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Review

Life cycle water inventory in concrete production—A review

Yazmin L. Mack-Vergara[a,b,*], Vanderley M. John[a]

[a] Universidade de São Paulo, Escola Politécnica, Department of Construction Engineering, 05508-900 São Paulo, SP, Brazil
[b] Universidad Tecnológica de Panamá, Experimental Center for Engineering, Panama, Panama

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ABSTRACT

High water consumption and wastewater generation in the concrete industry have become very important environmental issues; however, water inventory data for concrete production and its raw materials are limited and inconsistent. The water use for different components (aggregates and cement) and processes in concrete production cradle-to-gate were identified along with water inventory figures. A large dispersion was found. The aim of this paper is to review the various water inventory methodologies and understand their implications on the water inventory figures in concrete's life cycle to understand the wide dispersion of the inventory data that was found in the literature. The implications of the various methodologies on water inventory figures were tested in a hypothetical concrete production scenario. Our case scenario shows that methodology can give results that differed by a factor of approximately 3–4. Available data on water consumption should be use very carefully by LCA practitioners and the industry decision makers. This study concludes that there is a need for unification of the water inventory methodologies in order to have data that is actually comparable. Understanding the water inventory methodologies will result in more detailed and clarified water inventory and consequently a more thorough impact assessment will be possible. The results are of interest to the research community as well as to the stakeholders of the cement and concrete industries who seek sustainability in their products.

Contents

* Corresponding author at: Universidade de São Paulo, Escola Politécnica, Department of Construction Engineering, 05508-900 São Paulo, SP, Brazil.
E-mail address: yazmin.mack@lme.pcc.usp.br (Y.L. Mack-Vergara).

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1. Introduction

The water footprint concept was introduced by Hoekstra in 2002 (Hoekstra et al., 2009). This concept is defined as "the total volume of fresh water that is used, directly or indirectly, to produce the product" (Hoekstra et al., 2011). In 2014 the first ISO standard for Water Footprint was published; this standard defines the water footprint as "metrics that quantify the potential environmental impacts related to water" (International Organization for Standardization, 2014). Water related environmental impacts are of great concern because water scarcity is expected to worsen in many parts of the world due to urban population growth (Bodley, 2012), industrialization, and climate change (Holcim, 2010; Intergovernmental Panel On Climate Change, 2008; United Nations Global Compact, 2011; World Business Council for Sustainable Development, 2014a, 2012, 2009a). Today, water conservation, water footprints, and water management are of increasing importance in the sustainability agenda of many organizations (BASF, 2014; Holcim, 2012; Hu et al., 2016; Lafarge, 2014, 2012).

Water use can be classified as consumptive -water that is withdrawn from one source and discharged into a different source or not returned, such as water integrated into a product or evaporated- or degradative which entails changes in water quality (Ridoutt and Pfister, 2012; Pfister et al., 2015). Water consumptive and degradative use lead to a modification of resources availability which translates into environmental impacts of concern affecting human health, ecosystem quality, and resources (Curran, 2012).

The environmental impact assessment of water resources results from the numbers coming from a water inventory, pondered with local conditions such as local water scarcity and local water quality, precipitation and hydrological characteristics, and climatic characteristics (International Organization for Standardization, 2014; O'Brien et al., 2009; Pfister et al., 2009; World Business Council for Sustainable Development, 2012). As stated in (Pfister et al., 2015), regionalized water inventory, impact assessment and uncertainties represent quite a challenge. For instance, data from the Ecoinvent database do not include location on the watershed level or temporal aspects which is needed for impact assessment. Compared to CO_2 contribution to global warming, water environmental impact assessment is not yet a clear established topic and its application to concrete industry is limited. This may be due to the fact that CO_2 emissions have a global scale while water use related impacts are local, therefore more data is needed for water impact assessment.

From an environmental point of view, water impact assessment is crucial. Nevertheless, since water impact assessment depends on local conditions, the water inventory becomes relevant when it comes to comparison between companies or products at a global scale. Water inventory will allow to compare water that is used for the production process without considering local factors.

Available data related to cement and concrete life cycle is mostly concerned with CO_2 emissions and energy consumption (Amato, 2013; Hasanbeigi et al., 2012; US EPA, 2010; Van Oss and Padovani, 2003; World Business Council for Sustainable Development, 2009b; Worrell et al., 2001). For these aspects, large worldwide datasets are available (World Business Council for Sustainable Development, 2009b). Data coming from different sources are coherent and the reasons for the differences between sources are rather well understood. This allows the industry and its clients to take measures to minimize the associated environmental impacts. Although concrete production requires large amounts of water (Henry and Kato, 2014), the available inventory data associated with water is scarce and presents large dispersion of up to one order of magnitude (Cemex, 2015, 2013, 2012; Holcim, 2015, 2014, 2013, 2012; Lafarge, 2012) rendering impossible for the industry to act based on it. Explanation for such large differences are not immediately understood. Reasons for this may include different inventory criteria, technological routes as well as local conditions, such as rain regime. However, the exact contribution of each factor is not clear. The Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD), a group of the major cement producers with 15 plus years of inventory of CO_2 emissions and energy, introduced in 2013 (World Business Council for Sustainable Development, 2014a) a customized version of the WBCSD Global Water Tool (GWT) first launched in 2007. Despite the group effort, only three companies managed to publish data in their environmental reports. Values presented were sometimes 10–20 times lower than available inventory data from life cycle assessment (LCA) studies. In revised past values; time series presented sometimes 30% shifts, which is unexpected in average values of large international operations. This picture has a stark contrast with the coherence of data from CO_2 and energy inventory coming from both, companies' inventories and LCA databases. The fact that large, well organized and experienced companies have problems mastering water inventory, is worrisome. To allow the data to be used in the decision-making process of both industry and clients, a better understanding of the underlying reasons of such variation in water inventory published data is needed.

In general data on water use have been inconsistently reported and in some cases -for instance in the concrete industry-, water data for essential activities are neglected (Pfister et al., 2015). The concretes life cycle includes many activities in addition to concrete mixing as can be seen in Fig. 1. This research presents the sum of the available water inventory figures from literature since water consumption data on concrete production life cycle is not only scarce but also scatter on different references such as scientific papers, sustainability reports, etc.

The aim of this paper is to review the various water inventory methodologies and understand their implications on the water inventory figures in concrete's life cycle from cradle-to-gate. Understanding the water inventory methodologies will results in more detailed and clarified water inventory and consequently a more thorough impact assessment will be possible (Pfister et al., 2015). This work is our first step in establishing actions to improve water use efficiency in concrete production by defining its water footprint which is our forthcoming objective.

2. Methodology

In Fig. 1 we present the concrete's life cycle from cradle to grave for a better understanding of the water use in the different phases. The scope of the study is cradle to gate. This research covers not only concrete but also aggregates and cement production. Chemical admixtures production is not covered since there is a large variety and many possible production lines. However, as presented in Fig. 1 there is water in the production of admixtures which is one of the components of concrete. In a more specific study and where

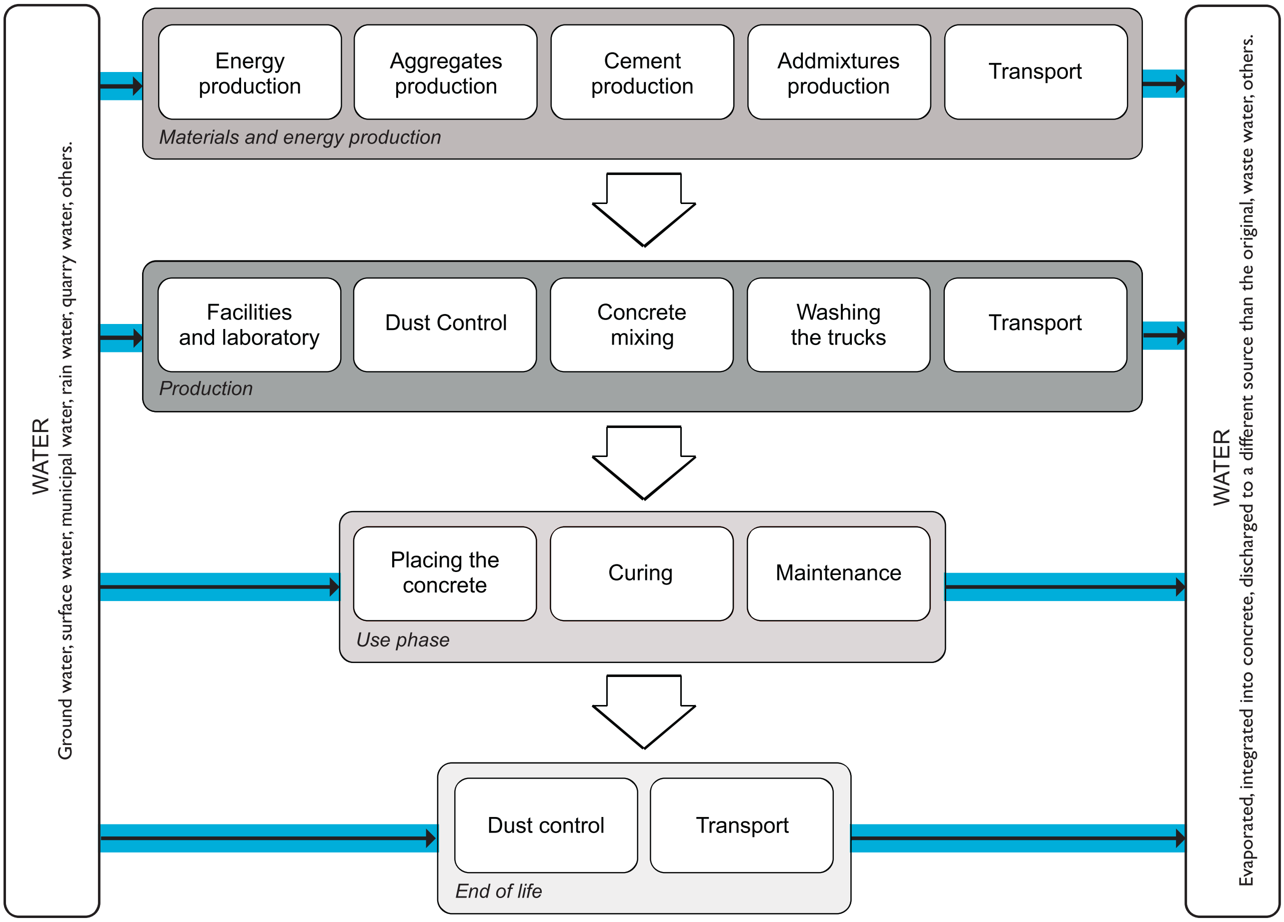

Fig. 1. Concrete's life cycle including four phases: materials and energy production, concrete production, use and end of life.

the type of chemical admixture is known, the use of water to produce the admixture should be considered. The water flows of the most common production routes for each of the major concrete components are investigated. Results are presented in Appendix A. Differences on various detected technological routes that affects water consumption were discussed. Water consumption for transport is mainly water for fuel production and water for washing the trucks which we do include. We did not go into detail on water consumption in fuel production – extraction and refinement (Lampert et al., 2015; Scown et al., 2011; Simons, 2016). Water for energy is considered indirect water use as can be seen in Fig. A1–A5 in Appendix A and depends on the type that is used and on the energy matrix of the region. Water consumption for energy is a complex subject and should be studied in detail. Data for infrastructure construction and equipment production, such as trucks, kills, etc., is not included.

In the Water Inventory Figures for Concrete Production section (Section 4) we present information found in the literature. However, those are not all the possible water flows for aggregates, cement and concrete production as it can be observed in Appendix A where contrary to Section 4 we present possible water flows without numbers.

Water use data for the main cementitious materials components and processes were identified from the literature and standards, product category rules (PCR), as well as public documents from cement and concrete industry organizations. The units of kilogram of water (H kg), kilogram of water per kilogram of product (H kg/kg) and kilogram of water per cubic meter of concrete (H kg/m^3) were used to estimate the flows. This was done in order to differentiate kilograms of water from kilogram of other materials. Since the concrete production chain is so short, all data presented in this paper is foreground data considering that it is specific to the production processes and do not includes data for the production of generic materials, transport or waste management. It is not possible to thoroughly study variability and uncertainties in this paper, because most of the data lack the information needed for this analysis.

For the purposes of this investigation, only water related terminology and water inventory are discussed. The term “water use” is the amount of water needed for the production process (International Organization for Standardization, 2014; Rudolf et al., 2013; World Business Council for Sustainable Development, 2013), while “water consumption” may include water that is diverted from natural flows but is not necessarily used in the production process (e.g., storm water management) in addition to the water actually used in production (Ecoinvent v3.1,” 2014; Global Water Tool for Cement Sector, 2013; European Commission, 2010a; Hoekstra et al., 2011; International Organization for Standardization, 2014; Rudolf et al., 2013; World Business Council for Sustainable Development, 2013). We do not estimate the water footprint -which entails water impact assessment according to the ISO 14046 Standard (International Organization for Standardization, 2014)- because performing a water impact assessment is not possible without defining a specific situation and this was not aligned to the objective of this paper.

