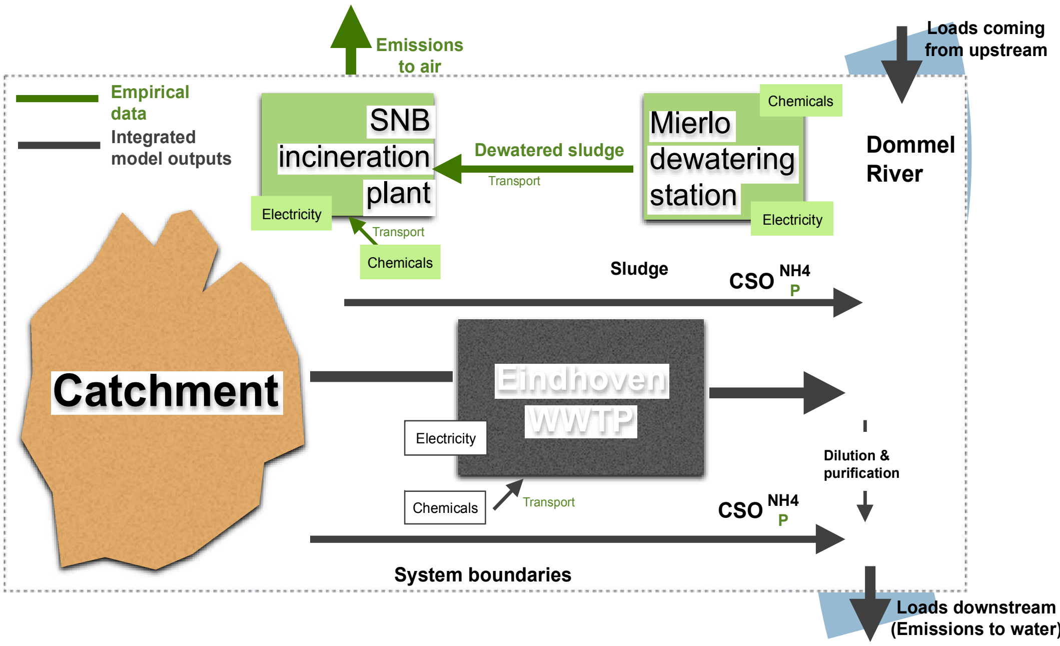


Figure 1 - System boundaries. For the Inventory Analysis: items in grey indicate model outputs; items in green indicate empirical data.

The goal of the LCA is to assess the environmental impacts caused by the current operation of the Eindhoven UWS and to compare them against the estimated environmental impacts by each of the proposed upgrading measures. The system boundaries include the catchment under study, the sewer system with its CSOs, the wastewater treatment plant, chemicals and energy used during the treatment, the river section within the catchment boundaries and discharged pollutant loads (phosphorus, ammonium, nitrate) leaving the studied river section (Figure 1). Construction of the WWTP and sewer systems have not been taken into account as they would be the same for all measures as well as the base case. The lifespan and maintenance of mechanical equipment and constructions of the proposed measures have also been included in the analysis.

For the sludge treatment, the dewatering installation at Mierlo and the sludge incineration facility (SNB) were taken into account along with the chemicals and energy used at said facilities. The transportation of chemicals and dewatered sludge to the incineration facility were also included. The functional unit is ten years of system operation treating approximately 546,550,190 m^3 of wastewater in total. This allowed the inclusion of climatic variability over that period as well as seasonal dynamics of influent wastewater.

Inventory analysis

The inventory data consist of: (i) inputs to the system (energy and chemical consumption and transport); (ii) outputs from the system (emissions to air and water); (iii) inputs and outputs of sludge treatment; (iii) inputs and outputs of construction of each measure (materials used and generated waste); and (v) infrastructure and equipment maintenance of each measure, presented in Table 2 and Supporting Information Tables S1 (for sludge treatment), S2 (for construction of each measure) and S3 (for the construction of the pumps needed in Measure A). The sludge treatment data were provided by the WdD[36] and the SNB incineration facility[37] for the year 2013. Information regarding the maintenance of infrastructure and equipment was provided by the WdD. Regarding maintenance, the lifespan of constructed infrastructure and equipment was taken into account. The lifespan of all mechanical equipment was assumed to be 15 years and 30 years for all civil constructions.

