Desalination 284 (2012) 42–54

Contents lists available at SciVerse ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Comparative life cycle assessment of water treatment plants

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ARTICLE INFO

Article history:
Received 11 May 2011
Received in revised form 28 July 2011
Accepted 19 August 2011
Available online 9 September 2011

Keywords:
Life cycle assessment
Drinking water
Nanofiltration
Conventional water treatment
Energy

ABSTRACT

The production of drinking water from fresh surface water involves several processes, energy consumption and chemical dosing, all having global environmental impacts. These should be considered in the choice of water treatment processes.

The objective of the present study was to conduct a comparative life cycle assessment of two water treatment plants: one enhanced conventional plant and one nanofiltration plant. One existing nanofiltration plant was chosen and investigated in great detail, including its operation and construction phases. This plant is located in the northern part of the Province of Quebec and has been in operation for over 10 years. A virtual conventional plant was designed for comparative purposes. The comparative life cycle assessment was performed using *SimaPro* software for inventory and impact assessment phases. The study revealed very different impacts for the two plants, drawing attention to the importance of the choice of water treatment chemicals and energy source.

1. Introduction

The main objective of water treatment is to deliver good quality drinking water to consumers. Treatment involves protection against microorganisms, removal of natural organic matter, removal of toxic substances, aesthetic quality, and protection of the distribution network against corrosion and recontamination. Traditional water treatment systems consist primarily of physical–chemical and chemical processes such as coagulation–flocculation, settling, granular filtration and chemical disinfection. More recently, pressure-driven membranes and UV disinfection have been used increasingly in the water industry [43]. Membrane processes offer an attractive alternative to traditional processes as they mainly require energy for water filtration through the membranes.

Generally, the choice of the "best" water treatment system is based first and foremost on economic and technical constraints. However, the water treatment industry may be responsible for significant global environmental impacts, the most common amongst which are the depletion of natural resources and indirect release of pollutants into the water, land and air through chemicals and energy consumption. To date, little information on those impacts is available, especially in the North American context and for new water treatment processes such as membranes.

Life cycle assessment (LCA) is a tool that could be used to generate information on the environmental impacts of water treatment systems. LCA serves to assess the global environmental damages potentially caused by a product, a process or a service in a "cradle to grave" approach [20]. Four stages are necessary to conduct an LCA [16]: goal, scope and functional unit definitions, life cycle inventory (LCI), life cycle impact assessment (LCIA), and Life cycle interpretation. LCA can be used to analyse and compare several processes or systems through their contribution to global environmental impacts. The definition of the functional unit is an important issue that allows fair comparison of different systems through LCA. Adopting a unique functional unit for all the studied water treatment systems (for example delivering 1 m^3 of water at a specified quality) guarantees that the impacts of these systems may be compared to each other. The LCI is a flow tree of all relevant processes used to produce, transport, use and dispose of the selected product. Inflows (raw material, energy, other processes, etc.) and outflows (emissions, wastewater, etc.) are listed for all relevant processes. The LCIA transforms inflows and outflows into a number of environmental impacts (climate change, resource depletion, etc.). Conducting an LCA requires the use of a software such as *SimaPro* [33] or *GaBi* [32]. These software products usually include several inventory databases (European reference Life Cycle Data system, U.S. Life-Cycle Inventory database, Ecoinvent, etc.) and impact assessment methods (*Impact2002+*, *Traci*, *Ecoindicator*, etc.). Since the databases were developed primarily in the European context, they usually have to be adapted when applied to other locations. Another important challenge is that several processes used for water treatment are not included in existing databases. This may limit the achievement of robust water treatment LCA.

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0011-9164/$ – see front matter
doi:10.1016/j.desal.2011.08.035

Few papers have been published on LCA applied to the field of drinking water. Several of them are listed in Table 1. Only one paper deals with the North-American context [37]. In most of the studies, the chosen functional unit is 1 m^3 of treated drinking water. This choice disregards the fact that two treated waters may meet quality standards without being of equal quality, and that raw water quality may be very different from one location to another. Also, and except for Friedrich [13], the LCA methodology is often not explained in great detail, i.e. the limits of the system are not clearly defined or the source and uncertainty for the inventory data are not provided.

In order to address some of these limitations, a detailed comparative LCA of a nanofiltration system (NF) and enhanced conventional system (CONV-GAC), producing treated water of equal quality from the same raw surface freshwater, was performed. The results of such comparative LCA are presented in this paper. The study was carried out in the context of the Province of Quebec (Canada), where electricity production is based mainly on hydropower, but comparisons with other energetic contexts are also discussed. The study also (i) integrated new items not included in LCA databases such as NF modules, liquid alum (aqueous solution of aluminium sulphate) and sodium bicarbonate, (ii) presented a detailed inventory taking into account for the transportation mode and (iii) tested several corrosion control scenarios needed to protect the distribution system.

2. Methodology

2.1. Goal definition

Two drinking water treatment plants were compared. The first is the NF plant of Lebel-sur-Quévillon (LSQ) located in the Abitibi-Témiscamingue district in the province of Quebec (Fig. 1). From 2006 to 2007, it supplied a population of 3140 inhabitants and provided about 2000 m^3 of drinking water per day. This plant was chosen because of the data availability following a one year monitoring of this plant completed in 2002–2003 [4]. The second water treatment plant, abbreviated CONV-GAC, is a virtual enhanced conventional plant with a design based on empirical water treatment modelling, and which construction inventory is based on a real conventional plant of similar size to the NF plant. The CONV-GAC system was designed in order to treat the same raw water and reach the same treated water quality as the NF system (Table 2). The actual source water of the NF-LSQ plant is a lake with a high natural humic organic content (TOC = 9.7 mg/L; DOC = 9.2 mg/L; (UV absorbance at 254 nm/DOC) = 4.5 L/(mg.m)) and low mineral content as well as microbiological contamination (Table 2). Since a conventional treatment would not allow the same organic matter removal as NF, and like Sombekke et al. [36], a granular activated carbon (GAC) unit was added as a post-treatment in order to theoretically provide the same treated water quality as the NF system (average DOC = 0.9 mg/L). NF and CONV-GAC treatment chains were also adjusted in order to provide the same level of protection against corrosion (target treated water characteristics: pH = 7.5, alkalinity = 40 mg $CaCO_3$/L, polyphosphate = 1 mg PO_4/L). These characteristics were selected based on design guidelines provided by the Ministry of Environment of Quebec [25]. Both systems meet the disinfection regulatory requirements of removing at least 4 log, 3 log and 2 log of viruses, *Giardia* cysts and *Cryptosporidium* oocysts, respectively. We choose to compare equal performances of real and virtual plants, with respect to treated water quality, instead of comparing two real plants producing different water quality since the latter approach would have led to a questionable definition of the functional unit.

2.2. Definition of the systems and functional unit

The NF plant (Fig. 2a) is basically composed of two serial pre-filtration devices (porosity of 5 μm and 1 μm), followed by a NF system and ending with chlorination and corrosion control using pH and alkalinity adjustments [4]. The NF system consists of two parallel membrane trains, each train totalizing 90 spiral-wound modules (diameter of 0.2 m, length of 1 m, and nominal active surface of 37 m^2 for each module) stacked in a 2 stage-array. One additional set of 90 modules, for a total of 270 modules, is used to temporarily replace fouled membranes whilst they are washed. The CONV-GAC plant involves the following virtual treatment steps: coagulation, flocculation, ballasted-floc settling, dual media granular filtration, GAC adsorption, chemical disinfection and corrosion control (Fig. 2b). Ballasted-floc settling consists in injecting sand in water prior to

Table 1
Life cycle assessments of drinking water systems.

Reference	Country	Goal	Source water	Functional unit	Software	Results
Sombekke et al. [36]	Netherlands	Conventional treatment versus nanofiltration	Groundwater	1 m^3 of DW[a]	*LCAqua* [23]	No significant difference between treatment chains; high impacts of GAC and energy
Friedrich [13]	South Africa	Conventional treatment versus ultrafiltration	River	1 m^3 of DW[b]	*Gabi* [32]	Comparable impacts for the 2 treatment chains; high impacts of energy (80%); minor impacts of construction (<15%); negligible impacts of membranes, chemical transport, decommissioning (<1%)
Mohapatra et al. [29]	Netherlands	Conventional treatment versus reverse osmosis	Groundwater	1 m^3 of DW	*LCAqua* [23]	No significant difference between treatment chains; high impacts of GAC, chemicals, conventional energy
Raluy et al. [34]	Spain	Compare desalination with big hydraulic infrastructure	Sea/River	25 000 hm^3 of DW	*SimaPro* [33]	Slightly higher impacts for desalination; Minor impacts of construction (<5%); negligible impacts of decommissioning and transport; high impacts of energy consumption
Stokes and Horvath [37]	USA (California)	Compare three supply system alternatives	River/sea/rainfall /recycled water	123 000 m^3 of water	*WEST* [37]	Higher impact for desalination; high impacts of operation phase (56% to 90%);high impacts of energy production
Barrios et al. [2]	Netherlands	Assess impact of changes of current conventional treatment	Polder/canal	1 m^3 of DW[c]	*SimaPro* [33]	High impacts of chemicals and GAC
Vince et al. [44]	France	Develop a tool for the environmental evaluation of potable water supply scenarios	Groundwater/ sea/surface water	1 m^3 of DW[d]	*Gabi* [32]	High Impacts of energy consumption, chemicals for coagulation and remineralisation;

[a] Drinking water.
[b] Drinking water at the quality specified by South Africa guidelines.
[c] Drinking water at the quality currently delivered.
[d] Drinking water at the quality specified by European guidelines.

