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Comparative analysis of selected water disinfection technologies with the use of life cycle assessment

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Abstract: The objective of the paper is to use life cycle assessment to compare environmental impact of different technologies used in the process of water disinfection. Two scenarios are developed for water disinfection life cycle at ZUW Raba water treatment plant: (1) historical, in which gaseous chlorine is used as a disinfectant and (2) actual, in which UV radiation and electrolytically generated sodium hypochlorite are used for that purpose. Primary data is supplemented with ecoinvent 3 database records. Environmental impact is assessed by IMPACT2002+ method and its midpoint and endpoint indicators that are calculated with the use of SimaPro 8.4 software. The focus of the assessment is on selected life cycle phases: disinfection process itself and the water distribution process that follows. The assessment uses the data on flows and emissions streams as observed in the Raba plant. As the results of primal analysis show, a change of disinfectant results in quantitative changes in THMs and free chlorine in water supplied to the water supply network. The results of analysis confirm the higher potential of THMs formation and higher environmental impact of the combined method of UV/NaClO disinfection in distribution phase and in whole life cycle, mainly due to the increase of human toxicity factors. However, during the disinfection phase, gaseous chlorine use is more harmful for environment. But the final conclusion states that water quality indicators are not significant in the context of LCA, while both disinfection and distribution phases are concerned.

Introduction

Freshwater resources and their allocation increasingly play a central role in poverty alleviation and urban water supply. Rapidly rising urban populations mount the pressure to shift water from agriculture to vastly expanding cities and to develop efficient treatment systems that could keep water circulating at a high enough speed. Additionally, global trade of manufactured goods and services, all of which require water at some point, fuel the demand for capturing the freshwater userelated environmental, economic, and social impacts (Koehler 2008). However, according to Koehler, despite obvious capabilities of LCA for capturing the details of the issue, the topic of freshwater use has received very limited attention in LCA for decades (Koehler 2008).

In the last few years, not-surprisingly, LCA methodology is developed with regard to water resources (Garfi et al. 2016, Jones et al. 2018). Nowadays, LCA methods are commonly used in the context of assessment of water treatment environmental impacts (Bajdur et al. 2016, Bortolini et al. 2017, Boulay et al. 2013, Opher and Friedler 2016, Raghuvanshi et al. 2017, Simms et al. 2017, Slagstad and Brattebø 2014). The methods catalogue has been recently updated concerning the water related impact categories. Also some new methods are developed, which fall into water footprint category, in order to get better cover of impacts on water resources (Boulay et al. 2013).

Water treatment, and more specifically, water disinfection and purification are also subject to LCA studies. Raghuvanshi et al. perform complex LCA study on water treatment plant. Their results show that the purification process has a significant share in overall water treatment impacts, contributing to such impact categories as climate change, global warming potential, fossil depletion and particulate matter formation (Raghuvanshi et al. 2017). Simms et al. take similar approach to the assessment of water recycling schemes that are introduced in Western Australia. The difference is related to the disinfection process that in this case is not solely chlorination but a combined process of UV disinfection and fluoride and chlorine additives at the final stage (Simms et al. 2017). Both of the studies agree on the major impact factor in water treatment plant that is electricity used and both show that the chemicals used in the treatment process are the second biggest impact factor (Raghuvanshi et al. 2017, Simms et al. 2017). Bortolini et al. present the assessment from the perspective of water treatment plant use in food & beverage industry. The system under assessment is an innovative wastewater treatment plant, and includes also purification processes. Disinfection is made in UV module, and according to the results, has minor share in overall impacts (Bortolini et al. 2017).

The objective of the paper is to use life cycle assessment to assess the environmental impact ultraviolet radiation and electrolytically generated sodium hypochlorite use in the process of water disinfection. Two scenarios are developed for water disinfection life cycle: (1) historical, in which gaseous chlorine is used as a disinfectant and (2) actual, in which UV radiation and electrolytically generated sodium hypochlorite are used for that purpose.

