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Environmental assessment of domestic water supply options for remote communities

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ABSTRACT

Access to clean water is one of the targets in the UN Sustainable Development Goals. However, millions of people are still without basic water services, predominantly in rural areas in developing nations. Previous studies have investigated the environmental impacts of water provision, but they mostly focused on large-scale urban systems. This paper considers for the first time the life cycle environmental impacts of different water supply options applicable to remote communities in developing countries. Focusing on the Southeast Asia-Pacific (SEAP) context, a cradle-to-grave approach is followed to estimate the impacts of locally-sourced groundwater, surface water and desalinated seawater as well as externally-sourced bottled water. The results reveal that surface water is environmentally the most sustainable alternative. Locally desalinated water, powered by diesel electricity, has two orders of magnitude higher impacts than surface water. However, externally-sourced water in plastic bottles is the worst option with 4–155 times higher impacts than desalinated water and up to three orders of magnitude higher impacts than surface water. This is largely due to the impacts related to the production of bottles. Doubling their recycling would reduce the impacts by 7–23% but bottled water would still be environmentally the least sustainable option. Although water in single-use bottles currently provides only 3% of the water supply of a representative remote community in the SEAP region considered in this study, it accounts on average for more than 50% of the total impacts from water consumption. By 2030, population increase could lead to greater reliance of remote communities on bottled water and 60–73% higher impacts of water consumption per household. Relying solely on local surface, ground and water desalinated using solar power and avoiding bottled water would reduce the impacts by 33–99% relative to the current situation. This would also improve considerably water availability and security in remote communities. The findings of this study will be of interest to national and local governments developing future policies aimed at increasing access of remote communities to clean water.

1. Introduction

One of the UN Sustainable Development Goals (SDG) is universal access to clean water and sanitation (UNDP, 2017). The UN's Indicators for water access evaluate the availability and protection of water sources from contamination and the collection time required. Satisfactory achievement of these indicators (e.g. <30 min collection time, available >12 h/day) is termed “basic water service”, which was available to 89% of the global population in 2015 (WHO UNICEF, 2017). However, this still leaves 844 million people who use contaminated water sources or require more than 30 min to collect water. There is also a significant gap in water access between urban and rural areas: 95% vs 80%, respectively (WHO UNICEF, 2017). While national budgets and development assistance for water are increasing, implementation in remote areas is lagging (WHO, 2017).

Given the volume of water required for human consumption,

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Nomenclature

1,4-DB	1,4-dichlorobenzene
ALOP	Agricultural land occupation potential
eq	Equivalent
FDP	Fossil depletion potential
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
GHG	Greenhouse gases
GWP	Global warming potential
HTP	Human toxicity potential
IRP	Ionising radiation potential
LCA	Life cycle assessment
m2a	m^2-year
MDP	Mineral depletion potential
MEP	Marine eutrophication potential
METP	Marine ecotoxicity potential
NLTP	Natural land transformation potential
NMVOC	Non-methane volatile organic compounds
ODP	Ozone depletion potential
PM10	Particulate matter (<10 μm)
PMFP	Particulate matter formation potential
POFP	Photochemical oxidant formation potential
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
ULOP	Urban land occupation potential
WDP	Water depletion potential

the environmental impacts of water technologies and supply have been studied at various scales using life cycle assessment (LCA). However, there are many more LCA studies at the process and plant scales than at the system level (Loubet et al., 2014). Studies comparing different technology options to utilise specific water resources (e.g. groundwater (Bhakar and Singh, 2018; Pradeleix et al., 2015) or seawater (Raluy et al., 2005)) have identified energy use as the common hotspot for environmental impacts. City- and regional-scale studies have found consistently that water from natural freshwater sources has the lowest impacts whether based in Europe (Garfí et al., 2016; Godskesen et al., 2011), Asia (Hsien et al., 2019; Li et al., 2016), or North America (Lyons et al., 2009). It has also been reported that desalination has higher impacts due to greater energy requirements, while the impacts of bottled water were mainly due to the manufacturing of the bottle (Garfí et al., 2016). Existing water networks, such as those in Mexico City (García-Sánchez and Güereca, 2019), Copenhagen (Godskesen et al., 2013), Trondheim (Slagstad and Brattebø, 2014), Segura Basin (Uche et al., 2014) and Sicily (Del Borghi et al., 2013), have also been evaluated using LCA. They have all found that the main hotspot for most impacts is electricity required for desalination and long-distance piping of water. Recommendations for improving existing water networks include promotion of electricity sources with lower impacts, or alternative sources such as water reuse.

At the highest geographic level, the water supply mixes for different countries and basins have been modelled under current conditions (Leão et al., 2018) and projected up to 2040 (Leão et al., 2019b) for application in LCA. Changes in climate, demographics and technology were used as driving factors to estimate water supply and consumption in future scenarios. The regionalisation of water supply, including the underlying electricity mix, was found to influence significantly the environmental impacts for different user types (Leão et al., 2019a, 2019b). While these studies were limited by data availability, their methods and application to environmental assessment support the use of locally-adapted inventories consistent with the scope of the LCA performed.

While LCA has been applied to many urban water systems, there is a lack of studies of water supply to remote communities without access to the mains. Water supply planning requires attention in developing rural communities, especially where use for irrigation is high. When water withdrawals from local sources are limited by well capacity or irrigation demand, households may utilise low quality or contaminated water sources or purchase bottled water to meet domestic water demand. However, these are not ideal solutions due to health risks and increased cost of living, respectively. Desalination may provide an answer to water supply in remote areas, but its feasibility will also depend on the electricity available at the location, as well as local capacity to manage operations.

To fill this knowledge gap, this study evaluates for the first time the life cycle environmental impacts of different water supply options in remote communities. The following sources of potable water are considered: groundwater, surface water, water in single-use 1.5-litre bottles and water delivered in 18.9-litre (5-gallon) reusable containers. Desalination of seawater is also included as a potential technology that could be deployed in remote communities in the future. The study focuses on the Southeast Asia region which has over 119 million rural residents (9.6% of total rural population in the region) without basic access to water (WHO UNICEF, 2017). Both the current situation and possible future (2030) scenarios for water supply are evaluated. The insights gained from this work can be used to support development of more sustainable water-access programmes and policies in developing regions.

2. Methodology

Water supply options and future scenarios have been evaluated using the ISO 14040/14044 (ISO, 2006a, 2006b) guidelines for LCA. Following an attributional approach, the LCA modelling has been carried out in GaBi v7.3 (Thinkstep, 2016). The goal and scope of the study are described next, followed by life cycle inventory data and the impact assessment method used in this work.

2.1. Goal and scope

As previously mentioned, the goal of the study is to estimate the life cycle environmental impacts of water supply from the above-mentioned sources in remote communities with no access to water mains. A further goal is to determine the impacts of household water consumption based on the current and possible future supply with differing contributions of surface, ground, desalinated and bottled water. A scenario analysis has been used for evaluating future water supply. The scenarios consider the same time horizon (2030) as the UN SDGs. Potential improvements for identified environmental hotspots are explored through a sensitivity analysis. The ultimate aim of these analyses is to identify environmentally the most sustainable water supply sources and their mix, helping to inform policy development and its implementation in remote communities.

The scope of the study is from cradle to grave, comprising the following life cycle stages: raw materials extraction and processing, construction and installation, operation and maintenance, transport and end-of-life waste management (Fig. 1). Two functional units are considered, one related to the different water supply options and another to their mix in the current and future supply systems:

- water supply options: *1 m^3 of potable water at household*; and
- current situation and future scenarios: *197 m^3 per four-person household per year*, based on the estimated minimum volume required for socio-economic development (Chenoweth, 2008).

2.2. Inventory data

To anchor the study in a particular context, the inventory data are specific to the supply of water in the Philippines, which has numerous remote communities, particularly on its many islands. Similar conditions are found in rural communities in the rest of the Southeast Asia region and hence the outcomes of the study are generally applicable across the region. The data have been sourced from literature and the ecoinvent 3.1 database (Ecoinvent Association, 2014). The quality of the data used in this study has been evaluated through a pedigree matrix (Weidema et al., 2013); for the results of the evaluation, see Tables S6 and S7 in the Supplementary Information (SI).

