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Improving eco-efficiency of Amsterdam water supply: A LCA approach

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ABSTRACT

Amsterdam Water Supply produces 70 million m^3 drinking water per annum in its Leiduin plant and is considering increasing the plant capacity to 83 million m^3 per annum. The existing plant is a conventional surface water treatment plant. For capacity expansion, two alternative treatment schemes, each using reverse osmosis, are being considered. In these considerations, environmental impact plays an important role. Environmental impact of the plant was assessed with life cycle analysis. The total impact for annual production from the existing and the two future alternative schemes are 2.89E+04, 3.65E+04 and 3.44E+04 eco-points respectively. The significant impact contributors are the use of conventional energy, softening and the granular activated carbon process. Impact reduction up to 73% may be achieved by the use of 100% green energy, the use of an alternative chemical [Na_2CO_3 in place of NaOH] in the softening process and doubling the carbon run time.

Key words | eco-indicator, environmental impact, life cycle analysis, reverse osmosis, sensitivity analysis, water treatment

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INTRODUCTION

In recent years, great concern has been expressed to protect the environment from pollution. Industries cause degradation of the environment by release of harmful substances to air, land and water. These problems concern both the developed and the developing nations.

A drinking water industry may affect the environment by depleting water resources, using energy for transport of water and chemicals for production of water free from pathogens and impurities. The release of harmful substances to the environment during the production of conventional energy impacts on global warming, biotic and abiotic resources, acid rain, etc. Similarly, the production of chemicals and their consumption by the water industry have environmental consequences.

In this paper, the environmental impact of Amsterdam's Leiduin water treatment plant is estimated with life cycle analysis (LCA). The processes causing high environmental impact in both the existing treatment scheme and in the future treatment schemes are identified. Finally, impact reduction options are defined for both the present and the future treatment scheme.

BACKGROUND

Amsterdam water supply

Existing treatment scheme of Leiduin Plant

The drinking water supply of Amsterdam dates back to 1853. It was the first water utility in The Netherlands. Initially, the groundwater available in the sand dunes located west of Amsterdam was extracted and was supplied after treatment. When the lowering of groundwater tables was confirmed, the dunes were recharged with pretreated water, brought in from the River Rhine over a

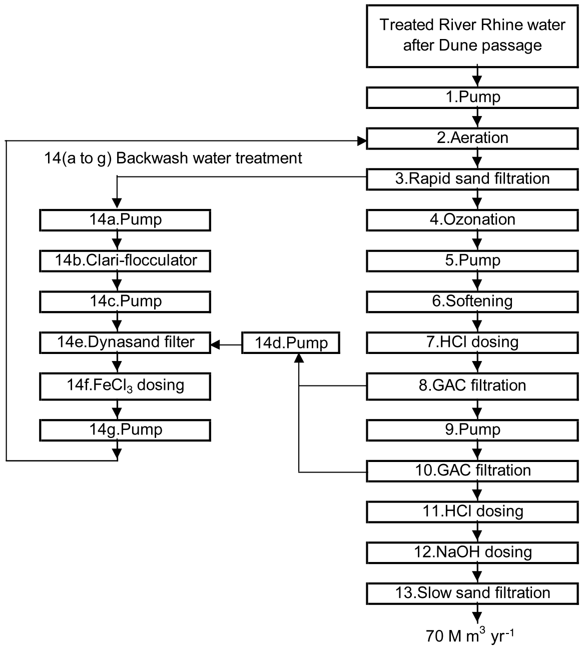

Figure 1 | Flow chart of the existing treatment scheme of the Leiduin plant (Van der Hoek & Groot 1999).

distance of 55 km, in order to maintain the hydrological balance in the dunes (Van der Veen 1985).

The water, extracted from the dunes, is treated in the Leiduin plant. This plant, with an annual production capacity of 70 million m^3, is a surface water treatment plant focusing on the removal of pathogens, micro-pollutants, pesticides and nutrients. In The Netherlands, conventional treatment consisting of coagulation, sedimentation and chlorine disinfection is no longer acceptable because of the formation of disinfection by-products caused by chlorine and also the occurrence of pesticides (Kruithof *et al*. 1994). Therefore, the Leiduin process consists of aeration, rapid sand filtration (RSF), ozonation (O3), softening, granular activated carbon (GAC) filtration and slow sand filtration (SSF). The backwash water from the rapid sand filters and the carbon filters is treated and returned to the aeration. The flow chart is shown in Figure 1 (Van der Hoek & Groot 1999).