Characteristics of the research object

Disinfection technology at ZUW Raba

The "Raba" Water Treatment Plant treats approx. 55% of water supplied to the distribution system in Cracow. Water from Dobczyce is also the basic source of supply for Dobczyce, Siepraw and Świątniki Górne communes, and in part for Myślenice, Wieliczka and Skawina as well. Due to so vast an area of supply, bacteriological safety of the water supplied to customers is very important. Up to now, this safety has been ensured by a chlorine gas based plant commissioned in 1995, which was supplied as part of the US government's assistance. This plant fulfilled its role very well, but it was necessary to think about upgrading due to its age. 500 kg barrels with chlorine constituted a certain kind of hazard, and even more so because sufficient supply of chlorine, which has also recently become increasingly difficult to purchase, had to be stored in order to ensure continuity of water production at the plant.

Seeking systematic improvement of the quality of water supplied to the residents of Cracow, a decision has been made to eliminate gas chlorine from the disinfection process at the largest plant, which is the last one using this type of disinfectant. It has been decided to use disinfection in the form of sodium hypochlorite obtained from common salt and, additionally, UV lamps whose radiation improves bacteriological safety of water and allows for decreasing the dose of disinfectant (MPWiK 2014, Żaba 2014).

New water disinfection technology

In order to change disinfection technologies, it was necessary to build a new chamber that will be the last stage of the disinfection process. A UV system is located in the lower part of the chamber, whereas electrolysers for sodium hypochlorite production, along with the necessary infrastructure, are located in the upper part. The process part includes two main components (Fig. 1). The first one is a set of UV lamps. The design envisages installation of three medium-pressure UV lamps in reactors with diameters of 900, 700 and 300 mm. The second element is the sodium hypochlorite dosing system (Żaba 2014).

The UV radiation disinfection system consists of four main components: UV reactor, level switch, power control panel and cleaning system. In the reactor, which has a cylindrical shape, appropriate UV lamps have been installed to generate UV radiation. The output of UV lamps can be controlled in order to adjust the dose of radiation to the flow of water. The level switch controls the water level in pipelines responsible for the water flow and protection of lamps in the event it decreases. The power control panel is responsible for supplying electricity to the UV lamps and it enables system output adjustment. The cleaning system allows for automatic cleaning of UV lamps' tubes in order to ensure optimum working conditions and the required output (Biedrzycka 2014, Żaba 2014).

Due to the fact that UV rays are an excellent disinfectant, albeit with a short-lasting effect, in order to obtain full microbiological safety, the use of a second stage of disinfection was envisaged, which, as already mentioned, will be sodium hypochlorite produced from common salt according to the current demand (Gibczyńska 2013, Kowal and Świderska-Bróż 2009, Papciak et al. 2011, Włodyka-Bergier and Bergier 2013). It will also be dosed into the water at three points: into Ø 900 and Ø 700 delivery pipes in the new chamber above the UV lamps and into Ø 300 pipe below the UV lamp in the Raba I pumping station. Four electrolyser assemblies have been installed in the new chamber being constructed, which will produce NaClO. At the beginning of the process, brine with a concentration of 25–30 g/l is produced, and then it undergoes the electrolysis process. The output of electrolysers will be 2 kg expressed as Cl_2 per hour while the electrolyser installed in the Raba I pumping station will have output of 0.5 kg of chlorine per hour. The produced sodium hypochlorite will have a concentration of 0.6%. Each electrolyser has been