		Base case	**A**	**B**	**C**	**D**
Inputs to the system						
Aluminium sulphate, powder	ton	61,590	37,708	61,716	68,555	63,380
Methanol (carbon source)	ton	-	-	-	17,266	-
Construction	-	-	12 deeper clarifiers	5 aeration stations	21 sand filter units	10 storage tanks
Construction maintenance cycle	years	-	30 for clarifiers 15 for pumps	15	30	30
Electricity, medium voltage	MWh	236,376	232,756	237,935	236,408	236,555
Outputs to water at the end of the river reach						
Phosphorus, total	ton	518	554	518	461	500
Ammonium	ton	1,802	1,307	1,794	1,802	1,770
Nitrate	ton	3,127	2,834	3,128	2,787	3,156
Transport						
Transport of aluminium sulphate	Mtkm	3.39	2.07	3.39	3.77	3.49
Transport of methanol	Mtkm	-	-	-	0.95	-
Sludge for treatment	Mm^3	5.80	5.78	5.79	5.84	5.93

Table 2 - Inventory table for system inputs and outputs. The 10-year operation of base case and the four evaluated measures are presented along with their construction. Inventory table for sludge treatment provided in Table S1 of supporting information. Inventory tables for construction provided in Tables S2 and S3 of supporting information.

The data regarding outputs to water, electricity use and sludge production were obtained using the integrated UWS model. The model has been implemented in the WEST® simulation software (www.mikepoweredbydhi.com) and has been calibrated, validated and extensively used for measure evaluations in previous studies within the KALLISTO project[3–6]. The UWS integrated model used is made up of the integration of three separate models – for the catchment and sewer system, the WWTP and the river. The hydraulics of the sewer system were represented as tanks-in-series in a detailed hydrodynamic sewer model built in InfoWorks version 9.5 (www.innovyze.com). A conceptual catchment model based on empirical relationships was developed to generate the influent water quality, as water quality modules in sewer models are still not considered sufficiently reliable[5,38]. Event mean concentrations were applied for the CSO outputs into the river, derived from two years of monitoring data of CSOs. The ammonium (NH_4^+) loads were given by the model, whereas the P loads were estimated based on empirical measurements. The WWTP was modeled using the ASM2d biokinetic model modified by Gernaey and Jørgensen (2004)[39] and Takács et al. (1991)[40] for settler modeling. A surface water model has been set up to represent the Dommel River and its main tributaries as tanks-in-series, using the Duflow Modeling Tool (Stowa/MX.Systems 2004). The DUFLOW model is based on the one-dimensional partial differential equation that describes non-stationary flow in open channels and allows for the construction of 1D-hydrodynamic models including substance transport and processes. 70 river sections and 34 discharge points, representing (clusters of) CSOs and the WWTP effluent are combined together to describe the Dommel River system. The processes in the river model with DO and ammonium as state variables include

BOD decay, re-aeration, plant production and respiration, nitrification and settling of particulate organic matter[5]. The equations of the implemented model are described by ordinary differential equations and are solved with the use of the numerical variable step size VODE solver included in WEST®. For each of the measures and the base case the integrated model is simulating the climatic and influent variability occurring in the system for the duration of ten years[5]. The ten-year time series was developed using monitoring data of precipitation, sewer water levels and flow, and water quality. A description of the development and calibration of the integrated UWS model and the monitoring data used is provided in extensive detail Langeveld et al. (2013)[5].

The outputs to water are the net loads released to the environment at end of the studied reach from the WWTP and CSOs. In this manner, the purification capacity of the receiving water is taken into account in the estimated emissions. The performance of each of the measures with regards to their principal targets (enhance nutrient removal, reduce CSOs, reduce river DO depletion) can then be seen looking at the “Outputs to water at the end the river reach” (Table 2) of each measure. The specific contribution of CSO events to the total outputs to water is provided in detail in Table S4 of the supporting information for the base case and measure D (storage tanks). The total contribution of CSO events to the ammonium loads emitted appeared to be a small part of the overall emissions (less than 1.2%), as well as the contribution of the phosphorus loads (7.7% and 4.8% for the base case and measure D equivalently), attributed to the fact that the total CSO volume is less than 4% the WWTP effluent volume over 10 years. Less clear are the benefits provided by the river aeration measure (B),and are discussed in more detail in the Results and Discussion sections.