2.2.1. Water supply options

Both locally- and externally-sourced water are considered. For the former, the infrastructure for utilising groundwater, surface water and seawater is assumed to be installed locally. Externally-sourced water, hereafter referred to as “imported” water, is produced further away in large freshwater treatment plants and shipped to the remote community in small (1.5 L) or large bottles (5 gal). The transfer of water from the collection point (e.g. from the hand pump, storage tank or purchase point of bottled water) to households is on foot for all options. Hence, this activity is not included in the modelling.

Groundwater is extracted using an open and tube well, equipped with a submersible pump with a capacity of 24 m^3/day. The useful life is 35 years for the open well, 20 years for the tube well, and 29,000 h for the pump (Pradeleix et al., 2015). Surface water can be collected from a river, lake, dam or pond in the locality. A construction similar to the open well is assumed to provide a protected collection point for surface water.

Data for the construction of the desalination plant have been obtained from Cherif et al. (2016), assuming a useful life of 20 years. The reverse osmosis modules require replacements every five years and their inventory data are from Lawler et al. (2015). A pumping station is considered for imported bottled water, assumed to last for 70 years, with the data sourced from ecoinvent (Ecoinvent Association, 2014). Further details can be found in Table S1 in the SI.

Operational requirements for the various water supply options are summarised in Table 1. Desalination of seawater is by reverse osmosis, the most common process for desalination (Byrne et al., 2015). The desalination process has been simulated in the WAVE software (Dow Chemical Company, 2017) with 50% water recovery to obtain the energy requirement for seawater reverse osmosis. Desalination is assumed to be powered by solar photovoltaics (PV) (Abdelkareem et al., 2018; Ghaffour et al., 2015) with the PV performance and inventory data sourced from the authors' previous work (Aberilla et al., 2020) and ecoinvent (Ecoinvent Association, 2014), respectively. The pumping station is powered by grid electricity, which in the Philippines comprises 50% coal, 32% gas, 8% hydropower, 7% geothermal and 3% oil (Philippine Department of Energy, 2017). The electricity for the groundwater pump and desalination plant is provided by diesel generators, as is the case in most off-grid communities (Philippine Department of Energy,

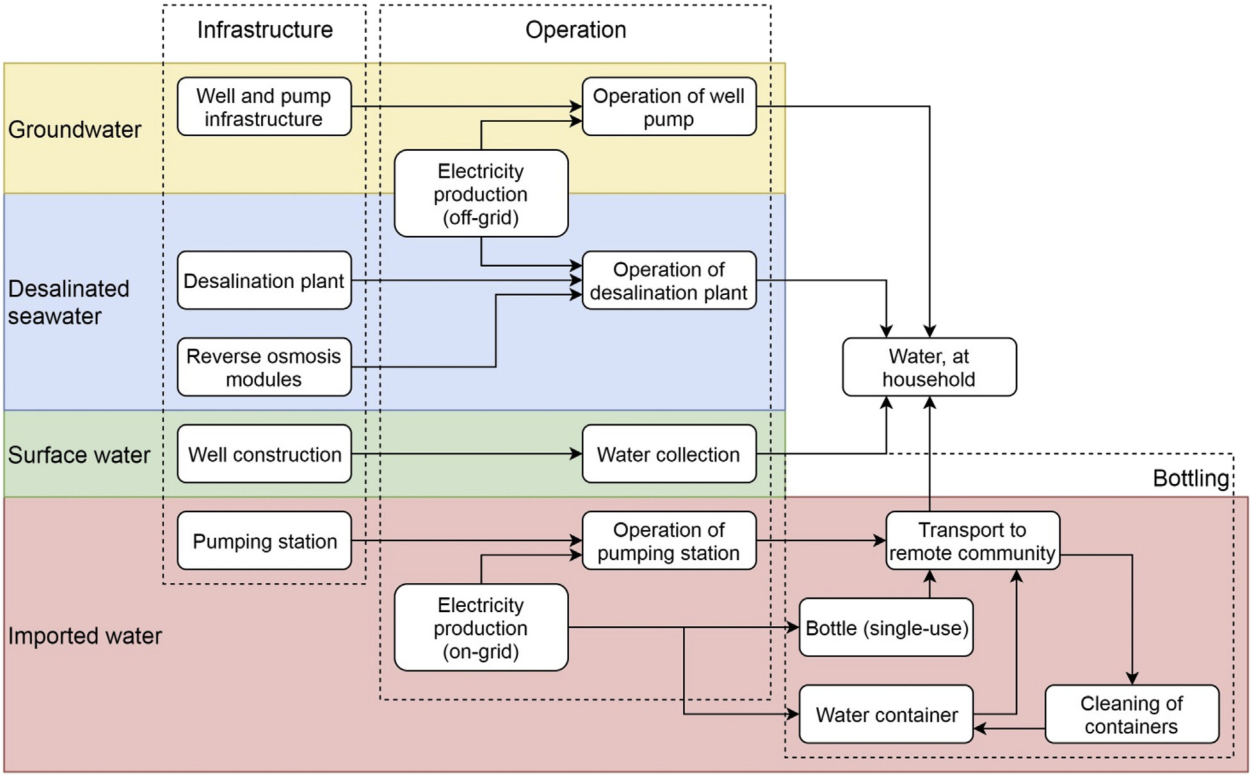


Fig. 1. System boundaries and the life cycle stages considered for different water supply options.
[For compactness of the figure, raw materials and end-of-life for infrastructure are not shown in the figure but details are presented in section 2.2].

Table 1
Inventory data for operation of water infrastructure per 1 m^3 water (Dow Chemical Company, 2017; Ecoinvent Association, 2014; Pradeleix et al., 2015; Shahabi et al., 2014).

Input	Units	Groundwater well	Surface water collection	Desalination	Pumping station
Electricity (low voltage)	kWh	0.35	–	3.92	–
Electricity (medium voltage)	kWh	–	–	–	0.40
Chlorine (liquid)	g	1.4	1.4	1.4	1.4
Seawater reverse osmosis module	m^2	–	–	0.002	–
Citric acid	g	–	–	0.2	–
Ethylenediamine tetraacetic acid (EDTA)	g	–	–	1.5	–
Iron(III) chloride (in 12% iron solution, no water)	g	–	–	20.6	–
Sodium hydrogen sulphite	g	–	–	23.7	–
Sodium hydroxide (in 50% solution, no water)	g	–	–	0.2	–
Sulphuric acid	g	–	–	10.8	–
Diesel (construction machinery)	MJ	–	–	–	0.02

2016).

As mentioned earlier, imported water is bottled in either 1.5-L single-use bottles (Garfí et al., 2016; Lagioia et al., 2012) or 18.9-L reusable containers (McFarlane, 2016; Philippine Primer, 2015; Sterling Containers LLC, 2018); see Table 2. This translates to approximately 667 single-use bottles or 53 reusable containers for 1 m^3 of water. These are transported 20 km by ferry to the remote community. Land transport prior to ferry transport is not considered due to a lack of representative data as these distances can vary significantly. Land transport after the ferry delivery is not expected as water is typically collected on foot in small remote communities and is therefore also excluded. The effect on the results of land transport of bottled water is discussed later in the paper.

The reusable containers are washed with 2% sodium hydroxide solution (Andoh et al., 2013) and reused 33 times (McFarlane, 2016). The produced wastewater is treated in a conventional wastewater treatment plant. Alternative cleaning agents, namely sodium metasilicate and detergent formula (Arendorf et al., 2014), are investigated in a sensitivity analysis (section 3.1.8).

At the end of life, plastics, aluminium, copper and iron are recycled at the rates of 30%, 47%, 44% and 39%, respectively, based on the recycling rates in the region (Glöser et al., 2013; JICA and EX Corporation, 2008); other materials are landfilled. As the recycled materials count towards the recycled fraction of materials used in manufacturing at the respective rates of 24% for plastics, 19% for aluminium, 34% for copper, and for 10% steel (BIR Ferrous Division, 2016; JICA and EX Corporation, 2008; Tse, 2015), the system has been credited for the balance for avoiding primary production, i.e. for 28% of aluminium, 29% of steel and 10% of copper. For plastics recycling, a bottle-to-pellet material efficiency of 95% is assumed, with 12% of the recycled fraction being returned to bottle manufacturing (Shen et al., 2011). For a single recycling loop, this translates to 0.22 kg of avoided virgin PET production per kg of PET used for bottles (Shen et al., 2011); for further details, see Fig. S1 and Table S2 in the SI.