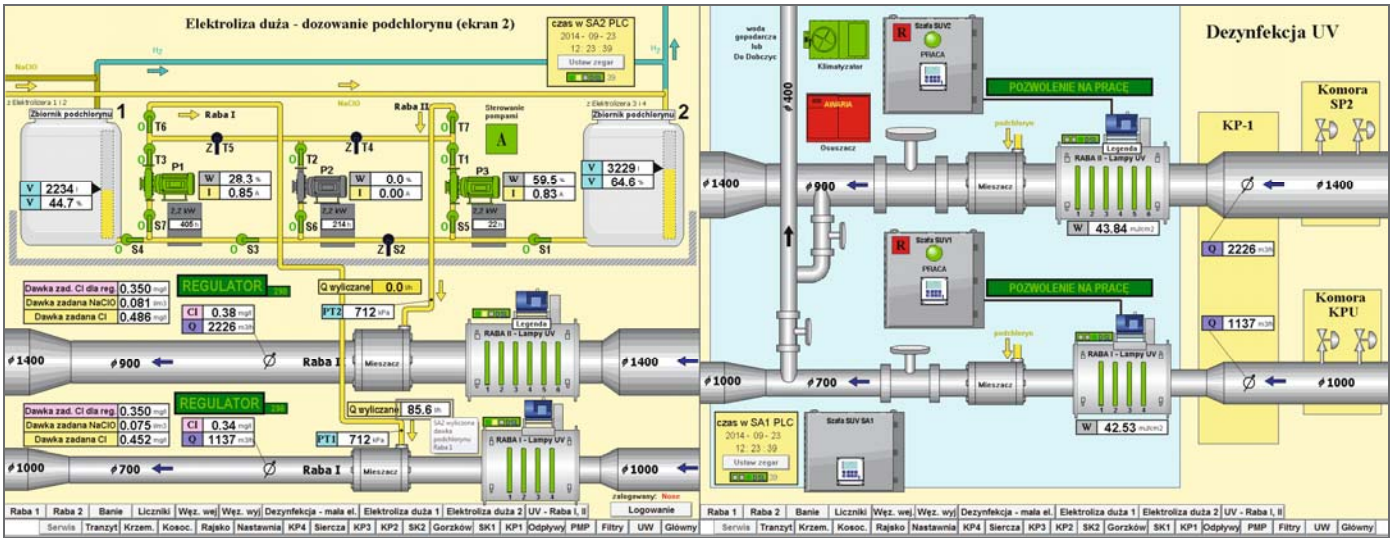

Fig. 1. Water disinfection system in ZUW Raba (MPWiK 2014)

equipped with an extraction system diluting hydrogen created during the production and an extraction system equipped with a hydrogen sensor preventing hydrogen from finding its way into the tanks with the product. It is assumed that the power consumption to produce 1 kg of Cl_2 will not be greater than 5.5 kWh. In contrast, to produce 1 kg of disinfectant and to regenerate the water softener, approx. 4.5 kg of common salt will be consumed (Biedrzycka 2014, Żaba 2014).

In order to correctly mix the disinfectant with the water flowing through, appropriately selected static mixers have been employed. For the control of conducted disinfection process, free chlorine meters have been installed, the task of which will be to cooperate with the NaClO dosing system and maintain constant preset free chlorine content. The entire disinfection system operates in an automation system with remote supervision from the control room (MPWiK 2014, Żaba 2014).

Material and methods

Goal and scope of LCA assessment

According to ISO 14040 standards the goal of assessment should clearly indicate the use of the results, reasons of making assessment and supposed stakeholders of the results. The scope of the assessment should be limited in a quantitative and qualitative sense and should indicate time, space and technological framework, assessment type and system boundaries (PN-EN ISO 14040:2009).

Functional unit for the study is 1 kg of disinfected water that flows out from disinfection plant through the distribution systems to urban based users. The assessment of the cycle is limited to the process of disinfection and distribution only due to the objectives of the research. The functional unit is calculated for historical process of using gaseous chlorine for disinfection (referred to as “Cl_2 Water Disinfection” in following figures) and for currently implemented process of ultraviolet radiation and electrolytically generated sodium hypochlorite use in the process of water disinfection (referred to as “NaClO Water Disinfection”). The reasoning behind the comparison lies within the observed change of the amounts of THMs and free chlorine in water supplied to the network. The objective of the assessment is to check the overall environmental impact of two different methods of water disinfection process as calculated in this LCA study. This could provide useful knowledge for plant operators on actual changes in environmental pressures related to technological change that has been recently made.

The coverage of the assessment is ‘gate-to-gate’ type, assuming that disinfection and distribution that follows are phases that are operated by single decision making unit while all the other phases of pre- and post-treatment are omitted. The flow that is modelled within LCA could not be specifically referred to time framework, since the two compared disinfection methods have never been used simultaneously in the plant but a new one has replaced the historical one. Additionally, water quality indicators used as LCI input have been calculated for the years 2011–2017. Since the infrastructure processes are excluded from the study, the time framework is not specifically defined in order to enable comparison between historical and current practices of water disinfection. The geographical space that is covered is bordered by the range of the Raba plant distribution system (city of Cracow and its neighbouring towns). Table 1 presents the major assumptions for the range of the assessment.