Future treatment scheme

Amsterdam Water Supply will increase the capacity of the Leiduin plant from 70 million to 83 million m^3 $year^{-1}$ in the near future. For the expansion of capacity, Amsterdam Water Supply is considering the application of reverse osmosis (RO) as an alternative to the extension of dune infiltration by surface recharge of pretreated Rhine water, which is no longer allowed for environmental reasons. Two alternative treatment lines, both incorporating RO but different in the extent of pretreatment of RO feed water (one scheme equipped with an additional ozonation and GAC filtration step), have been studied in pilot plants for several years (Van der Hoek *et al*. 2000).

The expansion lines of the two alternative future treatment schemes for production of 13 million m^3 $year^{-1}$ are shown in Figure 2 (Van der Hoek & Groot 1999).

Environmental impact assessment with LCA

Life cycle analysis (LCA) is defined as a process to evaluate the environmental burden associated with a product or process by identifying and quantifying the energy and materials used, the wastes released into the environment and the impacts of those energy and materials used on the environment during the entire life cycle of a product or process (Lindfors *et al*. 1995). The life cycle encompasses the stages of extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, final disposal and all transport involved.

The LCA consists of four steps (ISO 1997), which are shown in Figure 3. The first step is the goal and scope definition of LCA. The intended application of LCA is defined in the goal definition step. The results of LCA may be applied for comparison of two or more different products/processes fulfilling the same function or for identification of improvement possibilities in further development of existing products/processes or design of new products. The following specifications are included in the scope definition of a LCA.

- The functional unit
- The system to be studied
- The types of impact and methodology of impact assessment
- Data requirement
- Assumptions, limitations, data quality, etc.

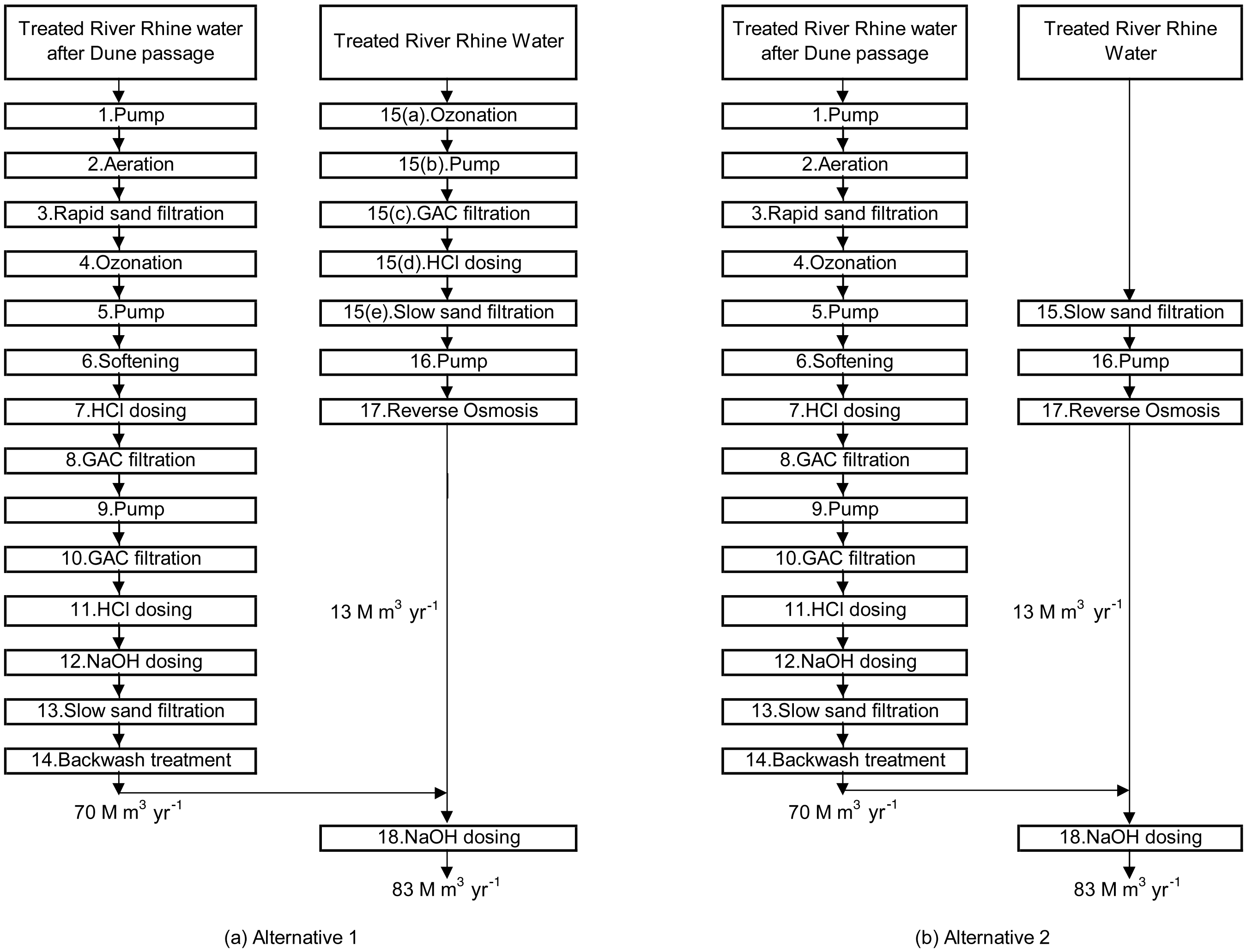

Figure 2 | Alternative treatment schemes for annual production of 83 million m^3 water. (a) With expansion treatment line consisting of ozonation, GAC and slow sand filtration, and (b) with expansion treatment line consisting of slow sand filtration only for reverse osmosis pretreatment.