Impact assessment

The data from the inventories were introduced into the Simapro® 8.0.3 software (http://www.pre-sustainability.com/) which allows for the modeling and analysis of complete LCAs in a systematic and transparent manner. To calculate the environmental impacts the ReCiPe Midpoint (H) (1.09)[41] method was used as it is based on the latest recommendations by the LCA community[42–44]. Midpoint indicators were chosen over endpoint indicators as they assume less uncertainty[10] and they were considered sufficiently relevant by the decision maker of this case study (WdD). The evaluated categories were: Climate Change (CC), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Human Toxicity (HT), and Freshwater Ecotoxicity (FET). Short descriptions and units of equivalence for each of the categories are supplied in Table S5 of the supporting information. The characterisation factors for the major inputs and outputs are provided in Table S6 of the supporting information. The electricity mix of the Netherlands for the year 2008 was used in the impact assessment.

Uncertainty of inventory values

Four factors - use of aluminium sulphate, use of electricity, sludge production and effluent loads (including ammonium, nitrate and phosphorus) – were selected to be studied in an uncertainty analysis of the estimated impacts. A Monte Carlo analysis was performed in Simapro® 8.0.3. The studied ranges for the four factors were from -25% to +25% of the applied inventory value and assumed to be described by uniform distributions.

SHADOW PRICES FOR MONETARY WEIGHTING OF LCA IMPACT CATEGORIES

The estimation of shadow prices is most often based on an estimation of the damages caused by the release of a pollutant (damage costs) or by calculating the costs associated to its avoidance and removal (abatement costs). The sets of prices used in this study were presented by de Bruyn et al.[23] for the ReCiPe midpoint impact categories and about 400 other pollutants for the Netherlands. A wide range of literature sources was employed reporting on abatement and damage costs to produce three sets of prices:

Set 1: Based on abatement costs, characterised at midpoint level

Set 2: Based on damage costs, estimated at ReCiPe midpoint level

Set 3: Based on implicit damage costs, estimated using ReCiPe endpoint factors

The exact shadow prices for 2008 for all three sets and short commentary on how they were obtained are provided in the supporting information (Table S7). To convert the prices to their 2014 equivalents, use was made of the Harmonised Index of Consumer Prices (HICP) for the Eurozone. The HICP is an indicator of inflation and price stability compiled by the European Central Bank for all countries of the European Union. The average annual rate of change of the HICP for the Eurozone between 2008 and 2014 is provided in Table S8 of the supporting information, while the resulting estimates of the three sets of shadow prices for 2014 in Table S9. Due to the disparity between the values as well as possible theoretical preferences (e.g. damage versus abatement) all three sets were applied for weighting, as a means of addressing the uncertainty behind their estimations and their relative importance.

RESULTS

INTERPRETATION OF LCA RESULTS

It is clear that the measure of deeper clarifiers (A) outperforms the base case and the other three measures in its environmental impact in all categories besides Freshwater Eutrophication (FE) (Figure 2). This can be attributed to the higher emission of phosphorus to water from this measure. The FE category is also the only category where measure C (installation of a sand filter) performs the best due to its reduction of effluent phosphorus. The generally bad performance of measure C in comparison with the other measures in all other categories can be attributed to its increased use of aluminium sulphate and methanol. Similarly, measure D (construction of storage tanks) only performs better than the base case in the Marine Eutrophication (ME) impact category by reducing the amount of CSOs released in the Dommel River and thus the ammonium load. Measure B (in-stream aeration) does not appear to have any significant impact compared to the base-case scenario. Figure 3 presents in more detail the contributing factors to each impact category.