Life cycle inventory

The primary data used for the assessment comes from disinfection plant and research made on water content while leaving the plant and in the distribution network. Secondly, the data is supplemented with appropriate records from ecoinvent 3.0 database that enables covering the environmental impacts and related damages. Such an approach to data use caused one important limitation of the study. Ecoinvent database does not cover impacts for microorganisms and therefore, their presence is neglected in the study. At this point, it is important to mention that the quantity of microorganisms observed in disinfected water is rather similar in both cases, so the limitation should not bias the results significantly.

The subject of research was water produced at the “Raba” Water Treatment Plant as drawn from the network. Microbiological tests and tests of selected water quality indicators (after the treatment process as well as at water supply network points) were carried out in years 2011–2017. The results of tests were made available by the Central Laboratory of Municipal Water and Sewerage Company in Cracow (MPWiK 2018).

The average concentrations of selected water quality parameters and chlorine, sodium chloride and electricity use are presented in Table 2 (Jachimowski 2018). Water quality indicators and the quantities of substances/electricity used are taken directly from the Raba plant, while their environmental impacts are modelled with appropriate ecoinvent 3.0 records. Electricity use is based on average electricity mix that is available in Poland, while disinfection substances are averaged for Europe due to lack of more specific data. The simplifying assumption that is made with LCI set-up is that 1 kg of disinfected water is matched with 1 kg of distributed water. Therefore, water quality indicators are interpreted as illustrating the content of disinfected water unit flowing directly through distribution system.

Table 1. Range of LCA

Indicator	Specification
Type of assessment	‘Gate to gate’ including water disinfection and its distribution
Time frames	2011–2017 (for calculation of water quality indicators)
Geographical reference	Munipalities of Dobczyce, Siepraw and Świątniki Górne, and in part for Cracow, Myślenice, Wieliczka and Skawina
Technology types	Two disinfection methods: (1) gaseous chlorine use and (2) UV radiation and electrolytically generated sodium hypochlorite use

The assessment uses the data on flows and emissions streams in Raba water treatment plant and connected distribution network. Environmental impacts are assessed by IMPACT 2002+ method in version 2.11 and its midpoint and endpoint impact category indicators are calculated with use of SimaPro 8.4 software.

The selection of IMPACT 2002+ method is related to the reference of its allocation and calculation default setups to Europe that enables reliable assessments for Poland. Secondly, it is one of the methods that could be calculated on midpoint and on endpoint level. As we applied different midpoint/endpoint methods (CML and ReCiPe) IMPACT 2002+ proved to give better coverage for water quality indicators with much wider perspective than water footprint methods at the same time.

The characteristic of the method used with regard to impact and damage category indicators is presented in Table 3. IMPACT 2002+ has 4 damage category indicators and 15 impact category indicators for midpoint and 13 for endpoint assessment. Each category presents only narrow impact related issue that has been allocated with the life cycle flows (PN-EN ISO 14044:2009).

Table 2. LCI indicators

ZUW Raba			
Indicator	**Unit**	**Before upgrade**	**After upgrade**
trichlorometane (chloroform)	µg·dm^{-3}	4.4	1.8
bromodichlorometane		0.9	0.0
dibromochlorometane		0.2	0.0
tribromometan (bromoform)		0.0	0.0
Σ THM		5.5	1.9
chlorine	g per kg of water	1.027	–
sodium chloride	g per kg of water	–	20.25
electricity	kWh per kg of water	–	0.02475
Raba distribution system			
Microorganisms*	CFU/100 ml	15.3	16.1
free chlorine	mg·dm^{-3}	0.1	0.0
TOC		1.6	1.6
STHM	µg·dm^{-3}	20.6	23.5

* total number of microorganisms at 22ºC
Source: the author's own work based on MPWiK's results

Table 3. Indicator structure of IMPACT 2002+ method (Frischknecht et al. 2007)

