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Health and environmental impacts of drinking water choices in Barcelona, Spain: A modelling study

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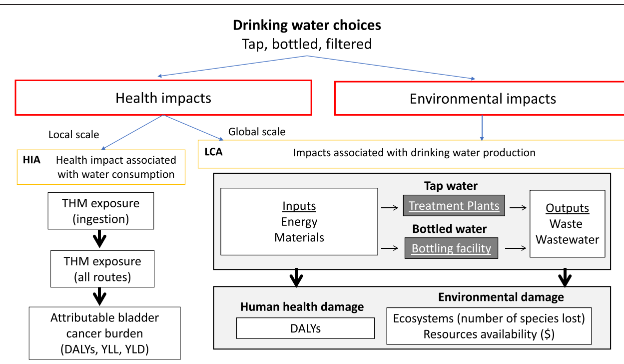
HIGHLIGHTS

- Quantified health and environmental tradeoffs of drinking water choices
- Novel approach integrating health impact and life cycle assessment
- Environmental impact of bottled water 1400–3500 higher than tap water
- Local health burden of tap water consumption equivalent to 2 h of life lost
- Filtered water considerably reduced health and environmental impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Quantitative evidence of health and environmental tradeoffs between individuals' drinking water choices is needed to inform decision-making. We evaluated health and environmental impacts of drinking water choices using health impact and life cycle assessment (HIA, LCA) methodologies applied to data from Barcelona, Spain. We estimated the health and environmental impacts of four drinking water scenarios for the Barcelona population: 1) currently observed drinking water sources; a complete shift to 2) tap water; 3) bottled water; or 4) filtered tap water. We estimated the local bladder cancer incidence attributable to trihalomethane (THM) exposure, based on survey data on drinking water sources, THM levels, published exposure-response functions, and disability-adjusted life years (DALYs) from the Global Burden of Disease 2017. We estimated the environmental impacts (species lost/year, and resources use) from waste generation and disposal, use of electricity, chemicals, and plastic to produce tap or bottled drinking water using LCA. The scenario where the entire population consumed tap water yielded the lowest environmental impact on ecosystems and resources, while the scenario where the entire population drank bottled water yielded the highest impacts (1400 and 3500 times higher for species lost and resource use, respectively). Meeting drinking water needs using bottled or filtered tap water led to the lowest bladder cancer DALYs (respectively, 140 and 9 times lower than using tap water) in the Barcelona population. Our study provides the first attempt to integrate HIA and LCA to compare health and environmental impacts of individual water consumption choices. Our results suggest that the sustainability gain from consuming water from public supply relative to bottled water may exceed the reduced risk of bladder

Abbreviations: BHS, Barcelona Health Survey; DALYs, disability-adjusted life-years; GBD, Global Burden of Disease; HIA, health impact assessment; LCA, life cycle assessment; OR, odds ratio; PAF, population attributable fraction; THM, trihalomethanes; YLLs, years life lost; YLDs, years lived with disability.

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cancer due to THM exposure from consuming bottled water in Barcelona. Our analysis highlights several critical data gaps and methodological challenges in quantifying integrated health and environmental impacts of drinking water choices.

1. Introduction

Bottled water consumption has sharply increased in the last years worldwide (Rodwan, 2018). This global trend is partly explained by subjective factors like risk perception and organoleptics (Doria et al., 2009), lack of trust in public tap water quality (Saylor et al., 2011), and marketing by the bottled water industry (Gleick, 2010). The recent increase in bottled water use globally has been driven by a sharp increase in demand in low- and middle-income countries (LMICs), despite parallel increases in access to piped water in some countries (Cohen and Ray, 2018). However, bottled water consumption involves much higher environmental impacts compared to public drinking water supply (Garfí et al., 2016).

Plastic production processes are responsible for non-renewable resource depletion and for the emission of harmful pollutants (e.g. greenhouse gases, particulate matter) into the environment. Even in the case of high-energy consuming technologies for drinking water treatments, tap water always shows better environmental performance in terms of global warming potential, compared to bottled water (Fantin et al., 2014). The growing use of bottled water also contributes to the sharp increase of plastic debris worldwide (Geyer et al., 2017), including microplastics (Brandon et al., 2019). Plastic debris are the most serious problem affecting the marine environment (UNEP, 2014) and also affect terrestrial ecosystems (de Souza Machado et al., 2017). The accumulation and fragmentation of plastics (Barnes et al., 2009) contributes to the ubiquitous presence of micro- and nanoplastics as an emerging contaminant in the food chain (Van Cauwenberghe and Janssen, 2014) and the water cycle, including drinking water (Schymanski et al., 2018).

Both municipal and bottled water may contain chemicals of health concern. However, research on drinking water quality has mainly focused on public supply, and less data are available on contaminants in bottled water. Current knowledge indicates that concentrations of disinfection by-products such as trihalomethanes (THMs) are usually higher in municipal vs. mineral bottled water (Font-Ribera et al., 2010). However, bottled water may contain higher levels of endocrine disruptors (Pinto and Reali, 2009; Real et al., 2015; Wagner et al., 2013; Wagner and Oehlmann, 2009) and microplastics (Koelmans et al., 2019) that may originate from plastic containers. In addition, inappropriate handling of bottled water can lead to microbial growth (Raj, 2005), and faecal contamination has been detected in bottled water, particularly among LMICs (Williams et al., 2015). THMs are of particular concern because of widespread exposure in countries where disinfection of drinking water is a common practice. THMs are volatile and skin permeable, thus inhalation and dermal contact are relevant exposure pathways in water-contact activities, beyond water ingestion (Ashley et al., 2005). Virtually the entire population is exposed through inhalation and dermal contact while showering and bathing, in addition to ingestion, and long-term exposure has been consistently associated with increased bladder cancer risk, a cancer site primarily affecting adults. Among the long list of health-relevant chemicals that can be present in drinking water, THMs are an attractive focus for health impact assessment because of widespread exposure in the population through multiple exposure routes (Villanueva et al., 2015), consistent epidemiological evidence showing a link between long-term THM levels as a marker of exposure to disinfection by-products and increased bladder cancer risk (Cantor et al., 2010; Costet et al., 2011), and available exposure-response relationship (Costet et al., 2011; Villanueva et al., 2004).