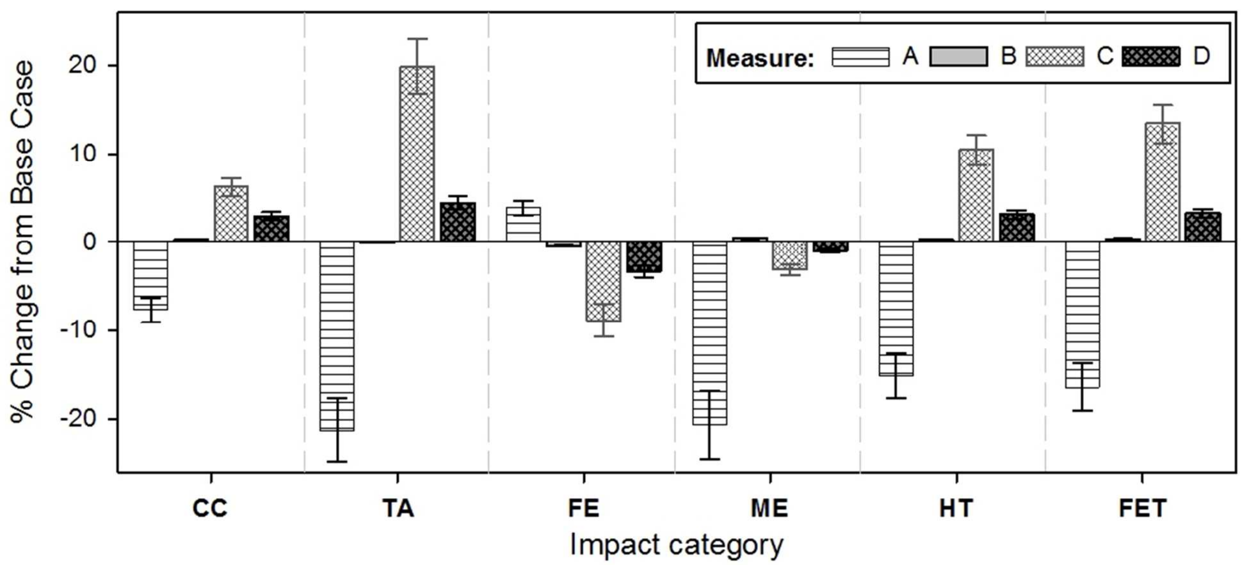


Figure 2 - Life Cycle Impact Assessment for ten years of system operation of the four assessed measures (A – Deeper clarifiers, B – In-stream aeration, C – Sand filter, D – Storage tanks) compared to the base case scenario and across the six evaluated impact categories (CC - Climate Change, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, ME – Marine Eutrophication, FET – Freshwater Ecotoxicity). The base case is supposed to be at a 0% of impacts. The error bars represent the 2.5^{th} and 97.5^{th} percentiles estimated during the uncertainty analysis, whereas the shaded bars represent the median.

Evidently and as expected, the effluent loads of all measures are the main contributing factor in the Freshwater and Marine Eutrophication categories. Across all other categories, significant effects appear to be caused by the use of aluminium sulphate, electricity and the production and treatment of sludge. This makes clear a trade-off between the increased use of resources and production of sludge and the reduction of phosphorus outputs to water, observed in all measures when compared to the base case. Regarding ammonium and nitrate, the trade-off is less clear.

For measures C and D the increased use of materials results in a nitrate and ammonium reduction equivalently. For measure A, these emissions are reduced even with a decreased material use. The trade-offs are less clear for measure B, as there is very little change in impacts when compared to the base case. The use of methanol as a carbon source by measure C also appears to have some effect, albeit lesser in comparison. In terms of construction, measure D causes the highest impacts. Nevertheless, in general the construction and maintenance of measures appear to have little relative effect on the total impacts in 10 years of operation (less than 2%). The effects of chemical transport seem to be of little significance (less than 0.5%).

