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Life cycle assessment of drinking water and rain water for toilets flushing

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ABSTRACT: Systems using rain water or reducing water consumption have been recently developed as an alternative to conventional toilet flushing. This article aims to quantify the environmental impacts of these systems and to identify key factors in each system. A Life Cycle Assessment (LCA) has been carried out to reach these goals.

Scenarios with conventional water supplies present a lower energy requirement and lower environmental loads than recuperation scenarios. Sensitivity analyses indicate that recuperation is energetically favourable only when the energy required for the water supply is higher than 0.8 kWh/m^3, assuming a complex drinking water treatment. The study also reveals that low-flow toilets should be promoted as they lead to significant reductions in energy consumption and in pollutant emissions. A combination of a conventional water supply and low water consumption (scenario CONVeco) is advantageous for all environmental problems.

INTRODUCTION

Regions where water shortages may occur are limited in countries like Switzerland. However, unpolluted water is becoming more of a scare resource and the cost of water supply and treatment is constantly increasing. A moderated use of water is therefore recommended by the Swiss water protection regulation [1]. Different ways to diminish water consumption have been proposed, among them the use of low-flow toilets (called 'economic toilets' in this article). Moreover, rain water recuperation has been proposed as an alternative to its evacuation in the sewage system when infiltration is not possible. Different systems using rain water or reducing water consumption have been recently developed as an alternative to conventional toilet supply.

Rain water recuperation is a much debated subject. For its supporters, it does not make any sense to transport water on long distances, to treat it, and then to use it for toilet flushing. Instead, rain water could be used as part of a sustainable management of water resources [2,3]. For the opponents of rain water recuperation, its use is questionable in areas where there is no shortage of water. Their arguments are that the energy savings are illusory and that some hygienic problems may occur [4].

No study with an overall view of the issues involved on the whole chain of water production and treatment has ever been presented, neither by supporters nor by opponents of the rain water recuperation. To fill this gap and to go beyond the dogmatic position concerning this subject, the research programme CYCLEAUPE I has been launched following a request from the Swiss Environmental Protection Agency (BUWAL). The environmental tool Life Cycle Assessment (LCA) has been selected, as it allows for a quantification of the environmental burdens on the whole chain of processes required for toilet flushing. The structure of this article is based on the four steps of an LCA, which are: goal definition, inventory, impact assessment and interpretation analysis [5]. The goal definition defines the aim and the scope of the study as well as the functional unit and the system boundaries. The inventory lists the pollutant emissions and the consumption of resources. The impact assessment evaluates the environmental impact of these emissions on both humans and ecosystems. The interpretation analysis finally discusses the results and carries out some sensitivity analyses.

GOAL DEFINITION

Aims

The study aims at quantifying the environmental impacts of systems which are using rain water or are reducing water consumption for toilet flushing. The advantages and disadvantages of these systems are identified. Conditions making each system interesting from an environmental point of view are also determined, as well as the processes responsible for the main environmental burdens.

It should be noted that this study was restricted to rain water use for toilet flushing. Garden watering is only studied in a sensitivity analysis and washing machine supply will be considered in a further project.

Scenarios

The main five scenarios presented in this article are described below. Variants of the drinking water treatment and supply, as well as variants of the storage tank and the pump, are discussed in the sensitivity analysis. (See ‘Comparison with the economic study’ below.)

Conventional scenario: CONV

This scenario is characterised by a conventional water supply for toilets. Rain water is infiltrated in the soil. As reference values for this study, we selected:

- A complex drinking water treatment (treatment with chlorine, activated carbon, ozone and flocculation).
- A Swiss average energy requirement of 0.35 kWh/m^3 for the water supply [6].
- A classic wastewater treatment plant.
- A two-level house (two families of four persons per level, 100 m^2 of living area for each family).
- A Swiss electricity supply for the water supply, as well as for the drinking water and the wastewater plant. Major energy sources for Swiss electricity generation are hydroelectricity (58.7%) and nuclear energy (38.3%) [7].
- Conventional toilets are characterised by a water consumption of 9 L/flushing [8]. An average of six flushings per person per day is assumed, leading to a water consumption of 54 L/personal-day.

Recuperation scenario: REC10

In this scenario, rain water is stored in a individual storage tank made of polyester and pumped towards the toilets (Fig. 1). Other additional sanitary installations such as filter pipes are required. As calculated in [9], a 10 m^3 storage tank leads to a recovery fraction of 57%. This fraction means that 57% of the water consumption for toilet flushing can be provided by the recuperation system; 43% of the consumption would be provided by the conventional water supply system. The house is still connected to the conventional water supply in order to flush the toilets when the storage tank is empty.

As a reference value for this study, an energy requirement of 0.09 kWh/m^3 for pumping the rain water from the storage tank to the toilets has been chosen [8].

Independent recuperation scenario, economic toilets: REC100%

A 20 m^3 storage tank leads to a recovery fraction of 100% if economic toilets are used [9]. This means that 100% of the water consumption for toilet flushing is provided by the recuperation system. Independence from the conventional water supply is therefore provided, allowing a reduction in the size of this.

Conventional scenario with economic toilets: CONVeco

This scenario is based on the same water supply system as that of the CONV scenario. The only difference is that economic toilets, characterised by a reduced consumption of 3.5 L/flushing, are selected in this case.