The concepts and definitions from seven water inventory methodologies (see item 3.2) that are applicable to cement and concrete materials were summarized. The implications of the various methodologies on water inventory figures were tested in a hypothetical concrete production scenario. Table 3 and Fig. 8 represent a hypothetical scenario based on figures from the literature and

Table 1
Comparison of the definition of water use, water withdrawal and water discharged for each methodology. The three methodologies on the right have the same criteria.

		Hoekstra (Hoekstra et al., 2011)	GaBi (Rudolf et al., 2013)	GWT cement (Global Water Tool for Cement Sector, 2013)	ILCD (European Commission, 2010a)	ISO 14046 (International Organization for Standardization, 2014)	PCR Concrete (World Business Council for Sustainable Development, 2013)	Ecoinvent (Ecoinvent v3.1, 2014)
Water use type								
In-stream			X			X	X	X
Off-stream		X	X	X	X	X	X	X
Water source								
Non-fresh water				X	X	X	X	X
Freshwater		X	X	X	X	X	X	X
Water withdrawal								
Used		X	X	X	X	X	X	X
Captured but not used		X			X	X	X	X
Water discharged deduction								
To different source	Quality changed		X[2]	X				
	Same quality		X[2]	X	X[3]			
To the same source from origin	Quality changed		X[2]	X		X[4]	X	X
	Same quality	X[1]	X[2]	X	X[3]	X[4]	X	X
Water consumption								
Water evaporated		X	X	X	X	X	X	X
Water integrated into product		X	X	X	X	X	X	X
Water discharged to a different source	Quality changed	X			X	X	X	X
	Same quality	X				X	X	X
Water discharged to the same source from origin	Quality changed	X			X			
	Same quality							

[1]To the same catchment, [2]Total freshwater release from the technosphere. Water release to the sea is not considered as water discharge but as water consumption, [3]Chemical substances that cause water quality to change are inventoried as separated elementary flows, [4]To the same drainage basin.

the authors own professional experience – details are provided in Appendix B and Appendix C. Cement, aggregates and admixtures production were excluded for simplification. Even though water use for energy is considered indirect water and is not thoroughly studied, it is included in the hypothetical case study in order to present an example of in-stream water use. The use of a hypothetical scenario was necessary because we found no suitable data set available with sufficient detail and/or including all water sources.

3. Water related terminology

3.1. The water footprint concept

According to the ISO Water Footprint Standard (International Organization for Standardization, 2014), the water footprint of a product includes all of the possible environmental impacts assessed. If a complete impact assessment is not performed, then the term "water footprint" should be accompanied by a qualifier. For example, "water scarcity footprint" when water scarcity is assessed, "water availability footprint" when water availability is assessed, or "water footprint profile" when a set of environmental impacts are assessed. Nevertheless, the standard fails to present a complete list of water-related environmental impacts.

Hoekstra et al. (Hoekstra et al., 2011) proposed blue, green and grey water footprints. Water characterization is divided into consumptive use (blue and green water footprints) and degradative use (grey water footprint). Water footprint considers freshwater use only (direct and indirect) and includes virtual water, which is water consumed or polluted elsewhere to manufacture the product. In this methodology, the location has to be included, which allows performing an impact assessment based on the water inventory.

The cement industry uses the Global Water Tool (GWT) for cement (Global Water Tool for Cement Sector, 2013) which does not include the water footprint concept. However, Cemex and Lafarge Sustainability reports, use the term "water footprint" for the water withdrawal, water discharge and water consumption figures of these companies (Cemex, 2015; Lafarge, 2012). Holcim also mentions the term "water footprint" in their sustainability reports; however, they do not define it (Holcim, 2015).

There are several methodologies for water footprinting. The ISO Water Footprint Standard (International Organization for Standardization, 2014) is clearly becoming a reference. Although there is some understanding between these methodologies, there are also many differences (Pfister and Ridoutt, 2014). The LCA tools GaBi and SimaPro (Pfister, 2012; Thylmann, 2014) also estimates water footprint through different water impact assessment methodologies.

3.2. Water inventory terminology

Seven water inventory methodologies were selected to be evaluated and compared. The water footprint assessment manual by Hoekstra et al. (Hoekstra et al., 2011), the GaBi Database and Modelling Principles (Rudolf et al., 2013), the International Reference Life Cycle Data System (ILCD) Handbook – Specific guide for Life Cycle Inventory data sets (European Commission, 2010a), the ISO Water Footprint Standard (International Organization for Standardization, 2014), and the Ecoinvent database ("Ecoinvent v3.1," 2014) present water inventory methodologies that can be applied to a wide range of products, services or companies, while the Concrete Product Category Rules (PCR) (World Business Council for Sustainable Development, 2013) and the Global Water Tool (GWT) for the Cement Sector (Global Water Tool for Cement Sector, 2013) focus on the concrete and cement industry. Even though the Concrete PCR (World Business Council for Sustainable

Development, 2013) is based on an ISO standard, we believe that it is worth studying because there are few methodologies for concrete water inventory.

For water inventory, the definitions of crucial terms such as "water withdrawal," "water discharge" and "water consumption" adopted by various methodologies ("Ecoinvent v3.1," 2014; Global Water Tool for Cement Sector, 2013; European Commission, 2010a; Hoekstra et al., 2011; International Organization for Standardization, 2014; Rudolf et al., 2013; World Business Council for Sustainable Development, 2013) are inconsistent. Table 1 presents the definition of water use, water withdrawal and water discharged for each methodology. The comparison of water inventory methodologies approaches provides a better understanding of the differences between methodologies. In addition, the term "water use" is defined as **use of water by human activity** (International Organization for Standardization, 2014; Rudolf et al., 2013; World Business Council for Sustainable Development, 2013). The first aspects to consider when comparing methodologies are the in-stream and off-stream water use (Bayart et al., 2010; World Business Council for Sustainable Development, 2013). In-stream water use refers to surface water resources, which are used directly in the watercourse. Some examples of in-stream water use related to the concrete industry are in-stream aggregate mining, transport of raw materials through navigation, hydropower generation, and pollution dilution in a water flow. Off-stream water use is water removed from its source during a product's life cycle. All the methodologies studied consider off-stream water use; the GaBi Database and Modelling Principles (Rudolf et al., 2013), the ISO Water Footprint Standard (International Organization for Standardization, 2014), the Concrete Product Category Rules (PCR) (World Business Council for Sustainable Development, 2013) and the Ecoinvent database ("Ecoinvent v3.1," 2014) also consider in-stream water use.

Next, the water withdrawal approaches are reviewed. The water footprint assessment manual by Hoekstra et al. (Hoekstra et al., 2011) and the GaBi Database and Modelling Principles (Rudolf et al., 2013) have a more restrictive definition for water withdrawal, as they only consider fresh water, whereas the other methodologies also include non-fresh water. Moreover, GaBi Database and Modelling Principles (Rudolf et al., 2013) and GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) are the only methodologies that do not account for water managed within the limits of the plant (in the concrete production case) but not used in the process.

Within their different approaches, the seven different water inventory methodologies consider different water sources. The main water sources found in literature are groundwater, surface water, municipal water, rain water and external waste water. As stated before, location is important for assessing water environmental impacts, and water sources should be registered when collecting water inventory data. Table 2 presents the water sources considered by the seven methodologies.

The water consumption could be defined as the water withdrawal minus de water discharged deduction in addition to water that is evaporated and or incorporated into the product. The water footprint assessment manual by Hoekstra et al. (Hoekstra et al., 2011) considers as consumption all of the water that is discharged into a different source than the original source plus all of the water that is returned to the same source with the quality changed. For the GaBi Database and Modelling Principles (Rudolf et al., 2013) and GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013), only water that is evaporated and or integrated into the product is considered consumed. Water transferred outside the organization gates – independent of the quality and origin-destination – is not accounted as consumed. For the ISO Water Footprint Standard (International Organization for Standardization, 2014), the Concrete Product Category Rules (PCR) (World Business Council for Sustainable Development, 2013) and the Ecoinvent database ("Ecoinvent v3.1," 2014), only the water that is discharged into a different source than the original source, even at the same quality, is considered to be consumed.

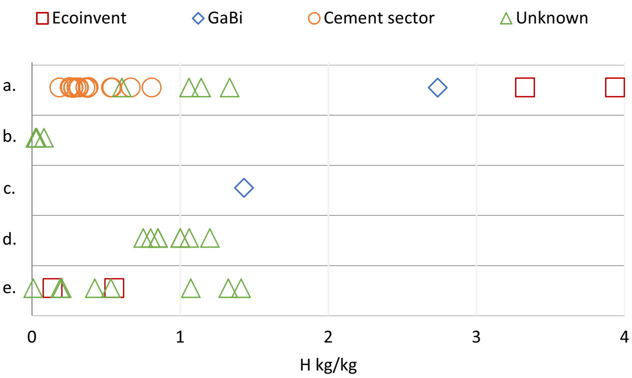

Fig. 2. Water inventory figures for cement production. a. Cement as total; b. Dust suppression; c. Gypsum; d. GBFS; e. Clinker. Data from: (Argos, 2014; Cemex, 2015, 2013, 2011; Chen et al., 2010a; Dunlap, 2003; European Commission, 2010b, 2006; Holcim, 2015, 2014, 2013, 2012; Josa et al., 2004; Lafarge, 2012; Liu et al., 2011; Marceau et al., 2006; Schweitzer, 2015; Valderrama et al., 2012; Zabalza Bribián et al., 2011).

Following the International Reference Life Cycle Data System (ILCD) Handbook – Specific guide for Life Cycle Inventory data sets (European Commission, 2010a), chemical substances that cause the water quality to change are inventoried as separated elementary flows, and the water discharged is considered a negative input, indicating its return to the hydrosphere (Romic Environmental Technologies, 2010).

The GaBi Database and Modelling Principles (Rudolf et al., 2013) and GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) only consider water used as water consumption. The rest of the methodologies (European Commission, 2010a; Global Water Tool for Cement Sector, 2013; Hoekstra et al., 2011; Rudolf et al., 2013) consider water not used but managed within the company's boundaries in addition to water used. This is a consequence of the water withdrawal definition for each methodology.

4. Water inventory figures for concrete production

Different water inventory figures for aggregates, cement and concrete production were found. Differences in water inventory figures for each concrete component and activity may result from differences between the water withdrawal, water discharge and water consumption definitions from each water inventory methodology and also due to different technological routes or even location differences. The results from different water inventory methodologies consist of primary and secondary data, which include databases such as Ecoinvent and Gabi. These data correspond to different situations and geographic locations. For instance, data from Europe and North America as well as companies with representative global data such as Cemex, Holcim and Lafarge are presented.

4.1. Water inventory figures for cement production

Fig. 2 reports data from cement production, including different cement components. In addition, water figures for site dust suppression were also reported separately.

The cement line technology plays a crucial role in water use. Valderrama (Valderrama et al., 2012) presented Ecoivent-based inventory data comparing a regular cement production line to a new line built according to the "Best available techniques

Table 2
Comparison of water sources considered by each methodology. Only PCR Concrete is consistent with ISO 14046.

Water sources	Hoekstra (Hoekstra et al., 2011)	GaBi (Rudolf et al., 2013)	GWT cement (Global Water Tool for Cement Sector, 2013)	ILCD (European Commission, 2010a)	ISO 14046 (international Organization for Standardization, 2014)	PCR Concrete (World Business Council for Sustainable Development, 2013)	Ecoinvent (Ecoinvent v3.1, 2014)
Ground water	X	X	X	X[2]	X	X	X
Surface water	X	X	X	X	X	X	X
Quarry water			X				
Seawater			X	X	X	X	X
Municipal water			X			X	
Rain water	X[1]	X	X		X	X	X
Soil water content and moisture	X[1]	X					X
External waste water			X				
Chemically bounded in raw materials		X					X

[1] Precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation, [2] Renewable.

(BAT)" (European Commission, 2010b). The water decreased from 0.556 H kg/kg in the regular line to 0.139 H kg/kg for clinker production. These results suggest that the technology has a great potential for reducing water use in cement production. Although the authors do not present any techniques for water reduction, the mere improvement in the process efficiency – lower amounts of energy and raw materials use – can help reduce water use. This is a clear example of technological variability.

Chen et al. (Chen et al., 2010a) gave figures of 0.200 H kg/kg for a French cement clinker production. Josa et al. (Josa et al., 2004) compared several European life cycle inventories (LCI), most of them from Holland, for clinker production, including water. In both studies, the water-related inventory methodology was not disclosed.

For limestone mining and quarrying, input figures of 1.05 H kg/kg (process water) and output figures of 1.13 H kg/kg (waste water) were found using the SPINE LCI dataset: Limestone quarrying ESA-DBP (Chalmers University of Technology, 1998). Data are also scarce for filler production; water input figures of 1.612 H kg/kg and output figures of 0.0386 H kg/kg were found in the European Reference Life-Cycle Database (European Commission, 2006).

For blast furnace slag granulation treatment, which involves very rapid cooling, there are figures for different production routes such as cold water system, cold water system with condensation, hot water system and dry granulation. Water inventory figures vary between 0.750 and 1.2 H kg/kg (Dunlap, 2003; Liu et al., 2011; Schweitzer, 2015).