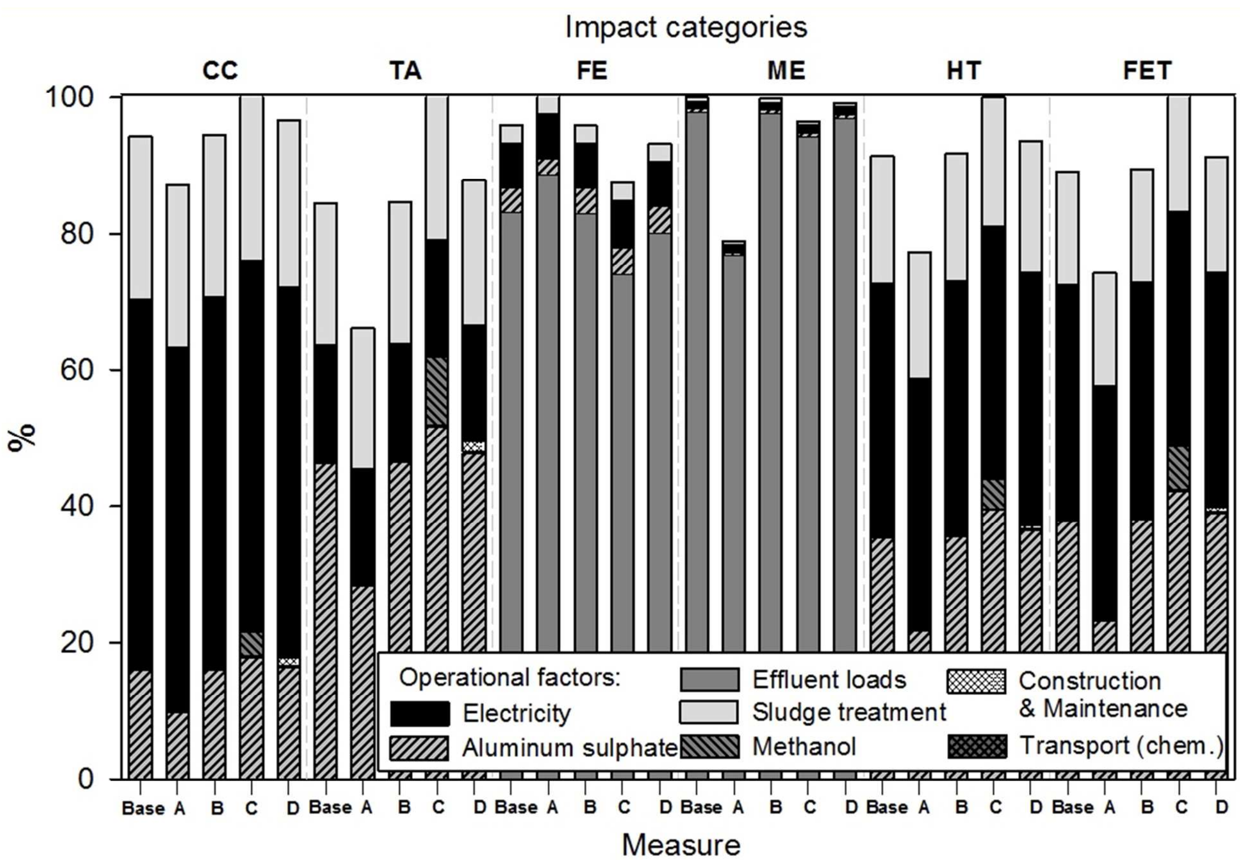


Figure 3 - Break-down of impacts for each of the investigated impact categories (CC - Climate Change, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, ME – Marine Eutrophication, FET – Freshwater Ecotoxicity) for base case and all measures (A – Deeper clarifiers, B – In-stream aeration, C – Sand filter, D – Storage tanks) after ten years of system operation.

After the uncertainty analysis of the four factors (use of aluminium sulphate, use of electricity, sludge production and effluent loads), the 5^{th} and 95^{th} percentiles of all the calculated impacts are presented for each of the measures across all categories in Figure 2. It can be seen by comparison that the performance of Measure A remains consistently preferable in all impact categories, barring Freshwater Eutrophication (FE).

SHADOW PRICES FOR WEIGHTING OF LCA IMPACT CATEGORIES

In order to attach weights of abatement and damage importance three sets of shadow prices were then applied to the environmental impacts estimated in the impact assessment phase. For Set 1, the estimated environmental costs can be an indicator of the environmental losses for the Dutch society stemming from its present and future emission goals. For Sets 2 and 3, the estimated environmental costs can be an indicator of the environmental losses for the Dutch society based on the damage caused by each pollutant. It is important to clarify at this point that the estimated environmental costs are originating and induced by the domestic, municipal and commercial activities producing the wastewater in this catchment rather than the treatment itself. In addition, the prices were estimated based on current abatement standards and therefore the results are meaningful if and only if applied for marginal changes in operation, such as applications of new measures.