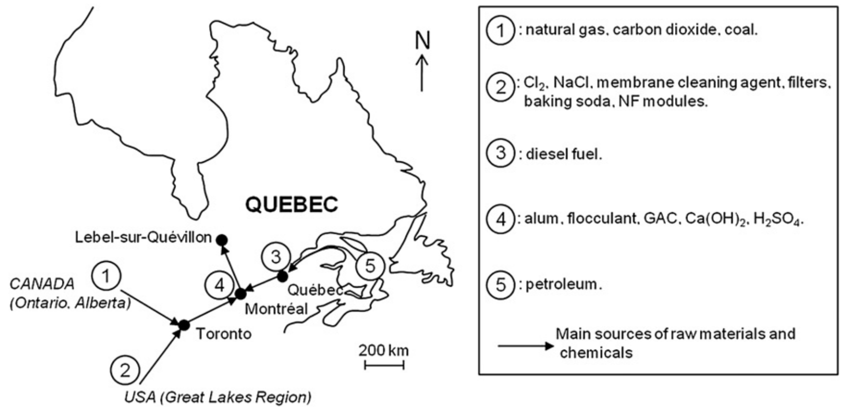

Fig. 1. Location of the study area and main sources of raw materials and chemicals.

flocculation in order to obtain heavier flocs with high settling velocities which allow a high overflow rate [26,9].

The functional unit for both systems was 1 m^3 of NF grade drinking water as described earlier. It is worth mentioning that the functional unit is based on 4 chemical parameters (pH, alkalinity, hardness and DOC; see Table 2) along with the disinfection requirements. Other water quality parameters were not included in the functional unit. Only the water treatment plant and its related processes were included within the system boundaries. The distribution network was excluded from the system. A discussion concerning wastewater produced during water cleaning is presented in Sections 2.4.2 and 2.5.2 for the NF and CONV-GAC plants, respectively. Three life cycle phases were considered for each system:

- Construction of the water treatment plant (including transport and materials, excluding equipment for building),
- Operation of the water treatment plant (including electricity, consumables and waste),
- Decommissioning of the water treatment plant (including decommissioning, sorting, recycling, end-of-life).

2.3. Methodology for inventory and impact assessment

The two LCA were carried out using *SimaPro* software version 7.3 [33] which allows life cycles to be modelled and analysed. This software was chosen because it includes several databases and impact assessment methods, a powerful graphical interface that easily shows the processes having the most impact and an uncertainty computation module. Tables 3 and 4 present a list of energy, materials and chemicals inventoried for the NF and CONV-GAC plant life cycles, respectively, as well as the methods that were used to assess each process needed for the production of 1 m^3 of drinking water. All the inventoried processes were normalised with respect to the functional unit. The *Ecoinvent 2.0* database [14] was chosen for the inventory analysis of inputs (resources, energy) and outputs (emissions) of each chemical and materials process. Since this database is primarily a European database, energy resources included in *Ecoinvent 2.0* were replaced by local energy resources depending on the location of the manufactured product (US energy or Quebec hydro-electricity energy). As can be seen in Appendix A [6], 94% of electrical resources for the Province of Quebec originates from hydropower. Transportation distances of materials and consumables that are found in the *Ecoinvent 2.0* database were replaced by driving distances between Canadian or US manufacturers and the municipality of LSQ (Fig. 1). Moreover, additional data were collected for items that are not included in the *Ecoinvent 2.0* database (GAC, NF modules, sodium bicarbonate, liquid alum). The following two sections respectively provide more details regarding inventory steps for the NF system and the CONV-GAC system, respectively.

Table 2
Quality of raw water, water before corrosion control and drinking water for both scenarios (annual average values).

	Raw water	Before corrosion control For NF	Before corrosion control for CONV-GAC	Drinking water[a]	Drinking water (scenario 1)[b]
pH	6.9	6.2	6.0	7.5	8.0
T (°C)	7.7	8.0	8.0	8.0	8.0
Alkalinity (mgCaCO3/L)	6.2	1.5	2.0	40	75
Hardness (mgCaCO3/L)	11.8	2.0	22.0	No constraint	75
TOC (mg/L)	9.7	0.9	0.9	0.9	0.9
DOC (mg/L)[c]	9.2	0.9	0.9	0.9	0.9
Fecal coliform count (CFU/100 mL)	<1				

[a] Scenario 0 is based on Quebec guidelines.
[b] Scenario 1 is based on French guidelines [30].
[c] It is assumed that TOC = DOC for filtered water.

2.4. Nanofiltration system life cycle inventory (LCI)

2.4.1. Construction/decommissioning phases

Most of the inventory for NF system building (Table 3) was obtained from field measurements and a database originating from the existing LSQ plant. The main building components (wall, insulation, foundation, etc.) and treatment components (pre-filters, pipes, tanks, etc.) were considered in the inventory. The life cycle of buildings was assumed to be 60 years whereas the useful life of motors, pipes and pumps was assumed to be 10 years. Inputs and outputs required for all of the materials constituting the inventoried components (steel, PVC, fibreglass, etc.) were drawn from the *Ecoinvent 2.0* database. Metal production was adjusted using a mix between

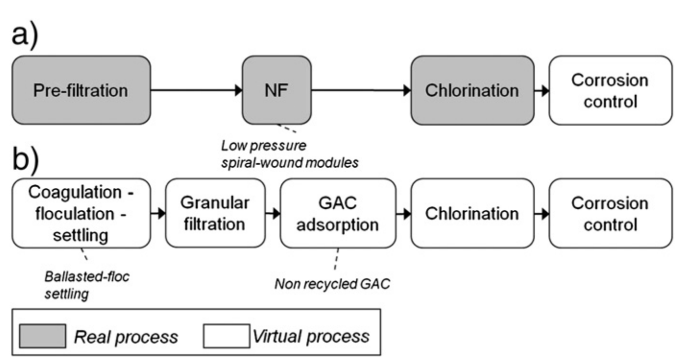

Fig. 2. Schematic representation of water treatment systems; a) existing direct nanofiltration plant (NF); b) virtual conventional plant (+ GAC adsorption) producing the same water quality as the NF plant.

Table 3
Inventory data for the nanofiltration system (NF).

Component	Value	Unit	Method
Construction			
Pumps (steel)	0.00005	kg/m^3	Field measures + plant database
Motors (steel + copper)	0.0001	kg/m^3	Field measures + plant database
Prefilters	0.00025	kg/m^3	Field measures + plant database
Backstairs + structural material (aluminium + steel)	0.0001	kg/m^3	Field measures + plant database
Storage tanks (fibreglass)	0.00007	kg/m^3	Field measures + plant database
Building-wall (steel)	0.00027	kg/m^3	Field measures + plant database
Building insulation (fibreglass)	0.00008	kg/m^3	Field measures + plant database
Doors (steel + polyurethane)	0.00001	kg/m^3	Field measures + plant database
Foundation (concrete)	0.003	kg/m^3	Field measures + plant database
Pipes (PVC)	0.00008	kg/m^3	Field measures + plant database
Electric cables	NC[a]	NC	–
Core grid (steel)	0.00045	kg/m^3	Approximation; [45]
Spiral-wound module stowage (PVC)	0.00004	kg/m^3	Field measures + plant database
Membrane housings	0.00008	kg/m^3	Field measures + plant database
Equipment	NC	NC	–
Operation (Electricity)			
Pumps (NF system)	0.49	kWh/m^3	Based on pressure and pumping rate [4]
Prefilter	0.035	kWh/m^3	Based on pressure and pumping rate [4]
Lighting	0.025	kWh/m^3	Approximation based on power of neon tubes
System cleaning (water heating)	0.0044	kWh/m^3	Energy required for water heating [15]
Ventilation system	NC	–	–
Monitoring system	NC	–	–
Operation (Chemicals)			
Phosphoric acid (scenario 0)	0.0011	kgPO_4/m^3	Literature ([25], chap. 13, vol.2)
CO_2 (scenario 0)	0.015	kgCO_2/m^3	Legrand–Poirier method [24]
$Ca(OH)_2$ (scenario 0)	0.007	kg$Ca(OH)_2$/m^3	Legrand–Poirier method [24]
CO_2 (scenario 1)	0.031	kgCO_2/m^3	Legrand–Poirier method [24]
$Ca(OH)_2$ (scenario 1)	0.031	kgCaO/m^3	Legrand–Poirier method [24]
H_2SO_4 (scenario 1)	0.036	kgH_2SO_4/m^3	Legrand–Poirier method [24]
Chlorine	0.0006	kgCl_2/m^3	*Ct* criteria ([25], chap. 10, vol.1)
Membrane cleaning agent (EDTA/NaOH)	0.0042	kg/m^3	Field measures
Filters for the prefilters	0.00026	kg/m^3	Field measures
NF spiral-wound modules	0.00051	kg/m^3	NF module autopsy
$NaHCO_3$	0.0034	kg$NaHCO_3$/m^3	Literature [27]
Decommissionning[b]			
Reinforced concrete	0.0036	kg/m^3	Reusing concrete for embankment and recycling steel
Steel	0.0011	kg/m^3	Recycling
Aluminium	0.00004	kg/m^3	Recycling
PVC	0.00018	kg/m^3	Landfilling
Fibreglass	0.00023	kg/m^3	Landfilling
Polypropylene	0.00015	kg/m^3	Landfilling
Polyester	0.00015	kg/m^3	Landfilling
Copper	0.00006	kg/m^3	Recycling
Polyurethane	0.00001	kg/m^3	Landfilling

[a] Not Considered.
[b] metal recycling in Canada: 100% of the produced copper is primary copper [5]; 65% of produced aluminium is primary aluminium and 35% is secondary aluminium [1]; 59% of produced steel is converted steel and 41% is electrical steel [7].

primary and secondary production [5,1,7]. For the dismantling phase of the NF plant, end-of-life of materials were chosen on the basis of local capacities, i.e. selecting only end-of-life processes available in the Abitibi-Témiscamingue region (sorting plants, metal recycling plants, plastic and fibreglass landfill, reuse of concrete for embankments). Energy consumption for decommissioning, transport and sorting phases was considered in the inventory. For decommissioning and sorting phases, processes already included in the *Ecoinvent 2.0* database were considered (disposal building process). For transport of decommissioned materials, distances between the water treatment plant and end-life process were considered.