Category	**Indicator/unit midpoint/unit endpoint**		
Impact category indicators	Carcinogens	kg C_2H_3Cl eq	DALY
	Non-carcinogens	kg C_2H_3Cl eq	DALY
	Respiratory inorganics	kg PM2.5 eq	DALY
	Ionizing radiation	Bq C-14 eq	DALY
	Ozone layer depletion	kg CFC-11 eq	DALY
	Respiratory organics	kg C_2H_4 eq	DALY
	Aquatic ecotoxicity	kg TEG water	PDF·m^2·yr
	Terrestrial ecotoxicity	kg TEG soil	PDF·m^2·yr
	Terrestrial acid/nutri	kg SO_2 eq	PDF·m^2·yr
	Land occupation	m^{2}org·arable	PDF·m^2·yr
	Aquatic acidification	kg SO_2 eq	n/a
	Aquatic eutrophication	kg PO_4 P-lim	n/a
	Global warming	kg CO_2 eq	kg CO_2 eq
	Non-renewable energy	MJ primary	MJ primary
	Mineral extraction	MJ surplus	MJ primary
Damage category indicators	Human Health	n/a	DALY
	Ecosystem Quality	n/a	PDF·m^2·yr
	Climate Change	n/a	kg CO_2 eq
	Resources	n/a	MJ primary

The values of impact category indicators are calculated on the basis of material, energy, waste and emission flows in life cycle with use of default allocation mechanisms in SimaPro software as proposed by (Goedkoop et al. 2013). IMPACT2002+ method calculates emissions and impact levels in a given cycle (step 1), assesses its impact on environment and human beings expressed in diversified impact category indicators (step 2) and its aggregation to damage category indicators and single score indicator (step 3). IMPACT2002+, used with SimaPro 8.4 software, automatically allocates values of specific emissions and flows to appropriate damage and impact categories. For detailed description of allocation, normalization and weighting indicators refer to methodological reports and articles (Frischknecht et al. 2007, Humbert et al. 2012).

The impact assessment is made on the three levels: characterization, normalization and weighting with calculation of single score indicator.

Results and discussion

Life cycle impact assessment

At first, the results of impact assessment are presented at the stage of characterization. The scheme for presenting the results is to compare the two disinfection methods with regards to the following impact indicators. The actual impacts are comparable between the disinfection methods for the sake of functional unit use (1 kg of disinfected water). Looking at Fig. 2, the first observation is that the newly implemented method has the higher impact due to electricity use, relatively high NaCl input and potentially higher THM level observed in the distribution system.

The only impact category, in which gaseous chlorine use has higher impact than the process of ultraviolet radiation and electrolytically generated sodium hypochlorite use is Ozone layer depletion. That is due to the devastating impact of chlorine on ozone layer. In all other categories the impact of currently used disinfection method exceeds the historical one.

Figure 3 presents the results in normalization phase, in which the impacts referred to average level of European citizen exposition to given impacts. The damage factors reported in ecoinvent are normalized by dividing the impact per unit of emission by the total impact of all substances of the specific category for which characterization factors exist, per person per year (for Europe). The normalization factors are used as default in SimaPro software, please refer to the literature for their values (Humbert et al. 2012, p. 22). Therefore, the impacts could be referred to one another in order to identify the key impact categories for investigated processes. The biggest impacts are observed for respiratory effects, global warming and non-renewable categories. The significance of impacts for respiratory effects is the 1st (Cl_2 disinfection) and the 2nd biggest (NaClO) while the for global warming effect is the other way around.

In order to figure out what are the substances behind the observed impacts, the share of disinfection stages, as expressed in single score indicator, is presented in Fig. 4. In both cases, the key impacts for environment occur in water disinfection phase while the impacts occurring afterwards are neglectible. The impacts in gaseous chlorine use come directly from Cl_2. In the combined method, the impacts come partly from NaCl use (23.6% of total impact) and electricity generation (76.4%). It is important to remember that all the water treatment plant processes that are not directly used for water disinfection purposes are omitted. The assumption is that their intensity would be the same or very similar no matter which disinfection method is used.