This allows for the monetary quantification of the total life cycle impacts induced by each measure. Figure 4 presents the total life cycle environmental costs for all measures and base case. The error bars indicate the 2.5^{th} and 97.5^{th} percentiles of the induced environmental cost of each measure including the uncertainty of the inventory values. The measure with the best relative performance (Measure A) provides a reduction in environmental costs between 10 and

17% relative to the base case. Human Toxicity (HT), Marine Eutrophication (ME) and Climate Change (CC) appear to be driving the environmental costs for sets 1, 2 and 3 respectively.

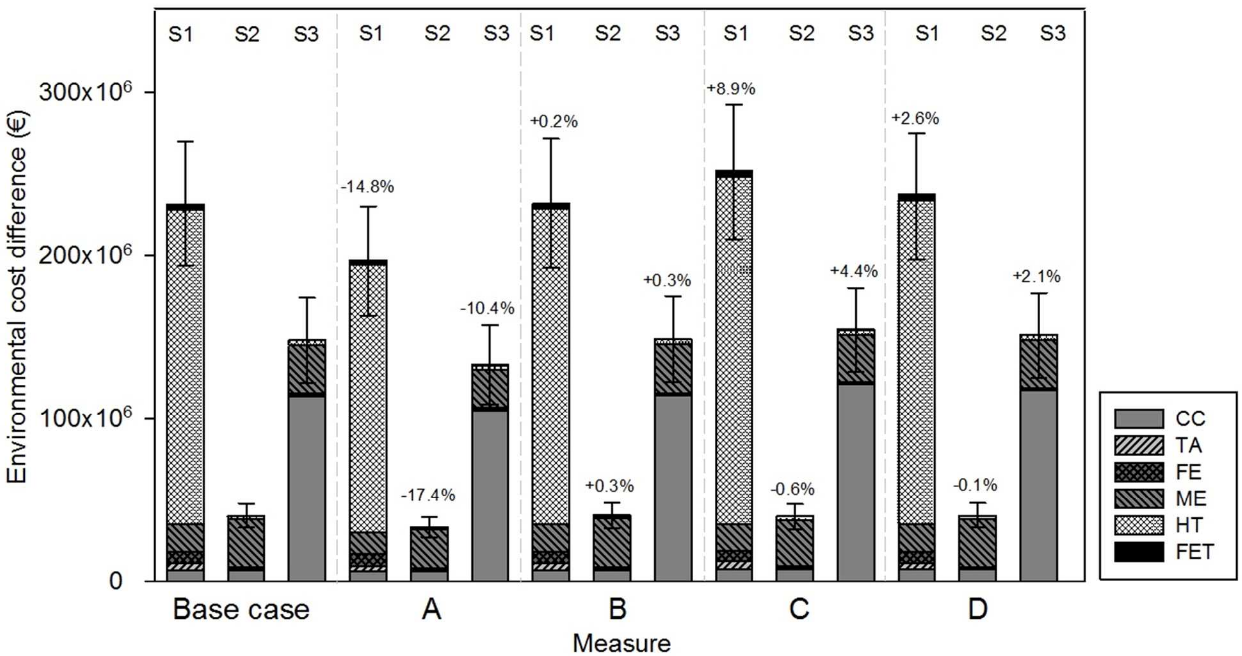


Figure 4 – Total Life Cycle environmental costs with respect to the emission goals of the Dutch society and their increase or reduction compared to the current base case (0€) after ten years of system operation. The error bars indicate the uncertainty on the total induced environmental cost of each measure (A – Deeper clarifiers, B – In-stream aeration, C – Sand filter, D – Storage tanks). The total environmental cost is the sum of all the environmental impacts per category (CC - Climate Change, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, ME – Marine Eutrophication, FET – Freshwater Ecotoxicity). S1, S2 and S3 represent the shadow price sets Set 1, Set 2 and Set 3 respectively.