2.2.2. *Current situation and future scenarios*

As shown in Fig. 2, the current water supply mix of a typical remote community comprises primarily of natural freshwater sources (65% groundwater and 22% surface water) while 13% is obtained from bottled water (1.5 L and 5 gal) brought in externally (Philippine Statistics Authority, 2017). The current situation is compared with four 2030 scenarios developed in this work: Business-as-usual (BAU), Independent, Advanced and Advanced Independent. The contribution of different water supply options in each is shown in Fig. 2, with the rationale for each described below.

In all future scenarios, it is assumed that total extraction of groundwater and surface water will increase up to the expected water stress level forecasted in the domestic sector by 2030 (Gassert et al., 2014). However, accounting for projected population growth (UN DESA Population Division, 2017), this results in a 12% net decrease of availability of natural freshwater sources per

Table 2
Inventory data for water bottle and container per 1 m^3 water (Arendorf et al., 2014; Garfí et al., 2016; Sterling Containers LLC, 2018).

Activity	Units	1.5 L bottle	18.9 L bottle
Bottling			
Electricity (medium voltage)	kWh	12	12
Epoxy resin (liquid)	kg	0.07	–
Packaging film (low density polyethylene)	kg	2.91	2.9
Polyethylene terephthalate (granulate, bottle grade)	kg	20	1.1
Polyethylene (granulate, low density)	kg	1	0.02
Printed paper	kg	0.9	–
Cleaning of containers			
Tap water (for cleaning)	kg	–	240
Wastewater (effluent, average)	m^3	–	0.24
Sodium hydroxide (in 50% solution, no water) [a]	kg	–	4.8
Sodium metasilicate pentahydrate [b]	kg		12.7
Detergent formula [b]	kg		
Sodium citrate dihydrate (as citric acid)	kg		2.4
Ethylenediaminetetraacetic acid (EDTA)	kg		0.2
Layered sodium silicate (SKS-6, powder)	kg		0.8
Polycarboxylates (40% active substance)	kg		0.5
Soda ash (dense)	kg		3.5
Sodium percarbonate (powder)	kg		0.6
Fatty alcohol sulphate	kg		0.2

[a] Base case detergent, diluted to a 2% solution.
[b] Alternative detergents considered in the sensitivity analysis.

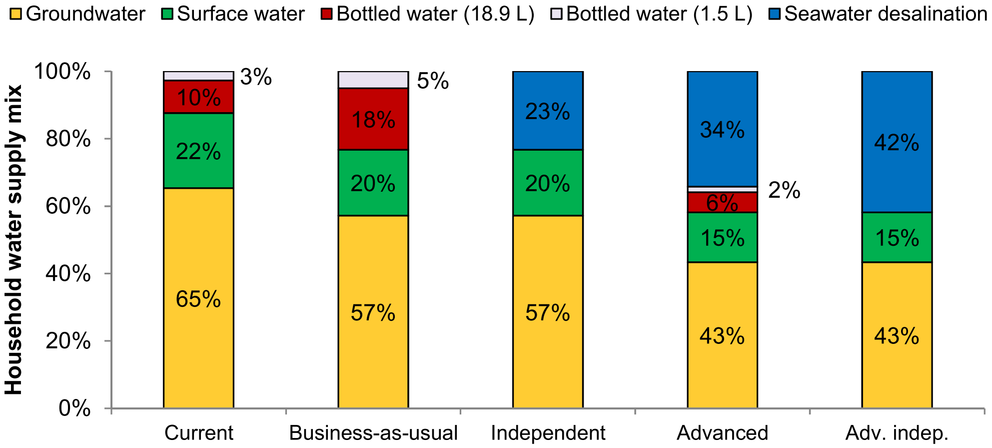


Fig. 2. Water supply mix for the current situation and future scenarios.

household. In the BAU scenario, the remainder of the water demand is supplied by imported water with the proportion of 1.5-L and 18.9-L bottled water the same as in the current situation. In the Independent scenario, imported water is replaced by local desalination to consider the implications of self-sufficiency in water supply. For the Advanced and Advanced Independent scenarios, an increase in water demand to 260 m^3 per household per year (national average (FAO, 2011)) is considered to represent improved living standards of the remote community. Desalination provides for the additional requirement in the Advanced scenario as well as replacing imported water in the Advanced Independent scenario. While it is assumed in the base case for the Advanced scenario that only desalination provides the additional demand, a sensitivity analysis is performed to examine the range that imported water can also contribute to satisfying the increased demand. Similar to the Independent, the Advanced Independent scenario represents a water supply mix that is sourced exclusively locally. These scenarios represent a community that has self-sufficient local water production and independence from imported bottled water.

The grid electricity mix assumed for the current situation and the BAU and Advanced scenarios corresponds to the current supply mix in the Philippines, i.e. 50% coal, 32% gas, 8% hydropower, 7% geothermal and 3% oil (see the previous section). In the Independent and Advanced Independent scenarios, diesel electricity generated locally and used for water abstraction and desalination is replaced by solar PV.

2.3. Life cycle impact assessment

The hierarchist midpoint indicators in the ReCiPe 1.08 method (Goedkoop et al., 2013) are used to estimate the environmental impacts. To streamline the discussion in the next section, the 18 indicators in the ReCiPe methodology are grouped into the following seven environmental issues:

- climate change: global warming potential (GWP), excluding biogenic CO_2;
- air pollution: ozone depletion (ODP), photochemical oxidant formation (POFP) and particulate matter formation potentials (PMFP);
- eutrophication and acidification: freshwater and marine eutrophication potentials (FEP and MEP, respectively) and terrestrial acidification potential (TAP);
- ecotoxicity: freshwater, marine and terrestrial ecotoxicity potentials (FETP, METP and TETP, respectively);
- resource depletion: fossil, mineral and water depletion potentials (FDP, MDP and WDP, respectively);
- land use: agricultural land occupation (ALOP), natural land transformation (NLTP) and urban land occupation potentials (ULOP); and
- human health: human toxicity (HTP) and ionising radiation potentials (IRP).

3. Results and discussion

This section first discusses the environmental impacts of different water supply options. This is followed in Section 3.2 by the environmental implications of future scenarios in comparison to the current situation. Each section also includes a sensitivity analysis carried out to test the effect of key parameters and assumptions that could influence the outcomes of the study.

3.1. Environmental impacts of water supply options

As can be inferred from Fig. 3, utilisation of locally-available resources, especially surface water, has the lowest impacts across all 18 categories. On the other hand, imported water in single-use bottles has the highest impacts in all categories with values 2-3 orders of magnitude higher than that of surface water utilisation. The only exception is ODP for which reusable bottles have the highest impact. A similar scale of difference in environmental impacts has been reported in previous studies comparing tap water and packaged water in developed urban areas (Garfí et al., 2016; Lagioia et al., 2012). Bottled water has also 4–155 times higher impacts than desalinated water, despite the latter relying on diesel electricity for the reverse osmosis process. Infrastructure has minimal contribution to the life cycle environmental impacts, except for surface water utilisation. However, poor maintenance of the infrastructure may lead to shorter lifetimes resulting in greater contribution to the impacts per amount of water supplied. The operation stage dominates the impacts of groundwater extraction and desalination, while manufacturing of bottles is the key hotspot for imported water. On average, water delivered in 18.9-L reusable bottles has 69% lower impacts than water in single-use 1.5-L bottles. Further discussion of each impact category follows.