Recuperation scenario with economic toilets: REC10eco

This scenario is similar to the REC10 scenario. The only difference is that economic toilets are selected here, leading to a recovery fraction of 97% [9].

Functional unit and system boundaries

The goal of the system is to have flushing toilets with a satisfactory level of hygiene. The functional unit is therefore Flushing per Person per Day, abbreviated to ‘FPD’. All inventory emissions must be reported to this unit.

Elements considered in the system boundaries are presented in Fig. 1. The drinking water distribution and treatment, the sanitary installations required for rain water recuperation and the wastewater treatment are all included in the parameters of the system. Rain water infiltration is also considered, as well as the energy production chain and the calorific loss due to the warming of flushing water in the house. As a whole, more than 160 different processes and sub-processes have been considered, together with their related emissions and use of raw materials.

Elements that are similar in the different scenarios can be excluded from the life cycle analysis. For instance, pipes with a diameter of less than 100 mm are omitted from the system

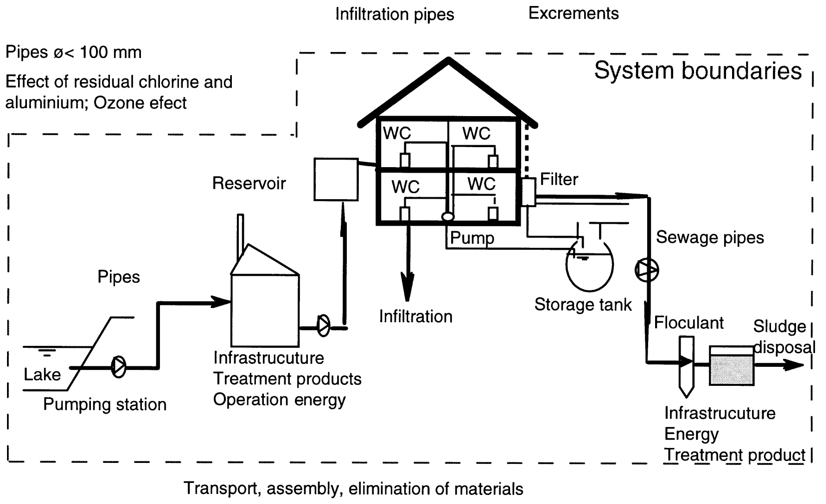

Fig. 1 Elements included and excluded of the system parameters. Only the main elements of the recuperation process are represented in this figure.

boundaries as their sizing depends on the requirements for fire protection. In addition, excrement and infiltration pipes are excluded from the system parameters as they are similar in each scenario. The transport, assembly and elimination of the different inputs are also excluded because of a lack of information (except for the wastewater treatment plant). The effect of residual chlorine and aluminium resulting from the drinking water treatment are excluded in the first stage, as well as the effect of ozone emissions at the drinking water treatment plant.

INVENTORY

Method

Emissions of air, water and soil pollutants, as well as energy consumption can be deduced from input flows and emission factors.

Input flows are the quantities of materials, energy or transport required for each sub-process. The input flows for the wastewater treatment plant are available in the study conducted by [10]. This study has determined the energy and product requirements as a function of wastewater quality. For drinking water distribution and treatment, as well as for the sanitary installations required for recuperation, input flows have been determined in a previous technical project [8].

Emission factors quantify the emissions and energy consumption per input unit. The emission factors proposed by [7] (1996) are retained. For products specific to drinking water treatment such as activated carbon, hydrogen peroxide and WAC (chemicals used for flocculation), specific research by the producers has been carried out.

The input requirements have been reported per m^3 for each infrastructure. The specific emissions in m^3 can then be automatically calculated. The fraction F of these emissions for each scenario, as well as the details of the inventory calculations, are presented in [9]. The basic concept is that the elements that are related in size to peak water demand (general reservoir, infrastructure of the drinking water treatment plant) can only be reduced if the supply to toilets is independent from the conventional water distribution system, even during dry periods. On the other hand, elements that are sized in relation to the mean flow in the water distribution system (pumping station, energy and product requirements for the drinking water treatment plant, energy for the water supply) can be reduced, even if the recuperation does not yield a recovery fraction of 100%.

Direct transfer of rain water pollutants

In addition to the emissions related to the various inputs, the direct transfer of pollutants contained in water should be evaluated. Pollutant concentrations in rain and drinking water have been evaluated on the basis of values reported by [11] and [12]. It appears that heavy metal content is much greater in rain water than in drinking water for some pollutants (Pb, Cu) and only slightly higher for other heavy metals (Zn, Cd) [9].

This difference in heavy metal concentrations in rain water and drinking water has to be considered as the fate of pollutants contained in water changes from one scenario to another. In conventional scenarios, rain water is infiltrated and drinking water used for toilet flushing is transferred to the waste water treatment plant. Pollutants arriving at the wastewater treatment plant are transferred to air, water and sludges. A transfer into food products occurs if sludges are used as a fertiliser in agriculture. In recuperation scenarios, rain water is sent to the wastewater treatment plant as long as the storage tank is not empty. In that latter case, drinking water is sent to the wastewater treatment plant. Infiltration occurs only when the storage tank is full.

It should be emphasised that pollutants contained in rain water are emitted by processes such as cars, industries and heating and could therefore be allocated to these activities. However, rain water recuperation modifies the fate of these pollutants. Therefore, the impact of these pollutants is presented in this article separately from the other processes.