In order to summarize the weighting phase, water quality parameters are singled out for the assessment. Figure 5 presents the IMPACT 2002+ impact category indicators for water quality parameters after the disinfection and in the distribution system with regard to different disinfection methods. The categories with no impact are skipped. Carcinogens and non-carcinogens are major impact categories while non-carcinogens and aquatic ecotoxity are the minor impacts despite the method and point of water quality check. A new method causes significantly higher impact at the distribution systems and significantly lower one right after the disinfection. The results do not include the time frame of the impacts and the differences could be more significant if the time horizon is prolonged.

Discussion

In general, the results of the study confirm the findings in different studies that showed the biggest share of electricity

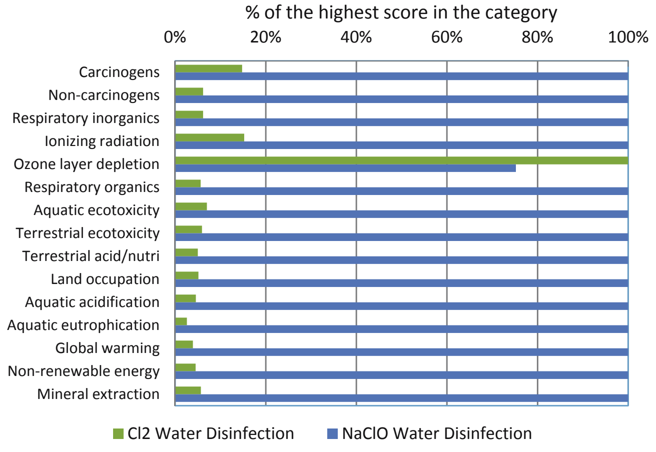

Fig. 2. Environmental impacts of water disinfection methods in characterization phase – IMPACT 2002+

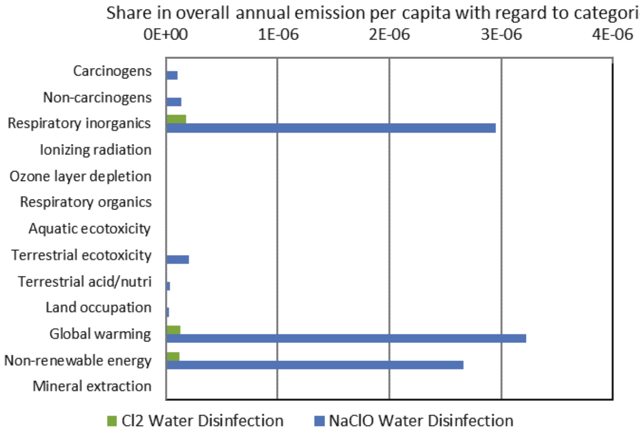

Fig. 3. Environmental impacts of water disinfection methods in normalization phase – IMPACT 2002+

and chemicals as far as environmental impact in disinfection process is concerned (Raghuvanshi et al. 2017, Simms et al. 2017). As opposed to this, while environmental impacts are concerned, the substances persisting in water after the process have very little impact on environment. This finding should be elaborated more, since the reasoning behind changing the disinfection method is quite strong (direct impact on human health), while it has no match while LCA results are concerned. It also shows some drawbacks of common LCIA methods, such as IMPACT2002+, while water quality indicators are concerned. Surprising findings on significantly higher overall impacts of new disinfection methods could be softened by developing a better framework for the water quality issue or rather performing hybrid assessment that combines LCA method with water quality indicators.

It is worth to notice that the impact categories that are affected by water quality indicators level are mainly limited to human toxicity factors. On the one hand, it confirms the importance of the technological change drivers, which are focused mainly on end-user wellbeing. On the other hand, the total amount of impacts, calculated directly on water quality indicators, does not show a significant change with technological shift. If we add the possible increase of impacts due to the electricity and NaClO use then the justification for the technological shift would be more difficult to formulate.