2.4.2. Operation phase

Consumables and energy required for water treatment were considered in the inventory (Table 3). Operating energy was based on real electricity consumption of LSQ plant. Total energy consumption was about 0.55 kWh per m^3 of drinking water. The average operating pressure of membranes was 90 PSI (620 kPa). Consumables included filters for pre-filtration, NF modules, chemicals for corrosion control, chlorine for disinfection, membrane cleaning agents, and sodium bicarbonate for testing the integrity of the modules. More details are provided below for NF modules and chemicals inventory. We assumed that the modules were included in the operation section because, like other consumables, NF modules are components (270 modules) that must be changed regularly. The lifetime of an NF module was assumed to be 10 years. This seemed reasonable since a significant part of the original modules was still in operation in this plant at the moment of the study.

An autopsy of a spiral-wound NF module was performed to assess each component of the module (Table 5). The main part of the NF module is the membrane, in this case, a thin film composite membrane consisting of three porous layers: a polyester support (120 µm), a polysulfone interlayer (40 µm), and an ultrathin polyamide barrier layer (0.2 µm). A number of organic solvents and reagents are used to cast the membrane: N,N dimethylformamide solvent and isopropanol (IPA) swelling agent for the polysulfone membrane, 1,1,2-trichloro-1,2,2-trifluoroéthane solvent (CFC-113) and trimesoyl chloride (TMC) reactive for the polyamine layer (Table 5). We

Table 4
Inventory data for the conventional system (CONV-CAG).

Component	Value	Unit	Method
Construction			
Pumps (steel)	0.000028	kg/m^3	Field measures + plant database
Motors (steel + copper)	0.000057	kg/m^3	Field measures + plant database
Biological filter (steel)	0.00039	kg/m^3	Field measures + plant database
Coagulation–flocculation tanks (steel)	0.00054	kg/m^3	Field measures + plant database
Backstairs (aluminium)	0.000009	kg/m^3	Field measures + plant database
Storage tanks (fibreglass + LLDPE)	0.000081	kg/m^3	Field measures + plant database
Building-wall (steel)	0.00048	kg/m^3	Field measures + plant database
Building insulation (fibreglass)	0.00014	kg/m^3	Field measures + plant database
Doors (steel + polyurethane)	0.000018	kg/m^3	Field measures + plant database
Foundation (concrete)	0.015	kg/m^3	Field measures + plant database
Pipes (PVC)	0.00016	kg/m^3	Field measures + plant database
Electric cables	NC[a]	NC	–
Core grid (steel)	0.0023	kg/m^3	Approximation; [45]
Equipment	NC	NC	–
Operation (Electricity)			
Mixing tanks	0.035	kWh/m^3	Barbeau, 2009; pers. com. [46]
Heating (building)	0.09	kWh/m^3	Simplified Fourier's law [15]
Lighting	0.006	kWh/m^3	Approximation based on power of neon tubes
System cleaning	0.0024	kWh/m^3	Kawamura [21]
Ventilation system	NC	–	–
Monitoring system	NC	–	–
Water pumping	0.029	kWh/m^3	Kawamura [21]
Operation (Chemicals)			
Phosphoric acid	0.0011	kgPO$_4$/m^3	Literature ([25], chap. 13, vol.2)
CO_2	0.014	kgCO$_2$/m^3	Legrand–Poirier method [24]
$Ca(OH)_2$	0.007	kgCa(OH)$_2$/m^3	Legrand–Poirier method [24]
NaOH	0.06	kgNaOH-H$_2$O/m^3	Legrand–Poirier method [24]
Chlorine	0.0006	kgCl$_2$/m^3	*Ct* criteria ([25], chap. 10, vol.1)
GAC	0.076	kg/m^3	Literature [11]
Alum	0.08	kg/m^3	Literature [10]
Polymer (flocculant ≈ polyacrylamide ≈ acrylonitrile)	0.0003	kg/m^3	Literature [26]
Decommissionning[b]			
Reinforced concrete	0.017	kg/m^3	Reusing concrete for embankment and recycling steel
Steel	0.0037	kg/m^3	Recycling
Aluminium	0.000009	kg/m^3	Recycling
PVC	0.00016	kg/m^3	Landfilling
Fibreglass	0.00022	kg/m^3	Landfilling
LLDPE	0.000005	kg/m^3	Landfilling
Copper	0.000028	kg/m^3	Recycling
Polyurethane	0.000018	kg/m^3	Landfilling

[a] Not Considered.
[b] metal recycling in Canada: 100% of the produced copper is primary copper [5]; 65% of produced aluminium is primary aluminium and 35% is secondary aluminium [1]; 59% of produced steel is converted steel and 41% is electrical steel [7].

assumed no recycling of N,N dimethylformamide solvent, and a 95% recycling goal for CFC-113. Inputs and outputs needed for most of the items constituting the NF modules were those found in the *Ecoinvent 2.0* database. However, some items were not included in this database. LCI for N,N dimethylformamide solvent and polysulfone was derived from Friedrich [13]. LCI for TMC was based on US patent 3364259 [39], and LCI for MPD (polyamide layer) is based on Fierz-David [12] and Kirk [22]. The manufacturing of spiral-wound modules (energy, equipment) was not considered in the inventory due to the lack of available data. Inputs and outputs of sodium bicarbonate process were based on Davis et al. [8] and US DOE [38]. Concentrate stream continuously produced during operation (30% of feed water which corresponds to an actual recovery rate of 70%) was not considered as wastewater since there is no chemical dosing upstream of the NF system and the concentrate stream is directly rejected into the lake (no net release of matter), as agreed by the authorities. The disposal of the used NF modules cleaning solution (active agents on a mass basis: 4% NaOH; 8% Ethylene Diamine Tetra-acetic acid, EDTA; 0.0041 m^3 of used cleaning solution/m^3 of drinking water) was not considered in the inventory for the following reasons. We assumed that pre-treatment of this solution consisted of neutralising the sodium hydroxide with sulphuric acid. The impacts of such pre-treatment represent less than 0.5% of the impacts for the NF plant life cycle. Further treatment of this neutralised solution at the municipal wastewater treatment plant was also excluded from the inventory because the composition of this solution differs greatly from the municipal wastewater composition. Including the treatment of 0.0041 m^3 of municipal wastewater/m^3 of drinking water would have led to erroneous impact allocations, i.e. a large overestimation of the impacts of the used cleaning solution disposal. The latter solution actually contains much less nitrogen compounds, sulphur dioxide and metals than municipal wastewater, the contaminants that cause most of the wastewater treatment impacts on human health and ecosystems. Finally, it is worth mentioning that the amount of energy required for the treatment of the used cleaning solution at the municipal wastewater plant (0.00084 kWh/m^3) is negligible compared to the energy consumption of the NF plant life cycle (0.55 kWh/m^3).

The chemical dosages required for corrosion control (carbon dioxide, $Ca(OH)_2$, sulphuric acid) were evaluated theoretically through calco-carbonic equilibrium calculation [24], according to Quebec guidelines for corrosion control (see Table 2). A dose of 1 mg PO_4/L of orthophosphate (phosphoric acid) was considered to ensure adequate protection of pipes against corrosion. Chemical disinfection consists in dosing 0.6 mg

Table 5
Inventory data for the NF spiral-wound modules.

Component	Value[a]	Unit	Method
Polyester	0.00014	kg/m^3	Module autopsy
Polysulfone	0.00003	kg/m^3	Module autopsy
N,N dimethylformamide	0.00012	kg/m^3	US patent 4277344 [40]
MPD (meta-phenylene diamine)	1.35E-06	kg/m^3	US patent 4277344 [40]
TMC (trimesoyl chloride)	3.48E-06	kg/m^3	US patent 4277344 [40]
Solvent CFC-113	0.00017	kg/m^3	US patent 4277344 [40]
Fibreglass/plastic epoxy (outer shell)	0.000075	kg/m^3	Module autopsy
Phosphoric acid	9.36E-06	kg/m^3	US patent 4765897 [41]
Polypropylene (spacers)	0.00015	kg/m^3	Module autopsy
Epoxy resin (glue)	0.000034	kg/m^3	Module autopsy
Hardener (glue)	0.000021	kg/m^3	Module autopsy
PVC (permeate tube)	0.000052	kg/m^3	Module autopsy
Modules transport	0.00078	tkm/m^3	Modules manufactured in Michigan, USA
IPA (isopropanol)	0.000017	kg/m^3	US patent 4970034 [42]
Energy for CFC-113 recycling	0.0005	kWh/m^3	Evaporation rate of solvent [22]

[a] Based on 270 modules.