The functional unit of a LCA related to drinking water could be 1 m^3 of drinking water produced. The system boundaries define which unit processes related to the product or process under study are to be taken into account in the LCA.

The second step of LCA is the inventory phase. All input and output data collected in the inventory phase are normalised to the functional unit. The input and output data include the use of materials and energy and releases to air, land and water associated with the processes.

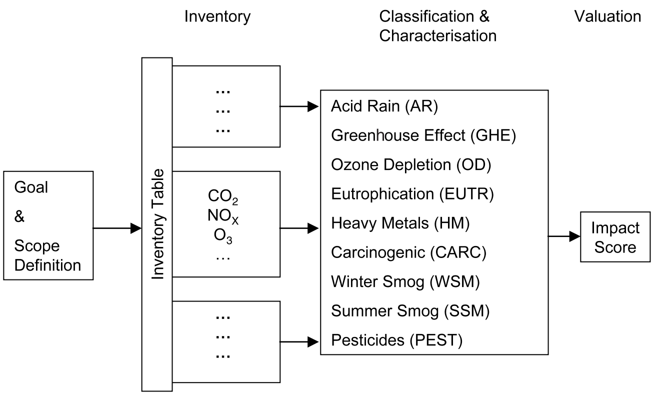

Figure 3 | Life cycle analysis steps of impact assessment.

Impact assessment is the third step in LCA. In this step, the environmental impacts of the inventory data are identified, classified and quantified according to their impact on the environment and human health (Heijungs & Hofstetter 1996). This step has two sub steps such as classification and characterisation.

Many impact categories have been proposed for life cycle impact assessment such as abiotic resources, biotic resources, land use, global warming, ozone layer depletion, ecotoxicological impacts, human toxicological impacts, photo chemical oxidant formation, acidification and eutrophication.

In the classification step, the input and output data are sorted into categories according to the impact they have on the environment. Some data may be grouped in more than one impact category. For example, NOx emissions are toxic, acidifying and cause eutrophication.

The impact of each environmental emission contributing to a certain impact category is calculated using an equivalency factor, which expresses the impact of the emission relative to the impact of the same amount of a reference emission. The mathematical translation of this approach, known as the characterisation step, is as follows (Heijungs *et al.* 1997):

$$\text{Impact score}_{\text{category}} = \Sigma_{\text{type}}\ \text{equivalency factor}_{\text{category, type}} \times \text{intervention amount} \quad (1)$$

For example, if the environmental interventions are atmospheric emissions of 12 kg CO_2 and 4 kg CH_4, and the global warming equivalency factors are 1 kg CO_2-equivalent per kg CO_2 and 11 kg CO_2-equivalent per kg CH_4, the global warming effect score is:

(1 kg CO_2-equivalent per kg $CO_2 \times 12$ kg CO_2) + (11 kg CO_2-equivalent per kg $CH_4 \times 4$ kg CH_4) = 56 kg CO_2 equivalent.

The last step in life cycle impact assessment is called valuation and is meant to interpret the data gathered in terms of what these really mean. Valuation may be done by the eco-indicator approach developed and used in The Netherlands.

The Dutch Eco-Indicator 95

An eco-indicator is a value that expresses the environmental impact of a product or a process or service in a single figure. The value is based on the LCA method. In the Eco-indicator 95 approach, valuation has two steps. The first is normalisation and the second is weighting.

The environmental effects of each of the impact categories are normalised relative to a reference. The reference used to obtain the normalisation factors for each of the impact categories is related to the environmental impacts in each of the impact categories that an average European person causes in one year. This step results in impact scores for each of the categories. In the second step, the impact scores are multiplied by weight factors to get impact scores or eco-points for each impact category. The impact scores of all impact categories can be aggregated to get one single score or eco-point for each unit process and product. The weight factors have been determined from the distance-to-target principle. In this principle, it is assumed that the distance between the current level of an impact and the target level is representative of the seriousness of the emission (Goedkoop *et al.* 1996).