The city of Barcelona, Spain, is supplied by different water sources and treatment plants and has been characterized by high THM levels in the past in some water supply zones (i.e. areas receiving water from common treatment plants, thus having homogenous quality). Concentrations of THMs were drastically reduced after technological improvements in the drinking water treatment plants in 2009. Annual average concentrations of THMs were above 100 μg/L in some areas prior 2009, decreasing to ≈50 μg/L after 2009 (ASPB, 2012). Barcelona is also characterized by high levels of bottled water consumption. Bottled water was the primary source of drinking water among 50% of the population in 2006 (Font-Ribera et al., 2017), increasing to 60% in 2016 (ASPB, 2019) despite the improvements in the quality of the public drinking water supply. Most bottled water sold in Spain is mineral water (Heras, 2018), defined as spring water with a constant composition of minerals, intended for human consumption in their natural state and bottled at source (EC, n.d.). From this point forward bottled water consumption in Barcelona refers to mineral water.

While Life Cycle Assessment (LCA) of water treatment processes and health impact assessment (HIA) have been conducted previously in the context of drinking water treatment options (Ribera et al., 2014), to our knowledge, no previous study has linked the two methodologies to provide a comprehensive, quantitative assessment of the health and environmental tradeoffs associated with individual drinking water choices. We address this gap by estimating the health and environmental impacts under four drinking water consumption scenarios for the city of Barcelona, which we selected as a case study based on availability of data. We aimed to estimate the burden of bladder cancer in the local population attributable to THM exposure and the environmental impact linked to the production of drinking water.

2. Methods

2.1. Drinking water consumption scenarios

Drinking water consumption patterns in the Barcelona population were ascertained from the Barcelona Health Survey (BHS) conducted in 2016–2017 by the Barcelona Public Health Agency (Bartoll et al., 2018). Briefly, 4000 district-stratified Barcelona residents (400 per district, 10 districts) representative of the general population, were randomly sampled and interviewed at their residence. Participants answered a questionnaire covering self-perceived health and health risk factors, including drinking water consumption patterns through the closed-ended question "*How frequently do you drink tap water without filtering, filtered tap water, bottled water, and water from natural sources*?" Answer options included: *usually, occasionally, never*. The survey did not collect data on the type of filter, that could include any domestic device such as countertop pitchers with activated carbon, under the sink reverse osmosis units, or faucet mounted filters (March et al., 2020).

Our goal was to estimate the burden of bladder cancer attributable to total THM exposure that could be avoided by changing drinking water source among the adult (≥20 years old) population of the city of Barcelona (1,349,570 inhabitants ≥20 years old in 2017, INE, 2018) and link each scenario with associated environmental impacts. We considered three sources, following the BHS: tap water with no filtration, filtered tap water using a domestic device, and bottled mineral water. We defined the drinking water consumption scenarios (S1–S4) with variable drinking water source as follows:

- S1: Current: Currently observed drinking water sources (based on the BHS)
- S2: All tap: 100% of drinking water supplied as tap water without domestic filtration
- S3: All bottle: 100% of drinking water supplied as bottled water
- S4: All filtered tap water: 100% of drinking water supplied as tap water filtered with domestic filters (any type).

Given that THM levels in the public water supply remain the same across scenarios, we assumed the THM exposure patterns from inhalation and dermal absorption did not change across scenarios. We compared health impacts in each scenario (S1–S4) to a reference exposure level in which there was no THM exposure due to ingestion. We included S2 to S4 in which the full population adopted a specific drinking water source in order to explore the full range of modifiable health and environmental impacts linked to drinking water source. Drinking water sources for S1–S4 are described in Table 1.

2.2. Municipal water supply

Barcelona city is supplied by four drinking water treatment plants. The "Abrera" and "Sant Joan Despí" drinking water treatment plants treat, respectively, around 3.5 and 5 $m^3\ s^{-1}$ of surface water from the Llobregat river. Both include conventional treatment consisting of pretreatment, coagulation, flocculation, sedimentation, filtration (sand filters), adsorption (activated carbon filters), and disinfection (chlorine-based, and ozone), in addition to membrane processes such as reverse electrodialysis (Abrera), and reverse osmosis (Sant Joan Despí). The "Cardedeu" drinking water treatment plant treats around 8 $m^3\ s^{-1}$ of surface water from reservoirs in the Ter basin, which is less impacted by anthropogenic activity compared to the Llobregat river. Accordingly, this plant only includes conventional treatments (i.e. pretreatment, coagulation, flocculation, sedimentation, and filtration in activated carbon filters). The fourth plant is located in El Prat de Llobregat and produces drinking water through desalination of seawater from the Mediterranean during drought periods, with a treatment capacity up to 2 $m^3\ s^{-1}$ of seawater (ACA, 2019; ASPB, 2012).

Barcelona has 3 water supply areas (ASPB, 2012) (Fig. 1): 1) Llobregat area (≈16% of the water supply) receives water from the drinking water treatment plants located in Abrera, Sant Joan Despí, and the desalination plant; 2) Llobregat and Ter area (≈77% of the water supply) receives water from the three drinking water treatment plants in Llobregat and Ter basins, and the desalination plant; and 3) Ter area (≈7% of the water supply) receives water from the Cardedeu drinking water treatment plant. THM levels were measured in 2016 as part of the Barcelona Public Health Agency surveillance programme in the three municipal water supply areas. Median values were: 31.1 μg/L ($n = 5$) in the Llobregat area, 40.1 μg/L (n = 5) in the Ter area, and 46.3 μg/L ($n = 10$) in the Llobregat + Ter area. The different sampling dates, unbalanced Ter/Llobregat proportion, and the THM formation in the distribution system explain the higher levels in the Llobregat + Ter area.

2.3. Estimating trihalomethane exposure

We estimated the population in each water supply area by spatially joining water supply area boundaries provided by the Barcelona Public Health Agency with residential census tract data (Fig. 1). We used adult (≥20 years old) population counts for each census tract in January 2017 (INE, 2018) to estimate the adult population in each water supply area (Table 1). Incidence rates before 20 years of age are very low, and tend to be linked to genetic factors rather than environmental exposures. For Scenario 1, we grouped BHS participants ($N = 4000$) in water supply areas according to their residential census tract and estimated usual water consumption source based on BHS data (Table 1).