Only two water inventory figures for calcium sulfate were found, both from Germany (European Commission, 2006). The first one, of 1.430 H kg/kg, is a generic value for gypsum ($CaSO_4 \cdot 2H_2O$), considering both underground and open pit mining processes, grinding and concentration. The second one, 2.737 H kg/kg, is for anhydrite ($CaSO_4$), produced by mixing one-third natural anhydrite and two-thirds a thermal anhydrite, a calcined by-product from hydrofluoric acid synthesis or flue gas desulfurization in hard coal power plants. A simple extraction of purer gypsum in open quarries followed by grinding will require water only for dust abatement.

The water inventory in cement plants published by Cemex, Holcim, Lafarge and Argos which are large companies participating in the CSI project (Argos, 2014; Cemex, 2015, 2013, 2011; Holcim, 2015, 2014, 2013, 2012; Lafarge, 2012) varies from 0.185 H kg/kg to 0.808 H kg/kg. These values are consistent with data produced by the LCI of cement production carried by the PCA from North America, which gives 0.606 H kg/kg for cement production with pre-calciner, 1.059 H kg/kg for wet process, 1.141 H kg/kg for cement production with pre-heater and 1.333 H kg/kg for dry process (Marceau et al., 2006). These data include water that goes directly into the process and water identified as non-process for dust abatement and laboratory uses. The European reference Life-Cycle Database presented a water input of 1.693 H kg/kg for a CEM I Portland Cement (European Commission, 2006). In addition, Zabalza et al. (Zabalza Bribián et al., 2011) presented figures above 3 H kg/kg for European cement production, values that are outliers.

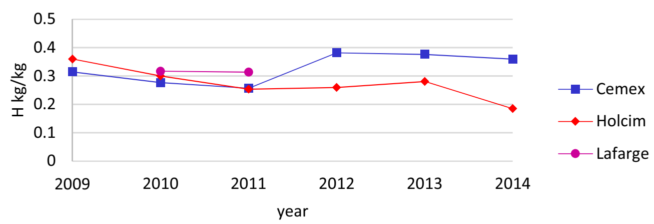

Fig. 3. Water consumption in cement production, global averages data from Cemex, Holcim and Lafarge (Cemex, 2015, 2013, 2011; Holcim, 2015, 2014, 2013, 2012; Lafarge, 2012).

Chemically bounded water data were not found and is clearly a limitation in water inventory, however it has to be included for water balance (Pfister et al., 2015). In the case of cement production, considering the chemically bounded water in clay that is released during clinker production is interesting. For a raw estimation, considering 300 kg of clay per ton of clinker and 10% water content, 30 H kg/kg are released during clay decomposition.

Differences between these figures may be due to the methodology used for their estimation, which demonstrates once again the importance of having a well-defined methodology and accordance in definitions. For instance, water for cooling processes in cement production may be reused, resulting in lower figures for water consumption. However, water data are still scarce in LCI and there are even cases where water is not included in the cement LCI at all for instance in the Swedish CPM LCA database (Chalmers University of Technology, 1998).

Water use in activities that may be considered accessory to the production process can be important. An example of this is dust suppression in cement production, which according to the PCA Portland Cement LCI depends on the type of process: wet process (0.024 H kg/kg), dry process (0.032 H kg/kg), process with pre-heater (0.082 H kg/kg) or pre-calciner (0.023 H kg/kg) (Marceau et al., 2006).

Fig. 3 presents global data from Cemex, Holcim and Lafarge for the total direct water consumption in cement production (Cemex, 2015, 2014, 2013, 2012, 2011, 2010; Holcim, 2015, 2014, 2013, 2012, 2011, 2010; Lafarge, 2012). These data do not include water consumption by industrial op erations from suppliers off site. The data show important variations over time, a feature not expected from such large global operation companies. These variations may be due to revisions and changes in the measurement methodol-

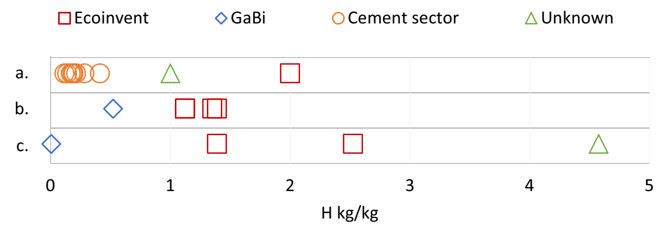

Fig. 4. Water inventory figures for aggregates production. a. Fine aggregates; b. Coarse aggregates; c. No specification aggregates. Cement Sector are global averages from various companies. Data from (Bourgeois et al., 2003; Cemex, 2015, 2013, 2012; "Ecoinvent v3.1," 2014; European Commission, 2006; Holcim, 2015, 2014; Lafarge, 2012; O'Brien et al., 2009).

ogy and estimation of water consumption or even changes in the companies' water related policies.

4.2. Water inventory figures for aggregates production

Fig. 4 summarizes the water inventory figures for aggregates. The data comes from Europe, Switzerland and Australia, referencing Ecoinvent and Gabi methodologies (Ecoinvent v3.1," 2014; European Commission, 2006); global average data published by Cemex, Holcim and Lafarge (Cemex, 2015, 2013, 2012; Holcim, 2015, 2014; Lafarge, 2012); and data from unknown methodologies (Bourgeois et al., 2003; O'Brien et al., 2009).

Dispersion seems to be high even when considering the global average figures generated with the same methodology; for example, the data produced by Cemex, Holcim and Lafarge varies between 0.116 and 0.413 H kg/kg (Cemex, 2015, 2013, 2012; Holcim, 2015, 2014; Lafarge, 2012).

The differences are probably a combination of the companies' water management practices as well as the production process setups (e.g., aggregate washing reported by Cemex) and recycling practices. Another reason could be different interpretations of the water terminology. For instance, it was observed that the water consumption figures published in the Holcim Sustainability Reports (Holcim, 2013, 2012) were updated. Holcim declared in their 2014 Sustainability Report that before 2013 (Holcim, 2015) they only measured water withdrawal for a

ggregates and not water consumption. They had published water withdrawal data as water consumption. The impact of the revisions is significant, as presented in Fig. 5 where it can be observed data calculated with the same methodology for different companies. Some companies that participate of the CSI project

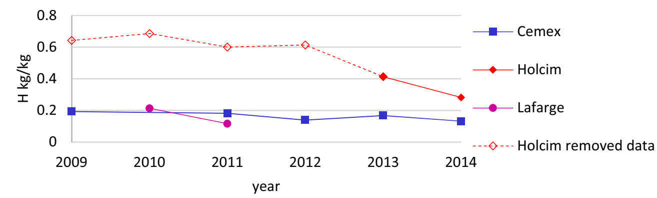

Fig. 5. Original and reviewed water consumption in aggregate production, global average data for Cemex, Holcim and Lafarge (Cemex, 2015, 2013, 2012; Holcim, 2015, 2014, 2013, 2012; Lafarge, 2012).

acknowledge to use the GWT Water Tool for the Cement Sector but publish no data. From a personal communication with an employee of one of the companies, we found out that they still are not confident enough to publish their inventory results because they are struggling to properly train company's employees scattered in several plant and various countries and installing and operating additional measurement devices in each plant. The structure required to conduct water inventory is much complex and costly than the one required to measure CO_2 and energy which relays mostly in data normally available in the company's information system.

Quarry water inventory may also be a source of variability since it has irregular geometry that varies with time, is affected by evaporation, a local variable and may include groundwater and rain water in unknown quantities. Measuring water captured and used is relatively straightforward. But estimating water captured but not used require more complex measurement devices and complex estimation model with many assumptions.

Apart from these global averages, there are extremely low values of 0.004 (European Commission, 2006). Bourgeois et al. (2003) presented figures of 1 H kg/kg, O'Brien et al. (2009) presented 2 H kg/kg and Ecoinvent presented 2.5 H kg/kg for aggregate production; these values are significantly higher than all the others. The 4.5 H kg/kg presented by the Gabi database seems to be an outlier, perhaps reflecting a particular situation.

4.3. Water inventory figures for concrete production plants

Fig. 6 presents data limited to the direct use of water in the plant, excluding water use outside of the plant. Within the concrete production activities, water figures for cleaning the yard and cleaning the trucks were also found. Data of the water use in concrete formulations from 29 countries is presented for the same concretes used by Damineli to measure the cement use efficiency in terms of

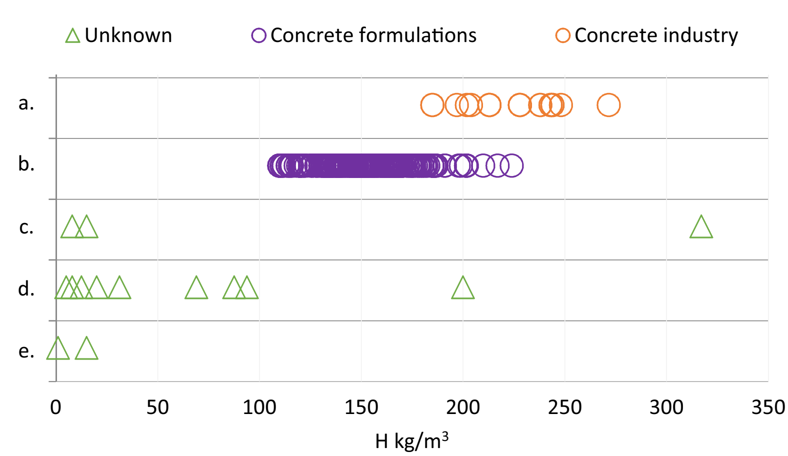

Fig. 6. Water inventory Figures for concrete production. a. Concrete total; b. Concrete mix water; c. Washing trucks off; d. Washing trucks out; e. Cleaning the yard. Data from: (Cemex, 2015, 2013, 2012; Chini et al., 2001; Concretos del Sol, 2015; Damineli et al., 2010; Ekolu and Dawneerangen, 2010; Holcim, 2015, 2014, 2013, 2012, 2010; Jaques R., 2001; Lafarge, 2012; Maranhão, 2015; Nisbet et al., 2002; Paolini and Khurana, 1998). Data does not include water used for raw materials.

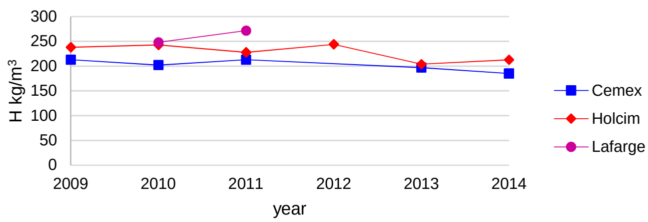

Fig. 7. Water consumption in concrete production, global average data for Cemex, Holcim and Lafarge (Cemex, 2015, 2013, 2012; Holcim, 2015, 2014, 2013, 2012, 2010; Lafarge, 2012).

the binder intensity and CO_2 intensity (Damineli et al., 2010). The amount of water specified in the formulations is usually higher than the actual batch water added to the mixture because the aggregates, particularly the fine fraction, carry some humidity, which explains how the total direct use of water can be only slightly higher (or even be lower) than the formulation water.

Concrete total in Fig. 6 -which includes all the water consumption for concrete production as reported by Holcim, Cemex and Lafarge-, does not differ significantly from the formulation water and in some cases is even smaller. This result may be due to the high water recycling rate of these companies or because the humidity in the aggregates is not accounted for as consumption but is subtracted from the water formulation, which is the sum of aggregates' moisture and mixing water.

The truck washing data show a large dispersion. The methodology is not always clear and certainly contributes to variability. However, there are other variability sources, which include factors that may influence washing frequency such as weather, concrete formulation and time between loads. A truck transporting the same concrete formulation within a short distance or a very fast return time can be reloaded without washing. Conversely, if the time between loads is long or the concrete formulation is changed, the truck will definitely need to be washed before every batch. Recycling practices are also very influential for actual wash water consumption. The highest figure for truck wash out—200 H kg/m^3 (Concretos del Sol, 2015)—may include water for truck wash off as well.

The reported values for cleaning the plant yard vary between 500 H kg and 1500 H kg per day (Jaques R., 2001). The amount of concrete produced in a plant varies significantly. Assuming that a typical concrete plant produces between 100 and 500 m^3 per day, the typical figures are relatively low considering other bills, varying from 1 H kg/m^3 to 15 H kg/m^3.

Fig. 7 presents the data published by Cemex, Holcim and Lafarge concerning the direct total water consumption for concrete production between 2009 and 2014 (Cemex, 2015, 2014, 2013, 2012, 2011, 2010; Holcim, 2015, 2014, 2013, 2012, 2011, 2010; Lafarge, 2012). In the case of Lafarge, the report does not show the units used for specific water consumption in concrete; assuming liters/ton for the units and considering a typical concrete of 2400 kg/m^3, the figures shown in the chart were calculated. Assuming liters/m^3 as the units, the figures would be well below the figures presented by Cemex and Holcim and below the typical figures for concrete mixing.

5. Discussion

There is a large diversity in water inventory methodologies. The more recent methodologies appear to be converging to the new ISO Water Footprint Standard (International Organization for Standardization, 2014) and the PCR Concrete methodology already matches this standard. However, the ISO Water Footprint Standard (International Organization for Standardization, 2014) does not include chemically bounded water, meaning that we are ignoring approximately 30 liters of water per ton of clinker for the cement production.