3.1.1. Climate change (GWP)

The GWP of surface water is estimated at 44 g CO_2-eq./m^3 while that of ground water is almost ten times higher due to the electricity used for pumping. High energy consumption for desalination

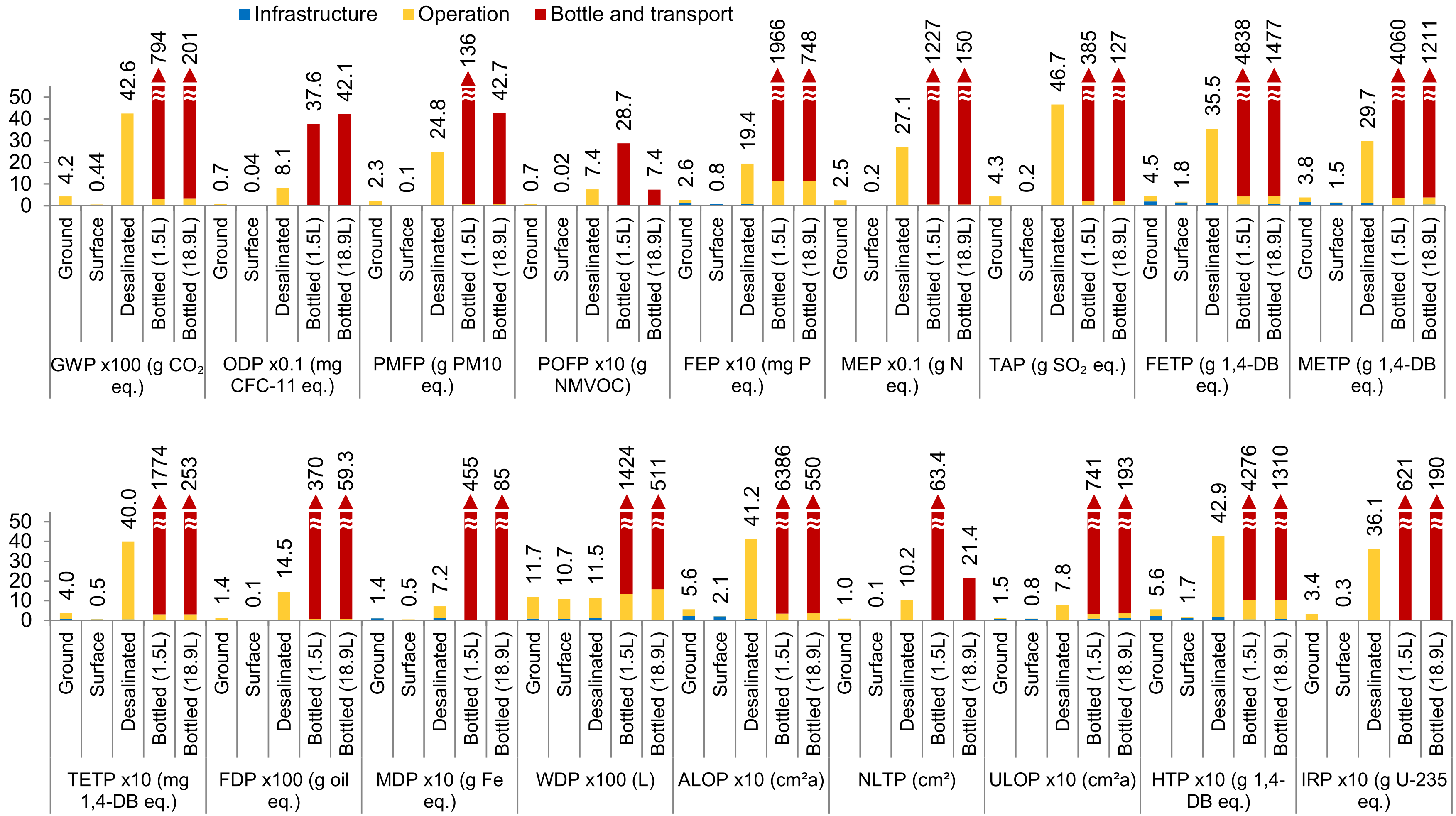


Fig. 3. Life cycle environmental impacts of different water supply options.
[All impacts are expressed per m^3 of water. For the life cycle stages in the legend, see Fig. 1. Data labels are cradle-to-grave totals to be multiplied by factors on the x-axis where relevant. GWP: global warming potential; ODP: ozone depletion potential; PMFP: particulate matter formation potential; POFP: photochemical oxidant formation potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; TAP: terrestrial acidification potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; TETP: terrestrial ecotoxicity potential; FDP: fossil depletion potential; MDP: mineral depletion potential; WDP: water depletion potential; ALOP: agricultural land occupation potential; NLTP: natural land transformation potential; ULOP: urban land occupation potential; HTP: human toxicity potential; IRP: ionising radiation potential].

also results in a GWP almost 100 times higher than for surface water. Electricity use accounts for 89% and >99% of the impact from groundwater extraction and seawater desalination, respectively. However, imported bottled water has a GWP 1-3 orders of magnitude higher than any of the local options: 20.1 kg CO_2-eq./m^3 for reusable large bottles and 79 kg CO_2-eq./m^3 for single-use smaller bottles. This is largely due to the impact from the production of the bottles: 3.9 kg CO_2-eq./m^3 for reusable and 70 kg CO_2-eq./m^3 for single-use bottles. Electricity used in the bottling stage has a GWP of 9.2 kg CO_2-eq./m^3, while caustic soda for washing of reusable containers adds 6.4 kg CO_2-eq./m^3. Transportation of bottled water is responsible for 841 g CO_2-eq./m^3, which contributes <4% to the total GWP of imported water. The rest of the impact is generated during water production (380 g CO_2-eq./m^3 at the pumping station), primarily due to the coal-dominated electricity mix.

The results obtained in this work are generally comparable to the values reported previously in literature. For example, GWP values for 1.5-L bottled water range from 75 (Garfí et al., 2016) to 178 kg CO_2-eq./m^3 (Jungbluth, 2006), with the impact of 79.4 kg estimated in the current work being closer to the lower end of the literature range. The GWP estimates for grid-connected desalination vary from 1.3 (Godskesen et al., 2017) to 8.9 kg CO_2-eq./m^3 (Hu et al., 2013), with the GWP of 4.26 kg CO_2-eq./m^3 determined here being in the middle of the range. However, the GWP for groundwater extraction determined here is higher (420 g CO_2-eq./m^3) than a literature value of 190 g CO_2-eq./m^3 (Godskesen et al., 2017). This is due to the latter considering an urban treatment plant in Denmark with a lower energy consumption (0.27 compared to 0.35 kWh/m^3 in this study). Similarly, conventional urban supply from surface water has a higher GWP than in the current work (44 g CO_2-eq./m^3) which span a wide range of values, from 58 (Hu et al., 2013) to 802 g CO_2-eq./m^3 (Hsien et al., 2019), depending on the level of treatment prior to distribution. For reusable 18.9-L water bottles, a study by Jungbluth (2006) reported a 4.5 times higher GWP (90 kg CO_2-eq./m^3) but the transportation distance was three times higher than here.

3.1.2. Air pollution (ODP, PMFP, POFP)

Surface water has the lowest ODP, PMFP and POFP. Electricity from diesel generators is the primary (>95%) source of air pollution impacts from the groundwater and desalination processes. Electricity used for desalination is ten times higher than that for the pumping station, but contributions to air pollution impacts are 40–114 times higher. Almost all (>98%) of the ODP, PMFP and POFP of imported water is attributed to the bottling stage. For water bottled in 18.9-L reusable containers, 88% of the life cycle ODP (3.71 mg CFC-11 eq./m^3) comes from the cleaning step due to CCl_4 emissions in the production of caustic soda.

3.1.3. Eutrophication and acidification (FEP, MEP, TAP)

Desalination has 65% higher FEP, 48 times higher MEP and 22 times higher TAP than the pumping station at the operation stage. Off-grid groundwater pump operation also has four times higher MEP and double the TAP of the on-grid pumping station due to higher NO_x emissions from off-grid electricity relative to the grid mix. However, considering the overall life cycle, bottled water has 30–763 higher eutrophication and acidification than groundwater. More than 60% of the FEP, MEP and TAP of water in 1.5-L bottles is attributed to the bottle. For water in 18.9-L bottles, the bottle contributes 41% to the MEP, but energy use in the bottling stage is the main source (>45%) of FEP and TAP.

3.1.4. Ecotoxicity (FETP, METP, TETP)

Ecotoxicity impacts of surface water collection are 0.005-1.8 g 1,4-DB eq./m^3. Most of the impacts (>82%) are generated in the infrastructure stage, specifically due to associated emissions in the production of concrete. The operation stage contributes 58–84% of the ecotoxicity potential of groundwater extraction and >96% for desalination. The impacts of imported bottled water are 2-3 orders of magnitude higher than that of surface water, with almost all of the impacts attributed to the bottling stage. For water in single-use smaller bottles, production of plastics is the key hotspot, contributing 85% in FETP and METP and 51% in TETP. For the larger reusable bottles, cleaning agents used for the cleaning cause 75% to FETP and METP and 40% to TETP.

3.1.5. Resource depletion (FDP, MDP, WDP)

Trends similar to the previous categories are also found for resource depletion, i.e. surface water has the lowest and 1.5-L bottled water the highest impacts. The FDP of the desalination and groundwater extraction is significantly higher than for the other options due to the use of diesel-generated electricity. The MDP is dominated by the infrastructure stage in the groundwater and surface water systems (69% and 97%, respectively), but the desalination process leads in MDP contribution (81%) due to the greater use of the diesel generator. Production of single-use bottles is responsible for almost all of the MDP of water in 1.5-L bottles (94%). Cleaning of reusable bottles is the main hotspot for 18.9-L bottles, contributing 63% to the total MDP.