Sensitivity analysis

Sensitivity analysis is the systematic procedure for estimating the effects of variations in the values of impact parameters of a model on the output of the model. Sensitivity analysis may be done by systematically changing the values of different input parameters. A more proper way to do sensitivity analysis is to change the input parameters systematically by using Monte-Carlo simulations (Jensen *et al.* 1997).

By defining sensitivity as the percentage change in output 'I' to the percentage change in input 'P', a dimensionless value of sensitivity is obtained for each parameter. The sensitivity 'S' is calculated by the following expression:

$$S = \left(\frac{\Delta I/I}{\Delta P/P}\right) \times 100 \quad (2)$$

The sensitivity of parameters can be ranked according to their sensitivity values. A higher 'S' value means higher sensitivity. For parameters having a high 'S' value, a slight change in the parameter value will give a high change in impact. In other words, impact reduction may be achieved by changing the value of the parameters that have high 'S' value.

MATERIALS AND METHODS

Impact assessment with LCAqua

LCA of the Leiduin water treatment plant was carried out with the help of the software LCAqua 2.0 developed by Kiwa N.V. Research and Consultancy, The Netherlands. The software follows the Dutch Eco-indicator 95 approach and environmental impact categories such as acid rain, greenhouse effect, ozone layer depletion, eutrophication, heavy metals, carcinogens, winter smog, summer smog and pesticides are included (Kiwa 1998).

The software calculates environmental impact as eco-point per m^3 of water produced for each unit process as well as impact in terms of the aforementioned impact category. The use of green energy, i.e. the energy produced by wind and non-polluting on the environment, can also be incorporated in the software. In order to use LCAqua, the first step is to draw the process flow chart. A mass balance of water flowing through the system is then incorporated in the flow chart. Some of the input parameters of the unit processes, which are also input to the software, are given in Table 1. The values of the parameters are those from the plant's production in 1996 and from the pilot study in case of the expansion lines (Van der Hoek & Groot 1999). The normalisation factors and weight factors are as per Kiwa (Kiwa 1998).

Sensitivity analysis

The procedure for sensitivity analysis is given below.

- For a selected process parameter, ten values are generated in the range of $\pm 50\%$ of the parameter value by Monte-Carlo simulation.
- The total impact from the treatment scheme, comprising all the unit processes, is calculated by LCAqua 2.0 for each generated value of the selected process parameter, keeping the remaining parameters constant.
- The total impact is plotted as a function of the selected and simulated process parameter. A mathematical relation is obtained from the plotted trend line.
- The value of $\frac{\Delta I}{\Delta P}$ is calculated from the mathematical equation obtained in the preceding step.
- Sensitivity 'S' is calculated by equation (2).

RESULTS AND DISCUSSION

Impact assessment

The total impact from the existing and two alternative treatment schemes for 1 m^3 production as well as annual production is shown in Table 2. The impact increases by about 26% in case of Alternative 1 and about 19% in case of Alternative 2 with an increase in annual production of about 19%.

In Alternative 1, the impact from the 70 million m^3 production line is 2.55E + 04 eco-point while the impact from the 13 million m^3 expansion line is 1.10E + 04 eco-point. The corresponding impacts from the two production lines of Alternative 2 are 2.55E + 04 and 0.89E + 04 eco-point, respectively. So, for 1 m^3 production of water in the expansion line, impacts from the expansion lines of Alternative 1 and Alternative 2 are 8.46E-04 and 6.84E-04 eco-point respectively, which are greater than the impact from the existing scheme (4.14E-04 eco-point). The higher impact from the expansion lines compared with the existing scheme is due to the application of RO.

The impact from the individual process steps in the existing and alternative treatment schemes is shown in Figure 4. Processes 1–14 are part of the existing treatment scheme and processes 15–18 comprise the expansion line of the alternatives. The major environmental impact in the existing and also in the future two alternative schemes is

Table 1 | Some input parameters of LCAqua

Unit process	Parameter	Quantity	Unit
Pump	Energy consumption	0.051	kWh m^{-3}
	% conventional energy	100	%
Softening	Water loss	0	%
	Hardness of raw water	2.36	mmol l^{-1}
	Hardness of finished water	1.76	mmol l^{-1}
	Sand consumption	373,300	kg $year^{-1}$
Activated carbon filtration	Water loss	0.02	%
	Number of filters	16	filters
	Bed height	2.5	m
	Bed surface area	58	m^2
	Organic carbon removal	1	mg l^{-1}
	Density of activated carbon	380	kg m^{-3}
	Number of regeneration	6	No.
	Carbon run-time	24	months
	Carbon loss in regeneration	10	%
	Backwash water	0.51	%
	Oxygen dosing	1	mg O_2 l^{-1}
NaOH dosing	NaOH concentration	100	weight %
	NaOH dosing	8.54	mg l^{-1}
HCl dosing	HCl concentration	36	weight %
	HCl dosing	16.75	mg l^{-1}
Reverse osmosis	Water loss for recovery of 85%	2.67	%
	Membrane weight (type TFC)	0.0564	kg m^2
	Membrane renewal (type TFC)	12,000	m^2 $year^{-1}$
	Detergent	0	kg $year^{-1}$
	HCl for reverse osmosis	3,360	ton $year^{-1}$
	HCl concentration	30	weight %