Inventory results

Energy

Figure 2 presents the primary energy requirement of the main scenarios. On the one hand, the recuperation scenarios lead to an energy consumption that is slightly higher than the conventional ones. On the other hand, systems that reduce water consumption lead to a strong decrease in required energy. Economic toilets are therefore beneficial in regard to energy consumption. The scenario REC100% shows that total independence from the conventional water supply is unfavourable in comparison with the scenario CONVeco, as the energy required for the additional installations is not compensated by the reduction in the conventional water supply system.

Figure 2 also indicates that calorific loss represents a high energy consumption whichever the scenario. It decreases with the economic toilets, proportionally to the reduction of water consumption. This loss occurs from the temperature increase of the cold water in the pipes and from flushing. Detailed calculations of the calorific loss are presented in [9]. They indicate that calorific loss amounts to nearly 3% of the energy consumption of a well-insulated building.

The main contributions to energy consumption are as follows: For the drinking water supply, the energy required to operate the drinking water treatment plant (44%) and to supply the water (38%) take the main share in energy consumption. Treatment products such as activated carbon and ozone also play a significant role (10%). Pipes (50%) and infrastructure (40%) represent the highest energy requirement for the wastewater treatment plant, while polyester (68%) and steel (16%) are the main contributions for the sanitary installations.

Emissions

Emissions for more than 60 pollutants have been calculated. [9].

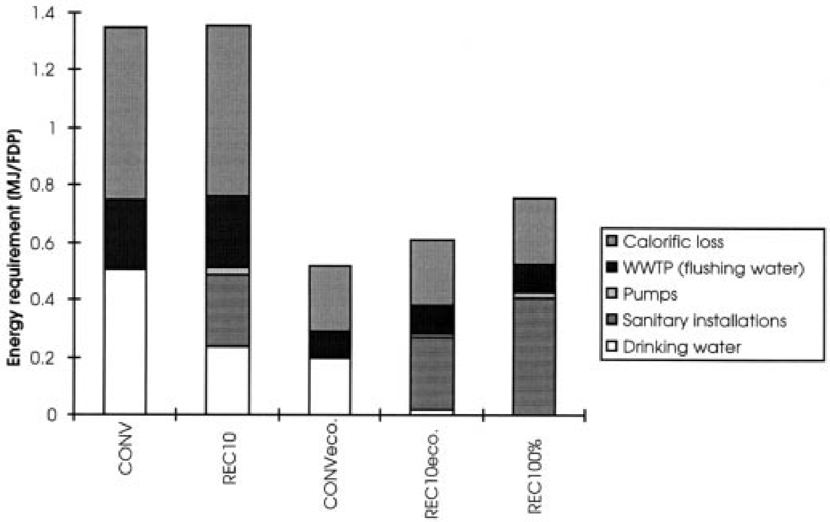

Fig. 2 Energy requirement for the main scenarios per FPD (Flushing for one Person during one Day). WWTP = waste water treatment plant. CONV = conventional water supply, conventional toilet. REC10 = rain water recuperation $V = 10\,\mathrm{m}^3$, conventional. CONVeco = conventional water supply, economic toilet. REC10eco = rain water recuperation $V = 10\,\mathrm{m}^3$, economic toilet. REC100% = rain water recuperation $V = 20\,\mathrm{m}^3$, economic toilet.

Table 3 (see Appendix 1) presents the energy consumption and emissions for water supply per m^3 of drinking water, for different supply conditions.

Table 1 summarises some of the main emissions for the different scenarios over the complete life cycle; it is discussed in this section.

Air and water pollutants. The emissions of pollutants into the air and water are linked to energy consumption. They are lower for a conventional water supply. Recuperation scenarios are highly unfavourable for N and C substances (NH_3, COD) due to their higher concentration in rain water and their transfer at the wastewater treatment plant.

Table 1 indicates that toilets with a low water consumption tend to have lower emissions. The scenario CONVeco is the most favourable, while scenario REC100% frequently presents higher emissions than scenario REC10eco because of the larger size of its storage tank.

Heavy metals. Heavy metal emissions must be discussed specifically, as they mainly result from their transfer from rain water and drinking water. Water emissions are higher in the recuperation scenarios due to the higher heavy metal content in rain water than in drinking water, and because of their transfer at the wastewater treatment plant. Soil emissions cannot be directly compared, as they occur in different types of soil. Transfer of metals contained in flushing water at the wastewater treatment plant leads to emissions into agricultural soil following the application of sludges as a fertilizer. Emissions in the infiltration soil occur when rain water is infiltrated. For these emissions, it is essential to consider the fate of heavy metals and their respective impacts on humans and the ecosystems. The impact assessment presented below is therefore required to weight the emissions.

IMPACT ASSESSMENT

Principle

The impact assessment aims at evaluating the impact on humans and ecosystems of the emissions listed in the inventory table (Table 1). Its three steps are classification (determination of the environmental problems to study), characterisation (weighting of the emissions within each environmental class) and evaluation (determination of the relative importance of each class) [13].

It has been decided to give attention to the relevant environmental classes mentioned in [14]. Land use, odour and noise have been excluded, mainly because of the lack of information.