The values for WDP shown in Fig. 3 include the amount of water delivered to the consumer (i.e. the functional unit of 1 m^3); hence, the value after subtracting that amount from the total can be interpreted as the virtual or embedded water depletion. Surface water has 70 L/m^3 of embedded water, mostly due to the construction of the infrastructure. Groundwater and seawater desalination have similar embedded water, estimated at 150–170 L/m^3. Significantly higher embedded water depletion (50–141 m^3/m^3) is seen for the bottled water, resulting from plastics production and bottle cleaning.

3.1.6. Land use (ALOP, NLTP, ULOP)

Land use impacts of groundwater and desalination are proportional to the electricity consumption due to upstream impacts in the extraction and processing of diesel. Similar to the other impacts, the bottled water has the highest land use impacts due to plastics production (>50% for ALOP, NLTP and ULOP) and printed paper used for labelling the single-use bottles (48% for ALOP).

3.1.7. Human health (HTP, IRP)

The HTP and IRP are the lowest for surface water (17 g 1,4-DB eq./m^3 and 3 g U-235-eq./m^3, respectively). Around a half of the HTP is attributable to emissions of manganese and zinc from concrete and steel production. Emissions of Rn-222 and C-14, mainly from concrete production, are the major sources of IRP. The HTP of infrastructure in the groundwater and desalination systems is comparable to that of surface water, but the hotspot in the life cycle of these options can be traced to the diesel supply chain for the production of electricity. While the HTP and IRP per kWh are higher for the grid than for diesel electricity, the operation stage of imported water (i.e. pumping station) has lower impacts per m^3 due to the lower energy requirement. Nonetheless, imported water has up to three orders of magnitude higher HTP and IRP than locally-produced water because of the impacts associated with the bottle. Single-use bottles are responsible for >80% of human health impacts, while caustic soda in the cleaning of reusable bottles contributes 62% to HTP and 77% to IRP.

3.1.8. Sensitivity analysis for bottled water

The results show that imported bottled water has significantly higher impacts than the locally-sourced water, mainly due to plastic bottles and caustic soda used for washing reusable water containers. To evaluate the potential effects of these two parameters on the total impacts of bottled water, a sensitivity analysis has been carried out considering different plastics recycling rates and cleaning chemicals.

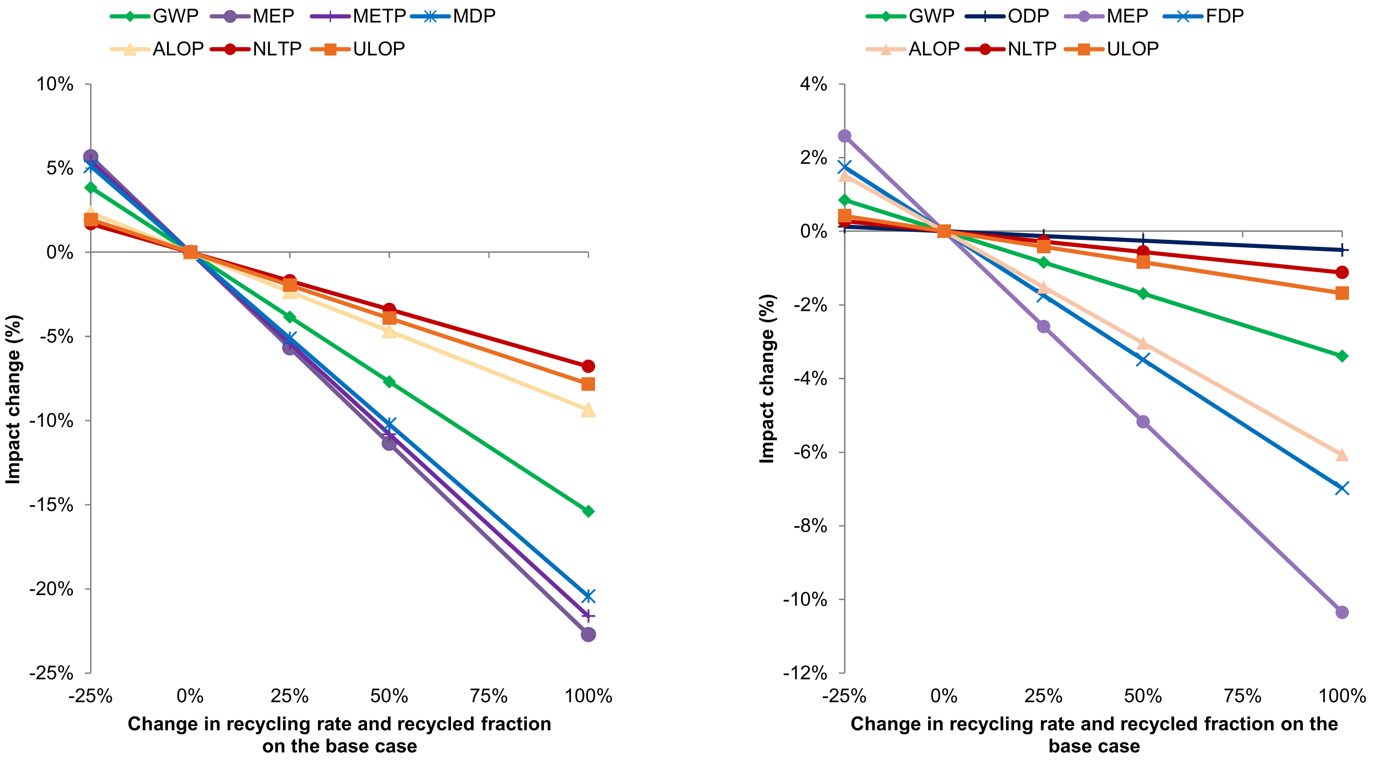
3.1.8.1. Plastics recycling. As mentioned in Section 2.2.1, the end-of-life recycling rate and the recycled fraction of plastics in the base case are 30% and 24%, respectively. Here, they are varied from −25% to +100%, yielding end-of-life recycling rates of 22.5–60% and recycled fractions of 18–48%. The lower values approach the global average recycling rates of 14–18% (OECD, 2018), while the higher values may have already been achieved in informal sectors in developing countries (Wilson et al., 2009). The changes in the seven most-affected impact categories are presented in Fig. 4 for both bottle sizes. The results suggest that doubling the recycling of plastics lowers the life cycle impacts by 7–23% for water in 1.5-L bottles and 0.5–10% for water in reusable 18.9-L containers. The most sensitive impacts are FETP, METP and MEP, while land use (ALOP, NLTP and ULOP) and ODP are the least affected. In addition to the production process, the landfilling of plastics is a main contributor to FETP, METP and MEP. Therefore, an increase in recycling rate and recycled fraction results in greater reductions in these categories due to avoided impacts in both the production and end-of-life stages. For water in reusable containers, ODP is not particularly sensitive to the recycling values since the majority of the impact is attributed to the washing stage rather than the containers.

In summary, while there is substantial improvement in the environmental performance resulting from increased recycling (especially in developing areas), the impacts of bottled water per functional unit remain much higher than for the other options.

3.1.8.2. Bottle cleaning. Because cleaning of the reusable containers contributes 29–88% of the life cycle impacts of water in 18.9-L bottles, alternative detergents are considered in the sensitivity analysis. Sodium metasilicate is identified as a substitute for caustic soda as an alkaline detergent in food and beverage applications (Santos et al., 2017). A detergent formula for domestic and industrial dishwashers (Arendorf et al., 2014) is also considered. The cleaning agents are assumed to be substitutable based on equivalent sodium composition (i.e. 1 g NaOH = 2.65 g sodium metasilicate pentahydrate = 1.68 g detergent formula) given that alkali components are the main decontaminators in cleaning agents (Nitsch et al., 2003).

Fig. 5 shows that using these alternatives increases GWP by 62–111% and >100% in at least eight other categories. Since sodium metasilicate is produced from the reaction of sodium hydroxide and silica sand (Zah and Hischier, 2007), it is not surprising that the additional processing from hydroxide to metasilicate results in higher impacts for this alternative detergent. For the detergent formula, citric acid (which proxies for sodium citrate dihydrate (Arendorf et al., 2014)) represents 71% of the impacts of the detergent on average. The full dataset for citric acid in the ecoinvent database (Ecoinvent Association, 2014) is not publicly available, although it is inferred that the purification and waste treatment processes are the primary sources of environmental impacts.