As already mentioned, there seems to be an apparent trade-off between the environmental improvement of the reduced phosphorus load released and the damages brought about by the use of aluminium sulphate, electricity and sludge production. By use of shadow prices we present the environmental damage induced per factor (input, output and emission) per m^3 of treated wastewater. Accordingly, the evaluation of this trade-off is facilitated by the use of a single indicator. Table 3 lists the average environmental cost induced by each factor per m^3 of treated wastewater for the main inputs and outputs of this system. The numbers indicate a significantly higher environmental cost induced by the use of electricity and aluminium sulphate and the production of sludge per m^3 of wastewater, compared to the loads of phosphorus, ammonium and nitrate released as emissions per m^3 of wastewater.

Factor	Unit	€/(unit of factor)	(Total € per factor)/(m^3 of effluent)
Output - Effluent phosphorus	ton	5,364	0.0049
Output - Effluent ammonium	ton	3,580	0.0295
Output – Effluent nitrate	ton	1,021	0.0147
Input - Aluminium sulphate	ton	562.2	0.0603
Input - Transport (chemicals)	tkm	0.066	0.0003
Input - Methanol	ton	296.5	0.0094
Input - Electricity	kwh	0.223	0.0964
Sludge treatment	m3	4.371	0.0466

Table 3 - Estimated average (across the three sets) of environmental monetary cost: per unit of input/output; and total for input/output per m^3 of treated wastewater

DISCUSSION

The analysis investigates the environmental impacts of the measures by means of an LCA and then assigns relative weights of abatement importance (shadow prices) to each of the impacts. This facilitates: the ranking of impacts according to the present and future emission goals of the Dutch society; the relative ranking of the performance of each of the measures - through a single monetary indicator; and the prioritisation of efforts with regards to reducing environmental impacts for the decision maker (WdD in this case).

The life cycle evaluation of various impact categories allows for an investigation of the environmental impacts of each measure at the global scale. The environmental performance of the measures, compared against each other, seems to be fairly consistent during the uncertainty analysis. The applied ranges of [-25% to +25%] on the use of aluminium sulphate, electricity, sludge production and effluent do not appear to alter the relative performance of the four measures. More specifically, while measures C (sand filter) and D (storage tanks) have reduced outputs to water, their high use of materials - mainly aluminium sulphate and methanol - cause them to have the poorest overall environmental performance. The overall impacts from construction have appeared to be relatively low (less than 2%). Had salvage values of equipment and infrastructure not been accounted for, construction impacts would increase (at most by a factor of 3 for the case of civil constructions). Given the relatively low impacts however, this is not expected to affect the results of the analysis.

This issue brings about an obvious comparison between the use of such materials like aluminium sulphate and electricity and nutrient outputs to water. With the employment of shadow prices this task is facilitated, as the single monetary indicator allows for a direct comparison per m^3 of wastewater. Nonetheless, evaluating the trade-offs after the impacts have been weighted to the same unit simplifies the comparison between the two. The use of a monetary unit allows for their comparison with other aspects of operation and other economic activities[19]: for example, one can compare the environmental damage induced by the electricity required per m^3 of wastewater (now estimated in €**)** with the environmental damage induced by emitted pollutants per m^3 of wastewater (also estimated in €**)** and the actual market price paid to purchase the electricity. The much higher environmental cost of aluminium sulphate and electricity used per m^3 of wastewater in comparison to the environmental cost induced by phosphorus and ammonium per m^3 of wastewater can be very valuable information to prioritise operational decisions for the system. In the case of using alternative chemicals in place of aluminium sulphate or a different electricity mix with more renewable sources of energy, this trade-off and prioritisation would expectedly change.

With regards to the shadow prices used, it should be noted that they stem from both abatement efforts put into each environmental impact (Set 1) and estimated environmental damage costs brought about by each impact (Sets 2 and 3). That is to say that Set 1 represents costs with regards to how the society whence they are estimated and its policy perceive them to be; Sets 2 and 3 represent costs with regards to the value of environmental damage. Arguably, if sustainability is to be achieved, environmental policy should aim to equate the two and therefore reach an 'optimal' level of pollution where abatement equals damage. By example of one of the most significant impact categories in this study (HT) its shadow price value used is 2.51 €/kg1,4-DBeq. emitted to air for year 2014. The reported values based on damage costs are 0.022 and 0.042 €/kg1,4-DBeq. emitted to air for year 2014. Differences between the two damage-costs sets are also observed in the categories of CC, TA and HT. These discrepancies are attributed either to abatement costs being significantly higher than the damage costs generated with the release of some pollutants, due to the fact that future costs of Set 3 are not discounted[23] or due to the generally great uncertainty surrounding the valuation of some categories, particularly the HT category[45].