Cl_2/L (annual average dose) in the NF permeate whilst maintaining an average free chlorine residual concentration of 0.45 mg Cl_2/L at the exit of the reservoir [4]. The latter concentration and the disinfection credits from the NF process meet the mandatory disinfection requirements of 2, 3 and 4 inactivation log-units for respectively *Cryptosporidium*, *Giardia*, and viruses [25] as well as 3 log-units removal for parasites [27], respectively. LCI of chemicals used for corrosion control and disinfection steps originated from the *Ecoinvent 2.0* database.

The locations of the main sources of raw materials and chemicals are presented in Fig. 1. The transport of all these components from the manufacturers to LSQ was included in the LCI, given that the studied plant is located quite far from chemical manufacturing regions.

2.5. Conventional-GAC inventory

2.5.1. Construction/decommissioning phases

The building material inventory for the CONV-GAC plant was based on data from the water treatment plant of Saint-François-de-la-Rivière-du-Sud (Québec). This real conventional system was chosen as a reference for the construction phase because it has a similar production capacity and treatment train as the water system of LSQ. The main building components (wall, insulation, foundation, etc.) and treatment components (filters, coagulation–flocculation tanks, pipes, etc.) were collected from field measurements and the Saint-François plant database. LCI for all of the construction materials (steel, PVC, fibreglass, etc.) came from the *Ecoinvent 2.0* database. Data for the dismantling phase were the same as data for the NF plant, taking into consideration materials quantities of the CONV-GAC plant.

2.5.2. Operation phase

Energy and chemical consumption for coagulation–flocculation, granular filtration and GAC adsorption treatment steps were estimated from known design rules, process models and data originating from similar existing plants. For the coagulation–flocculation step, ratios of 0.75 mg of alum per mg of DOC [10] and 0.004 mg of polyacrylamide polymer per mg of alum (ratio estimated from [26]) were assumed along with a dosing of 31 mg/L of NaOH to compensate for the drop of alkalinity due to coagulant addition. The following EPA model [11] was used to estimate the *TOC* of the settled water:

$$\ln(TOC_o) = -0.1639 + 1.159\ln(TOC_i) - 0.4458\ln([alum]) - 0.06982\ln(TOC_i)\ln([alum]) + 0.05666pH\ln([alum]) \quad (1)$$

Where TOC_o is the outflow (settled water) total organic carbon (3.7 mg/L); TOC_i is the inflow (raw water) total organic carbon (9.7 mg/L); $[alum]$ is the coagulant dose (76 mg/L as dry alum); pH is the coagulation pH ($pH=6.0$, which is appropriate for NOM coagulation).

The energy required for coagulation–flocculation was based on a velocity gradient equation (Eq. (2)). Velocity gradient G was assumed to be equal to 400 s^{-1} for the coagulation and flocculation steps and 150 s^{-1} for the maturation step. The G value for flocculation (150 s^{-1}) is higher than the typical values of 15–75 s^{-1} because of the presence of sand ballasted flocs within the tanks which require high mixing so as not to settle [9]. Retention time is assumed to be equal to 120 s for the coagulation and flocculation steps, and 240 s for the maturation step. The overflow rate for the ballasted settler ranges from 60 to 80 m/h [26].

$$G = \sqrt{\frac{P}{V\mu}} \quad (2)$$

Where G is velocity gradient (s^{-1}); P is power input (W); V is volume of water in tank (calculated from the retention time in the tank); μ is dynamic viscosity (Pa.s).

The granular filtration design (filtration rate, backwash conditions) was based on guidelines from the manufacturer [26]. Regarding the adsorption system that follows granular filtration, another EPA model [11] was used to design the GAC system and particularly to evaluate the numbers of GAC bed replacements required to reach an average DOC of 0.9 mg/L, i.e. the average DOC of the NF permeate (Eqs. (3) to (5)). From this model, 4 bed replacements per year should be needed to meet this removal objective. This corresponds to a carbon usage rate (CUR) of 0.076 kg/m^3. It is worth mentioning that a bituminous GAC was considered in the inventory and that no GAC recycling was considered since there is no GAC recycling facility in the Province of Quebec.

$$TOC_o = \left[\frac{(TOC_i)^{n-1}}{1+Ae^{-rt}}\right]^{\frac{1}{n-1}} \quad (3)$$

$$r = 0.07426(EBCT)^{-0.4289} \quad (4)$$

$$A = 0.7570(EBCT)^{1.35} \quad (5)$$

Where TOC_o is the outflow total organic carbon; TOC_i is the inflow total organic carbon (3.6 mg/L); $EBCT$ is empty bed contact time (0.33 h = 20 min); n is a constant equals to 3.165 [11]. The filtration rate through the GAC bed is 4.5 m/h and the apparent density of this bed is 500 kg/m^3.

It was assumed that the chlorine dosage for the CAG-CONV plant would be close to the chlorine dosage for the NF plant, i.e. 0.6 mg Cl_2/L. This assumption seemed reasonable since both filtered water would have the same very low organic matter content, i.e., similar very low chlorine demand and slow chlorine decay. It was assumed that this chlorine dosage would allow maintaining a free chlorine residual concentration close to the actual concentration observed at the exit of the NF plant (0.45 mg Cl_2/L on average). This free chlorine concentration would allow the GAC-CONV system to meet the mandatory disinfection requirements considering that the physical–chemical treatment would allow 2 log-units removal for viruses and *Cryptosporidium* and 2.5 log-units removal for *Giardia* [25]. Similarly to the NF system, chemical dosages required for corrosion control (carbon dioxide, $Ca(OH)_2$, sodium hydroxide) were determined through calcocarbonic equilibrium calculation [24] and considering the Quebec's guidelines for corrosion control (see Table 2). A dose of 1 mg PO_4/L of orthophosphate was also considered. Wastewater is produced during settling and filter backwashing. This wastewater cannot be rejected directly into the environment because it contains high levels of aluminium (140 mg Al/L of wastewater). We dismissed the possibility of completing a volumetric based allocation. Such allocation would have led to a large underestimation of the environmental impacts associated with the wastewater coming from the CONV-GAC plant since the latter has much higher aluminium content than municipal wastewater. Instead, we assumed that all aluminium added during the coagulation process was ultimately spread on agricultural fields, i.e. we only considered the impacts of the emission of aluminium into the soil. This assumption seemed realistic since aluminium solids produced during coagulation end up in the sludge of the municipal wastewater plant. The sludge should then be spread on agriculture lands according to the provincial biosolid disposal policy [28].

Chemicals LCI for CONV-GAC operation originated primarily from the *Ecoinvent 2.0* database. However, GAC and liquid alum LCI could not be taken from *Ecoinvent 2.0* since this database only contains LCI for powder activated carbon and dry alum. Instead, the LCI of GAC production was based on the data from Ortiz [31] and Bayer et al. [3] whilst LCI of liquid alum production was based on the data from Kirk [22]. Due to the lack of data concerning the polymer manufacturing, it was also assumed that the LCI of polyacrylamide polymer was close to the LCI of acrylonitrile which is the main compound (monomer) in its production.

2.6. Life cycle impact assessment

The impact assessment was performed using *Impact 2002+* [19]. The input and output data of the LCI were weighted and sorted into 13 intermediate impact categories (ozone layer depletion, global warming, carcinogens, mineral extraction, etc.) that are called mid-point impacts. Mid-point impacts were weighted and grouped into four damage categories (end-point impacts): human health, ecosystem quality, climate change, and resource depletion. The results of the impact assessment are presented in Section 3 in terms of these four damage categories. However the results in terms of mid-point impacts are detailed in Appendix B.

2.7. Scenarios for the NF system

In addition to the reference scenario (0), three scenarios dealing with corrosion control strategy and electrical energy source, were developed. Scenario (0), in terms of corrosion control requirement, was based on Quebec's guidelines. Likewise, electricity for water treatment operation was based on the electricity production and import (grid mix of the Province of Quebec; see Section 2.4.2). For scenario 1, we proposed keeping the same electricity grid mix but testing an alternative corrosion control based on French guidelines ([30]; see Table 2). The purpose is to promote the formation of a protective $CaCO_3$ scale layer inside distribution pipes. This strategy requires higher pH, alkalinity and hardness compared to Quebec guidelines (see Table 2). The efficiency of these anticorrosion treatments in terms of pipe life and metal dissolution (zinc, lead, copper or iron) may be very different from one case to another [35,30,25,18]. In scenarios 2 and 3, the anticorrosion strategy was the same as scenario 0 but different energy grid mixes were tested. In Quebec, the electricity grid mix is about 94% of hydro-electricity, 2.3% of nuclear power, and 3.7% of other sources (scenarios 0 and 1). In France, the electricity grid mix includes some 77% nuclear power, 12% hydropower, 7% fossil fuels and 4% from other sources (scenario 2). In the USA, the electricity grid mix consists of 47% hard coal, 20% nuclear power, 17% natural gas and 16% of other sources (scenario 3). The LCI for the electricity grid mixes of France and USA originated from the *Ecoinvent 2.0* database.

2.8. Uncertainty analyses

A Monte-Carlo analysis was carried out for each scenario using the integrated uncertainty module of *SimaPro 7.3*. This analysis consists of estimating the effects of the variability of the processes on the environmental impacts. Basically, the processes retained for a Monte-Carlo analysis in *SimaPro 7.3* are all the unit processes included in the *Ecoinvent 2.0* database that have default uncertainty ranges. In our case, the uncertainty ranges of the processes that contribute the most to the impacts (contribution greater than 2% for at least one damage category) were adjusted as shown in Appendices C and D. Others uncertainty ranges were the default ones. For each Monte-Carlo analysis, 3000 iterations were conducted.