Different methods are available to perform the characterisation and evaluation steps. Approaches which have included a full fate and exposure analysis have been chosen. The Critical Surface–Time approach (CST95) [15] has a particular emphasis on empirically assessing the response of the environment to pollutants. In contrast, the CML96 approach is based on a model that was developed for risk assessment [16,17]. Characterisation scores are discussed in detail in the following section. The evaluation, presented in [9], leads to similar comments.

Characterisation results

Results with CST95

Results of the characterisation carried out using the CST95 method are presented in Fig. 3 for the chosen environmental classes. The score of the conventional scenario CONV is fixed at 100% as the reference scenario. In addition, the effect of pollutants contained in the flushing water is excluded. Scores of the scenario REC10 are higher then those of the scenario CONV. The recuperation scenario is particularly unfavourable for the aquatic ecosystem.

Table 1 Air, water and soil emissions of main pollutants per FPD (flushing for one person during one day) over the complete life cycle

Pollutants	Unit	CONV (unit/FPD)	REC10 (unit/FPD)	CONVeco (unit/FPD)	REC10eco (unit/FPD)	REC100% (unit/FPD)
Air						
CO	mg	106	155	41	91	117
CO_2	g	60	68	23	32	35
CH_4	mg	102	129	40	68	81
NMHC	mg	124	205	48	130	198
NO_x	mg	100	124	39	63	72
particles	mg	40	52	16	28	28
SO_x	mg	267	430	104	270	274
Water						
chloride	mg	451	564	175	292	371
COD	mg	3	19	1	13	14
Cu	mg	0.1	1	0.02	0.9	1
NH_3	mg	1	19	0.4	12	13
oil	mg	13	17	5	9	12
Pb	μg	126	224	49	122	123
phenol	μg	97	513	38	454	835
Zn	μg	479	597	186	280	284
Infiltration soil						
Cd	μg	11	0.4	4	2	2
Cr	μg	40	2	16	9	9
Cu	mg	7	0.3	3	2	1
Pb	mg	1	0	0.4	0.2	0.2
Zn	mg	1	0	0.4	0.3	0.2
Agricultural soil						
Cd	μg	2	2	0.7	1	1
Cr	μg	4	11	2	6	7
Cu	mg	0.01	1	0.005	0.9	0.9
Pb	μg	38	279	15	174	178
Zn	μg	275	340	106	151	154

Economic toilets clearly appear to be advantageous for all environmental problems. This is in accordance with the energy requirement and the emissions discussed above. The scenario CONVeco is the most favourable from an environmental point of view. This scenario is even more favourable than it appears in Fig. 3 if the effect of pollutants contained in flushing water is included. Indeed, these pollutants are transferred at the wastewater treatment plant. As this transfer is proportional to the water contamination, and as rain water is more polluted than drinking water, recuperation induces an extra load on the toxicity and eutrophisation classes. The hypothesis of whether to allocate heavy metals to the recuperation process or not is therefore crucial for the toxicity classes.

Results with CML96

The impact assessment has to be carried out with different methods to determine if they give comparable results. Characterisation scores according to the CML96 methodology [16,17] are presented in Fig. 4. The scenario CONVeco is always the most favourable for all environmental classes. The general trend is therefore the same as with the CST95 approach. Eutrophisation scores are lower with CST95, as this approach considers a regional sensibility to nutrients by excluding *N* emissions. The orders of magnitude are the same for the toxicity classes, whichever method is employed. Acidification scores, as well as global warming and ozone formation scores, are not represented in Fig. 4 as they are the same in CML96 and CST95, both methods applying the same characterisation coefficients.

Contribution

Pollutants which play a key role according to CST95 can be determined. The importance of heavy metals for human toxicity and for both aquatic and terrestrial ecosystems is underlined. The effect of these substances emitted in air does not mainly occur by inhalation, but through deposition on agricultural soils and transfer to food. The effect of heavy metal emissions in soils also occurs through their transfer to food

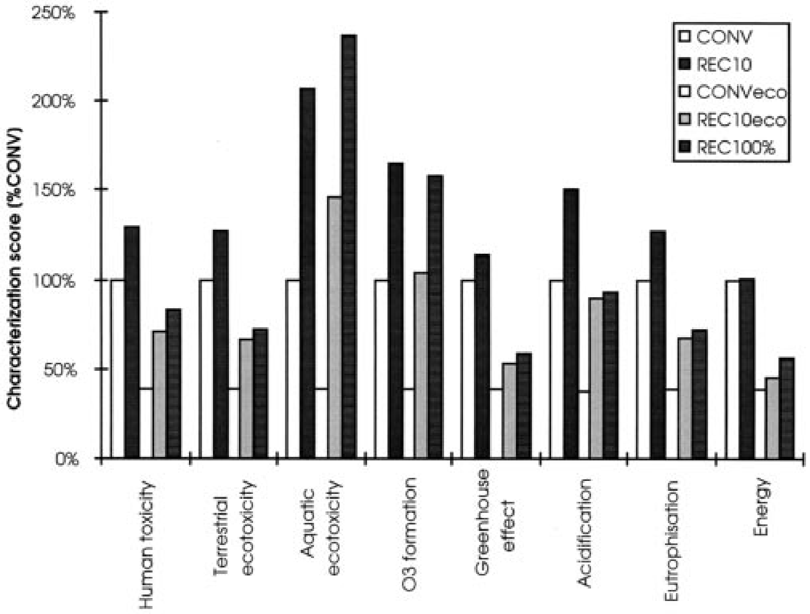

Fig. 3 Characterisation scores; pollutants contained in flushing water are excluded (CST95).