We assumed 59.8% of the total water THMs exposure occurred via water ingestion, while dermal contact and inhalation accounted for the remaining 40.2% of the exposure based on a previous study (Jo et al., 1990). We assumed that domestic water filters reduced THM levels by 89%, based on the removal capacity of a 150 L aged activated carbon pitcher type filter (Carrasco-Turigas et al., 2013). We assumed a THM concentration of 0.3 μg/L in bottled mineral water based on a report assessing 15 different popular brands of bottled water consumed in the study area (Font-Ribera et al., 2010). We derived total THM exposure levels by computing a weighted mean of exposure pathways. THM exposure levels for drinking water (ingestion) and all exposure routes (ingestion, dermal absorption, and inhalation) according to water supply area and drinking water consumption source are described in Table 2.

2.4. Health impact assessment

HIA provides a framework and procedure for estimating the impact of an intervention on a selected environmental health issue for a defined population. In this study, we obtained years of life lost (YLLs), years lived with disability (YLDs), and disability-adjusted life years (DALYs) for bladder cancer in Spain from the Global Burden of Disease (GBD) 2017 estimates (IHME, 2018), for 5-year age groups. We scaled YLLs, YLDs, and DALYs from Spain to Barcelona proportional to the adult population by 5-year age groups, leading to 3070 YLLs, 324.7 YLDs, and 3394.8 DALYs in the city of Barcelona for both sexes (Table 5).

We used published exposure-response functions for the association between total THM levels (encompassing all exposure pathways) and bladder cancer (Costet et al., 2011). Based on a pooled database including data from 6 case-control studies (Costet et al., 2011), Evlampidou and colleagues estimated an odds ratio (OR) of 1.004 (95% CI 1.002, 1.006) for a unit increase in the continuous THM exposure expressed

Table 1
Proportion of tap, filtered and bottled water consumption (mean, 95% confidence interval) and adult population and by water supply area in the city of Barcelona for each drinking water consumption scenario.

Water supply area		Llobregat	Llobregat + Ter	Ter	Barcelona City
Scenario 1 (Current)	Tap (%)	13.2 (9.1, 17.3)	24.8 (23.1, 26.4)	46.3 (40.9, 51.6)	26.1 (24.6, 27.6)
	Filtered (%)	15.3 (11.0, 19.7)	16.7 (15.3, 18.1)	10.9 (7.5, 14.2)	16 (14.7, 17.3)
	Bottled (%)	71.4 (66.0, 76.9)	58.5 (56.6, 60.4)	42.9 (37.6, 48.1)	57.9 (56.2, 59.6)
Scenario 2 (All tap water)	Tap (%)	100	100	100	100
	Filtered (%)	0	0	0	0
	Bottled (%)	0	0	0	0
Scenario 3 (All bottled water)	Tap (%)	0	0	0	0
	Filtered (%)	0	0	0	0
	Bottled (%)	100	100	100	100
Scenario 4 (All filtered tap water)	Tap (%)	0	0	0	0
	Filtered (%)	100	100	100	100
	Bottled (%)	0	0	0	0
Adult population		112,495	1,096,627	140,448	1,349,570

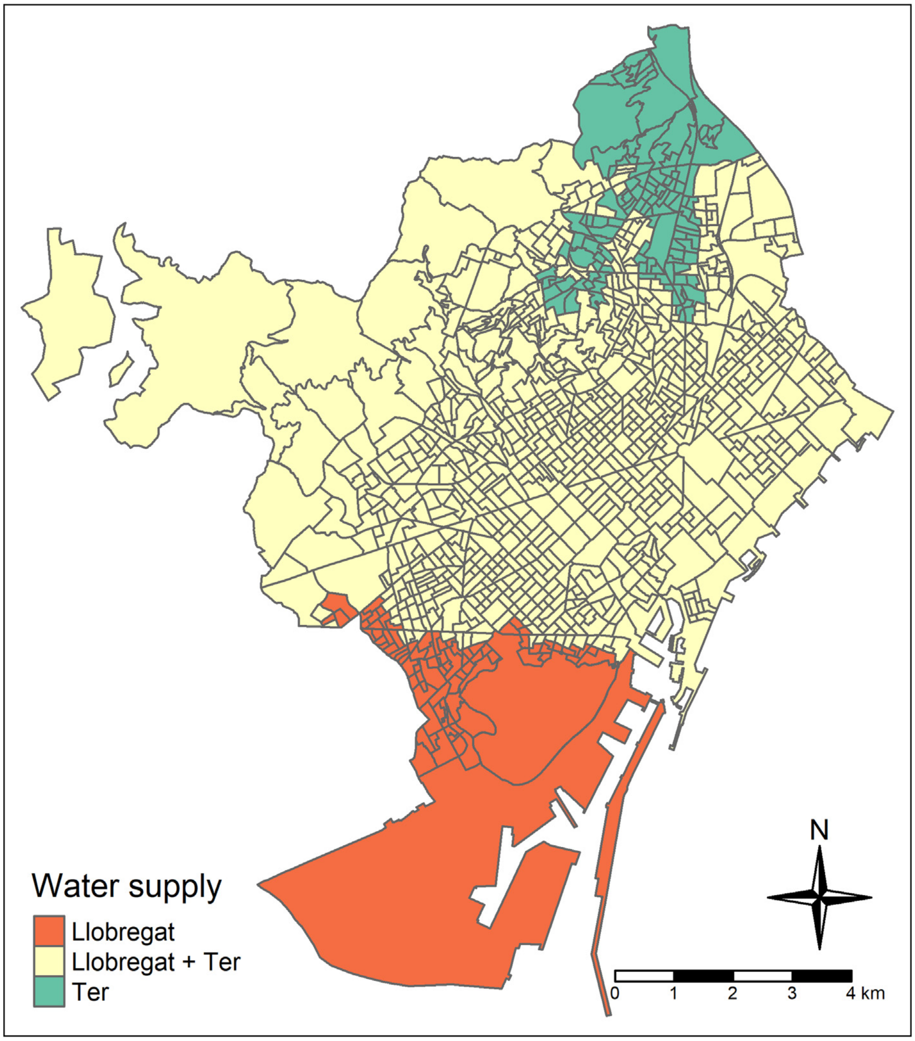

Fig. 1. Census tracts in the City of Barcelona according to water supply area.