3. Results and discussion

3.1. Conventional plus GAC system versus NF system

Fig. 3 presents the environmental damages for both water treatment plants for scenario 0. Results indicate the larger impact of the CONV-GAC system in comparison with the NF system. The impact of CONV-GAC is over 12 times greater than NF for human health, climate change and resource depletion categories, and over 5400 times greater for the ecosystem quality category. This differs from the studies of Sombekke et al. [36], Friedrich [13] and Mohapatra et al. [29] where similar impacts were found for both the conventional-GAC system and membrane processes. This discrepancy originates from the nature of the energy resource. Even though the NF system uses much more energy than the CONV-GAC system (0.55 and 0.16 kWh/m^3 for NF and CONV-GAC, respectively), this does not lead to greater impacts for the NF system because hydroelectricity is the primary source of energy used in the Province of Quebec (Appendix A). Note also that the present NF system is a relatively low-pressure membrane system (trans-membrane pressure varies from 300 to 800 kpa) which requires lower energy than high-pressure systems like reverse osmosis membranes.

The processes that contribute the most to the environmental damages for both systems and different scenarios are shown in Fig. 3 and Appendix C. For scenario 0, it appears that the major environmental impacts of the CONV-GAC system are caused by the use of GAC and by wastewater treatment and disposal. GAC production actually accounts for 62% of total human health impact, and close to 88% of total climate change and total resource depletion. This is understandable since the GAC used in our analysis is made from coal (impact on resource depletion) and is physically activated in industrial furnaces (impact on human health and climate change through the release of contaminants into air). One way to reduce this impact could be to replace GAC produced from coal with GAC produced from another type of raw material such as, for example, coconut shell leading to lower impacts on resource depletion (emission of biogenic CO_2). Activation alternatives, such as chemical acid activation, could also be compared in future works with physical (thermic) activation. Moreover, the regeneration of GAC could lead to significant impact reductions. However LCI for such alternative processes was not available at the time of the study.

The very high impact on ecosystem quality for the CONV-GAC system comes almost entirely from wastewater treatment that ultimately leads to significant emissions of aluminium into the soil (see Section 2.5.2 and Appendix C). One way to reduce this impact could be to use ferric salts (ferric sulphate, ferric chloride) instead of alum as a coagulant, as the impact factor of the iron ion on ecosystem quality is considered negligible in most impact assessment methods including *Impact 2002+*. However, in order to properly compare the use of two coagulants, a complete LCA should be carried out for each product. Moreover, the comparison should also take into account for other criteria such as coagulation performance, cost and corrosiveness [47].

Whereas the impacts of the CONV-GAC system come primarily from two processes, namely GAC manufacturing and wastewater, the impacts of the NF system are more evenly distributed amongst the processes than for CONV-GAC as shown in Appendix C. For the NF system (scenarios 0 and 1), the larger contributions come from the electricity consumption for spiral-wound modules operation, manufacturing of chemicals for corrosion control, NF modules manufacturing and transport of materials and chemicals. Lorry transport impact is based mostly on direct emissions of diesel combustion.

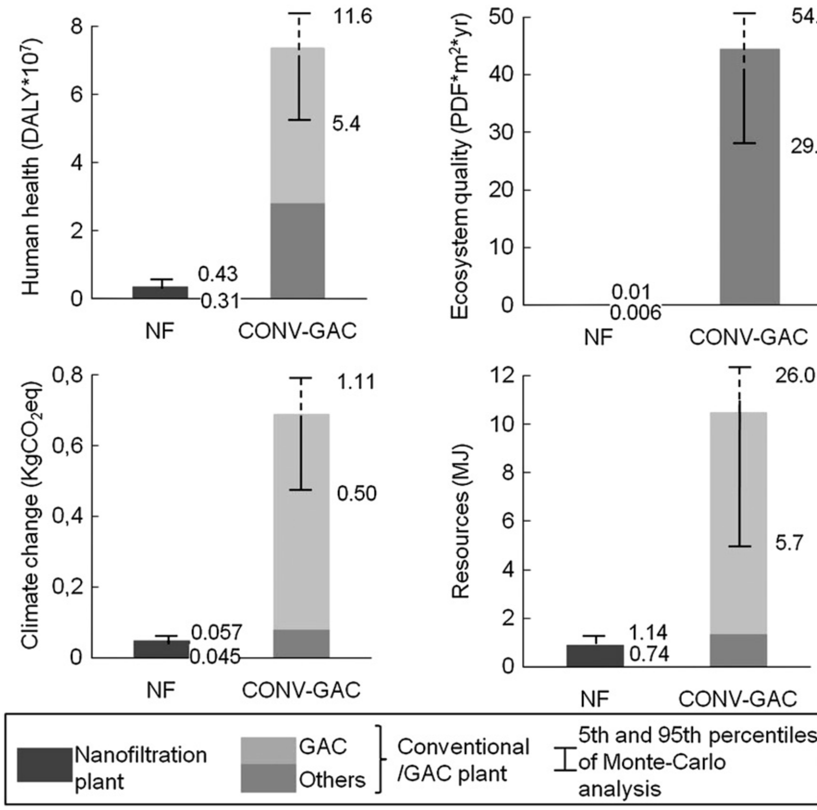

Fig. 3. Comparison of NF plant versus CONV-GAC plant on environmental impacts for each damage category using the *Impact 2002+* method.

The impact of NF is relatively high for 2 mid-point impact categories (see Appendix B): ionising radiation (0.8 times of the CONV-GAC damage value) and ozone depletion layer (4.2 times higher than CONV-GAC damage value). Ionising radiation is mainly due to Radon-222 emission into the air during uranium extraction for nuclear power production (see the electricity grid mix for the Province of Quebec in Appendix A). The depletion of the ozone layer is due mostly to tetrachloromethane emissions into the air during solvent production used to manufacture NF polyamine membrane.

3.2. Impact of chemicals and main NF treatment steps

Fig. 4 shows that the NF operation phase is the dominant phase compared to the construction and decommissioning phases of the NF system. The impacts of the operation phase are 3 to 9 times greater than those of the construction phase. However, the construction phase impacts are not negligible. On the contrary, the decommissioning phase impacts are negligible, and even slightly negatives due to steel recycling. Thus, impact reduction should rather be achieved through improvements of system operation. As an example, the chemicals used for anticorrosion treatment have a large environmental impact (Fig. 4). From an LCA perspective, this treatment step appears to be an environmental "hot point" for conventional treatment. In our study, carbon dioxide, $Ca(OH)_2$ and H_2SO_4 were used to adjust pH, alkalinity and water hardness. Other chemicals, such as HCl, $CaCO_3$ or Na_2CO_3 could be tested in order to reduce the global environmental impact of water treatment.

3.3. Results of scenario analysis

Of the two alternative corrosion control strategies, scenario 0 causes less impact compared with scenario 1 (Fig. 5). The potential environmental damages of scenario 1 are 30 to 50% greater than scenario 0. Thus, in our case, the choice of corrosion control has a large impact on LCA results. However, the functional unit does not take into account for the efficiency of these two corrosion control strategies therefore limiting the scope of this conclusion. If the distribution network was included in the system and if the effects of these corrosion control strategies could be predicted, the comparison of scenarios 0 and 1 would be improved. However, this kind of prediction is presently very difficult to make since many local variables affect the corrosion phenomena.

Fig. 6 illustrates that hydropower energy makes a huge difference on environmental damages for the NF system. The alternative use of coal energy (US) would cause impacts some 8 times greater than hydroelectricity energy. Scenario 0 (hydropower resource) and scenario 2 (nuclear resource) are comparable for climate change, ecosystem quality and human health for both CONV-GAC and NF plants. However, the impact of nuclear power is about 8 times larger than hydroelectricity for resource depletion, as nuclear power is based on uranium consumption. Conversely, the impact of modifying the energy resource for the CONV-GAC plant is weaker compared to the NF plant because the quantity of electricity used for the CONV-GAC plant operation (0.16 kWh/m^3) is lower than the electricity used for the NF plant (0.55 kWh/m^3). For climate change, resource depletion and human health, the difference between both systems is lower for coal energy (US) than for hydro-electric energy (Quebec), which is in agreement with the results found by Sombekke et al. [36] and Friedrich [13]. Scenario 3 shows that even in the context of coal energy (US), impacts of the CONV-GAC plant continue to prevail on those of the NF plant but, as shown below, the uncertainty analysis prevents from having a strong conclusion about that. However, this confirms the relevance in future works of completing LCA on alternative GAC manufacturing and GAC regeneration.