Table 2 | Impact from the existing and alternative treatment schemes

Treatment scheme	Annual production capacity (million m^3)	Impact: Eco-point/m^3 production	Impact: Eco-point/annual production
Existing	70	4.14E-04	2.89E + 04
Alternative 1	83	4.40E-04	3.65E + 04
Alternative 2	83	4.15E-04	3.44E + 04

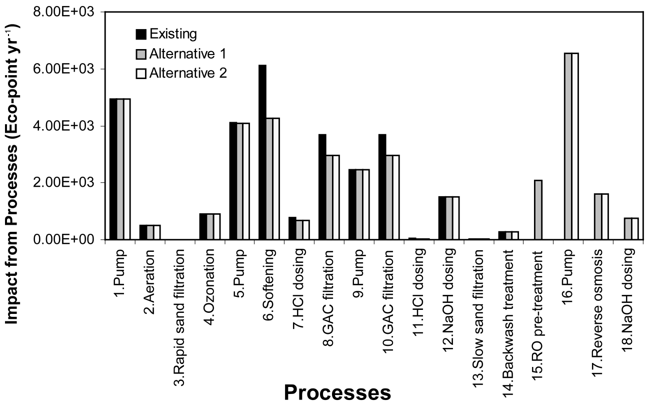

Figure 4 | Impact from the individual process steps in the existing and future treatment schemes.

caused by the use of conventional energy, the softening process and the activated carbon filtration process. Together these contribute about 92% of the impact of the existing scheme, 87% of the impact of Alternative 1 and 86% of the impact of Alternative 2. The use of conventional energy is responsible for about half of the total impact. As a percentage of total impact, it is about 46%, 55% and 57% in the existing, Alternative 1 and Alternative 2 schemes, respectively.

Impact from the softening process in Alternative 1 and 2 is lower than that from the existing scheme (Figure 4). The reason is that, in the 70 million m^3 $year^{-1}$ production line of the two alternatives, the hardness is reduced from 2.4 mmol l^{-1} to 1.76 mmol l^{-1}, whereas in the existing scheme the hardness is reduced from 2.4 mmol l^{-1} to 1.5 mmol l^{-1}. In both alternatives, a final hardness of 1.5 mmol l^{-1} is attained by blending with the water produced in the expansion line, which is softened by RO. Some of the existing GAC beds will be used in the expansion line. This shows a lower impact from the GAC filtration (process no. 8 and 10) in Alternative 1 and 2 compared with that in the existing scheme.

Impacts from processes such as rapid sand filtration, slow sand filtration and the treatment of reverse osmosis feed water by slow sand filtration are negligible. Dosing of chemicals (HCl and NaOH) adds about 8% of the total impact in each of the three schemes. The backwash treatment process causes less than 1% of the impact.

Figure 5, showing impacts from the three schemes in terms of the various environmental effect categories, indicates that for each of the three schemes, the effects of acid rain and heavy metals dominate. This could be the result of the use of conventional energy. The effects of the three treatment schemes on eutrophication are the lowest of all impacts and there is no pesticide effect.

The overall environmental impact of the Leiduin plant is the result of intensive treatment processes such as softening and biological activated carbon filtration. These processes are necessary for the preparation of a high-quality drinking water from the dune infiltrated water from the river Rhine, a highly polluted river in Western Europe.

Sensitivity analysis

Sensitivity analysis was carried out to determine the effect of variations in the chosen process parameter values on the total environmental impact of the system under investigation. The relationship between the simulated values of the process parameters and the total impact from the existing scheme is shown in Figure 6. Generally, the steeper the curve, the higher the potential to affect the environmental impact by changing parameter values. The mathematical relations of the impact versus process parameters and the R^2 values for the three schemes as well as the sensitivity values for the two future alternative schemes, are given elsewhere (Mohapatra 2000).

The sensitivity values of the process parameters of the existing treatment scheme are shown in Table 3. The

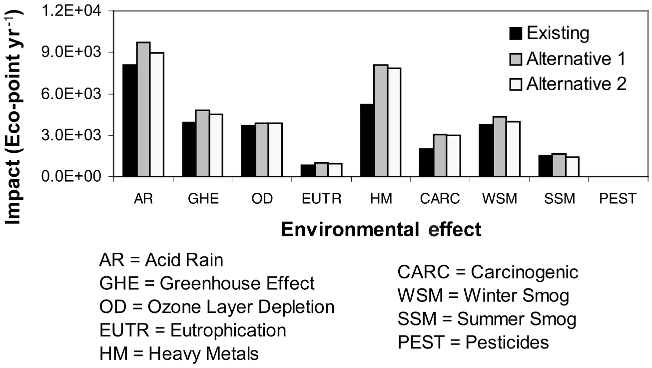

Figure 5 | Environmental effect profile for an annual production of 70 and 83 million m^3 respectively for the existing and the future alternative treatment schemes.