Measures B and D have already been investigated in previous studies of the system[3–6] with two principal aims: target the depletion of DO in the river for critical fauna species and reduce the release of CSOs. The studies have found significant improvements in reducing DO depletion in the river with the application of the river aeration measure (B), which showed clear advantages over the other measures[6]. However, the investigation of the environmental benefits provided by this measure is still limited when applying LCA, even when the most affected sections of the stream are included within the evaluation boundaries. This is mainly due to the fact that the impacts of DO depletion, particularly for river biodiversity, are not accounted for in LCAs. Even though attempts to develop and include biodiversity aspects in LCA have been on-going for more than a decade now, standardised methodologies are still in their primal stages[11,46]. Studies taking into account local specific conditions and characteristics of the receiving medium have not been very apparent in the literature – arguably due to limitations of this methodological framework[45,47]: impacts are regarded as generic in space, aggregated over long time horizons, strongly dependent on the chosen functional unit, and with distinct impact pathways so as to avoid double counting. Even though new approaches are being developed to improve on the resolution of geographical and temporal scales of characterisation factors, no general consensus has been reached yet [11]. In these efforts for improved regionalisation of life cycle impacts, deterministic modeling of the systems can be a valuable tool. As previously mentioned, to the best of our knowledge, we consider this the first LCA study for an UWS that employs a deterministic integrated model taking into account hydraulics as well as biochemical processes of the whole system.

Inherent limitations to the modeling process of UWSs also exist, mainly regarding model uncertainty or the lack of certain processes in the WWTP and the sewer (e.g. N_2O production) or pollutants (e.g. micro-pollutants) in current tools. This is mainly due to the fact that there is not yet a general consensus on a deterministic model for these processes. Modeling uncertainty for this integrated model and system has already been studied during other studies[6,48] on the same system. The inclusion of additional processes and pollutants would expectedly increase the estimated impacts, particularly in the Climate Change (CC) category with added greenhouse gas emissions and in the toxicity categories with the inclusion of micro-pollutants and heavy metals. Furthermore, the emission of suspended solids has demonstrated a reduction with the application of measures A and D during the analysis. However as no characterisation factor was available these loads were not taken into account during the impact assessment.

On these grounds, this investigation is meant to complement the other studies performed for this particular UWS, principally looking into the most cost-effective upgrades to reach qualities set by the EU Water Framework Directive (WFD) at the Dommel River[6]. Measure B (river aeration) has a clear advantage in this respect[6] (most cost-effective reduction of DO depletion and NH_4^+ peaks). On the other hand, measure D (storage tanks) with its significantly higher costs and poor performance with regards to the WFD objectives[6] is clearly inferior to the other measures – a result also supported by the outcomes of the LCA presented in this study. Exact cost figures cannot be provided at this moment, but preliminary cost estimates indicate that the installation of the sand filter (measure C) and the deepening of secondary clarifiers (measure A) have costs of the same magnitude, yet significantly lower investment costs than measure D and slightly higher than the installation of river aerators (measure B).

The results of this analysis are meant to complement the investigations for the identification of the most appropriate measure with weighted life cycle impacts of each of the options. The use of shadow prices to weight the impact categories simplifies the process of prioritising for the water management agency as costly and time-consuming methods of gauging social perceptions are avoided.

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SUPPORTING INFORMATION

Supporting information includes: inventory tables for sludge treatment (dewatering and incineration) (S1), construction of measures (S2 & S3), CSO contribution to outputs to water (S4), description of impact categories used in LCA (S5), characterisation factors used during the Impact Assessment phase (S6), estimated shadow prices for 2008 and commentary on how they were obtained (S7) and annual average rate of change of the Harmonised Index of Consumer Prices (HICP) (S8). This information is available free of charge via the Internet at http://pubs.acs.org/.

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