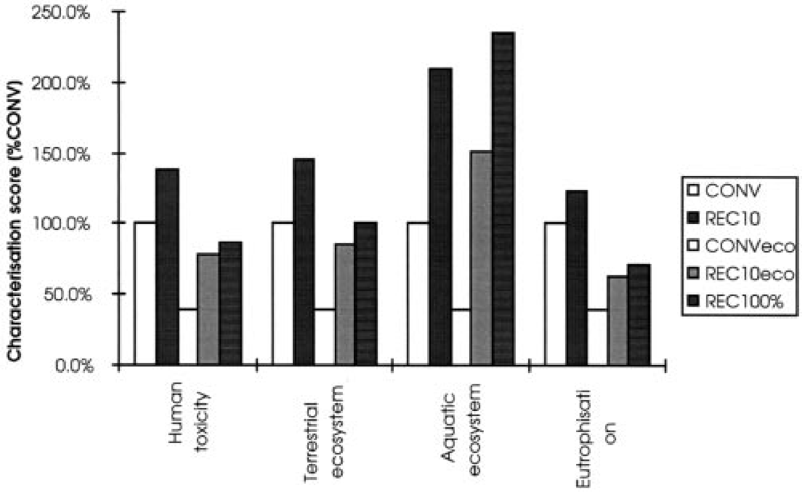

Fig. 4 Characterisation scores; pollutants contained in flushing water are excluded (CML96).

products. In addition to heavy metals, oil and phenol are also important contributors to the aquatic ecosystem score.

It should be mentioned that the average Swiss disposal of sludge (49% agriculture, 32% incineration and 19% landfill) has been chosen in the calculations. The effect on humans would be lower if a 100% incineration scenario were selected. In addition, it has been assumed that rain water infiltration has no effect on the terrestrial ecosystem, as the infiltration is localised and occurs in deep soil layers.

INTERPRETATION

Sensitivity analysis

Inventory and characterisation results have been presented for the five main scenarios. Sensitivity analyses have been carried out to find out how changes in key parameters influence the results. Only economic toilets are investigated here, as it has been shown that they are clearly favourable.

Figure 5 indicates that the scenario REC10eco remains energetically unfavourable, even if an extreme drinking water treatment is selected for conventional water supply. Its energy requirement is similar to that of the scenario CONVeco if a European electricity supply is selected. The scenario REC10eco becomes advantageous only if the energy required for the water supply is extreme. A threshold value of 0.8 kWh/m^3 for complex drinking water treatment and of 1.3 kWh/m^3 for a simple treatment have been deduced. Above these thresholds, the scenario REC10eco is energetically advantageous, but still remains unfavourable for all the other environmental classes.

The reference value for the pump energy requirement (0.09 kWh/m^3) is based on a total water pressure of 1.5 bar.

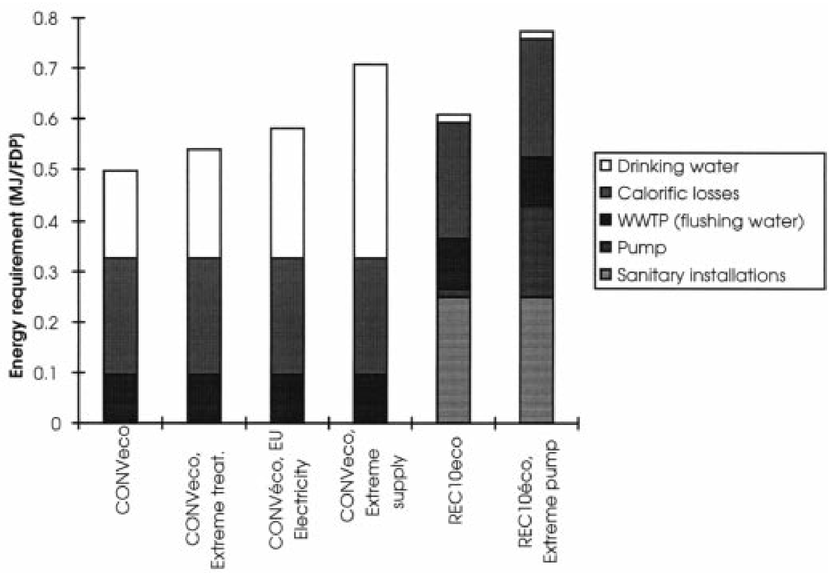

Fig. 5 Energy requirement for extreme treatment and energy consumption as well as for an European electricity supply. Extreme supply corresponds to an energy requirement of 1.5 kWh/m^3. EU = European Union.