3.4. Results of the uncertainty analyses

Monte-Carlo analyses results are shown in terms of 5th and 95th percentiles of the damage distributions for both systems. For scenario

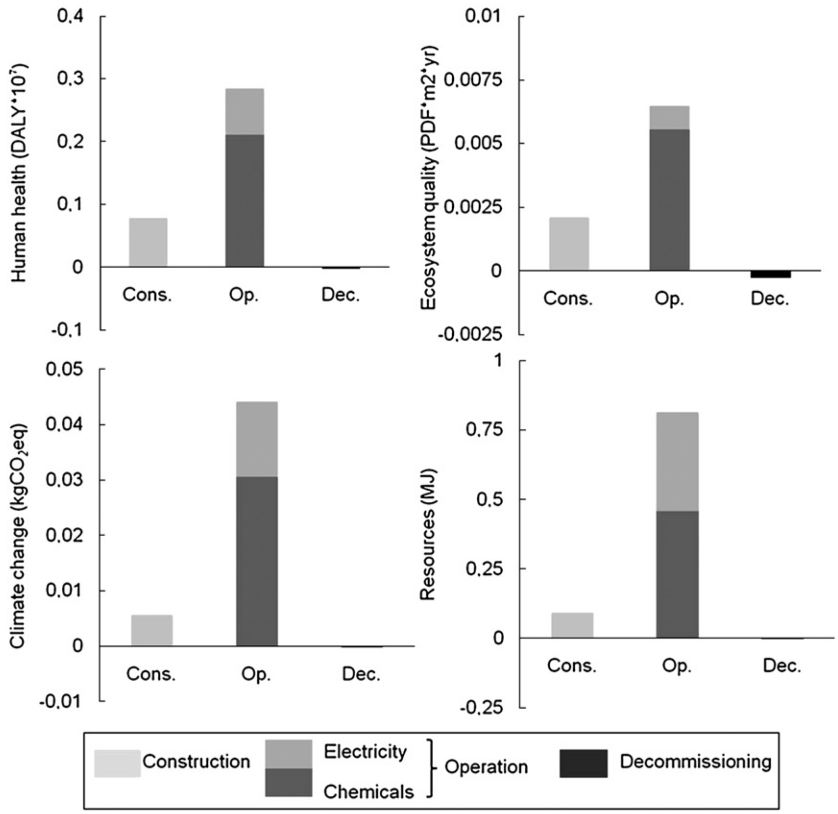

Fig. 4. Comparison of the three main phases of existence of a NF plant on environmental impacts for each damage category.

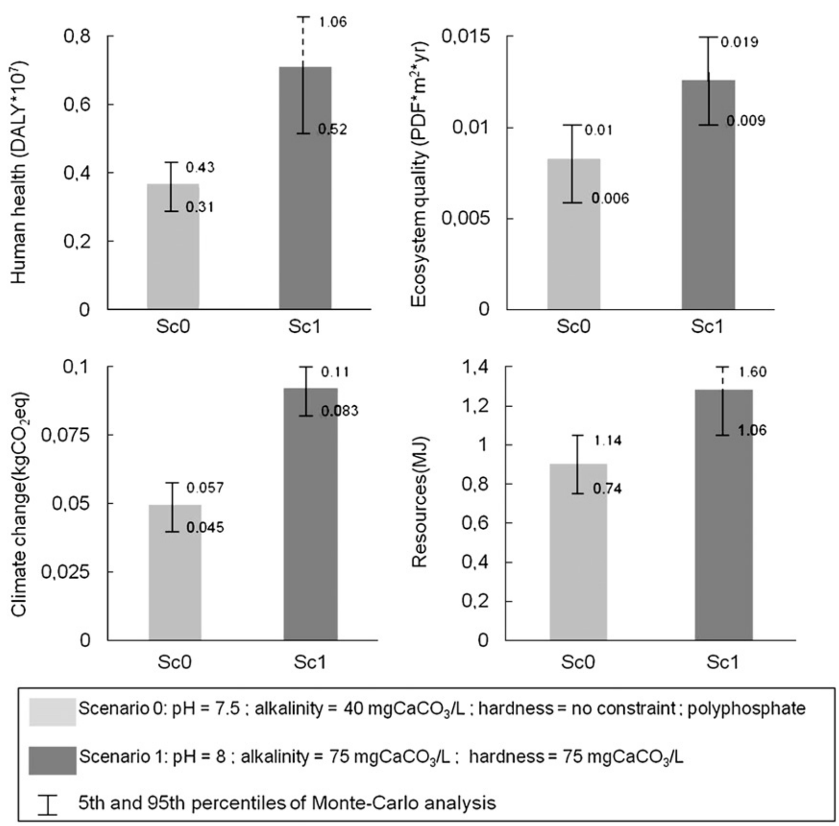

Fig. 5. Comparison of Quebec's usual corrosion control strategy (scenario 0) with the French criteria (scenario 1) on environmental impacts for each damage category of NF system.

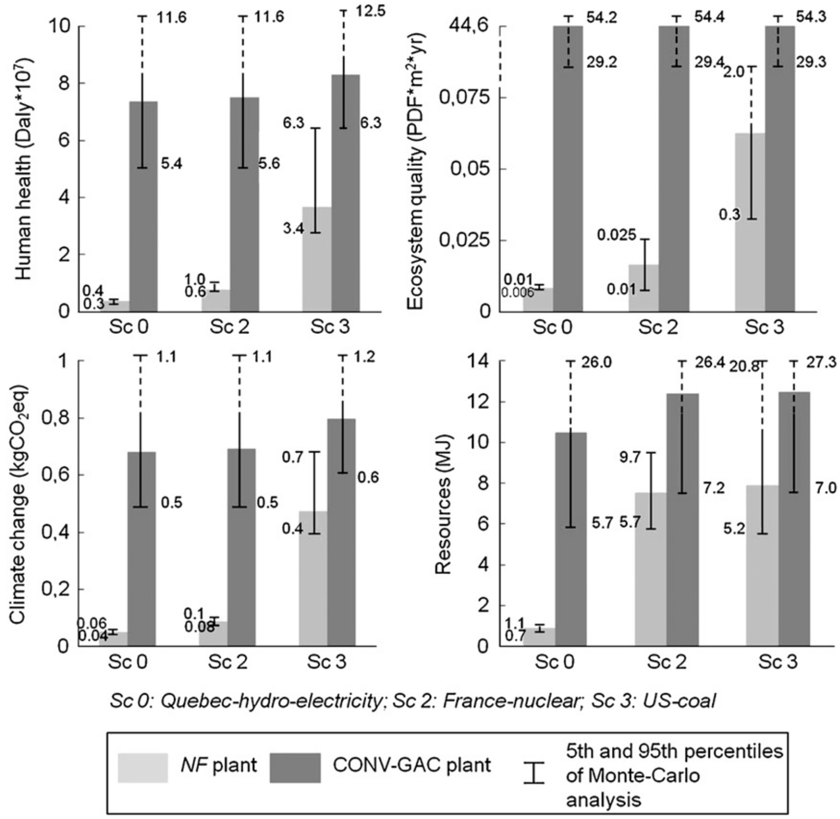

Fig. 6. Effect of electricity source of NF and CONV-GAC plants on environmental impacts for each damage category.

0 (Fig. 3), there is relatively low damage variability for the NF system, ranging from about 12, 16, 21 and 25%, respectively, for climate change, human health, resource depletion and ecosystem quality damages categories. The damage variability for the CONV-GAC system is larger than NF system, ranging from about 30, 36, 38 and 65%, respectively, for ecosystem quality, human health, climate change and resource depletion damage categories. This may be explained by the uncertainty about the GAC life-time, as explained by Jacangelo et al. [17], and uncertainty concerning the alum dose. It can be concluded that, in the context of the Province of Quebec, CONV-GAC impacts are significantly higher than for the NF system for scenarios 0 and 1 because damage variability ranges do not intersect each other (Figs. 3 and 5).

The difference between the impacts of the two systems is still significant for scenario 2 except for the resource depletion damage (Fig. 6). For scenario 3, the considered uncertainty on electricity consumption makes the impact comparison between the two water treatment systems more difficult especially for the resource depletion damage (Fig. 6). In the case of electricity produced primarily from fossil fuels, this illustrates how an uncertainty of $\pm 4\%$ for electricity consumption (Appendix D) may result in a large uncertainty of the environmental damage. This emphasises the importance of uncertainty analysis in LCA and the importance of narrowing, as much as possible, the uncertainty ranges for the most contributing processes by improving the quality of the LCI.

4. Conclusions

A comparative LCA was performed on two drinking water plants (an existing NF and a virtual CONV-GAC plants) treating the same raw water and providing the same treated water quality in order to make a fair comparison of two different treatment chains. The study took place in the context of the Province of Quebec. Both LCA included the construction, operation and decommissioning phases. The operation phase has the highest potential environmental damages. The results also indicate greater environmental damages for a CONV-GAC system compared to a NF system, in the context of the Province of Quebec where hydroelectricity is largely dominant. Where electricity is produced from hard coal or nuclear power, the CONV-GAC system still exhibits stronger potential impacts than the NF system but to a lesser extent. The greater environmental damages caused by the conventional system are mainly explained by the use of coal-based GAC as a post-treatment for additional NOM removal. GAC manufacturing actually depletes coal resources and releases pollutants into air during furnace activation. The damage caused by the CONV-GAC plant in terms of ecosystem quality, may be explained by the use of aluminium based coagulant. Surprisingly, it also appeared that the environmental impacts of corrosion control chemicals are significant. Future works will concern LCA on full systems including distribution networks and comparative LCA on different coagulants and adsorbents. As well, the integration of environmental and economic LCA on drinking water systems should be covered.

Acknowledgements

This study was mostly funded by a grant from the Canadian Water Network. We acknowledge the contributions of the Cities of Lebel-sur-Quévillon and Saint-François-de-la-rivière-du-sud, and the collaboration of Bruno Gilbert of the Engineering Division of the City of Sainte-Marie, Jacques Trudel of the Engineering Division of the City of Lebel-sur-Quévillon, and Jean-Francois Menard of the Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et services (CIRAIG) for his useful contribution to LCA modelling.