Therefore, these results demonstrate that using caustic soda for cleaning is environmentally more sustainable than sodium metasilicate or detergent formula.



(a) (b)

Fig. 4. The effect on impacts of recycling rate and recycled fraction of plastics for (a) 1.5-L bottles and (b) 18.9-L bottles.
[The impacts nomenclature can be found in Fig. 3. For the remaining impacts, see Table S3 in the Supplementary Information.].

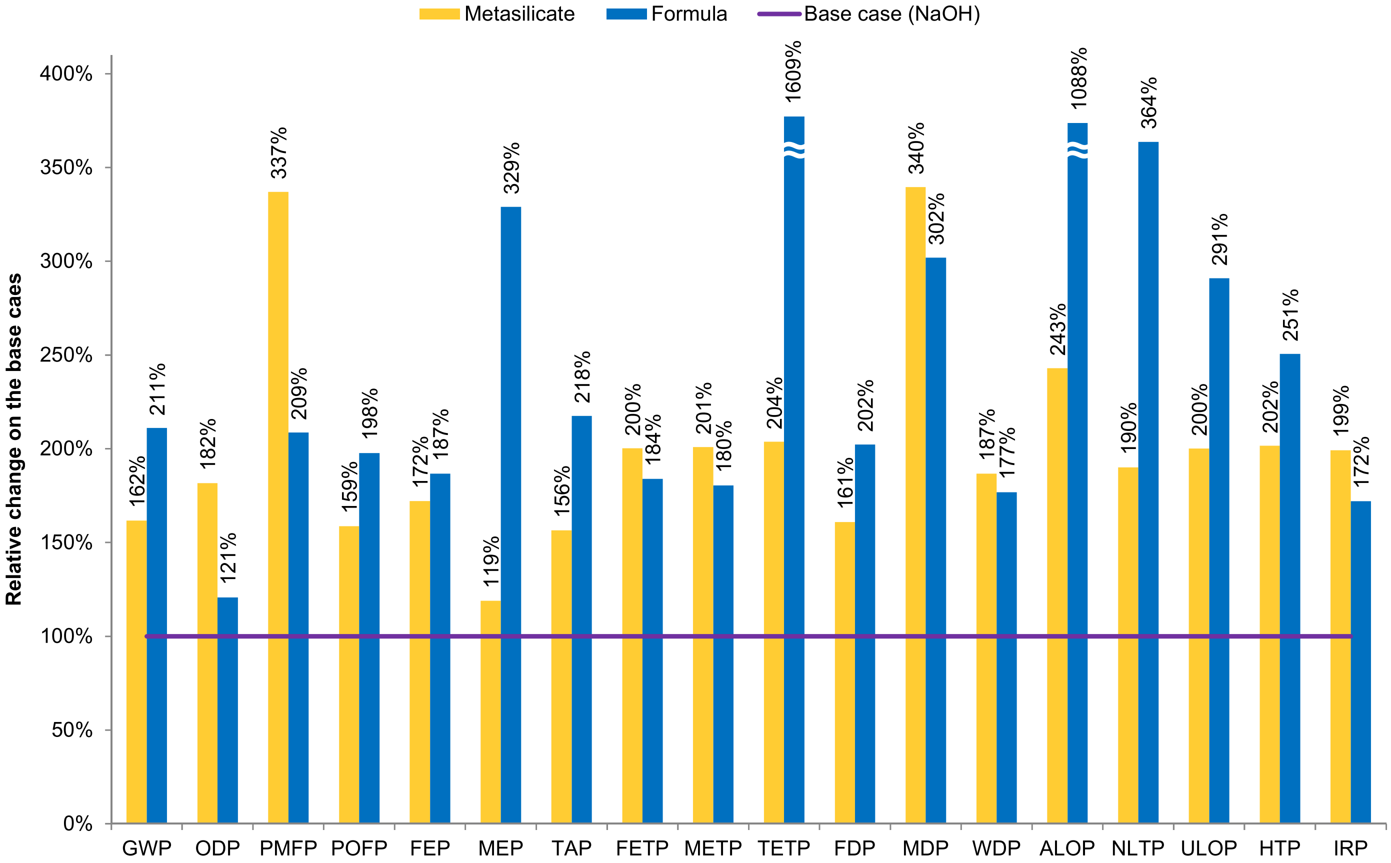


Fig. 5. The effect on the impacts of type of detergent used for cleaning reusable water bottles.
["Formula" in the legend refers to detergent formula. The impacts nomenclature can be found in Fig. 3].

3.2. *Environmental impacts of current water supply and future scenarios*

Compared to the current situation, the BAU scenario has 60–73% higher impacts while the Independent scenario has 33–99% lower impacts across the 18 categories (Fig. 6). The higher water demand in the Advanced scenario results in increased impacts in ten categories relative to the current situation but a 1–9% reduction in the other eight (FEP, FETP, METP, MDP, WDP, ALOP, ULOP and HTP). The Advanced Independent scenario, which also assumes a higher water consumption rate, sees an increase in impacts versus the current situation only in ULOP; all the other impacts are reduced by 72–98%. The Advanced Independent scenario has higher impacts per household than the Independent, mainly due to greater water consumption. Overall, the Independent scenario is the best option for all impact categories because of the absence of bottled water. The following sections discuss the results in more detail. The discussion refers to the impacts per household; for impacts per 1 m^3, see Table S4 in the SI. For the contribution analysis for different water supply options in each scenario, see Fig. S2 in the SI.

3.2.1. *Climate change (GWP)*

The GWP of annual water consumption is estimated at 922 kg CO_2 eq. per household. The large majority of this is attributed to bottled water (51% to smaller and 43% to larger bottles). The BAU scenario has 68% higher impact due to reduced access to local freshwater resources and consequently higher reliance on imported water. In contrast, the Independent scenario has 44 times lower GWP (21 kg CO_2 eq.), achieved by replacing imported water with local desalination. The Advanced scenario has a lower impact per unit of water than the current situation (Table S4), but the higher household demand increases it by 25% per household. The Advanced Independent scenario demonstrates how a higher water demand can be satisfied while reducing GWP by 96% on the current situation by relying on solar-powered desalination and groundwater extraction.

3.2.2. *Air pollution (ODP, PMFP, POFP)*

At present, imported bottled water contributes disproportionately to the air pollution impacts compared to its share in the supply mix (13%). Water in the smaller single-use bottles has the largest contribution to PMFP (41%) and POFP (42%) because of plastics production. Furthermore, water in the larger reusable bottles causes 72% of the ODP due to the cleaning. Groundwater also has a significant contribution to PMFP (15%) and POFP (22%) because of the electricity for pumping.

The BAU scenario has 54–70% higher air pollution impacts than the current situation, while the Advanced shows an increase of 44–147%. The increased impacts in the BAU scenario are due to the higher amount of bottled water, while in the Advanced scenario the increase is mainly attributed to the electricity from diesel used for desalination. As a result, the latter has a higher contribution to the air pollution impacts in the Advanced scenario than bottled water. The impacts of the Independent and Advanced Independent scenarios are reduced on average by 97% and 95%, respectively, due to the absence of bottled water in the supply mix.