Table 2
Drinking water, total, and reference median trihalomethane (THM) exposures in 2016 by water supply area and drinking water consumption source.

Drinking water source by water supply area	THM concentration in drinking water (μg/L)	Total THM exposure (μg/L)[c]	THM exposure through skin contact and inhalation (μg/L) (reference)
Llobregat			
Tap water	31.1	31.1	12.5
Tap filtered[a] water	3.4	14.6	12.5
Bottled[b] water	0.3	12.7	12.5
Llobregat + Ter			
Tap water	46.3	46.3	18.6
Tap filtered[a] water	5.1	21.7	18.6
Bottled[b] water	0.3	18.8	18.6
Ter			
Tap water	40.1	40.1	16.1
Tap filtered[a] water	4.4	18.7	16.1
Bottled[b] water	0.3	16.3	16.1

[a] Filtered water THMs concentrations are assumed to be 89% lower than the corresponding tap water exposures (Carrasco-Turigas et al., 2013).
[b] Bottled water THMs concentrations are assumed to be 0.3 μg/L for all areas (Font-Ribera et al., 2010).
[c] Total exposure estimates assume 59.8% of total exposure occurs via ingestion and 40.2% via dermal contact and inhalation of tap water (Jo et al., 1990).

in μg/L (Evlampidou et al., 2020). We scaled the ORs for the THM level corresponding to each drinking water consumption scenario compared to the reference exposure, in which there is no THM exposure due to ingestion. We then estimated the population attributable fractions (PAFs), i.e. the proportion of disease in the population that would be attributable to a certain exposure, using standard formulas for burden of disease analyses (WHO, 2014):

$$PAF\% = ((OR-1)/OR) * 100 \quad (1)$$

With these PAFs, we estimated the YLLs, YLDs, and DALYs attributable to THM levels in the study area for S1–S4 compared to the reference exposure by using this formula:

$$\text{Attributable DALYs} = \text{annual DALYs} * \text{PAF} \quad (2)$$

2.5. Life cycle assessment

LCA is a systematic tool for identifying, quantifying, and assessing environmental impacts through the whole life cycle of a product, process or activity (ISO, 2006). It includes energy and material uses and releases to the environment from cradle to grave (e.g. raw materials extraction, production, use and final disposal). According to the ISO 14040, there are four main stages in an LCA: i) goal and scope definition,

ii) inventory analysis, iii) impacts assessment and iv) interpretation of the results (ISO, 2006).

The goal of this LCA was to estimate the potential environmental impacts associated with producing 1 L of drinking water for each municipal water supply area in Barcelona and for bottled water (mineral water in PET bottles). For the case of tap water, the treatment processes of each drinking water treatment plant are described in Section 2.2. Environmental impacts associated with the production of drinking water in each drinking water treatment plant were calculated and then combined considering the water flow supplied by each plant in each area. The additional environmental impacts of domestic filtration using a carbon filter were not included, since they are likely to be small (<1% of the overall impact) (Garfí et al., 2016; ILCD, 2010; SO, 2009). For the case of bottled mineral water, the production includes: i) pumping from aquifers; ii) washing the PET bottles using detergents (i.e. potassium hydroxide, hydrochloric acid) and disinfectants (i.e. foaming agent, potassium hydroxide); and iii) filling the bottles with drinking water.

Environmental impacts referred to the production of 1 L of water (the functional unit). System boundaries accounted for input and output flows of material (mainly chemicals and materials for packaging) and energy resources (electricity). The phases of construction, maintenance and decommissioning of the facilities were not included, since they account for minor environmental impacts (<1% of the overall impact) (Foley et al., 2010; ILCD, 2010; Lorenzo-Toja et al., 2016).

We report inventory data in Table A1 per 1 L of drinking water for each drinking water treatment plant and bottled water. Inventory data were provided by the local authorities and companies involved in the production and distribution of both tap water and bottled mineral water. Data consist of the annual average (2019) levels of required materials and energy, and waste generated through the production of both tap water and bottled mineral water. All environmental data regarding inputs and emissions of each material and waste analysed were obtained from *Ecoinvent 3.5* databases (Weidema et al., 2013). Environmental impacts were evaluated using the software SimaPro® (PRé Consultants, 2019) and the Recipe2016 endpoint (H) method (Huijbregts et al., 2016). The goal of the ReCiPe method is to transform the long list of life cycle inventory data into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. Indicators in ReCiPe are organised at two levels: 17 mid-point and 3 end-point impact categories. The former focus on the environmental impacts, while the latter take into account the damage on the 3 areas of protection (human health, ecosystem quality and resource scarcity). In this study, the primary end-point impact categories were considered:

1) damage to ecosystems, expressed in species per year, which refers to the number of species lost integrated over time;
2) damage to resource availability, expressed in dollars, which refers to the cost of raw materials extraction.

We also considered the following end-point category:

3) damage to human health, from environmental factors linked to drinking water production (e.g. particulate matter emissions), expressed as DALYs in the global population.

These indicators quantify the global damage to ecosystems, contribution to resource scarcity, and human health impacts caused by the production of 1 L of water. They are obtained by combining the mid-point impact categories using standard characterisation factors (Huijbregts et al., 2016). For instance, damage to human health is obtained by considering the diseases caused by particulate matter emissions, ionizing radiation, ozone depletion and toxicity due to materials and energy used, as well as waste and emissions generated through the whole life cycle of the product, process or activity considered.

In order to integrate the LCA with the HIA results, we estimated the annual environmental impacts of meeting drinking water needs under S1–S4 by combining estimates of impact per L of water with population data in each water supply area, assuming each individual consumes 2 L/d of drinking water. Health impacts of ingestion were estimated for the Barcelona population as explained in the HIA section, while the environmental and health impacts of production derived from LCA were estimated at a global scale (Huijbregts et al., 2016). Integrating both tools can provide a more comprehensive view of the health and environmental impacts associated with the consumption and production of drinking water.