Table 2 Comparison of the profitability of the different scenarios

	CONV max	CONV eco	REC10 max	REC10 eco	REC10 eco Society cost	REC100% max
Installation cost	0	0	11 633	12 700	12 700	2200
Mortgage + paying off			700	762	762	1318
Maintenance cost			267	293	293	267
Total expenses			965	1055	1055	1585
Number of persons	16	16	16	16	16	16
Total cost per person (fixed cost)	0	0	60	66	66	99
Flushing water consumption (m^3)	315	123	315	123	123	315
Flushing water consumption per person (m^3/person)	19.7	7.7	19.7	7.7	7.7	19.7
Recovery fraction	0	0	0.57	0.97	0.97	0.57
m^3 of recycled water to pump	0	0	11.2	7.5	7.5	11.2
Cost for the pumping electricity $/person-year	0	0	0.16	0.11	0.11	0.16
Drinking water consumption m^3/person	19.7	7.7	8.5	0.2	0.2	8.5
Total cost of 1 m^3 of drinking water $/m^3	2	2	2	2	2	2
Contribution of fixed cost (90%)					1.8	
Contribution of variable cost (10%)					0.2	
Cost for drinking water ($/year)	39	15	17	0.5	0.5	17
Cost drinking water, in equivalent fixed cost					13	
Cost for waste water treatment ($/year) (2.1 $/m^3)	42	17	42	17	17	42
Annual total cost ($/pers)	82	32	120	83	96	158
%	256	100	375	260	300	494
Annual extra cost per family of 4	199	0	351	205	258	505

This pressure is specifically adapted to toilet flushing. As such, it is not appropriate for other uses, such as watering the garden with sprinklers. If a pressure of 4 bar is required for sprinkler use, a high energy requirement (1 kWh/m^3) is required for pumping. This utilisation of rain water is to be avoided, as it induces an increase in the energy consumption of about 30% for the scenario REC10eco (Fig. 5). A zero energy requirement for the water supply and a minimum water treatment, as well as a storage tank in concrete, also penalises recuperation.

Other sensitivity analyses than those presented in Fig. 5 have been performed. It has been assumed above that rain water infiltration has no effect on humans and on the aquatic ecosystem. This assumption may not be borne out in fact. A sensitivity analysis which assumed that all pollutants contained in infiltration water reach the ground water has been carried out. It has indicated that infiltration has a negligible effect on humans in comparison with the transfer via food products. In contrast, its effect is significant on the aquatic ecosystem, which score becomes similar for the scenarios CONVeco and REC10eco if infiltration is taken into account.

A centralised recuperation scenario, composed of a group of five individual houses, has also been studied as an alternative to individual water collection. It indicated that collective or individual water recuperation leads to a similar environmental burden.

Comparison with the economic study

The cost of the maintenance of the equipment (fixed expenses) as well as the cost of one m^3 of drinking and wastewater and of the additional expenses for recuperation (variable expenses) have been evaluated. An annual interest rate of 5% and a pay off rate of 1% have been considered in these calculations. The results are presented in Table 2.

Economic toilets lead to a significant reduction in expenses for toilet flushing, amounting to US$49 per year. Recuperation scenarios appear to be unfavourable from an economic point of view. Compared to the most advantageous scenario CONVeco, the extra cost is US$50 per year, a 161% increase over the REC10eco scenario. In order for the REC10eco scenario to become favourable, a drinking water price of US$9/m^3 is required, without taking wastewater treatment into consideration. The REC100% scenario does not appear to be economically viable.

The extra costs amount to US$65 per year if the overall cost for society is considered, that is, considering that only variable costs are reduced by a decrease in water consumption. This is consistent with the consideration that only elements that are sized in relation to the mean flow, linked to variable costs in the water distribution system, can be reduced if the recuperation does not yield a 100% recovery fraction.

CONCLUSION

This article provides a quantitative database for decision making concerning the domestic use of rain water and the reduction of water consumption. It notes that toilets with low water consumption are favourable for all environmental problems, in comparison to conventional toilets. Moreover, they are economically attractive. Recuperation scenarios appear to be unfavourable from both an economic and an environmental point of view. Recuperation becomes energetically favourable only when the energy requirement for the water distribution is extremely high.

Different recommendations can be deduced from this study:

- A reduction of the water consumption for toilet flushing is to be promoted. This is a clear priority.
- An insulation of the flushing tank could significantly diminish the calorific loss.
- Pollutant transfer towards the water table has to be minimised by adequate infiltration systems. Similarly, sand filters should be developed which can retain the pollutants contained in rain water.
- If rain water recuperation is undertaken, a pump adapted to the situation is needed. For toilet flushing, a pressure of 1.5 bar is sufficient and there is no necessity to use a pump characterised by a high energy consumption. Rain water recuperation for garden watering under pressure should be avoided.

Future research topics to complete this study include the use of rain water for washing machines. As rain water is softer than drinking water, it allows a reduction in the quantity of detergent required for laundry. Results could therefore be noticeably different from those presented above for toilets flushing. Other developments should focus on the optimisation of the storage tank size, an estimation of the uncertainty in the results, as well as a further evaluation of the fate of pollutants with an emphasis on heavy metals.

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BIBLIOGRAPHY

1 VGL. *Protection des eaux: nouvelles perspectives: utilisation écologique de l'eau.* VGL Information, 1996.

2 Schudel. *Macht Regenwasser nutzen Sinn?* VGL Information, 2/96 1996.

3 Vahrenholt. *Regenwassernutzung im Haus, Umweltbehörde Hambourg*. Hambourger Wasserwerke GmbH, 1992.

4 Kamm U, Michel P. Utiliser l'eau de pluie comme eau domestique: une économie mal placée. *Bull L'ofefp* 1995; **2/95**: 20–22.

5 ISO. *Management environnemental, Analyse du cycle de vie,*

Principes et cadre. Norme internationale ISO/FDIS 14040, 1997.