Differences in the water inventory approaches will certainly influence the impact assessment phase. For instance, methodologies that include in-stream water use could reach a more comprehensive impact assessment as they include all water used. The problem is that there is no clear methodology for in-stream water use estimation.

The distinction between water used and water managed but not used is quite important as well. The first term has to do with the production process, while the latter term depends mainly on the plant's location. For instance, a cement plant located in Panamá city with an annual precipitation of 2000 mm has to address rain water even though this water is not necessarily used in the production process. In contrast, a cement plant located in Lima, Perú with only 13 mm of annual precipitation barely has enough water for the production process and since there is little rain water there is no need to divert this water. For purposes of comparison between technological routes and process efficiency, methodologies that only account water used are adequate since they are focused on direct water consumption in the processes. Taking into consideration water captured but not used would be important in the case that this water is discharged into a different source than the original, as a result water consumption would be higher and could contribute more to potential water scarcity for instance. Nevertheless, since it is not directly related to the production process, it should be reported separately.

All of the methodologies consider **surface water** and **groundwater** as water sources. The ILCD Handbook for LCI (European Commission, 2010a) differentiates renewable water within groundwater which will allow a more thorough water availability assessment. GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) presents **quarry water** as a separate water source. Quarry water is usually a mix between groundwater and rain water with mix proportions difficult to measure or estimate accurately. Quarry water is not explicitly present in the new ISO Standard 14046 despite being interesting in the case of cementitious materials value chain, which heavily relies on materials extraction.

The water footprint assessment manual by Hoekstra et al. (2011) and the GaBi Database and Modelling Principles (Rudolf et al., 2013) do not consider **seawater**, opposite to the rest of the methodologies. The justification of these two methodologies for not including seawater as a water source is that they mainly focus on assessing limited resources such as freshwater in contrast to seawater, which is available on a large scale (Hoekstra et al., 2011; Rudolf et al., 2013). The use of non-fresh water, especially when it can be used without purification, can be a tool to reduce pressure over limited fresh water sources. The extraction and purification of seawater for many uses is becoming more plausible (González-Bravo et al., 2015; Junjie et al., 2007; McGinnis et al., 2013; Peñate and García-Rodríguez, 2012; Qadir et al., 2007; Zhao et al., 2012) and the newest methodologies for this purpose are already reflecting that fact. Within cementitious materials production, seawater becomes a relevant water source, for instance, when performing aggregate extraction from sea beds (Singleton, 2001), as this water comes incorporated into the aggregates. Other examples of relevant seawater use are cooling water in a cement plant, power stations (Constant et al., 2010; Junjie et al., 2007; Nebot et al., 2007) and water for washing the aggregates (Hewlett, 2003; Raina, 2007). Depending on the location, the amounts of seawater used should not be disregarded since it could result in environmental aspects related to desalination and other seawater uses (Cooper et al., 2007; Elimelech and Phillip, 2011; Wahidul K. Biswas, 2009). Since the use of non-fresh water reduces the procure on fresh water, a fair weighting for environmental assessment should be applied in a way

Table 3
Hypothetical scenario of water requirement per activity for concrete production.

Activity	Concrete mix	Facilities	Laboratory	Truck washing	Water for hydro-power generation	Dust suppression	Yard washing
(H kg/m^3)	200	5	5	90	250	10	3

that the related environmental impacts are not neglected yet its use can still be encouraged.

Municipal water is considered a water source only by the GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) and the Concrete PCR (World Business Council for Sustainable Development, 2013). The actual sources of municipal water are highly variable and usually unknown. Notwithstanding that accounting of the original sources seems ideal, there are advantages of considering municipal water as a water source within the water inventory. In developing countries, the public water infrastructure is frequently under stress; therefore, measuring the contribution of cementitious materials production to the demand can be an incentive to reducing municipal water use in this industry. Through municipal water inventory it is possible to assess impacts on human health due to water consumption since potable water is a need of society. Moreover, the water utility usually measures municipal water, making the data readily available.

All of the methodologies other than the ILCD Handbook for LCI (European Commission, 2010a) consider **rain water** explicitly. The water footprint assessment manual by Hoekstra et al. (Hoekstra et al., 2011) even has a very specific definition: 'Precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation.' This water source definition of rain water is more relevant for agriculture. For cement based materials, a more meaningful definition would be "Precipitation on land that does not run off or recharge the groundwater but is stored in reservoirs or diverted from its usual cycle." Apart from rain water stored in reservoirs, there is rain water that falls over aggregates during transportation and open storage. It may be mixed with underground water from a quarry pit or into remains from washing operations. In these scenarios, it is difficult to estimate the actual source of water, and the mix proportions will vary with time due to weather. Modeling this will require a specific protocol.

The only methodology that includes **external waste water** as a water source is GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013). The cement industry can use waste water without further treatment in many practical situations (Ekolu and Dawneerangen, 2010), a strategy that reduces the demand of potable water. This practice can become relevant in concrete production that occurs in urban regions, and should be incentivized because it will reduce the pressure on scarce treated potable water, resulting in lower environmental impact.

The concept of water withdrawal for concrete production is not thoroughly defined. For instance, **chemically bounded water from raw materials,** i.e., the released of water bounded into clay minerals into the environment, is not considered by methodologies such as GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) and the Concrete Product Category Rules (PCR) (World Business Council for Sustainable Development, 2013); however, in the GaBi Database and Modelling Principles (Rudolf et al., 2013) and the Ecoinvent database ("Ecoinvent v3.1," 2014) water flows titled "water contained in products" and "products water content" were found. It is not clear whether these flows can be considered as water sources or water receiving bodies. The Ecoinvent methodology states that "water balances also include water bound in extracted minerals, water bound in biological material harvested in the wild, and water in intermediate inputs" (Weidema et al., 2013). Being a porous material, concrete also have a significant volume of adsorbed water, which varies over time and is influenced by the local environment.

The water consumption definition varies greatly from methodology to methodology. All the methodologies consider water evaporated and water incorporated as water consumption. This is quite relevant in the concrete industry since the mixing water is part evaporated and part incorporated into the concrete. In addition, most of the water for dust suppression and cooling processes is evaporated. For cleaning processes part of the water is evaporated as well.

For destination and quality of the water, there are many possibilities. Water that is discharge in a different source than the original means this water will not be available at the original source anymore which could result in water scarcity problems even if the water is discharged with the same quality. Water discharge with quality changed will have an impact on its destination place as well. Considering these aspects will certainly encourage companies to improve their water management practices.

Due to the diversity of definitions, the available inventory data are not comparable without going into detail. Unification of these definitions would reduce variation in concrete production water inventory estimations. The parameters for characterization of water sources, such as physical and chemical characteristics, should be defined as well.

A large variation in water use factors was found as well. Part of this variation can be explained because of the different methodologies; there is also uncertainty due to measurement errors, differences on the technologies and geographical specificities (see Appendix D). We believe it is important to treat variability and uncertainties separately and their understanding is among the main gaps in concrete water inventory available data; however, it is not possible to thoroughly study variability and uncertainties in this paper, mainly because most of the data lack the information needed for this analysis. This limits the practical uses of the data. It seems desirable that water inventory data to be accompanied of a much detailed description of the methodology as well as the process as it is required for CO_2 and energy.

For the cementitious materials industry, estimating water consumption is quite complex. There is considerable variation and no information regarding the source of the water that comes with aggregates, which may be from the site (groundwater, rain water or a mixture of the two) or due to rainfall during transport and storage. Water obtained from the utility network is measured. However, the quantities of water extracted from other sources by companies are not accurate and are difficult to estimate. In this case, the company's practices should be registered to assist in the explanation of water consumption variation. It is important to account for all of the water withdrawal for mass balance. However, for comparison of production lines and technological routes or measuring the ecoefficiency of processes, it is better to clearly separate the amount of water that has been used from those not used. Regardless, the inventory has to be simple enough to be used by most organizations, including small and medium-sized enterprises.

Generating a benchmark in the form of a range (min-max) of water use for each typical variation of the production processes seems desirable, similar to those for CO_2 and energy. This benchmark could be used to promote technologies that are capable to reduce water use allowing a more rational use of water. The water used for concrete production processes can be estimated with less difficulty because the processes are more or less standardized.

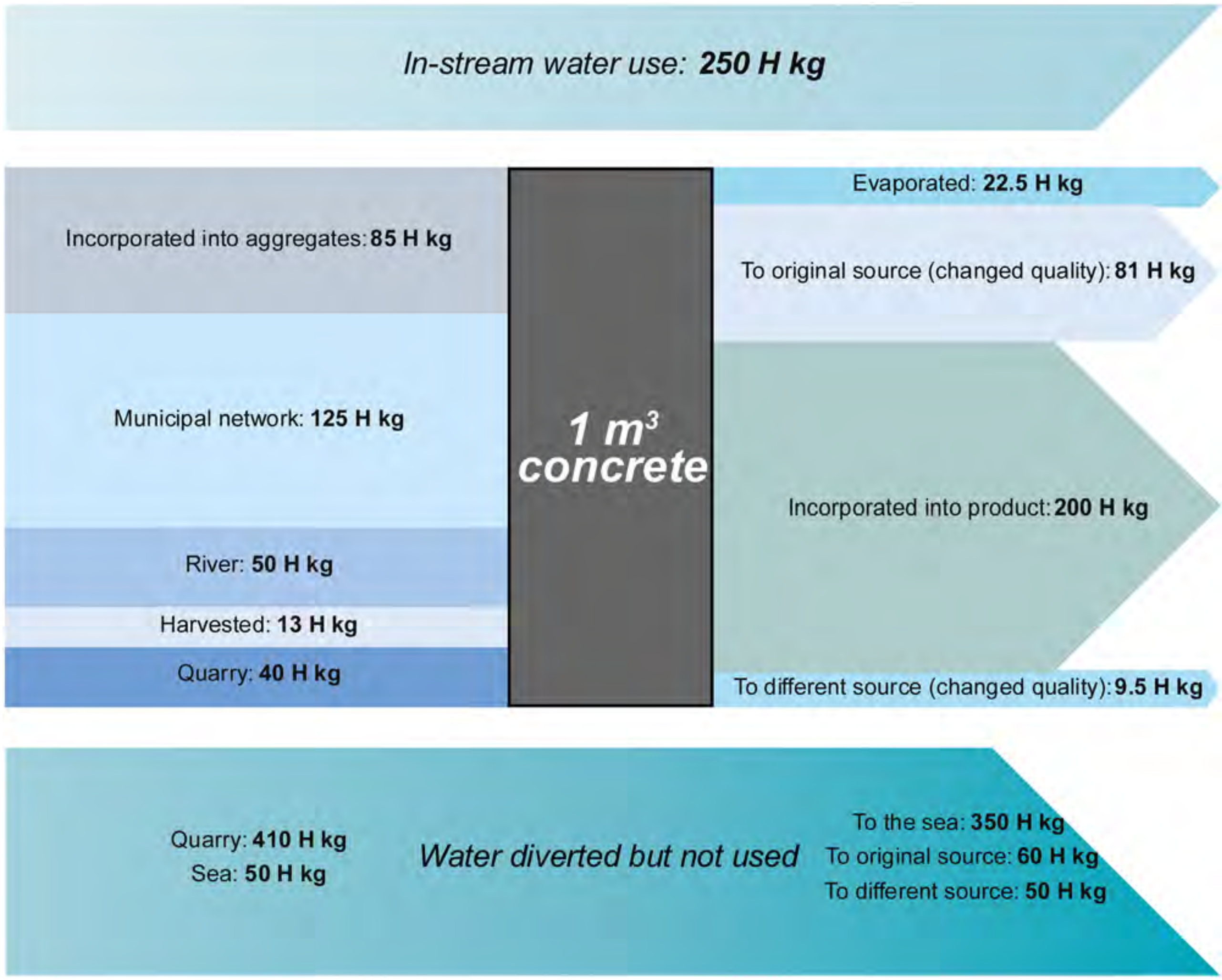

Fig. 8. Hypothetical scenario of the water balance for 1 m^3 concrete production.

However, water consumption, including water that is diverted due to local conditions but not used, e.g., quarry drainage and run-off management, and water for dust control, is also relevant and probably varies greatly from plant to plant since it depends on local factors among others. Therefore, the water consumption variability is expected to be much larger than the CO_2 emissions and energy and is sensitive to local conditions.