Table 3 | Sensitivity values of process parameters in the existing treatment scheme

Parameter	Quantity	Unit	Sensitivity
Hardness after softening	1.5	mmol l^{-1}	36.8
Carbon run-time	24	month	26.1
Pump energy	0.051	kWh m^{-3}	17.0
Number of carbon regeneration	6	number	7.5
NaOH dosing	8.54	mg l^{-1}	5.2
HCl dosing	19.6	mg l^{-1}	2.8

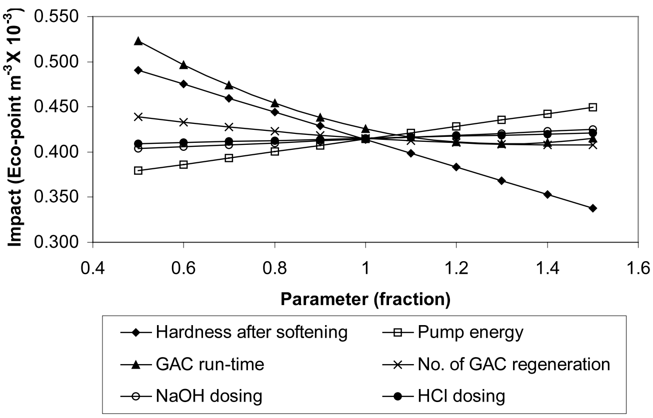

Figure 6 | Environmental impact as a function of the values of six process parameters in the existing treatment scheme.

impact assessment results indicate that energy, GAC filtration and softening together contribute 86–92% of the total impact. Sensitivity values indicate that GAC filtration, softening and pumping energy have a high potential for reducing the impact.

Impact reduction

The following impact reduction options are identified:

- Use of green energy
- Use of alternative chemicals [$Ca(OH)_2$ and Na_2CO_3] in the softening process to achieve the same hardness removal, and
- Changing the process parameters in the GAC filtration process (carbon run-time and number of times carbon is regenerated).

Estimates of the percentage impact reduction in the three schemes with the above three options are given in Table 4. The total impact reduction by the three steps in each of the three schemes is about 73% (Figure 7).

Cumulative eco-point profiles of the three schemes before and after impact reduction by the three options mentioned are shown in Figure 8. An effective way to improve the three schemes environmentally is the use of green energy. At present Amsterdam Water Supply uses 15% green energy. In the future, green energy use is likely to increase. Due to effective negotiations, Amsterdam Water Supply is able to procure green energy at the same cost as conventional energy. This implies reduction in impact of up to 43% in the existing plant by using 100% green energy at no additional costs.

Presently, NaOH is used in the softening process. This chemical is available in liquid form. Transport, storage and dosing are easy relative to the alternative chemicals, Na_2CO_3 and $Ca(OH)_2$. Of the two alternative chemicals, Na_2CO_3 causes less impact compared with $Ca(OH)_2$ but introduction of a new chemical may have other drawbacks. In terms of water quality, using Na_2CO_3 will result in a higher Na^+ content, while using $Ca(OH)_2$ will result in a low HCO_3^- content in the finished water. However, the concentration in the

Table 4 | Potential impact reductions in the existing treatment scheme and in the alternatives

	% Impact reduction			
Treatment scheme	**100% green energy**	**Doubling carbon run-time**	**Alternative chemical (Na_2CO_3) in softening**	**Total reduction (%)**
Existing	43	13	17	73
Alternative 1	53	10	10	73
Alternative 2	55	8	10	73