6 Pelli T, Spreng D, Gujet W, Kamm U, Bonoli F, Nipkow J, Rosemayr D. *L'épargne énergétique dans les services d'approvisionnement en eau*. Office fédéral des questions conjoncturelles, RAVEL, 1996: 100.

7 Frischknecht R, Hoffstetter P, Knoepfel I, Ménard M. *koinventare von Energiesystemen*. Gruppe Energie-Stoff-Umwelt ETHZ, Sektion Ganzheitliche Systemanalysen PSI, 1996: 1800.

8 Orlando S, Cuanillon J-M. *Avant projet technique: inventaire des matériaux utilisés, projet CYCLEAUPE*. Bureau Ingénieur-Conseil RWB S.A., 1997.

9 Crettaz P, Jolliet O, Cuanillon J-M, Orlando S. *Projet CYCLAUPE. Analyse du cycle de l'eau et gestion de l'eau potable et récupération de l'eau pluviale*. Information de l'OFEFP concernant la protection des eaux; en préparation, 1998.

10 Zimmermann P, Doka G, Huber F, Lahardt A, Ménard M. *koinventare von Entsorgungsprozessen*. Grundlagen zur Integration des Entsorgung in kobilanzen, 1996: 356.

11 Truffer. *Fax du 14.11.97*. Sation de traitement des eaux de Lutry, Commune de Lausanne, direction des services industriels, 1997.

12 Mottier. *Qualitative aspects of roof runnoff*. Eight Junior Workshop Urban Rainwater: Resourcefully used; Deventer, Netherlands, 22–25 September 1995.

13 SETAC. *Guidelines for Life Cycle Assessment: a Code of Practice*. Society of Environmental Toxicology and Chemistry, Brussels, 1993: 69.

14 Udo De Haes HA. *Discussion of general principles and guidelines for practical use, published in 'Towards a methodology for Life Cycle Impact Assessment'*. Report of the Europe working group on Life cycle Impact Assessment. With written contributions from Bovy, Finnveden G, Frischknecht R, Giegrich J, Guinée JB, Hauschild M, Heijungs R, Hofstetter P, Jensen AA, Jolliet O, Lindeijer E, Müller-Wenk R, Nichols Ph, Potting J, Wenzel Christensen H, White P. SETAC 1996; pp. 1–30.

15 Jolliet O, Crettaz P. *Critical surface-time 95, an impact Life Cycle Assessment methodology including exposure and fate*. Swiss Federal Insitute of Technology, 1997: 79.

16 Heijungs R, Guinée JB, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels PG, van Duin R, Goede HP. *Environmental Life Cycle Assesment of products, Background and Guide*. Centre for Environmental Science (CML), NL-2300 RA Leiden, 1992.

17 Guinée, Heijungs Van Oers, Van de Meent, Vermeire Rikken. *LCA impact assessment of toxic release, generic modelling of fate, exposure and effect for ecosystems and human beings with data for about 100 chemicals*. Center of Environmental Science (CML), NL-2300 RA Leiden, 1996.

APPENDIX 1

Table 3 (overleaf) presents the energy consumption and substance emissions to air, water and soil, for different drinking water supply conditions, excluding used and wastewater treatment. The contribution of the infrastructure (pumping and reservoir) is given separately. Emissions are given for average Swiss conditions (0.35 kWh/m^3 for pumping), both with and without treatment, as well as for the extremes of the Swiss conditions (1.5 kWh/m^3 for pumping). European and Swiss electricity supply are distinguished.

Table 3 Energy requirements and emissions to air, water and soil for different drinking water supply conditions: Only infrastructure (pumping and reservoir), average Swiss condition (0.35 kWh/m^3 for pumping) with and without treatment, extreme Swiss condition (1.5 kWh/m^3 for pumping). The case is similar for the European electricity supply. CH: Switzerland; EU: European Union. (Used and wastewater treatments are excluded)