6. Influence of the methodologies on inventory results—a case study scenario

The water requirement for the hypothetical scenario of 1 m^3 concrete production is presented in Table 3. Fig. 8 presents the water flows origins and destinations for the proposed scenario. Two scopes are considered: including direct water within the plant boundaries and indirect water for energy generation, analogous to the Scope 2 approach of the Greenhouse Gas Protocol (Sotos, 2015). This concrete production scenario does not include indirect water for raw materials production, which would be a third scope. The water requirement for the concrete mix is 200 H kg/m^3, this value was taken from (Zhu and Gibbs, 2005) and considering a mid-value from the range presented by Damineli et al. (2010) which goes from 102 to 267 H kg/m^3. The water used in the facilities and laboratory was estimated assuming water use of 2500 H kg per day and a daily concrete production of 500 m^3 (Cementos Pacasmayo, 2012). Water requirement for truck washing was estimated using data from a concrete plant located in the Vila Olimpica project in Rio de Janeiro (Maranhão, 2015). Water consumption for energy production and in-stream water use are not quite clear in the literature and we intend to clarify these subjects more deeply in future studies. In this case scenario water use for hydro power was estimated based on data found in the literature: 3.2 kWh/m^3 of concrete (Cemex, 2015; Marceau et al., 2007) * 79 H kg/kWh (Judkoff et al., 2003) = 250 H kg/m^3 of concrete. 79 H kg/kWh was used for water consumption for energy production; however, this value is for a specific hydro power plant and location and varies depending on the plants height, river flow and plants efficiency. Assuming an area of 6000 m^2 (were dust control is needed), using a washing application rate of 0.846 H kg/m^2 (Nisbet et al., 2002) of concrete plant area and a daily concrete production of 500 m^3 (Cementos Pacasmayo, 2012) we estimated water use for dust suppression at the concrete plant. Using 1500 H kg/day (Jaques R., 2001) and a daily concrete production of 500 m^3 (Cementos Pacasmayo, 2012) we estimated water use for yard washing. The production of 500 m^3 of concrete per day at Pacasmayo concrete plants (Cementos Pacasmayo, 2012) was used as a reference.

Table 4 summarizes the results of various water inventory methodologies applied to the scenario presented in Table 3 and Fig. 8. The differences between the water footprint methodologies are consequential because they choose to include or exclude different water flows. In all cases, the water inventory is higher than the typical amount of water directly used in concrete formula-

Table 4
Concrete production water inventory (direct use only) for the proposed scenario according to the methodologies under study. The Gabi, ISO 14046, PCR Concrete and Ecoinvent methodologies consider in-stream water use in their approaches.

(H kg/m^3)	Hoekstra (Hoekstra et al., 2011)	GaBi (Rudolf et al., 2013)	GWT cement (Global Water Tool for Cement Sector, 2013)	ILCD (European Commission, 2010a)	ISO 14046 (international Organization for Standardization, 2014)	PCR Concrete (World Business Council for Sustainable Development, 2013)	Ecoinvent ("Ecoinvent v3.1," 2014)
Water withdrawal	723	313	313	773	773	773	773
Water discharge	60	90.5	90.5	550.5	141	141	141
Water consumption	713	822.5	222.5	222.5	882	882	882
Water consumption (except in-stream)	713	572.5	222.5	222.5	632	632	632

tion, approximately 200 kg/m^3. GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) and the ILCD Handbook for LCI (European Commission, 2010a) result in a water consumption 2–3 times lower than all of the other methodologies. The Hoekstra et al. (2011) results are 2.2 times higher than GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) and the ILCD Handbook for LCI (European Commission, 2010a) but approximately 13–20% lower than the others. Removing in-stream water use from the inventory has no effect on GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013), the ILCD Handbook for LCI (European Commission, 2010a) or (Hoekstra et al., 2011), which becomes the higher result. However, the differences between GWT for the Cement Sector (Global Water Tool for Cement Sector, 2013) and the ILCD Handbook for LCI (European Commission, 2010a) become smaller, with results 1.6–2.2 times lower than all of the other methodologies.

These important differences are reflected in the currently available inventory data: without a clear definition of the methodology, it is impossible to compare and make decisions. Therefore, only experts on water inventory will be able to fully understand the exact meaning and implications of a given result.

7. Conclusions

The aim of this paper is to review the various water inventory methodologies and understand their implications on the water inventory figures in concrete's life cycle from cradle-to-gate. This was done in order to understand the wide dispersion of the inventory data that was found in the literature.

The water use for different components and processes in concrete production cradle-to-gate were identified along with water inventory figures. A large dispersion between the water inventory figures was found. This variability depends not only on the process used and the product obtained but also on the methodology used for its estimation, which may have different definitions in terms of water withdrawal, water discharge, and water consumption. The differences in the definitions have large implications on conducting inventories and footprints.

Within the limits of our scope we could say that the water used in the concrete production plant includes the batch water (150–200 H kg/m^3), dust control (500–1500 H kg/day), and truck washing (13–500 H kg/m^3). In addition to water from cement production (0.185–1.333 H kg/kg) and aggregate production (0.116–2.0 H kg/kg).

Our case scenario shows that methodology can give results that differed by a factor of approximately 3. Considering in-stream water use increases this factor to 4 times. Even without including water use from cement and aggregates production, the water use directly in concrete production is up to 4 times higher than the ~200 kg/m^3 typical for a concrete formulation.

Available data on water consumption should be use very carefully by LCA practitioners and the industry decision makers. Only the amount of water used, including water from all sources and qualities, without discounting water returned into the environment and excluding in-stream use, can allow objective comparison, since it reflects mostly the actual process needs and less local conditions.

The water inventory and footprint methodology is more complex than CO_2 inventory because is influenced by many local factors. The difficulty is delaying its implementation even in large, resourceful organizations. We believe that the development of a simplified methodology for the water inventory, consistent with ISO standard and based mostly in easily measured primary data, is desirable. Such methodology should be suitable for the decision-making process not only in large companies, but also in small and medium organizations, therefore maximizing its environmental benefits.

Acknowledgments

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Appendix A. Water in Concrete Production

A.1 Cement Production

Portland cement is made out of widely available raw materials such as limestone and clay (Aïtcin, 2000). Gypsum, which can be waste such as Flue-Gas Desulfurization (FGD) gypsum or a natural material (Ozkul, 2000) is added as a set controller (Marceau et al., 2006). Cement also contains supplementary cementitious materials (SCM) (American Concrete Institute, 2003, 2000; C09 Committee, 2014, 2010, 2004; O'Brien et al., 2009; Pickering et al., 1985; Yang et al., 2014) that contribute to the properties of hardened concrete through hydraulic or pozzolanic activity.

Each cement plant has a unique design due to technical decisions, climate variations, location, topography, available raw materials, fuels and dealers, environmental legislation and owners' preferences. This design decisions frequently impact the water use.

A.1.1 Water in Cement Production

Indirect water use includes those from raw materials suppliers and water for granulated blast furnace slag (GBFS) as it includes water in its treatment (Pickering et al., 1985; Mizuochi et al., 2002; Green Rating Project (GRP), 2012). Fig. A1 presents the BFSG treatment process and related water use. Indirect water in the energy production is also associated with cement production (O'Brien

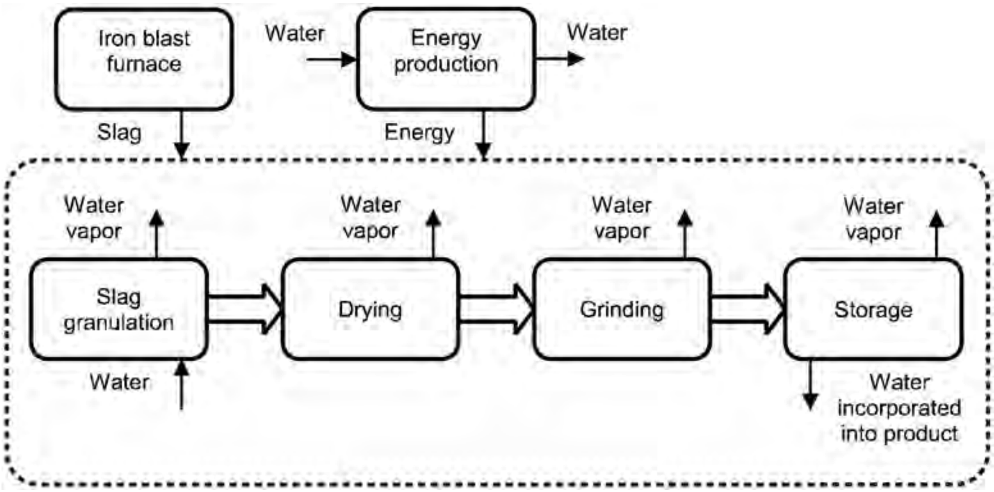

Fig. A1. BFSG treatment process and related water use.

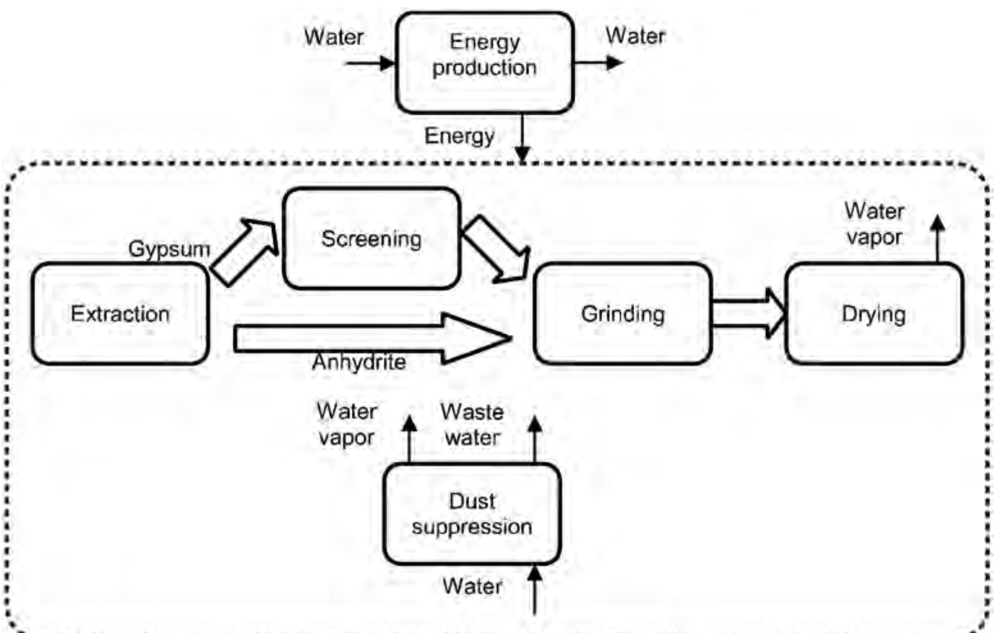

Fig. A2. Gypsum production process and related water use.

et al., 2009) and treatment of other SCMs such as fly ash (FA) (Chen et al., 2010b).

Conventionally, the granulated blast furnace slag (GBFS) rapid cooling is conducted with water, a process that has high water consumption (Leyser and Cortina, 2006), especially if the vapor is not recycled. This process could be performed with a cold water system, a cold water system with condensation or hot steam (Schweitzer, 2015). As an alternative, there are processes for producing a dry granulated slag with a high vitreous content (Liu et al., 2011; Mizuochi et al., 2002; Yoshinaga et al., 1982) (Fig. A1).

To control concrete setting, natural gypsum is added. A synthetic gypsum called desulphogypsum from flue gas desulfurization (FGD) or phosphogypsum are also used for cement production (European Commission, 2006). This desulphogypsum results from a wet purification procedure with natural lime (Sustainable Extraction, 2017). Since these are waste products from another industrial process, none of the burdens process would be allocated to it. Fig. A2 presents the process of gypsum production.

Depending on the cement production process, there are variations in water use. Because most of the clinker is currently produced by dry process, this research does not address the wet process method. The PCA LCI for cement production separates water use in process water used for raw meal slurry and non-process water used for contact cooling, including water sprayed directly into exhaust gases and water added to grinding mills, and non-contact cooling, which includes water for engine or equipment cooling, cement kiln dust landfill slurries, and dust suppression (Marceau et al., 2006). Fig. A3 presents the cement production process and water allocation for the different steps.

A.2 Aggregates Production

Aggregate extraction typically comprises mining and quarrying (Korre and Durucan, 2009) including sand and coarse aggregates extraction from water courses, an in-stream water use. Extraction can involve the use of explosives and heavy machinery as well as

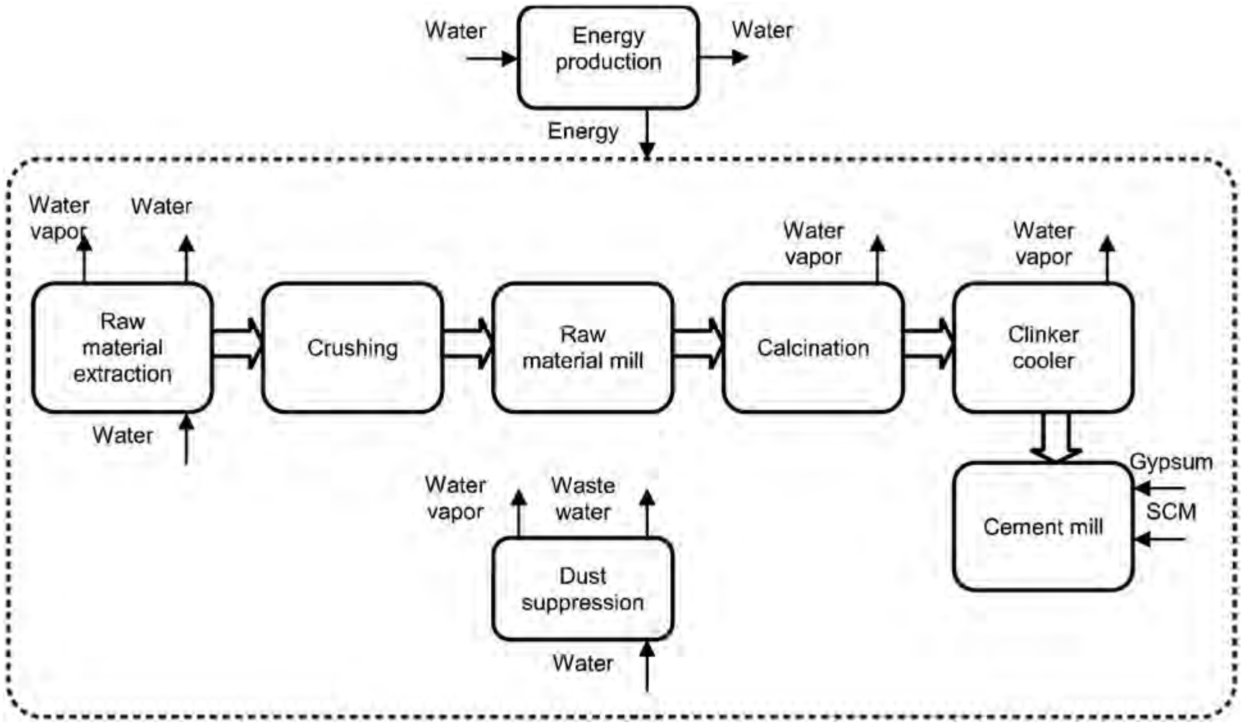

Fig. A3. Cement production process and related water use.