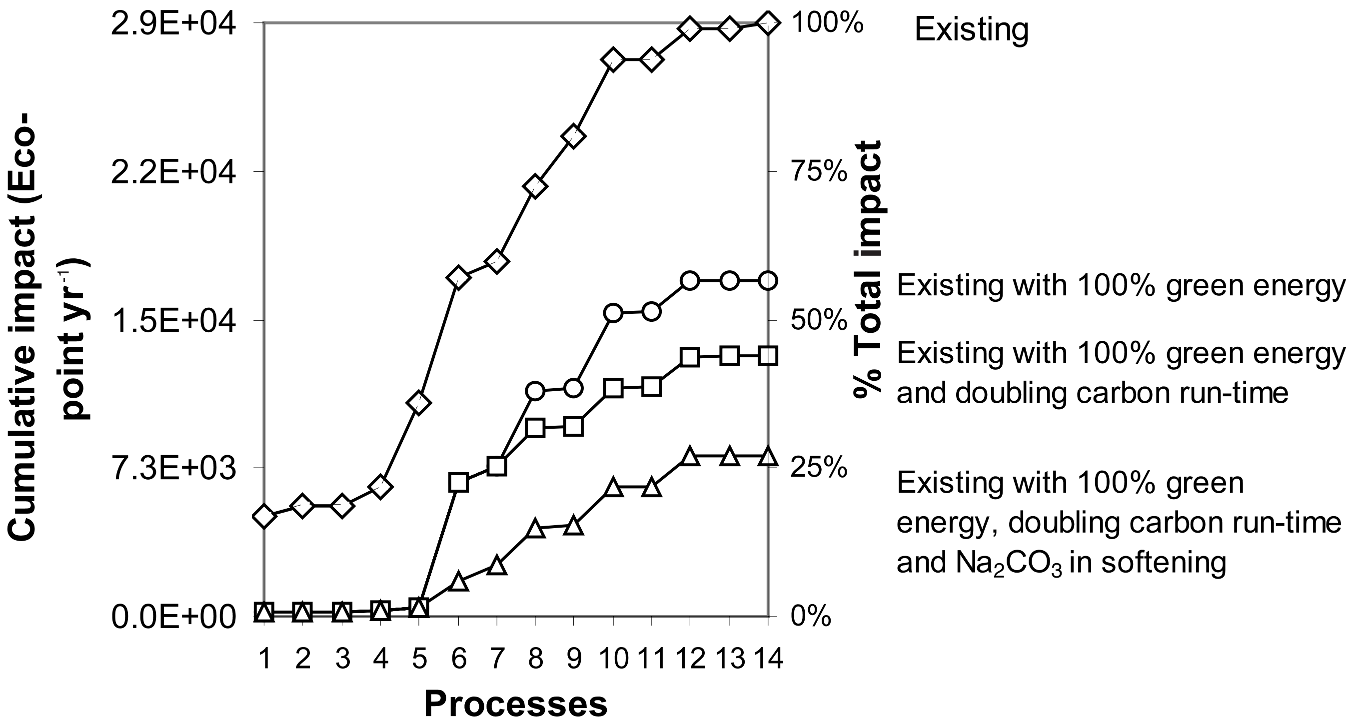

Figure 7 | Options for the reduction of impact from the existing treatment scheme.

finished water will still comply with the Dutch Drinking Water Directive.

The activated carbon beds are regenerated after 24 months of continuous use. Doubling the carbon run-time will reduce the cost of maintenance. The feasibility of doubling the run-time depends on the performance of the GAC beds to treat water effectively. Therefore, the effect of doubling the carbon run-time on quality of water needs to be assessed. The increase in carbon run-time is only permissible as long as it has no negative effects on water quality. The effect on water quality can be tested only in pilot plant research. Based on the pilot plant research conducted at Amsterdam Water Supply, it was concluded that extending the run-time from 1.5 to 2.5 years has no negative effects on water quality. Instead, there is a saving of up to US\$500,000 year^{-1}.

The existing and the two alternative schemes result in a finished water quality in compliance with the