Substance	Unit	Infra-structure only	Drinking water 0.35 kWh/m^3 without treatment CH	Drinking water 0.35 kWh/m^3 with treatment CH	Drinking water 1.5 kWh/m^3 with treatment CH	Drinking water 0.35 kWh/m^3 without treatment EU	Drinking water 0.35 kWh/m^3 with treatment EU	Drinking water 1.5 kWh/m^3 with treatment EU
Resources								
energy (undef.)	MJ	0.27	3.81	9.38	21.00	5.91	13.94	30.02
Emissions air								
benzo[a]pyrene	μg	0.23	0.26	0.52	0.63	0.35	0.71	1.00
Cd	μg	1.87	2.48	7.40	9.40	6.61	16.34	27.09
CO	mg	72.48	85.03	220.29	261.52	124.64	306.13	431.31
CO$_2$	g	19.50	28.41	110.69	139.95	222.12	530.41	970.17
Cr	μg	2.93	3.65	12.44	14.84	23.21	54.81	98.65
Cu	μg	129.33	133.87	255.92	270.82	185.70	368.22	492.95
H$_2$S	mg	0.14	0.16	0.40	0.48	0.34	0.79	1.25
HCl	mg	1.56	2.18	5.69	7.71	39.38	86.30	167.16
HF	mg	0.30	0.41	0.95	1.33	5.28	11.50	22.20
Hg	μg	0.76	1.08	3.89	4.93	12.72	29.10	54.81
methane	g	0.04	0.06	0.29	0.35	0.42	1.06	1.88
Mn	μg	99.51	115.45	217.83	270.20	145.87	283.76	400.61
N$_2$O	mg	0.33	7.87	18.69	43.45	9.54	22.31	50.59
NH$_3$	mg	0.04	0.08	0.21	0.36	0.77	1.71	3.33
Ni	mg	0.10	0.13	0.28	0.37	0.30	0.64	1.08
NMHC	mg	16.15	29.50	96.10	139.95	112.21	275.31	494.43
NO$_x$	g	0.04	0.06	0.24	0.30	0.39	0.96	1.72
P	μg	2.70	4.56	10.93	17.02	49.50	108.32	209.66
particles	mg	34.40	43.44	122.03	151.74	180.75	419.53	740.20
Pb	μg	19.24	33.66	108.83	156.21	74.45	197.21	331.02
SO$_x$	g	0.73	0.78	1.50	1.65	1.96	4.05	6.71
V	mg	0.09	0.11	0.34	0.42	0.75	1.72	3.13
Zn	μg	70.64	90.64	389.79	455.49	161.20	542.68	757.92
Water emissions								
Ag	μg	0.19	0.28	0.65	0.94	0.61	1.36	2.34
Al	mg	8.67	14.31	53.14	71.66	93.29	224.28	410.17
As	μg	17.50	24.08	95.70	117.32	184.14	442.49	803.28
Ba	mg	0.89	1.30	4.92	6.29	8.94	21.48	39.03
BOD	mg	0.25	0.29	0.57	0.72	0.38	0.76	1.09
Cd	μg	1.24	1.98	6.85	9.30	6.84	17.38	30.13
chloride	g	0.10	0.19	0.63	0.90	0.95	2.29	4.19
Cl$^-$	μg	0.25	0.28	0.53	0.65	0.32	0.60	0.79
Co	μg	18.15	23.61	93.97	111.92	181.89	436.89	790.23
COD	mg	0.40	0.60	1.69	2.34	1.81	4.33	7.56
Cr^{+3}	mg	0.09	0.13	0.50	0.62	0.93	2.23	4.04
Cr^{+6}	μg	0.01	0.01	0.03	0.05	0.18	0.39	0.75
Cu	mg	0.05	0.07	0.25	0.30	0.47	1.12	2.02
cyanide	μg	10.40	12.43	25.39	32.06	17.72	36.85	54.72
F	mg	0.41	0.51	1.05	1.37	0.76	1.60	2.47
Fe	mg	4.49	7.24	25.15	34.20	134.61	301.11	580.06
Hg	μg	0.12	0.15	0.32	0.41	0.29	0.62	1.00
hydrocarbons	μg	2.20	31.03	72.09	166.84	30.45	70.84	164.35

continued

Table 3 Continued

Substance	Unit	Infra-structure only	Drinking water 0.35 kWh/m^3 without treatment CH	Drinking water 0.35 kWh/m^3 with treatment CH	Drinking water 1.5 kWh/m^3 with treatment CH	Drinking water 0.35 kWh/m^3 without treatment EU	Drinking water 0.35 kWh/m^3 with treatment EU	Drinking water 1.5 kWh/m^3 with treatment EU
Water emissions (continued)								
Mn	mg	0.19	0.55	1.70	2.89	2.19	5.24	9.90
NH_3	mg	0.14	1.04	2.57	5.53	1.53	3.63	7.62
Ni	mg	0.06	0.07	0.26	0.31	0.47	1.13	2.03
nitrate	mg	0.14	0.35	1.05	1.73	2.08	4.82	9.17
oil	mg	1.50	2.95	9.18	13.94	12.54	29.96	55.05
Pb	mg	0.09	0.19	0.51	0.85	0.59	1.38	2.56
phenol	μg	23.11	34.40	90.64	127.73	107.01	247.96	438.91
phosphate	mg	0.52	0.69	2.81	3.37	5.45	13.11	23.75
Se	mg	0.12	0.15	0.88	0.97	0.54	1.73	2.66
sulfide	μg	2.81	5.22	15.63	23.54	22.52	53.12	97.68
TBT	μg	0.47	0.61	1.57	2.03	2.49	5.63	10.06
Zn	mg	0.11	0.16	0.56	0.72	0.98	2.34	4.22
Soil emissions								
As	μg	0.04	0.08	0.26	0.39	0.38	0.90	1.65
Cd	μg	0.003	0.005	0.015	0.020	0.015	0.038	0.067
Co	μg	0.002	0.004	0.013	0.020	0.018	0.043	0.080
Cr	μg	0.53	1.04	3.52	5.20	4.72	11.48	20.95
Cu	μg	0.01	0.02	0.06	0.10	0.09	0.22	0.40
Fe	mg	0.21	0.42	1.41	2.08	1.89	4.60	8.40
Hg	μg	0.0004	0.0007	0.0020	0.0030	0.0028	0.0066	0.0120
Mn	μg	4.24	8.34	28.08	41.55	37.71	91.72	167.43
Ni	μg	0.02	0.03	0.10	0.15	0.14	0.33	0.60
Pb	μg	0.05	0.10	0.30	0.45	0.42	0.99	1.82
Zn	μg	1.70	3.34	11.18	16.56	15.06	36.58	66.80