Alternatively, the results shown above should be treated as an introduction to a more in-depth analysis of short- and long-term effects of water disinfection. The limitations of the study (‘gate-to-gate’ scope of the study, exclusion of non-disinfection

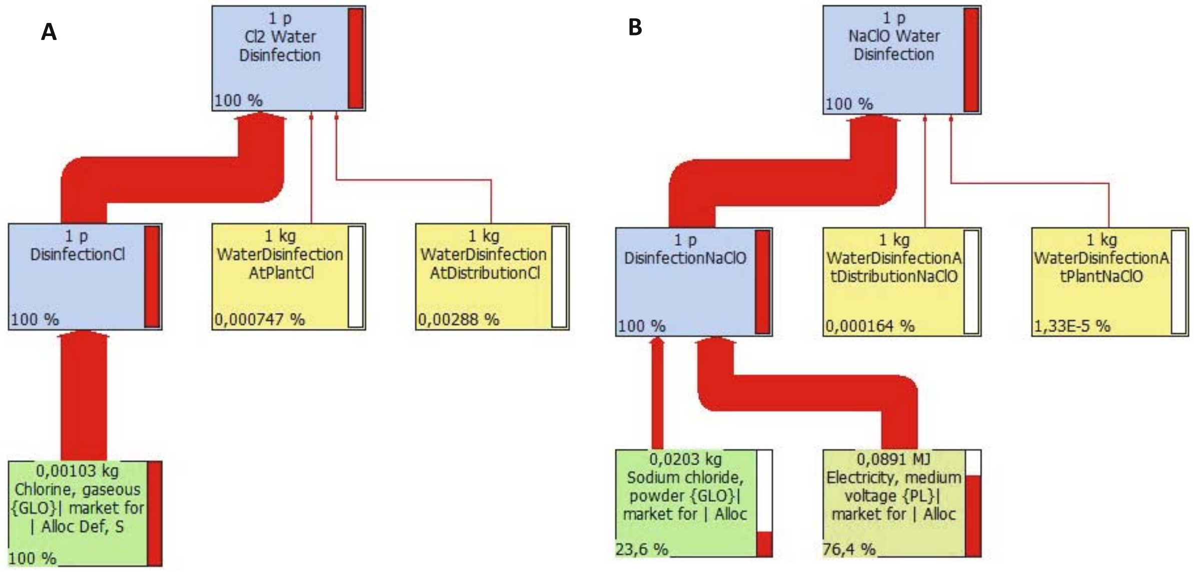

Fig. 4. Comparison of IMPACT 2002+ single score indicators (weighting phase) for water disinfection methods: (A) gaseous chlorine method, (B) combined ultraviolet radiation and electrolytically generated sodium hypochlorite method

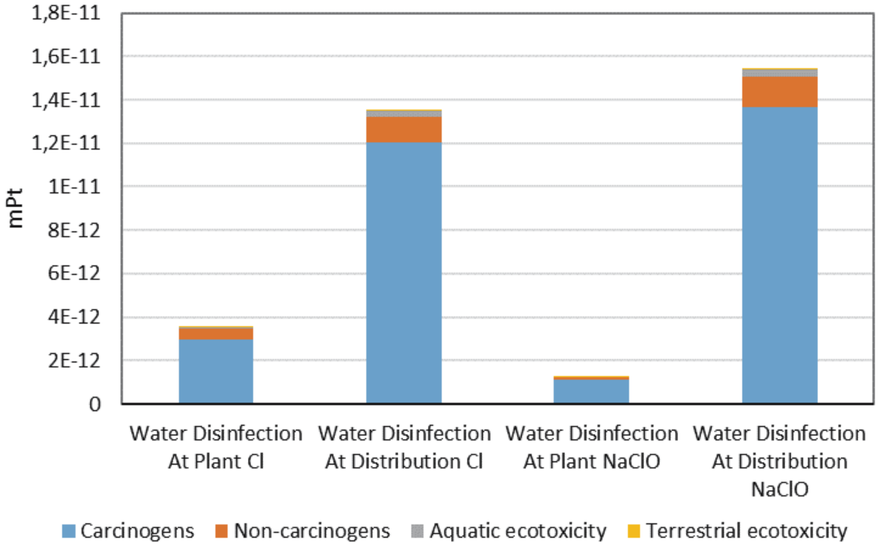

Fig. 5. Comparison of IMPACT 2002+ impact category indicators (weighting phase) for the water quality parameters after the disinfection and in the distribution system (categories with results = 0 skipped)

related processes in water treatment, lack of coverage for other factors and processes influencing water quality, especially in distribution network, etc.) does not allow to treat the results as definitive but rather as an indication of an issue in water disinfection process that is yet to be investigated. The study does not give clear answer whether the technological shift in water disinfection improves water quality in the long-run. For that kind of interpretation some additional measurements are needed, preferably with extended time frame and possibly with different technological variants analyzed within comparative study with similar approach.