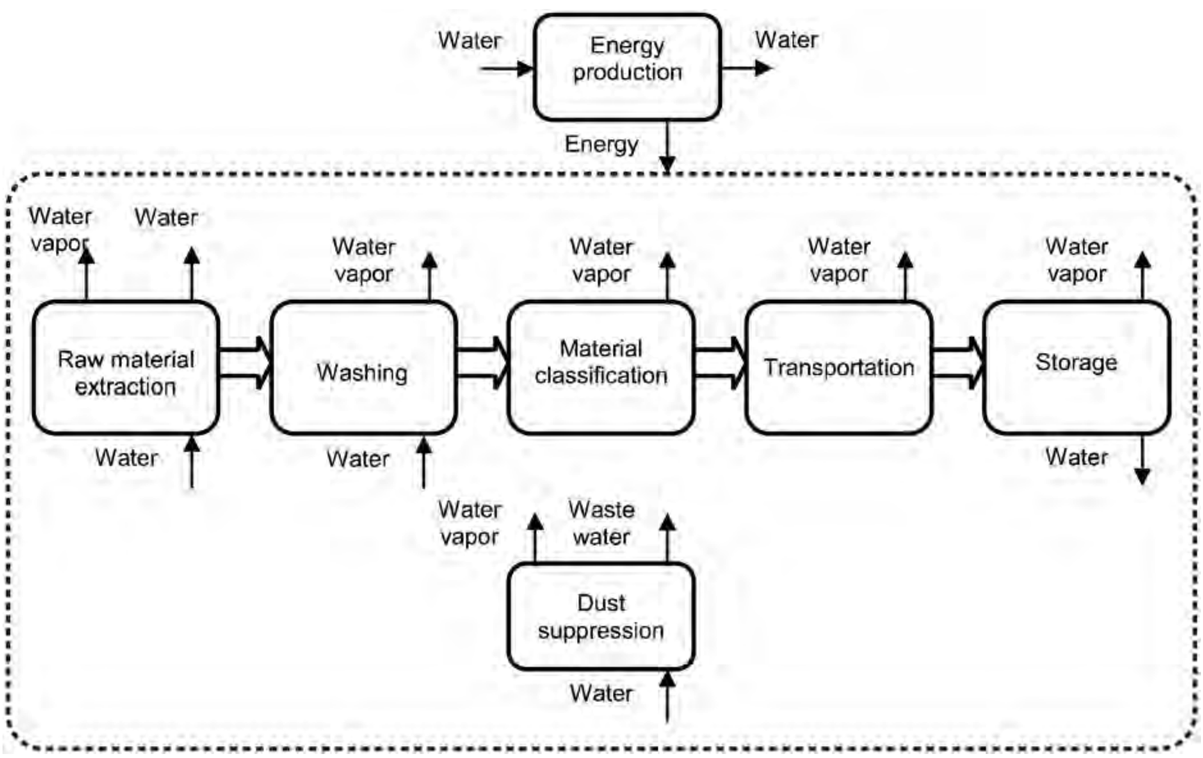

Fig. A4. Aggregates production and related water use.

hydro-excavation, which uses a high-pressure water system for digging (Gyori et al., 1994).

The production of fine and coarse aggregate covers mineral extraction, comminution, sieving for size classification and storage (Korre and Durucan, 2009). Separation of contaminants such as clay, wood, kaolin, carbon, and metal is also needed.

A.2.1 Water in the Production of Aggregates

Water consumption varies for each type of extraction process (Korre and Durucan, 2009). Water for aggregate production is highly difficult to estimate because it may come from different sources and even a mixture of sources. For instance, rain water and ground water may come within extracted aggregates. In some cases, after extraction, raw materials are washed. During classifi-

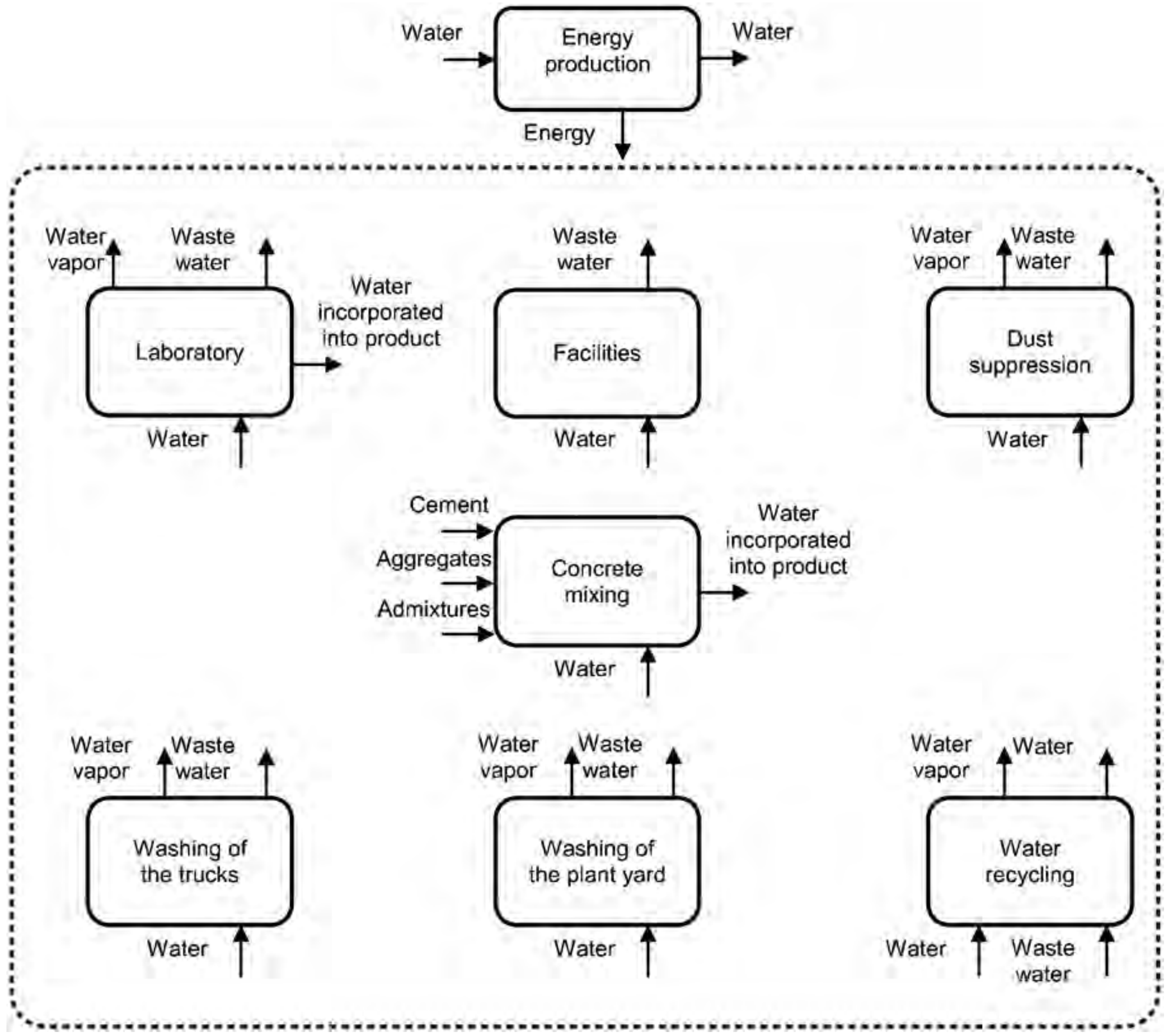

Fig. A5. Concrete production process and related water use.

cation, transport and storage of aggregates, they can gain moisture due to precipitation, air humidity, etc. During storage, there is water that runs off the pile and another part evaporates. Water for energy production should be considered as well. In addition, dust suppression by spraying water is a common practice in quarries (World Business Council for Sustainable Development, 2014b). Fig. A4 presents the aggregates production process and related water use.

A.3 Concrete Production

In its most simple form, concrete is a mixture of cement paste and aggregates. In addition, admixtures, which are solid or liquid substances added before or during mixing of the concrete that have multiple functions, may be used (C09 Committee, 2013). Portland cement chemistry reactions starts in the presence of water (Aïtcin, 2000). During the mixing stage, the different components come together to produce a uniform mass.

A.3.1 Water in Concrete Production

As indirect water use, there is the chemical admixtures suppliers' water inlets and water for energy production. Regarding direct water use, water formulation is the sum of the water coming in aggregates (integrated into aggregates, gained during transport and/or storage), which is approximately 5% of the weight of aggregates, and the water added during mixing (Jaques R., 2001).

Water use in the concrete plant includes water for washing the yard (Sealey et al., 2001), cleaning the trucks (interior and exterior) (Chini et al., 2001; Portland Cement Association, 2002; Ekolu and Dawneerangen, 2010; Paolini and Khurana, 1998), and dust suppression (Ekolu and Dawneerangen, 2010). Water use in buildings and offices should also be considered (Holcim, 2013). When the water used for different production processes is combined with the rain water runoff, large amounts of waste water are generated (Ekolu and Dawneerangen, 2010). There is also water use in the plant's laboratory as they prepare concrete samples and let them cure for posterior tests. All processes involved in concrete production are presented in Fig. A5.

Appendix B. Water Inventory for Concrete Production Proposed Scenario

See Table B1.

Table B1
Water inventory for concrete production proposed scenario.

Water withdrawal per source (H kg/m^3)		Use (H kg/m^3)		Evaporated (H kg/m^3)	Incorporated into product (H kg/m^3)	Release into sea (H kg/m^3)	Returned changed quality to different source (H kg/m^3)	Returned the same quality to different source (H kg/m^3)	Returned changed quality to same source (H kg/m^3)	Returned the same quality to same source (H kg/m^3)	In-stream use (H kg/m^3)	Total water use (H kg/m^3)
Water incorporated into aggregates	85	Off-stream	Concrete mix	0	85	0	0	0	0	0	0	85
Municipal water	115	Off-stream	Concrete mix	0	115	0	0	0	0	0	0	115
	5	Off-stream	Facilities	0	0	0	5	0	0	0	0	5
	5	Off-stream	Laboratory	0.5	0	0	4.5	0	0	0	0	5
River water	50	Off-stream	Washing of the truck	5	0	0	0	0	45	0	0	50
	250[a]	In-stream	Hydro-power	0	0	0	0	0	0	0	250	250
Rain harvested water	10	Off-stream	Dust suppression	10	0	0	0	0	0	0	0	10
	3	Off-stream	Washing of the yard	3	0	0	0	0	0	0	0	3
Quarry water	40	Off-stream	Washing of the truck	4	0	0	0	0	36	0	0	40
	350	Off-stream	Not used	0	0	350	0	0	0	0	0	350
	60	Off-stream	Not used	0	0	0	0	0	0	60	0	60
Sea water	50	Off-stream	Not used	0	0	0	0	50	0	0	0	50
Total (H kg/m^3)	1023			22.5	200	350	9.5	50	81	60	250	1023

[a] For our case scenario, in-stream water use for hydro power was estimated based on data found in the literature: 3.2 kWh/m^3 of concrete (Cemex, 2014; Marceau et al., 2007) * 79 H kg/kWh (Judkoff et al., 2003) = 250 H kg/m^3 of concrete. 79 H kg/kWh was used for water consumption for energy production; however, this value is for a specific hydro power plant and location and actually varies depending on the plants height, river flow and plants efficiency. Water consumption for energy production and in-stream water use are not quite clear, we intend to clarify these subjects more deeply in future studies.

Appendix C. Water Consumption Scenario for Concrete Production Proposed Scenario According to the Different Methodologies

See Figs. C1–C5.