Fig. 2 presents the conceptual model showing how we integrated data on water supply area, population exposure to THMs, and water treatment technologies in a combined health impact and life cycle assessment to estimate the health burden of consumption and environmental impacts of production of meeting drinking water needs of the Barcelona population.

3. Results

Drinking water source share in S1 varied across water supply areas, with 71% of participants in the BHS residing in the Llobregat water supply area drinking bottled water compared to approximately 58% of the population in Barcelona as a whole (Table 1). Total THM exposure levels were lowest in the Llobregat water supply area, with a median concentration in 2016 of 31.1 μg/L in Llobregat water supply area and 40.1 μg/L in Ter water supply area (Table 2). Total THM exposure was highest in the scenario where all drinking water was supplied by tap without domestic filtration (S2) and lowest in the scenario with all drinking bottled water (S3) (Table 3).

The environmental and global health impacts associated with drinking water in each water supply area are shown in Tables 4 and A2. Bottled water production showed the highest environmental impacts, from 500 to 50,000 times higher than tap water depending on the water supply area and impact categories. Considering only tap water, the production of drinking water in the Llobregat area showed the highest environmental impacts: impacts in Llobregat area were 2 times higher than in Llobregat + Ter area, and 30 times higher than the Ter water supply area. As expected, the environmental impacts were highest for the scenario in which all drinking water was bottled (S3) (Table 4). We estimated 1.43 species per year would be lost due to the production of bottled water to meet the drinking water needs of the Barcelona population, whereas the damage to ecosystems would be negligible if all drinking water was from the tap. We estimated considerable costs of raw materials extraction for the current drinking water source share in Barcelona (S1). The cost of raw material extraction would be nearly eliminated through a complete shift to tap water (around $24,000 per year, which means that each resident would be responsible for $0.02 per year), but it would increase by $83.9 million through a complete shift to bottled water (which means that each resident would be responsible for around $60 per year). The production of bottled water to meet the drinking water needs of Barcelona population was estimated to result in 625 DALYs per year in the global population (Table A2). This burden would be reduced to 0.5 DALYs if only tap water, or filtered tap water were consumed.

Our results indicate that under the current drinking water source share, 3% of new (incident) bladder cancer cases annually are attributable to THM exposure from drinking water, resulting in 94 years of life lost in the Barcelona population (Table 6). A complete shift to tap water without domestic filtration would increase the number of life years lost to 309 (on average approximately 2 h of lost life expectancy if borne equally by all residents of Barcelona). Adding domestic filtration would reduce the number of life years lost to 36. A complete shift to drinking bottled water would essentially remove the health burden to THM exposure through drinking water. Most of the attributable health burden due to THM exposure from drinking water was from years of life lost rather than lived in disability.

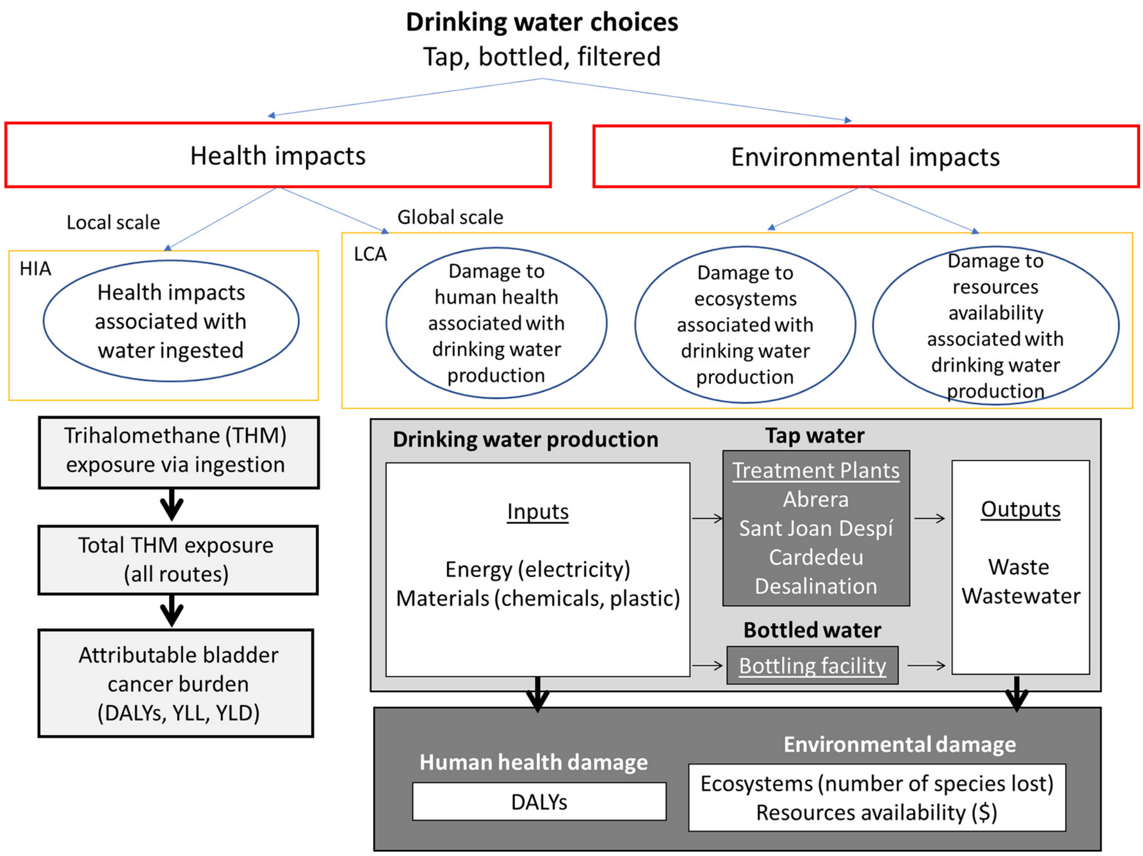

Fig. 2. Conceptual model showing the integrated health impact assessment (HIA) and life cycle assessment (LCA) of drinking water consumption choices.