Appendix A. Electricity grid mix for the Province of Quebec (production plus import) for 1 kWh (CIRAIG, 2009)

Components of *SimaPro* software	Value	Unit
Electricity, hydropower, at run-of-river power plant/based on production in Switzerland	0.298319	kWh
Electricity, hydropower, at reservoir power plant, alpine region/EUR[a]	0.474163	kWh
Electricity, nuclear, at power plant boiling water reactor/GER[b]	0.023248	kWh
Electricity, oil, at power plant/GER	0.00095	kWh
Electricity, oil, at power plant/GER	5.7E-06	kWh
Electricity, at wind power plant 800 kW/EUR	1.59E-05	kWh
Electricity, hydropower, at reservoir power plant, non alpine regions/EUR	0.147043	kWh
Electricity, hydropower, at run-of-river power plant/EUR	0.003253	kWh
Electricity, hydropower, at reservoir power plant, non alpine regions/EUR	0.028635	kWh
Electricity, hard coal, at power plant/based on production in Croatia	0.007197	kWh
Electricity, oil, at power plant/GER	0.001643	kWh
Electricity, industrial gas, at power plant/based on production in Belgium	0.004798	kWh
Electricity, nuclear, at power plant boiling water reactor/GER	0.00864	kWh
Electricity, at wind power plant 800 kW/EUR	0.002083	kWh
Electricity, at cogen ORC 1400kWth, wood, allocation energy/based on production in Switzerland	6.7E-06	kWh

[a] Based on production in Europe; [b] based on production in Germany.

Appendix B. Mid-point impacts for the *NF* and CONV-GAC plants

Mid-point impact	Unit[a]	*CONV-GAC*			*NF*			
		Sc 0[b]	*Sc 2*[c]	*Sc 3*[d]	*Sc 0*	*Sc 1*[e]	*Sc 2*	*Sc 3*
Carcinogens	kg C_2H_3Cl eq	0.0070	0.0071	0.0150	0.0014	0.0016	0.0015	0.0308
Non-carcinogens	kg C_2H_3Cl eq	0.1038	0.1039	0.1060	0.0022	0.0022	0.0024	0.0103
Respiratory inorganics	kg PM2.5 eq	0.00061	0.00062	0.00069	0.00003	0.00008	0.00007	0.000356
Ionising radiation	BqC-14 eq	4.1	22.3	7.0	2.5	2.9	70.7	13.8
Ozone layer depletion	kg CFC-11eq	3.13E-08	3.20E-08	3.47E-08	1.30E-07	1.34E-07	1.32E-07	1.42E-07
Respiratory organics	kg C_2H_4 eq	0.000117	0.000117	0.000129	1.63E-05	2.68E-05	2.08E-05	6.71E-05
Aquatic ecotoxicity	kg TEG water	25 255	25 259	25 265	3.7	4.9	19.2	40.1
Terrestrial ecotoxicity	kg TEG soil	5473.4	5473.7	5475.0	0.9	1.3	1.7	6.4
Terrestrial acid/nutri	kg SO_2 eq	0.013	0.013	0.015	0.0008	0.0015	0.0015	0.0079
Land occupation	$m_2$org.arable	0.0036	0.0037	0.0039	0.0003	0.0006	0.0004	0.0013
Aquatic acidification	kg SO_2 eq	0.0045	0.0046	0.0054	0.0002	0.0007	0.0005	0.0033
Aquatic eutrophication	kg PO_4 P-lim	1.14E-05	1.17E-05	1.23E-05	2.71E-06	3.04E-06	3.4E-06	5.97E-06
Global warming	kg CO_2 eq	0.68	0.69	0.79	0.049	0.091	0.088	0.473
Non-renewable energy	MJ primary	10.5	12.4	12.5	0.9	1.3	7.5	7.9
Mineral extraction	MJ surplus	0.0136	0.0138	0.0138	0.0013	0.0021	0.0018	0.0018

[a] See Jolliet et al. [19] for more details about units; [b]reference scenario (Quebec usual corrosion control strategy and Quebec-hydro-electricity); [c]scenario 2 (French-nuclear energy); [d]scenario 3 (US-coal energy); [e]scenario 1 (French usual corrosion control strategy).

Appendix C. Contribution analysis: list of processes that contribute more than 2% to at least one damage category

Process	Human health (%)	Ecosystem quality (%)	Climate change (%)	Resources (%)
CONV-GAC (scenario 0)				
GAC	61.9	0.3	88.3	87.2
Wastewater (Al emission)	26.4	99.7	<0.1	<0.1
Alum	4.2	<0.1	1.9	2.2
NaOH	3.2	<0.1	3.8	4.3
Polymer	0.6	<0.1	1.1	2.2
Lorry transport	3.3	<0.1	3.2	3.6
CONV-GAC (scenario 2)				
Electricity for operation	1.8	<0.1	2.0	15.0
GAC	60.8	0.3	86.5	74.0
Wastewater (Al emission)	26.0	99.7	<0.1	<0.1
Alum	4.1	<0.1	1.9	1.8
NaOH	3.2	<0.1	3.7	3.6
Lorry transport	3.2	<0.1	3.1	3.1

Appendix C (*continued*)

Process	Human health (%)	Ecosystem quality (%)	Climate change (%)	Resources (%)
CONV-GAC (scenario 3)				
Electricity for operation	11.0	<0.1	14.7	15.7
GAC	75.3	0.3	75.3	73.5
Wastewater (Al emission)	23.5	99.7	<0.1	<0.1
Alum	3.7	<0.1	1.7	1.8
NaOH	2.9	<0.1	3.2	3.6
Lorry transport	3.0	<0.1	2.8	3.1
NF (scenario 0)				
Electricity for NF system	16.7	9.2	22.3	32.3
Membrane cleaning agent	5.0	7.0	5.2	5.7
$NaHCO_3$	7.2	9.7	7.5	7.1
NF spiral-wound modules	12.8	21.5	6.8	8.6
CO_2	12.8	16.7	17.3	15.6
$Ca(OH)_2$	3.2	4.8	18.1	5.7
Phosphoric acid	14.2	4.8	4.2	3.6
Spiral-wound module storage (PVC)	2.2	<0.1	0.2	0.3
Motors (steel + copper)	2.2	7.6	0.4	0.4
Building-wall (steel)	2.4	3.4	1.9	1.7
Pipes (PVC)	4.5	<0.1	0.4	0.6
Core grid (steel)	2.5	3.3	1.7	1.5
Lorry transport	12.7	18.8	8.3	7.9
NF (scenario 1)				
Electricity for NF system	10.6	7.4	14.7	27.9
Membrane cleaning agent	2.6	4.6	2.8	4.0
$NaHCO_3$	3.7	4.6	3.5	4.2
NF spiral-wound modules	6.6	14.1	3.7	6.1
CO_2	13.7	22.7	19.3	22.9
$Ca(OH)_2$	7.2	13.7	42.6	17.5
H_2SO_4	43.1	15.1	5.4	6.5
Motors (steel + copper)	1.2	6.1	0.3	0.3
Lorry transport	8.7	16.4	5.9	7.4
NF (scenario 2)				
Electricity for NF system	63.5	55.7	59.4	92.7
Membrane cleaning agent	2.3	3.5	2.9	0.7
$NaHCO_3$	3.3	4.8	4.2	0.9
NF spiral-wound modules	5.9	10.7	3.8	1.0
CO_2	5.9	8.3	9.7	1.9
$Ca(OH)_2$	1.5	2.4	10.1	0.7
Phosphoric acid	6.5	2.4	2.4	0.4
Lorry transport	5.9	9.5	4.7	1.0
NF (scenario 3)				
Electricity for NF system	92.2	88.3	92.4	93.1
NF spiral-wound modules	1.3	2.9	0.7	1.0
CO_2	1.3	2.2	1.8	1.8
Lorry transport	1.3	2.6	0.9	1.0

Appendix D. Uncertainty ranges for Monte-Carlo analysis that differ from the default uncertainty ranges found in *Ecoinvent 2.0*

Component	Min	Max	Method
CONV-GAC			
Electricity (kWh/m^3)	0.086	0.094	Assumption (+/− 4%)
GAC (kg/m^3)	0.049	0.135	Jacangelo et al. [17]
Alum (kg/m^3)	0.05	0.1	Edzwald and Tobiason [10]
NaOH (kg/m^3)	0.047	0.073	Assumption (+/− 10%)
Polymer (kg/m^3)	0.0002	0.0004	Assumption (+/− 10%)
Transport, lorry (km)	Ref. − 50%	Ref + 50%	Assumption (+/− 50%)
NF			
Electricity for NF system (kWh/m^3)	0.47	0.51	Assumption (+/− 4%)
Membrane cleaning agent (kg/m^3)	0.0037	0.0045	Assumption (+/− 10%)
$NaHCO_3$ (kg/m^3)	0.003	0.0037	Assumption (+/− 10%)
NF spiral-wound modules	0.00026	0.0006	Assumption (lifetime from 8 to 15 years)

(*continued on next page*)

Appendix D (*continued*)

Component	Min	Max	Method
CO_2 (kg/m^3) (scenario 0)	0.013	0.017	Assumption (+/− 10%)
$Ca(OH)_2$ (kg/m^3) (scenario 0)	0.008	0.01	Assumption (+/− 10%)
Phosphoric acid (kg/m^3) (scenario 0)	0.0012	0.0018	Assumption (+/− 10%)
CO_2 (kg/m^3) (scenario 1)	0.028	0.034	Assumption (+/− 10%)
$Ca(OH)_2$ (kg/m^3) (scenario 1)	0.028	0.034	Assumption (+/− 10%)
H_2SO_4 (kg/m^3) (scenario 1)	0.032	0.040	Assumption (+/− 10%)
Spiral-wound module stowage (PVC) (kg/m^3)	0.000036	0.000044	Assumption (+/− 10%)
Motors (steel + copper) (kg/m^3)	0.00005	0.00012	Assumption (lifetime from 8 to 15 years)
Building-wall (steel) (kg/m^3)	0.00018	0.00032	Assumption (lifetime from 50 to 80 years)
Pipes (PVC) (kg/m^3)	0.00004	0.0001	Assumption (lifetime from 8 to 15 years)
Core grid (steel) (kg/m^3)	0.0003	0.00053	Assumption (lifetime from 50 to 80 years)
Transport, lorry (km)	Ref. − 50%	Ref + 50%	Assumption (+/− 50%)

References

[1] AAC, L'aluminium, Association de l'aluminium du Canada, 2009, http://aac.aluminium.qc.ca/f302b.html.