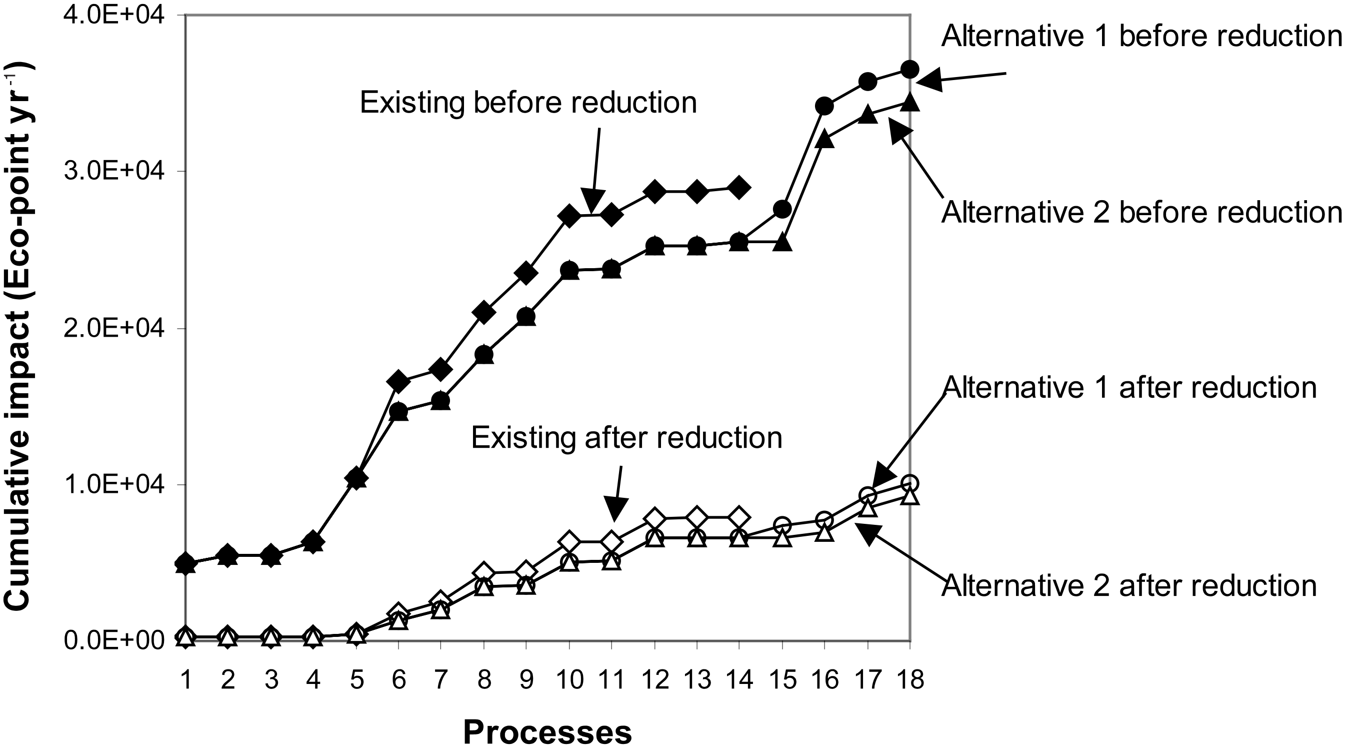

Figure 8 | Cumulative eco-point profiles of the existing and the two alternative schemes before and after implementing the impact reduction options: using 100% green energy, doubling the carbon run-time and using Na_2CO_3 in the softening process.

Dutch Drinking Water Directives. Both the alternative schemes produce similar finished water quality since the expansion line in each comprises reverse osmosis, a process providing a more or less absolute barrier for micro-pollutants. However, a distinction can be made between the expansion lines in terms of the concept of a barrier for disinfection and micro-pollutants. The expansion line in Alternative 1 comprising O3-GAC-SSF-RO provides a dual barrier, O3-GAC being the first barrier and RO the second. The expansion line in Alternative 2 comprising SSF-RO provides only a single barrier. The Alternative 1 scheme is preferred by Amsterdam Water Supply, as the 'dual barrier concept' is very important for treatment of surface water.

The environmental effect profiles of the existing scheme before and after several impact reduction measures are shown in Figure 9. Heavy metals (HM) and carcinogenic effects (CARC) are almost completely reduced with green energy use. The significant environmental effects of the treatment plant, i.e. the acid rain (AR) and ozone layer depletion (OD) are only partially reduced.

It must be borne in mind that LCA accounts for global impacts only, meaning that local effects, such as the

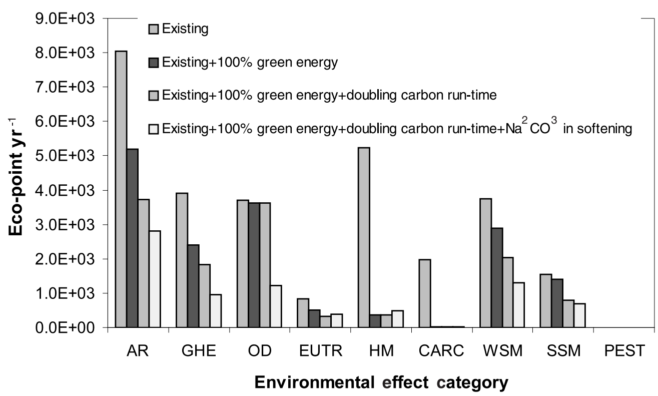

Figure 9 | Environmental effect profiles of the existing treatment scheme before and after impact reduction.

discharge of the brine of the RO process, are not taken into account. Further, in this study the LCA boundary has been limited to the Leiduin treatment plant. Softening is seen to cause impact on the treatment plant side. On the other hand, supply of soft water reduces lead and copper dissolution in the distribution system, reduces consumption of detergents and reduces scaling which would otherwise adversely affect the heat transfer in heating equipment. Therefore, at the consumer side, there is a positive impact on the environment as a result of softening of water (Regueira 2000).

CONCLUSIONS

The following conclusions emerge from the impact study of the Leiduin plant:

- The use of conventional energy, GAC filtration and the softening process are major contributors to the overall impact from the existing and the two alternative schemes for the future treatment process at Leiduin Water Treatment Plant.
- The processes causing the major impact also show a high impact reducing potential.

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