Fig. 3 shows the combined health and environmental impacts of the four drinking water source scenarios, highlighting the large environmental benefits and modest health trade-offs of moving from the current drinking water source share in Barcelona to tap water.

4. Discussion

Our study, based on a novel integration of health impact and life cycle assessment applied to the city of Barcelona, resulted in several key findings. First, meeting drinking water needs for the city of Barcelona with bottled water resulted in high ecosystem and resource damages compared to tap water. Second, current drinking water source choices result in 103.9 DALYs (that equals on average 40 min if borne equally by all Barcelona residents). The scenario where all the population in Barcelona consume tap water yielded the lowest impact on ecosystems, resources and health, while the scenario where the entire population drinks bottled water yielded the highest impacts of water production. Relative to S2 (all drink tap water), S3 (all drink bottled water) led to approximately 1400 times more species lost/year and 3500 times more resource use (in $). At the local scale, S3 led to lowest bladder cancer burden in the Barcelona population (2.4 DALYs), and S2 led to the highest (341.8 DALYs).

Table 3
Estimated average total THM exposure (μg/L) by water supply area for each drinking water consumption scenario.

Water supply area	Llobregat	Llobregat + Ter	Ter	Barcelona City
Scenario 1: Current	15.4	26.1	27.6	24.4
Scenario 2: All tap water	31.1	46.3	40.1	42.7
Scenario 3: All bottled water	12.7	18.8	16.3	17.3
Scenario 4: All filtered tap water	14.6	21.7	18.7	20.0

The higher environmental impact of bottled water was attributed to the high input of materials (i.e. packaging) and energy needed for bottled water production as compared to tap water. Indeed, raw materials and energy required for bottle manufacturing accounted for the majority of the impact of bottled water use (up to 90% of the impact in all indicators), consistent with previous studies (Garfí et al., 2016; Lagioia et al., 2012; Papong et al., 2014). Regarding tap water, the production of drinking water in the Llobregat area had the highest potential environmental impacts (from 2 up to 30 times higher compared to the other water supply areas). Since water of Ter reservoirs have better quality compared to Llobregat river, the corresponding drinking water

Table 4
Environmental impacts of drinking water production in the study area, from the life cycle assessment.

	Ecosystems (Species/year)	Resources ($)
Per 1 l of drinking water produced in:		
Drinking water treatment plants		
Sant Joan Despí	2.25E-12	5.93E-05
Abrera	3.59E-13	4.35E-06
Desalination plant	6.32E-12	8.06E-05
Cardedeu	1.56E-13	1.71E-06
Bottled water	1.45E-09	8.52E-02
Per 1 l of drinking water in supply areas:		
Llobregat area	2.43E-12	4.62E-05
Llobregat + Ter area	9.92E-13	2.47E-05
Ter area	1.56E-13	1.71E-06
In the drinking water consumption scenarios:		
S1: Current	0.852	5.00E+07
S2: All tap water	1.01E-03	2.37E+04
S3: All bottled water	1.43	8.39E+07
S4: All filtered tap	1.01E-03	2.37E+04

Table 5
Years of life lost (YLLs), years lived with disability (YLDs), disability-adjusted life-years (DALYs) of bladder cancer in Spain scaled to the Barcelona adult population (both sexes).

Age	Spanish population[a]	Spanish YLLs[b]	Spanish YLDs[b]	Spanish DALYs[b]	Barcelona population[a]	% population	Barcelona YLLs[c]	Barcelona YLDs[c]	Barcelona DALYs[c]
20–24	2,260,951	19.5	3.2	22.7	79,062	3.5	0.7	0.1	0.8
25–29	2,518,768	30.4	6.7	37.1	106,489	4.2	1.3	0.3	1.6
30–34	2,961,782	84.5	18.3	102.9	122,353	4.1	3.5	0.8	4.2
35–39	3,717,438	235.9	49.6	285.5	134,575	3.6	8.5	1.8	10.3
40–44	3,961,109	594.9	86.6	681.5	133,557	3.4	20.1	2.9	23
45–49	3,743,094	1549.3	200	1749.3	118,332	3.2	49	6.3	55.3
50–54	3,524,989	3529.2	487.3	4016.5	113,041	3.2	113.2	15.6	128.8
55–59	3,151,845	6089.7	784	6873.7	102,949	3.3	198.9	25.6	224.5
60–64	2,637,235	8925.8	1055	9980.8	90,465	3.4	306.2	36.2	342.4
65–69	2,370,618	10,652.2	1215.5	11,867.6	86,264	3.6	387.6	44.2	431.8
70–74	2,055,842	11,914.8	1341.1	13,255.9	77,501	3.8	449.2	50.6	499.7
75–79	1,534,114	10,967.3	1157.2	12,124.5	59,962	3.9	428.7	45.2	473.9
80–84	1,449,210	12,669.2	890.7	13,559.9	59,453	4.1	519.7	36.5	556.3
85–89	918,124	8663.1	781.3	9444.4	41,136	4.5	388.1	35	423.2
90–94	390,357	3378.9	401.5	3780.4	19,016	4.9	164.6	19.6	184.2
≥95	103,370	588	76.7	664.6	5415	5.2	30.8	4	34.8
All adults	37,298,846	79,892.7	8554.5	88,447.1	1,349,570	–	3070.0	324.7	3394.8

[a] Source: INE (2018).
[b] Source: Global Burden of disease 2016 (IHME, 2018).
[c] Barcelona YLLs, YLDs, and DALYs calculated as Spanish burden of disease metrics multiplied by the fraction of the Barcelona population over the Spanish population by age group.

treatment plant (i.e. Cardedeu) only includes conventional treatments. Thus, chemicals and energy consumption are lower compared to the Llobregat drinking water treatment plants. On the other hand, the higher impact of the production of drinking water in the Llobregat area was due to the advanced treatments (i.e. reverse electrodialysis, reverse osmosis, desalination) taking place in the drinking water treatment plants supplying this area (i.e. Abrera, Sant Joan Despí and the desalination plant). Indeed, reverse electrodialysis, reverse osmosis and desalination require high energy consumption (up to 4 kWh/m^3 of water) compared to the conventional treatments (Crittenden et al., 2005). In conclusion, the better the quality of the source of water, the simpler the treatment, the lower the environmental impact, illustrating the cost-effectiveness of improving the quality of drinking water sources.