[2] R. Barrios, M. Siebel, A. van der Helm, K. Bosklopper, H. Gijzen, Environmental and financial life cycle impact assessment of drinking water production at Waternet, J Clean Prod 16 (2008) 471–476.

[3] P. Bayer, E. Heuer, U. Karl, M. Finkel, Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies, Water Resour 39 (2005) 1719–1728.

[4] C. Bouchard, D. Ellis, M. Sydor, Suivi 2002–2003 du fonctionnement de l'usine de nanofiltration de la Ville de Lebel-sur-Quévillon (63 pp.), Rapport Final, Université Laval, Québec, 2004, http://www.lebel-sur-quevillon.com/Greffe/travaux_publics/suivi%20usine%20nanofiltration.pdf.

[5] CCBDA, Cuivre, Matériau écologique de choix, Canadian Copper and Brass Development Association, 2007, (Publication N°43 F, 6 pp.).

[6] CIRAIG, Personal data, Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et services, Montreal, Canada, 2009.

[7] CSSBI, Environmental Fact Sheet, Canadian Sheet Steel Building Institute, 2008 (Number 1, 4 pp.).

[8] G.A. Davis, P. Dickey, D. Duxbury, B. Griffith, B. Oakley, K. Cornell, Household cleaners: environmental evaluation and proposed standards for general purpose household cleaners, Center for clean products and clean technologies, University of Tennessee, 1992 (106 pp.).

[9] C. Desjardins, B. Koudjonou, R. Desjardins, Laboratory study of ballasted flocculation, Water Res 36 (2002) 744–754.

[10] J.K. Edzwald, J.E. Tobiason, Enhanced coagulation: US requirements and a broader view, Water Science and Technology (1999) 63–70 40–9.

[11] EPA, Water treatment plant simulation program, version 1.21, user's manual, USEPA—Office of Ground Water and Drinking Water Technology Transfer, Malcom Pirnie Inc, 1992.

[12] H.E. Fierz-David, The Fundamental Processes of Dye Chemistry, D. Van Nostrand Company, New-York, 1921 (240 pp.).

[13] Friedrich, E., 2001. Environmental life cycle assessment of potable water production, Master thesis of Chemical Engineering, University of Natal, South Africa.

[14] R. Frischknecht, N. Jungbluth, H.J. Althaus, G. Doka, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann, G. Wernet, Overview and Methodology, Ecoinvent Report No. 1, Swiss Centre for Life Cycle Inventories, Dübendorf, 2007, (68 pp.).

[15] D. Halliday, R. Resnick, J. Walker, Fundamentals of Physics, Wiley, New-York, 2008 (473 pp.).

[16] ISO, Environmental management — life cycle assessment — principles and framework, International Standard ISO 14040, Second Edition 2006-07-01, 2006.

[17] J.G. Jacangelo, J. DeMarco, D.M. Owen, S.J. Randtke, Selected processes for removing NOM: an overview, J AWWA 87 (1) (1995) 64–77.

[18] Y. Jaeger, S. Oberti, L. Guichot, J. Baron, Comparaison de traitements utilisés pour limiter la corrosivité des eaux douces dans les réseaux de distribution d'eau potable, Techniques sciences méthodes, génie urbain et génie rural 12 (2006) 83–94.

[19] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, R. Rosenbaum, Impact 2002+: a new life cycle impact assessment methodology, Int J LCA 8 (6) (2004) 324–330.

[20] O. Jolliet, M. Saadé, P. Crettaz, Analyse du cycle de vie. Comprendre et réaliser un écobilan, Presses Polytechniques et Universitaires Romandes, 2005 (242 pp.).

[21] S. Kawamura, Integrated Design and Operation of Water Treatment Facilities, John Wiley and Sons, New-York, USA, 2000 (691 pp.).

[22] R.E. Kirk, Kirk-Othmer Encyclopedia of Chemical Technology, 5th edition, Wiley-interscience, 2007 (1084 pp.).

[23] Kiwa, *LCAqua versie 2.0 Handleiding*, Kiwa, Nieuwegein, July, 1998 (in Dutch).

[24] L. Legrand, G. Poirier, P. Leroy, Les équilibres carboniques et l'équilibre calcocarbonique dans les eaux naturelles, Eyrolles Ed, France, 1981 (176 pp.).

[25] MDDEP, Guide de conception des installations de production d'eau potable, Ministère du développement durable, de l'environnement, et des parcs. Québec, Canada, 2006.

[26] MDDEP, 2009A. Actiflo®+Dusenflo®. John meunier inc. Fiche d'évaluation technique du comité sur les technologies de traitement en eau potable. Ministère du développement durable, de l'environnement, et des parcs. Québec, Canada. http://www.mddep.gouv.qc.ca/eau/potable/guide/actiflo.pdf

[27] MDDEP, Nanofiltration Lapierre (six modules par caisson). Crédits d'enlèvement et suivi d'intégrité, Fiche d'évaluation technique du comité sur les technologies de traitement en eau potable, Ministère du développement durable, de l'environnement, et des parcs, Québec, Canada, 2009, http://www.mddep.gouv.qc.ca/eau/potable/%85/nano-lapierre-credit.pdf.

[28] MDDEP, Politique québécoise de gestion des matières résiduelles- Plan d'action 2011–2015, Ministère du développement durable, de l'environnement, et des parcs, Québec, Canada, 2011, http://www.mddep.gouv.qc.ca/matieres/pgmr/index.htm.

[29] P.K. Mohapatra, M.A. Siebel, H.J. Gijzen, J.P. van der Hoek, C.A. Groot, Improving eco-efficiency of Amsterdam water supply: a LCA approach, J Water Supp Res Technol Aqua 51 (4) (2002) 217–227.

[30] A. Montiel, Traitement de potabilisation des eaux: garantie de teneurs minimales en micropolluants mineraux, Rev Fr Lab 364 (2004) 45–49.

[31] Ortiz, I.M., 2006. Life cycle assessment as a tool for green chemistry. Application of different advanced oxidation processes for wastewater treatment. PhD thesis. Barcelona. 258 pp.

[32] PE, GABI software: documentation manual, PE Europe GmbH, 2004.

[33] Pré Consultants, Introduction to LCA with SimaPro 7. Netherlands, 2008 (82 pp.).

[34] R.G. Raluy, L. Serra, J. Uche, A. Valero, Life cycle assessment of water production technologies. Part 2: reverse osmosis desalination versus the ebro river water transfer, Int J LCA 10 (5) (2005) 346–354.

[35] A. Rompré, D. Allard, P. Niquette, Optimisation de l'implantation des stratégies de contrôle de la corrosion interne dans les réseaux de distribution, Rapport final sur les stratégies recommandées pour le contrôle de la corrosion interne des réseaux de distribution d'eau potable, École polytechnique de Montréal, Canada, 1999, (87 pp.).

[36] H.D.M. Sombekke, D.K. Voorhoeve, P. Hiemstra, Environmental impact assessment of groundwater treatment with nanofiltration, Desalination 113 (1997) 293–296.

[37] J. Stokes, A. Horvath, Life cycle energy assessment of alternative water supply systems, Int J Life Cycle Ass 11 (2006) 335–343.

[38] US DOE, Energy and environmental profile of the U.S. chemical industry, U.S. Department of Energy, Office of Industrial Technologies, 2000 (220 pp.).

[39] US patent 3364259, 1968. Preparation of trimesoyl chloride. United states patent office.

[40] US patent 4277344, 1981. Interfacially synthesized reverse osmosis membrane. United states patent.

[41] US patent 4765897, 1988. Polyamide membranes useful for water softening. United states patent.

[42] US patent 4970034, 1990. Prodess for preparing isotropic microporus polysulfone membranes. United states patent.

[43] B. Van der Bruggen, J.Q.J.C. Verberk, J. Verhack, Comparison of pressure-driven membrane processes and traditional processes for drinking water production in Europe based on specific impact criteria, Water SA 30 (2004) 413–420.

[44] F. Vince, E. Aoustin, P. Breant, F. Marechal, LCA tool for the environmental evaluation of potable water production, Desalination 220 (2008) 37–56.

[45] B. Gilbert, personal communication with Bruno Gilbert, civil engineer at Engineering Division of the city of Sainte-Marie, Canada, (2008).

[46] B. Barbeau, personal communication with Benoit Barbeau, professor at Department of Civil, Geological and Mining Engineering of École Polytechnique de Montréal, Canada, (2009).

[47] P. Niquette, F. Monette, A. Azzouz, R. Hausler, Impacts of substituting aluminum-based coagulants in drinking water treatment, Water Qual. Res. J. Canada 32 (2004) 303–310.