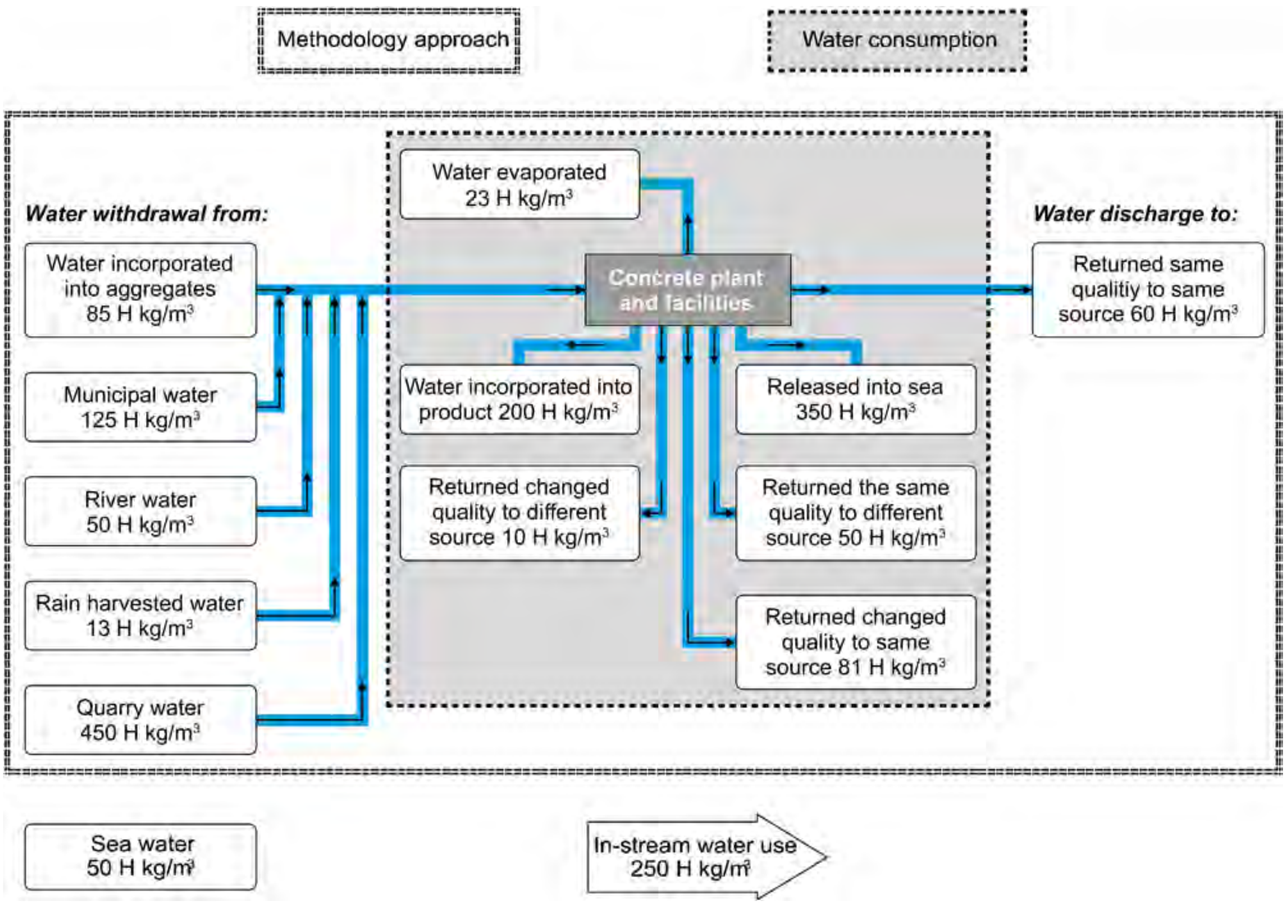

Fig. C1. Water consumption scenario for concrete production according to The water footprint assessment manual by Hoekstra et al. (Hoekstra et al., 2011).

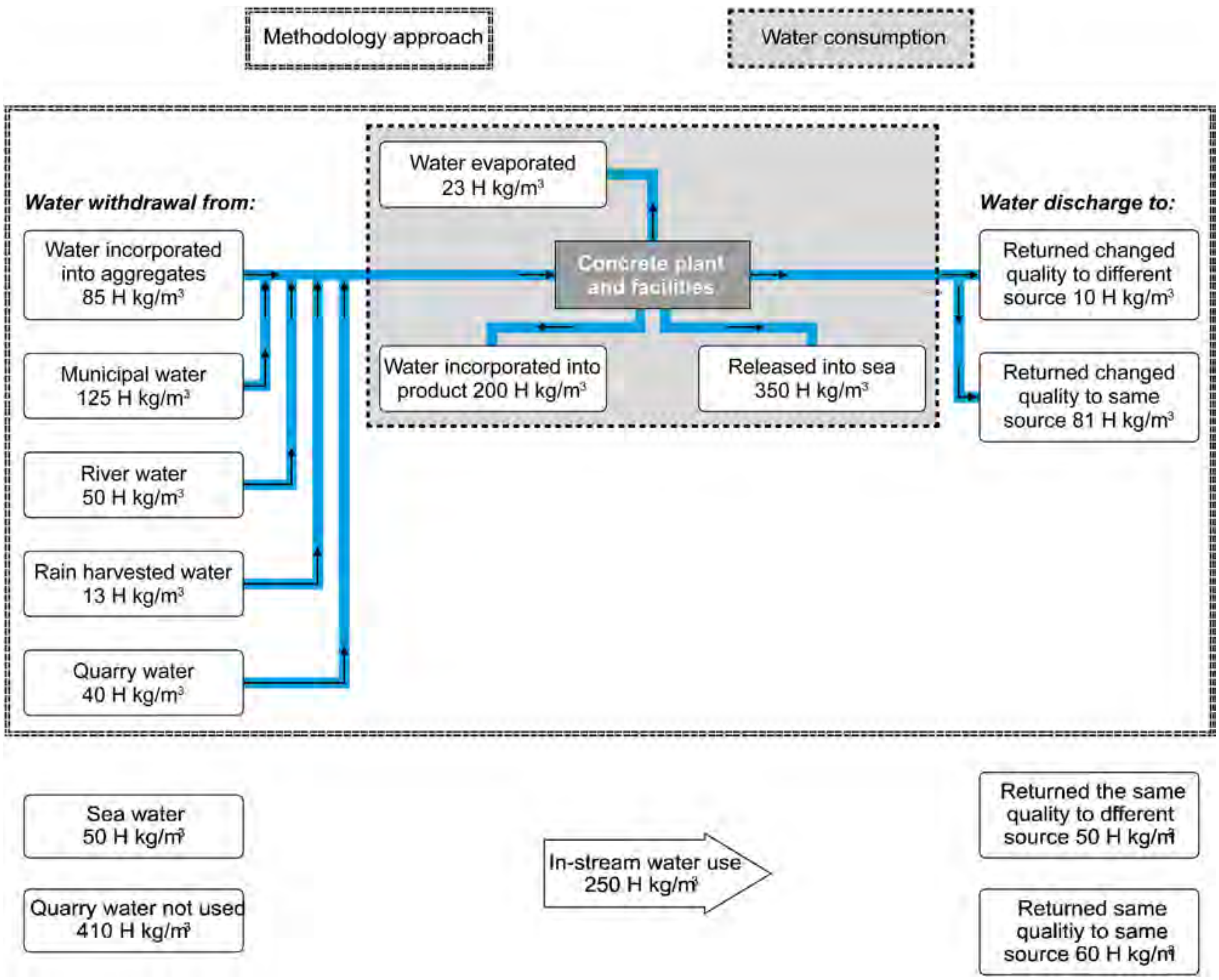

Fig. C2. Water consumption scenario for concrete production according to the GaBi Database and Modelling Principles (Rudolf et al., 2013).

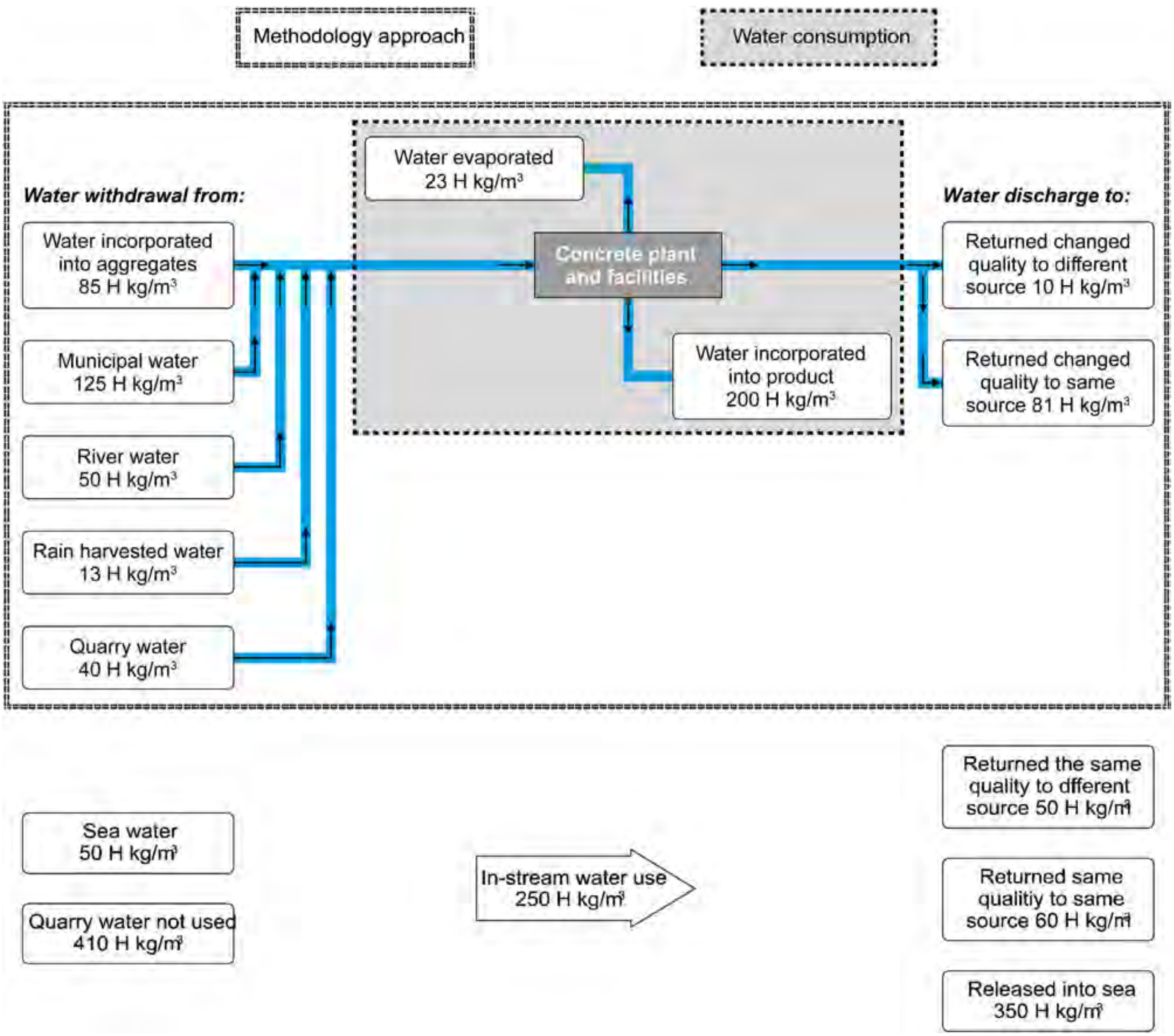

Fig. C3. Water consumption scenario for concrete production according to GWT for Cement Sector (Global Water Tool for Cement Sector, 2013).