Our study contributes new knowledge on how health and environmental tradeoffs of drinking water source choice can be integrated. We apply our integrated assessment approach to the city of Barcelona, which severs as a useful case study to explore these tradeoffs for several reasons. Barcelona includes 1) a range of water treatment technologies; 2) intermediate THM levels comparable with other countries in Europe (Evlampidou et al., 2020); 3) high levels of bottled drinking water, which are comparable to Italy, Germany or Portugal (Conway, 2020). Findings from our case study provide valuable insights into the health and environmental tradeoffs of drinking water source choice that are informative for similar populations and settings in Europe. Our analytical approach could be applied in further work including a larger set of water treatment and population behaviour contexts to explore whether the balance of tradeoffs are context dependent.

Total THM levels were slightly lower in the Llobregat compared to the Ter water supply area (≈30 vs. 40 μg/L). Since it was usually the opposite in the past (ASPB, 2012), current concentrations illustrate the reduction of THM occurrence and improvement of drinking water quality after incorporating advanced water treatments (e.g. reverse osmosis, reverse electrodialysis) in ≈2009. Unexpectedly, this has not been mirrored by a lower bottled water consumption in the Llobregat water supply area, where approximately 71% of the population consumes usually bottled water, vs. 43% in the Ter area. Indeed, bottled water consumption has increased throughout Barcelona, from approximately 54% in 2006 (Font-Ribera et al., 2017) to approximately 58% in 2016 (ASPB, 2019). These findings suggest that bottled water consumption could be motivated by subjective factors other than objective water quality.

Our results support the argument that bottled water consumption should be reduced in settings where public drinking water is safe. In the European Union, the new drinking water directive (EC, 2020) aims to reduce plastic bottle consumption by increasing confidence in and improving access to tap water to meet drinking water needs. Understanding the reasons that influence drinking water preferences and personal choices is necessary to eventually design interventions. A main explanatory variable for bottled water consumption is perception of poor tap water quality (March et al., 2020). In turn, risk perception of drinking water quality is influenced by organoleptics (especially flavour), perceived water chemicals, external information, past health problems, and trust in public suppliers (Doria et al., 2009).

In-house water treatment systems are emerging as an alternative to bottled water when tap water is unattractive due to bad taste, odour, or lime presence (March et al., 2020). In our study population, 16% of subjects report the use of domestic drinking water filters as main drinking water choice. However, given the lack of specific input data, our HIA and LCA estimates for the scenario where all the population uses domestic filters requires several simplifying assumptions. First, we lacked information on specific filters used by the population. We assigned values corresponding to carbon filter jars, which appear to be popular choices

Table 6
Mean (95% confidence interval) population attributable fraction (PAF), years of life lost (YLLs), years lived with disability (YLDs), and disability-adjusted life years (DALYs) for bladder cancer in the Barcelona population attributable to THM under the four drinking water consumption scenarios, based on health impact assessment.

Local health impacts (bladder cancer)				
Scenario	PAF (%)	YLLs	YLDs	DALYs
S1: Current	3.1 (1.5, 4.6)	93.9 (46.6, 142.1)	9.9 (4.9, 15)	103.9 (51.5, 157.1)
S2: All tap water	10.1 (5.2, 14.7)	309.1 (158.7, 451.7)	32.7 (16.8, 47.8)	341.8 (175.5, 499.4)
S3: All bottled water	0.1 (0, 0.1)	2.2 (1.1, 3.3)	0.2 (0.1, 0.3)	2.4 (1.2, 3.6)
S4: All filtered tap	1.2 (0.6, 1.7)	35.6 (17.9, 53.2)	3.8 (1.9, 5.6)	39.4 (19.8, 58.9)

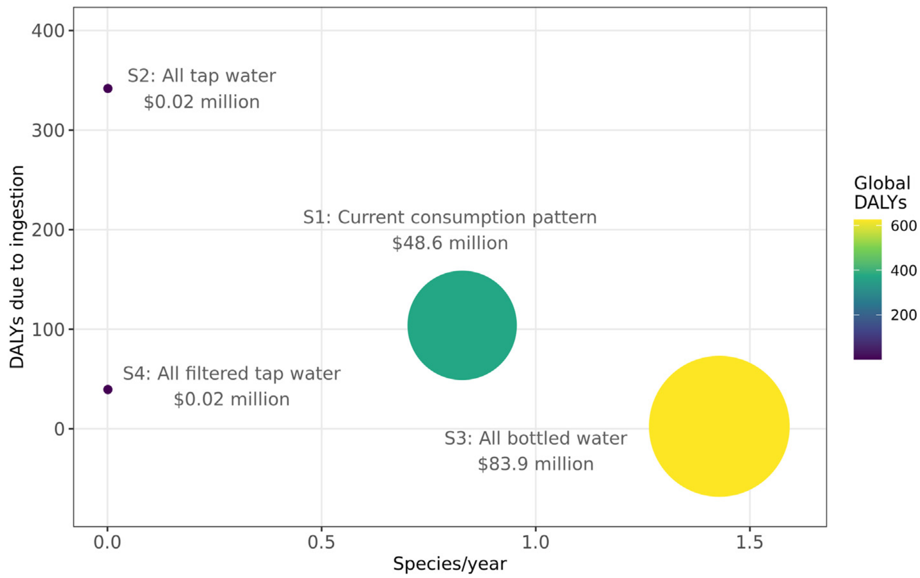

Fig. 3. Integrated health and environmental impacts of drinking water source scenarios in Barcelona.*
*Dot plot size proportional to value of raw material costs in $. Two measures of health impacts (in DALYs are shown). DALYs due to ingestion refer to bladder cancer in the Barcelona population. Global DALYs refer to human health impacts in the global population due to emissions in the production of drinking water to supply the Barcelona population.

among domestic filter users in the study area (March et al., 2020). However, different filters may have different THM removal efficacies (Carrasco-Turigas et al., 2013), which is not reflected in our estimates. Second, given the lack of specific input data for the LCA, we have equated domestic filter use with tap water use, which ignores the materials and energy used for the production of the filters. Although these results should be cautiously interpreted, our findings suggest that domestic filters reduce both local health and global environmental impacts compared to other drinking water options, and appear as a compromise option between bottled and tap water. However, correct maintenance of domestic filters is an important issue, given that a number of studies raised issues on microbiological safety for membrane filters (Zhang et al., 2013) and jar-type filters (Daschner et al., 1996).