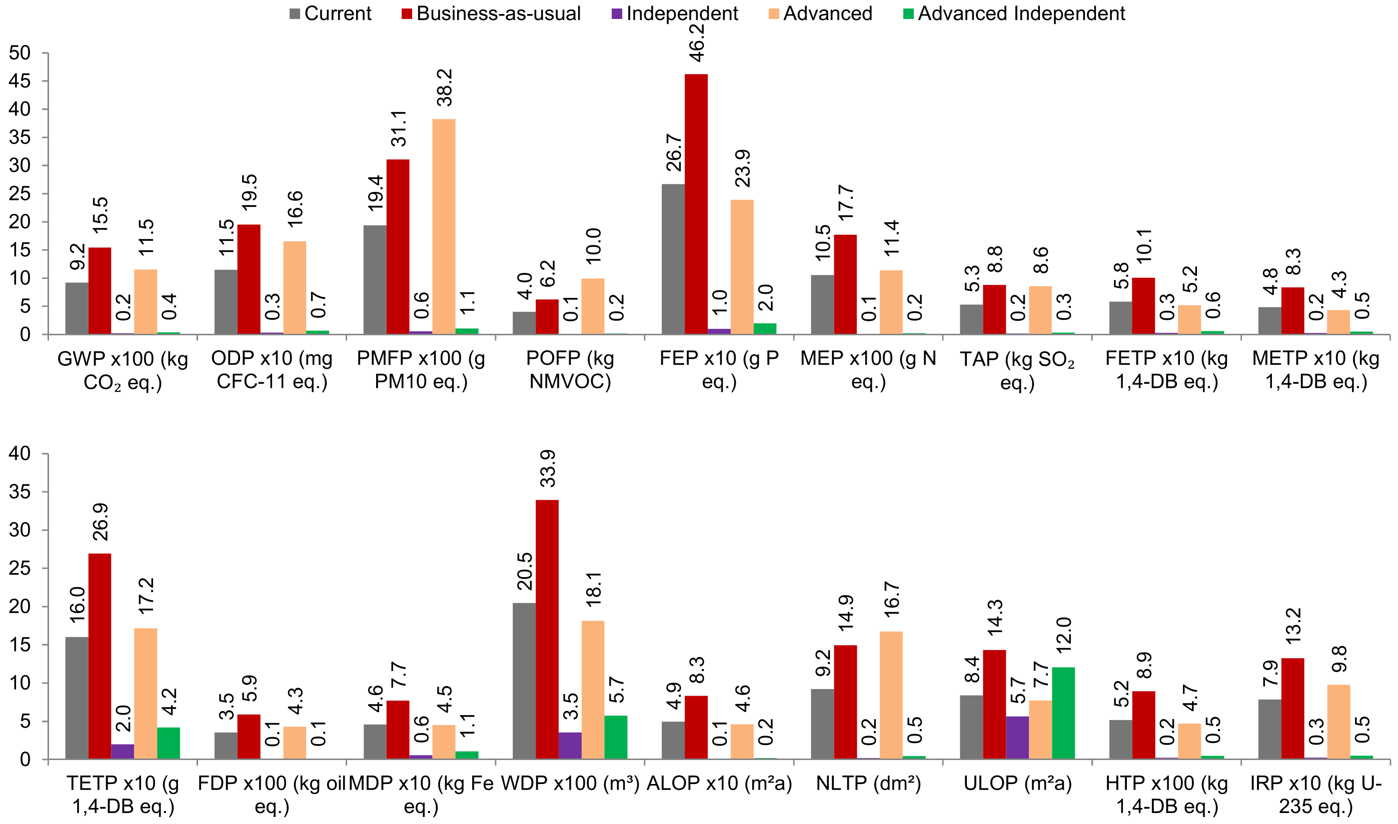


Fig. 6. Life cycle environmental impacts of the current water supply and future scenarios.
[All impacts are expressed per annual amount of water consumed by a household: Current situation, Business-as-usual and Independent: 197 m^3; Advanced and Advanced Independent: 260 m^3. Data labels are cradle-to-grave totals to be multiplied by factors on the x-axis where relevant. For impact nomenclature, see Fig. 3 and for the scenario definitions, see section 2.2.2].

3.2.3. *Eutrophication and acidification (FEP, MEP, TAP)*

Almost all (>97%) of the eutrophication impacts (FEP, MEP) in the current situation are from bottled water. It is also the main contributor to TAP (90%), with groundwater causing the rest of the impact. The impacts of the BAU scenario are higher for all three impact categories than the current situation. In contrast, the Advanced scenario has 11% lower FEP despite its higher water demand due to the addition of desalination to the supply mix. Both the Independent and Advanced Independent scenarios have significantly lower FEP, MEP and TAP than the other scenarios, with the former being a better option.

3.2.4. *Ecotoxicity (FETP, METP, TETP)*

The ecotoxicity potentials of the current water supply are dominated by the bottled water, with both the smaller and larger bottles having almost equal contributions to FETP and METP but smaller bottles resulting in twice as high TETP as the large containers. Increased consumption of bottled water in BAU leads to 68–72% higher impacts than at present. Independent and Advanced Independent, the two scenarios without bottled water, have 74–95% lower ecotoxicity potentials than the current water supply. In the Advanced scenario, aquatic ecotoxicity potentials (FETP and METP) are 11% lower, but TETP is 7% higher. Bottled water is the main cause of the impacts in this scenario (77–93%), but desalination also contributes significantly to TETP (21%).

3.2.5. *Resource depletion (FDP, MDP, WDP)*

In the current situation, water in 1.5-L bottles causes 41–62% of resource depletion, while water in 18.9-L containers is responsible for 33–49%. This is due to the production of plastic bottles. As with the previous impact categories, the BAU scenario has 66–68% higher resource depletion than the current situation because of the greater use of bottled water. On the contrary, the Independent and Advanced Independent scenarios have the lowest depletion potentials. Per m^3 of water, the Advanced scenario has lower FDP (8%), MDP (25%) and WDP (33%) than the current water supply. However, taking into account the annual household demand, the higher consumption in the Advanced scenario offsets the reductions per m^3, resulting in 21% higher FDP and almost equal MDP. On the other hand, despite the higher consumption, total WDP per household is 11% lower in the Advanced scenario compared to the current situation due to lower reliance on imported water.

3.2.6. *Land use (ALOP, NLTP, ULOP)*

Land use impacts, especially ALOP, in the current situation are primarily (41–76%) caused by water in 1.5-L bottles. Water in the larger containers contributes a further 22–46% to land requirements. As expected, the higher share of bottled water in BAU results in 62–71% higher land use impacts, while its absence in the Independent scenario reduces land use by 33–98%. Interestingly, the Advanced scenario has 7% lower land occupation (ALOP and ULOP) than the current situation, but 81% higher land transformation potential (NLTP). Contribution analysis of this scenario indicates that 54% of the NLTP is attributed to desalination, more than double that for the bottled water. This is associated with diesel-derived electricity used for desalination as diesel has a high NLTP in the oil extraction stage. In the Advanced Independent scenario, reductions in ALOP and NLTP relative to the current situation (95–96%) are related to the lower impacts of solar-powered desalination which displaces bottled water. However, the ULOP is 43% higher in this scenario due to the urban land occupied by ground PV installations (Ecoinvent Association, 2014).

3.2.7. Human health (HTP, IRP)

Almost all (>94%) of the human health impacts in the current situation are attributed to bottled water. All future scenarios, except the BAU, have lower impacts per m^3 than the current situation due to lower fractions of imported bottled water in the mix. However, the higher household consumption in the Advanced scenario counteracts the IRP reduction, resulting in a net 24% higher impact per household in this scenario. As with most other impact categories, the BAU scenario has the highest HTP and IRP per household, while the Independent has the lowest. In the Advanced and Advanced Independent scenarios, desalinated water is the most significant contributor to human health impacts (72–87%), mostly attributed to the solar PV system that powers the desalination plant.

3.2.8. Sensitivity analysis for advanced scenario

The results discussed in the previous section indicated that the Advanced scenario has lower impacts per m^3 in all categories aside from air pollution (ODP, PMFP and POFP), TAP and NLTP. However on the basis of the annual household demand, the higher water use in this scenario leads to higher impacts in ten categories compared to the current situation.

Unlike the other high-consumption scenario (Advanced Independent) which meets its higher water demand solely through desalinated water, the Advanced could meet these requirements with any combination of desalinated and bottled water. Therefore, this sensitivity analysis aims to evaluate the robustness of the above results with respect to the assumed supply mix for the Advanced scenario. This can also be interpreted as identifying additional sub-scenarios with a common basis of increased household water demand. The original definition for this scenario assumes the same level of consumption of bottled water as at present, with desalination supplying 34% of water to address the shortfall in demand. This share of desalinated water is varied from 0% (i.e. the same as the current situation and BAU) to 42% (same as Advanced Independent scenario), with bottled water filling the supply gap; the ratio of water supply in 1.5-L and 18.9-L bottles is kept constant as in the base case for this scenario (see Fig. 2). In international contexts, the lower desalination shares can represent areas with no access to seawater (e.g. inland communities), while the higher end of the sensitivity analysis can refer to regions with greater support for desalination, such Middle East and North Africa (International Water Association, 2016).