Conclusions

The important conclusion is that from the point of view of LCA methodology water quality parameters obtained in different disinfection methods are rather not significant in a sense of environmental impact, especially, when referred to overall impact of disinfection process. What truly matters for the impact is the processes of disinfection, and the electricity and chemicals used. The study shows that the newly implemented method for water disinfection has significantly higher impact in whole life cycle than the gaseous chlorine use. Since the impacts are related mostly to the use of NaCl and electricity in combined UV radiation and sodium hypochlorite method, the focus should be on optimization of these processed. In that sense, our results go in line with those presented in the literature. Also the minor share of disinfection process impacts in overall impact of water treatment processes is confirmed. Concerning the structure of impacts, the results of our study show that electricity use categories are mostly responsible for overall impacts while whole disinfection process is concerned. When the assessment is focused on water quality after the process, the human toxicity indicators are becoming the dominant ones.

Disinfection with UV rays in combination with sodium hypochlorite is a new method which is increasingly used by large water treatment plants. Therefore, the results of the concentration of chlorination by-products in the water supply network are not fully known in the long term. However, the studies carried out by Jachimowski show that concentrations of ∑ THM in water from the distribution network supplied from the “Raba” Water Treatment Plant, where chlorine gas had been used, the mean being 20.6 $\mu g \cdot dm^{-3}$. After the chlorination plant upgrade, the concentration of this indicator, with the mean value (23.5 $\mu g \cdot dm^{-3}$) increased by 14% (Jachimowski 2018). What may cause the concentration of chlorination by-products to increase is the use of UV rays which has a considerable impact on the formation potential of these compounds before chemical disinfection (Choi and Choi 2010, Lyon et al. 2012, Weng et al. 2012).

The question we have raised at the beginning about the impacts of water disinfection process, including the water outflow of the disinfection plant, led us to the conclusion that the water quality indicators, focusing especially on THM content, are not significant on both disinfection and distribution levels. This conclusion could indicate the gap between water quality issues and impact of water treatment on environment that is yet to be addressed by further investigations.

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Porównawcza analiza wybranych technologii dezynfekcji wody przy wykorzystaniu środowiskowej analizy cyklu życia

Streszczenie: Celem artykułu było pokazanie wykorzystania środowiskowej oceny cyklu życia (LCA) do porównania wpływu na środowisko różnych technologii stosowanych w procesie dezynfekcji wody. Dla cyklu życia procesu dezynfekcji wody w zakładzie uzdatniania wody Raba Miejskiego Przedsiębiorstwa Wodociągów i Kanalizacji (MPWiK) w Krakowie w niniejszej pracy zostały sformułowane dwa scenariusze: (1) historyczny, w którym dezynfektantem jest chlor gazowy oraz (2) bieżący, w którym tę rolę spełnia układ dwustopniowy z promieniowaniem UV i podchlorynem sodu. Podstawowe dane były uzupełniane rekordami bazy danych ecoinvent 3. Oddziaływanie środowiskowe poddano ocenie przy wykorzystaniu metody IMPACT2002+. Pośrednie i końcowe wskaźniki kategorii wpływu wyliczono przy wykorzystaniu oprogramowania SimPro 8. Analiza obejmowała wybrane fazy cyklu życia: sam proces dezynfekcji i następujący po nim proces dystrybucji wody. W ocenie wykorzystano dane ilościowe o przepływach i emisjach w procesie dezynfekcji wody z wybranego zakładu uzdatniania wody. Wyniki wstępnych analiz pokazują, że zmiana dezynfektanta powoduje zmiany ilościowe trihalometanów (THM) i chloru wolnego w wodzie dostarczanej do sieci wodociągowej. Analiza wskazuje, że w fazie dezynfekcji użycie chloru gazowego jest bardziej szkodliwe dla środowiska. Natomiast wyniki analizy potwierdzają wyższy potencjał tworzenia się THM i większy wpływ na środowisko połączonej metody dezynfekcji UV/NaClO w fazie dystrybucji wody.