Our estimates provide the first comparative data of the health and environmental impacts of different water consumption choices; however, interpretation of our findings should take into account several limitations of our study. We consider a limited set of scenarios, including extreme scenarios that may not be probable. Nonetheless, these scenarios provide a useful envelop of potential impacts related to changing drinking water source. Our HIA is based on a number of assumptions. We applied the national bladder cancer incidence to the city of Barcelona, given that local statistics were not available. There is very limited evidence on the relative contribution of each exposure route (ingestion, inhalation, dermal) for THMs, and we used estimates from the only single study that was identified. Our estimates of exposure relied on the limited available evidence regarding the prevalence of specific types of filters, the reduction of THM levels, and the THM concentrations in bottled water, highlighting an important data gap. We assumed that the exposure-response relationship was the same for the different exposure routes (ingestion, non-ingestion) and applied the available exposure-response function that is estimated based on total THM levels in tap water, regardless of personal behaviour. The exposure-response function is estimated based on bladder cancer incidence, which do not fully correspond to DALYs. In addition, the burden of disease attributable to THMs is interpreted as future projections over each individual's lifespan assuming the current disease incidence, population and age distribution. Our HIA relies on the assumption that the association between THM exposure and bladder cancer is causal; however, several uncertainties about this relationship remain such as the mechanisms of action, difference in risk between men and women, among others. Our models are based on individuals' primary drinking water source, and do not take into account variability in individuals' drinking water source (e.g. at residence, work, in restaurants). Finally, we considered the local health impacts from a single exposure pathway (THMs), with substantial epidemiological evidence linking it to health. There may be other contaminants relevant for health that we have not included due to lack of available epidemiological evidence.

Similarly, several limitations are involved in the application of LCA and the ReCiPe2016 endpoint (H) method to our research question. In general, impacts are not spatially-resolved in ReCiPe2016, which is a major limitation to integration with HIA. We did not have sufficient data to quantitatively account for uncertainties across impact categories. We considered global DALYs in the LCA as a secondary impact category due to several important uncertainties including the lack of spatial resolution needed to identify which population is exposed, and lack of documentation of the selection of potentially toxic substances that are modelled and which health endpoints are included in the DALYs. Limitations and target areas for methodological improvements in LCA have been reviewed by others (Finkbeiner et al., 2014). Key limitations relevant to our analysis include lack of specificity regarding time horizon and level of certainty in the calculation of characterisation factors for some impact categories (e.g. photochemical ozone formation, terrestrial acidification, freshwater eutrophication, land use and fossil resource scarcity) (Huijbregts et al., 2016). Inclusion of emerging activities and substances, such as nanoparticles, are important areas for future development (Huijbregts et al., 2016). Considering these limitations, we draw our conclusions based on comparisons across scenarios, rather than on the absolute values of impacts, consistent with recommendations in the literature (Golsteijn, 2016). Other limitations of LCA make comparisons across studies challenging: studies can have different system boundaries, thereby including different impacts or processes (Curran, 2014; van der Meer, 2018). Nonetheless, LCA is the best available tool to provide a comprehensive, holistic, and complete understanding of the potential impacts generated across all stages of production (van der Meer, 2018).

5. Conclusions

Our study provides the first attempt to compare health and environmental impacts of individual water consumption choices through the integration of HIA and LCA. Our findings suggest that the sustainability gain from consuming water from public supply relative to bottled water far exceeds the human health gain from consuming bottled water in Barcelona. Our findings are likely to have relevance for comparable cities in Europe; however, further research is needed to understand how results vary across settings. Our analysis highlights several important data gaps including: 1) relative routes of exposure to THMs; 2) the effect of different domestic filters on THM removal; and 3) levels of contamination in bottled drinking water as well as target areas for further development in LCA modelling.

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CRediT authorship contribution statement

Cristina M. Villanueva: Conceptualization, Methodology, Supervision, Writing – original draft. **Marianna Garfí:** Conceptualization, Formal analysis, Writing – review & editing. **Carles Milà:** Formal analysis, Writing – review & editing. **Sergio Olmos:** Formal analysis, Writing – review & editing. **Ivet Ferrer:** Conceptualization, Methodology, Writing – review & editing. **Cathryn Tonne:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1
Summary of the inventory (input and output data) for the drinking water treatment plants and bottled water per functional unit (1 L of water).

	Units	Drinking water treatment plants				Bottled water
		Abrera	Sant Joan Despí	Cardedeu	Desalination plant	
Input						
Electricity	kWh L^{-1}	1.90E-07	1.54E-03	9.43E-09	3.43E-03	2.18E-02
Chemicals	kg L^{-1}	6.28E-05	2.09E-04	2.38E-05	2.81E-05	2.15E-05
Plastics for packaging	kg L^{-1}	–	–	–	–	3.48E-02
Outputs						
Waste and wastewater	kg L^{-1}	3.75E-05	3.86E-03	2.86E-05	5.71E-06	3.88E-02

Table A2
Global health impacts (disability-adjusted life years, DALYs) from the life cycle assessment, associated with drinking water production in Barcelona at different scales: treatment plant, bottled water production, water supply area, and drinking water scenario.

	DALYs
Per 1 L of drinking water produced in:	
Drinking water treatment plants	
Sant Joan Despí	1.08E-09
Abrera	1.95E-10
Desalination plant	3.17E-09
Cardedeu	9.10E-11
Bottled water	6.34E-07
Per 1 L of drinking water in supply areas:	
Llobregat area	1.20E-09
Llobregat + Ter area	4.87E-10
Ter area	9.10E-11
In the drinking water consumption scenarios:	
S1: Current	372
S2: All tap water	0.498
S3: All bottled water	625
S4: All filtered tap	0.498

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