The results in Fig. 7 indicate that all impact categories are significantly affected by the assumed supply mix. FETP, FEP and METP are most sensitive as they show the highest differences between bottled and desalinated water (Fig. 3). By contrast, PMFP and POFP are the least sensitive since they are related to electricity used in the bottled-water and desalination systems: the former is dominated by coal (grid electricity) and the latter is generated from diesel, with both fuels having comparable PMFP and POFP. For the results for the rest of the impacts, see Table 4 in the SI.

In comparison to the other scenarios, the Advanced scenario with no desalination ("pessimistic") has per-household impacts four times higher than the current situation (Fig. 8). It also has more than twice the impacts of the BAU scenario despite having a water demand that is only 32% higher. Conversely, the "optimistic" variant with the highest desalination share (42%) has lower impacts than the current situation in 14 categories. While the optimistic case has the same supply mix as the Advanced Independent scenario, this case still depends on diesel generators to operate the desalination process. Hence, PMFP, POFP, TAP and NLTP remain higher than in the current situation due to high diesel use in this scenario.

4. Conclusions and recommendations

This study has presented the first life cycle assessment of different water supply options and 2030 scenarios for remote communities in developing countries. Under current conditions, utilisation of local freshwater resources (groundwater and surface water) has 7–99% lower impacts than off-grid desalination as the latter relies on electricity from diesel. However, imported bottled water has the highest impacts: 2-3 orders of magnitude higher than the local groundwater or surface water. Although bottled water transportation is a considerable contributor, the main hotspots for the bottled water are single-use bottles and the cleaning of reusable containers. Doubling the current recycling rate would reduce the impacts of water in single-use bottles by 7–23% and in reusable containers by 0.5–10%. However, bottled water would still remain the worst option. This work can also be expanded to include alternative water sources, such as water recycling and rainwater harvesting, as well as to add wastewater treatment in the scope.

Based on the current water supply mix of typical remote islands in the Southeast Asia-Pacific region, water in single use bottles accounts on average for 50% of the total environmental impacts of domestic water supply despite providing only 3% of the water. Due to population increase and forecasted constraints on local freshwater availability, greater reliance on imported bottled water is expected by 2030 in the Business-as-usual scenario, resulting in 54–72% higher environmental impacts than at present. The Independent scenario, wherein imported water is replaced by locally-desalinated water, shows significant reductions in all 18 impacts even though desalination requires ten times more energy than a pumping station per m^3 of water produced. The Advanced scenario, which assumes better quality of life and consequently greater household water demand, shows mixed results as eight impacts are reduced and the other impacts are increased compared to the current situation. Introduction of desalination to the supply mix of this scenario lowers the impacts per m^3, except in air pollution, acidification and land transformation. However, higher water use per household counteracts the impact reductions achieved by avoiding imports. Alternatively, if imported water provided for the new demand, the impacts of household water use would be more than four times higher than at present. Finally, the Advanced Independent scenario examines whether water security and demand growth can be satisfied while also reducing the impacts of water consumption. The results show that relying on solar-powered desalination can achieve these objectives and also lower almost all environmental impacts significantly relative to the current supply and demand of water.

Although the models used in this work correspond to Southeast Asia-Pacific conditions, the insights gained are applicable to remote communities with similar geographic and socio-economic conditions. For one, off-grid desalination is more energy-intensive than local water utilisation, and hence is less environmentally preferred especially if off-grid electricity is generated from traditionally-used diesel generators. However, desalination has significantly lower impacts than imported water which requires plastic bottles and transportation before it can be accessed by households in remote communities. The environmental impacts of off-grid desalination can be reduced by up to 98% by coupling it with renewable energy sources. The environmental savings can even be large enough to allow higher water consumption – which is required for community development – while simultaneously reducing the impacts per household.

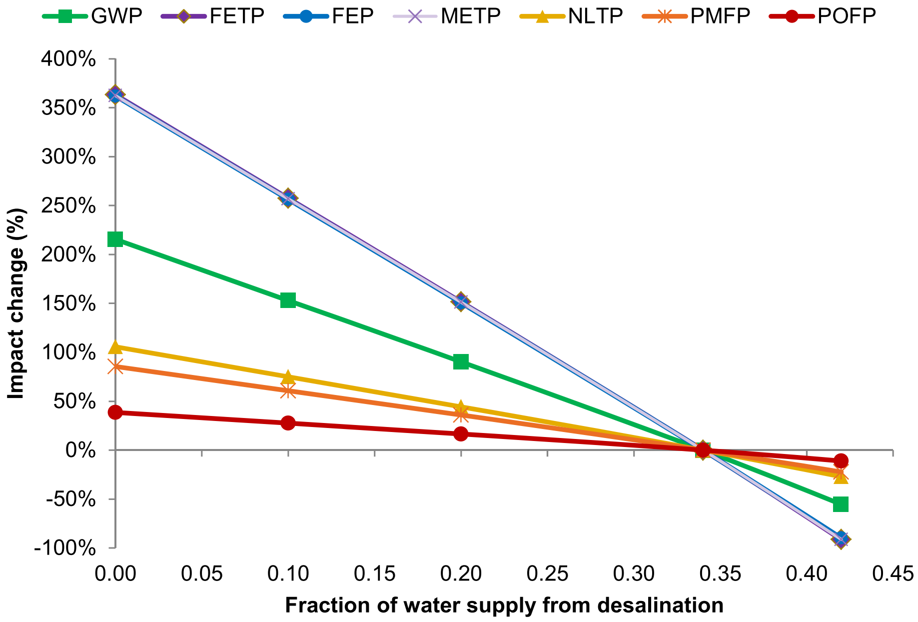


Fig. 7. The effect on the impacts of the share of desalinated water in the supply in the Advanced scenario.
[The impacts nomenclature can be found in Fig. 3 and the results for all impacts in Table S5 in the Supplementary Information. The Advanced scenario is defined in section 2.2.2].

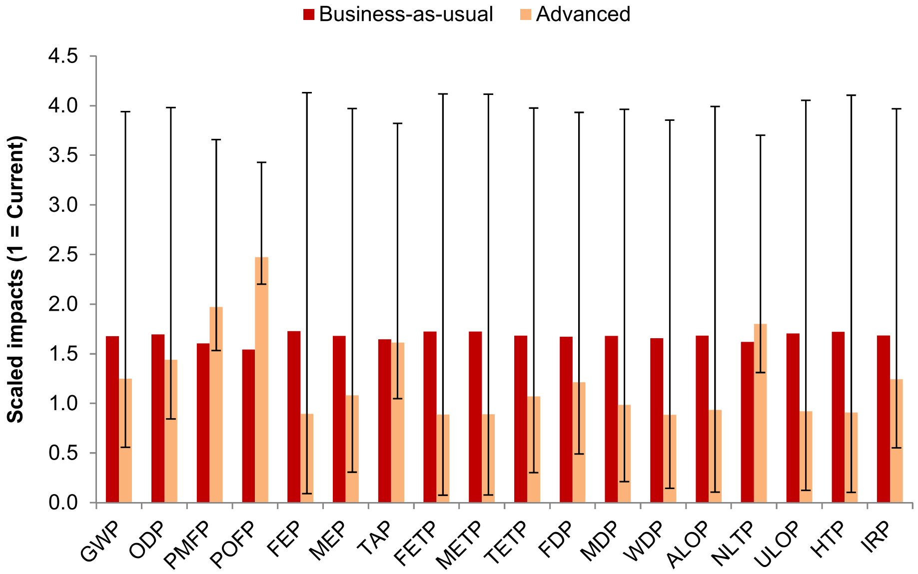


Fig. 8. Impacts of the Business-as-usual and Advanced scenarios relative to the current situation.
[The impacts nomenclature can be found in Fig. 3. The scenarios are defined in section 2.2.2. Error bars represent most optimistic and pessimistic cases for the Advanced scenario].

To adapt the results to specific local conditions, primary data will be needed on household water consumption and the water supply mix. These can then be used to develop future scenarios based on techno-economic or socio-political constraints. It is also recommended to engage with local stakeholders to elucidate aspirations that can be integrated into the scenario analysis. Alternative methods for estimating the impacts of water consumption, such as AWARE (Boulay et al., 2018) and water stress index (Pfister et al., 2013) can also be used, especially for regionalised water footprints.

The results from this study demonstrate the challenges in the water-energy nexus in remote communities and highlight that planning of water and energy supply systems need to be coordinated with each other if the Sustainable Development Goals are to be met. This can be achieved through integrated analyses of energy and water utilities in the context of developing communities. Furthermore, future work should also address the integrated planning and sustainability assessment of utility systems in remote communities.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2020.115687.

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