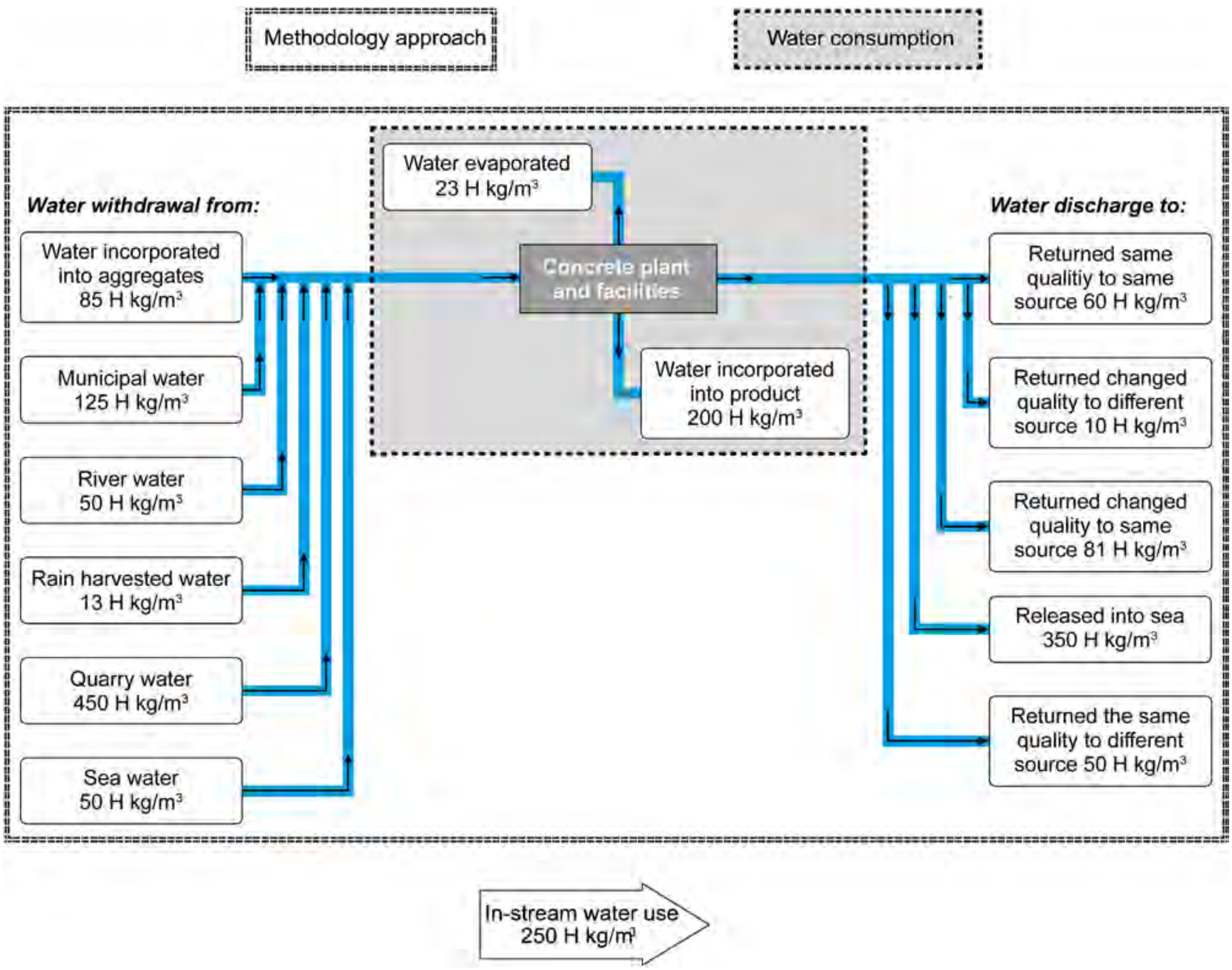

Fig. C4. Water consumption scenario for concrete production according to the ILCD Handbook for LCI (European Commission, 2010a).

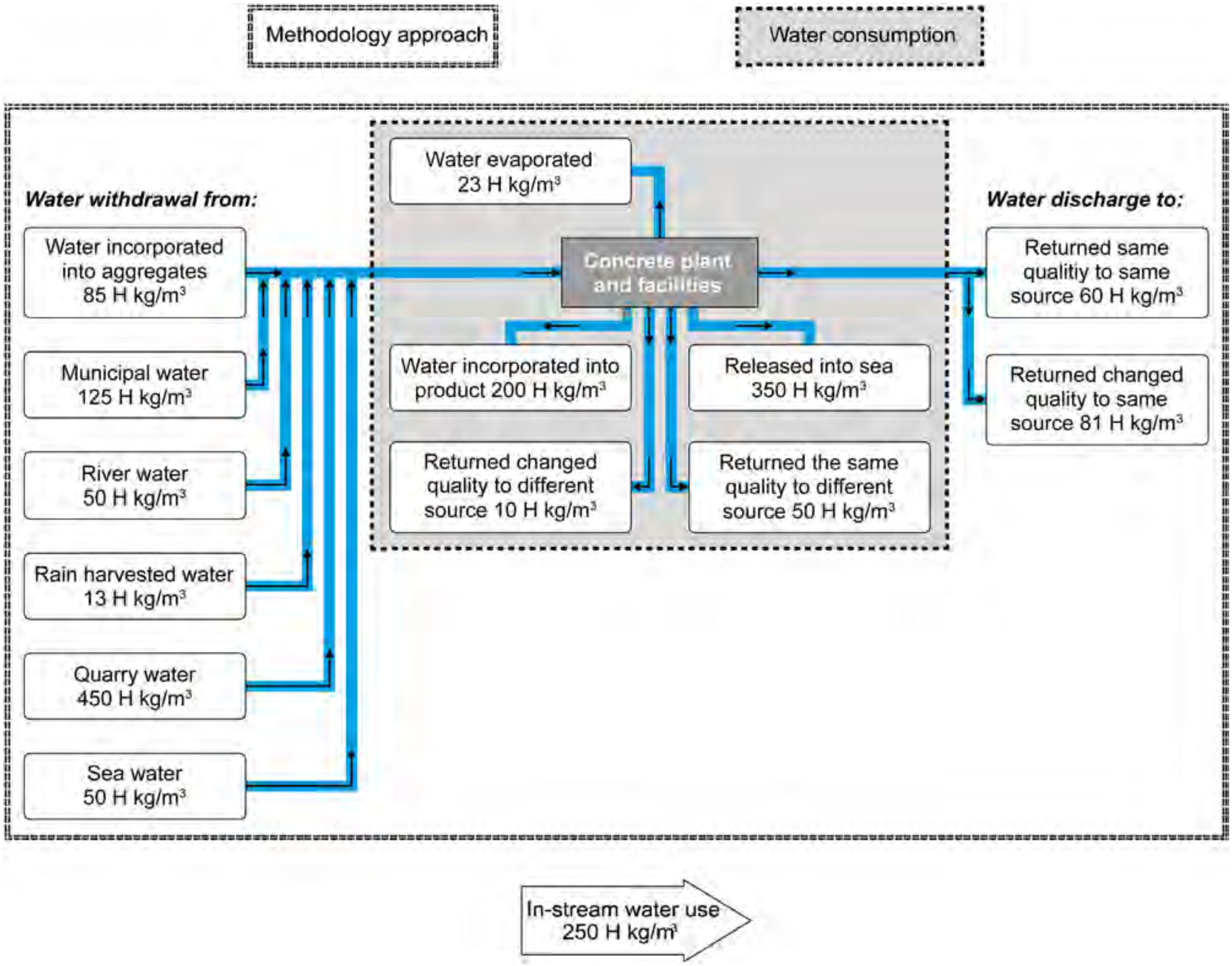

Fig. C5. Water consumption scenario for concrete production according to the ISO Water Footprint Standard (International Organization for Standardization, 2014), the Concrete Product Category Rules (PCR) (World Business Council for Sustainable Development, 2013) and the Ecoinvent database (Ecoinvent, 2014).

Appendix D. Water Inventory Figures for Aggregates, Cement and Concrete Production

See Tables D1–D11.

Table D1
Water inventory figures for fine aggregates production.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Sand–CH	Undefined	1.390	("Ecoinvent v3.1," 2014)	2014	LCI database	Switzerland	Switzerland
Sand– RoW	Undefined	2.526	("Ecoinvent v3.1," 2014)	2014	LCI database	Switzerland	World
Sand 0/2	Wet and dry quarry; production mix, at plant; undried (en)	0.004	(European Commission, 2006)	2006	LCI database	Europe	Europe
Very fine milled silica sand d50 = 20 micrometer	Production at plant (en)	4.576	(European Commission, 2006)	2006	LCI database	Europe	Europe/turkey

Table D2
Water inventory figures for coarse aggregates production.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Gravel	Undefined	1.350	(O'Brien et al., 2009)	2009	Paper	Australia	n/d
Gravel, crushed – CH	Undefined	1.124	("Ecoinvent v3.1," 2014)	2014	LCI database	Switzerland	Switzerland
Gravel, crushed – RoW	Undefined	1.124	("Ecoinvent v3.1," 2014)	2014	LCI database	Switzerland	Worldwide
Gravel, round – CH	Undefined	1.390	("Ecoinvent v3.1," 2014)	2014	LCI database	Switzerland	Switzerland
Gravel 2/32	Wet and dry quarry;production mix, at plant;undried (en)	0.520	(European Commission, 2006)	2006	LCI database	Europe	Europe

Table D3
Water inventory figures for aggregates production (average figures).

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Aggregates	Production includes washing	1.000	(Bourgeois et al., 2003)	2003	Paper	France	n/d
Aggregates	Production includes washing	0.193	(Cemex, 2012)	2009	Sustainability report	Mexico	Worldwide
Aggregates	Production includes washing	0.182	(Cemex, 2013)	2011	Sustainability report	Mexico	Worldwide
Aggregates	Production includes washing	0.139	(Cemex, 2014)	2012	Sustainability report	Mexico	Worldwide
Aggregates	Production includes washing	0.168	(Cemex, 2014)	2013	Sustainability report	Mexico	Worldwide
Aggregates	Undefined	0.413	(Holcim, 2014)	2013	Sustainability report	Switzerland	Worldwide
Aggregates	Undefined	0.282	(Holcim, 2015)	2014	Sustainability report	Switzerland	Worldwide
Aggregates	Undefined	0.214	(Lafarge, 2012)	2010	Sustainability report	France	Worldwide
Aggregates	Undefined	0.116	(Lafarge, 2012)	2011	Sustainability report	France	Worldwide
Sand or gravel	Undefined	2.000	(O'Brien et al., 2009)	2009	Paper	Australia	n/d

Table D4
Water inventory figures for clinker production.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region	Primary reference	Primary reference type
Clinker	Dry	0.007	(European Commission, 2010b)	2010	Reference Document on Best Available Techniques	Europe	Europe	CEMBUREAU, 2006	n/d
Clinker	Dry	0.556	(Valderrama et al., 2012)	2012	Paper	Spain	Spain	(Ecoinvent, 2014)	LCI database
Clinker	Undefined	0.139	(Valderrama et al., 2012)	2012	Paper	Spain	Spain	(Ecoinvent, 2014)	LCI database
Clinker	Undefined	0.200	(Chen et al., 2010a)	2010	Paper	France	France	ATILH, 2002	Environmental inventory
Clinker	Undefined	0.190	(Josa et al., 2004)	2004	Paper	Spain	Austria	F. Hoefnagels, V. de Lange, 1993	Reference not found
	Undefined							Intron, 1997	
	Undefined	0.423					Holland	H.M. Knoflacher et al., 1995	Reference not found
	Undefined							Intron, 1997	
	Undefined	0.532					Holland	A. Schuurmans, 1994	Reference not found
	Undefined							Intron, 1997	
	Undefined	1.071					Holland	P. Fraanje et al., 1992	Reference not found
	Undefined							Intron, 1997	
	Undefined	1.325					Holland	A. Schuurmans, 1994	Reference not found
	Undefined							Intron, 1997	
	Undefined	1.410					Holland	P. Fraanje et al., 1992	Reference not found
	Undefined							Intron, 1997	

Table D5
Water inventory figures for GBFS treatment.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Slag	Dry granulation	0.800	(Liu et al., 2011)	2011	Paper	China	China
Slag	Cold water system with	0.750	(Schweitzer, 2015)	2015	Personal communication	Luxembourg	Worldwide
	vapor condensation	0.850	(Schweitzer, 2015)	2015	Personal communication	Luxembourg	Worldwide
Slag	Cold water system	0.850	(Schweitzer, 2015)	2015	Personal communication	Luxembourg	Worldwide
		1.000	(Schweitzer, 2015)	2015	Personal communication	Luxembourg	Worldwide
Slag	Hot water system	1.000	(Schweitzer, 2015)	2015	Personal communication	Luxembourg	Worldwide
		1.200	(Schweitzer, 2015)	2015	Personal communication	Luxembourg	Worldwide
Slag	Granulating, grinding and storage	1.060	(Dunlap, 2003)	2003	Report	USA	USA

Table D6
Water inventory figures for gypsum production.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Gypsum stone ($CaSO_4$-dihydrate)	Underground and open pit mining; production mix, at plant; grinded and purified product	1.430	(European Commission, 2006)	2005	LCI database	Europe	Germany
Anhydrite ($CaSO_4$)	Technology mix of natural (33%), thermal (33%) and synthetic (33%) produced anhydrite; Production mix, at plant; grinded and purified product.	2.737	(European Commission, 2006)	2002	LCI database	Europe	Germany

Table D7
Water inventory figures for cement production.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Cement	Undefined	0.533	(Argos, 2014)	2014	Report	Colombia	Worldwide
		0.540					
		0.666					
		0.808					
Cement: clinker, gypsum, limestone. (Density: 3150 kg/m^3)	Undefined	3.937	(Zabalza Bribián et al., 2011)	2011	Paper	Spain	Europe
Cement paste: cement and sand (density: 1525 kg/m^3)	Undefined	3.329	(Zabalza Bribián et al., 2011)	2011	Paper	Spain	Europe
Cement	Undefined	0.315	(Cemex, 2011)	2009	Sustainability report	Mexico	Worldwide
Cement	Undefined	0.277	(Cemex, 2013)	2010	Sustainability report	Mexico	Worldwide
		0.257		2011	Sustainability report	Mexico	Worldwide
Cement	Undefined	0.382	(Cemex, 2014)	2012	Sustainability report	Mexico	Worldwide
		0.376		2013	Sustainability report	Mexico	Worldwide
Cement	Undefined	0.360	(Holcim, 2011)	2009	Sustainability report	Switzerland	Worldwide
Cement	Undefined	0.300	(Holcim, 2013)	2010	Sustainability report	Switzerland	Worldwide
Cement	Undefined	0.254	(Holcim, 2014)	2011	Sustainability report	Switzerland	Worldwide
		0.260		2012	Sustainability report	Switzerland	Worldwide
		0.281		2013	Sustainability report	Switzerland	Worldwide
Cement	Undefined	0.185	(Holcim, 2015)	2014	Sustainability report	Switzerland	Worldwide
Cement	Undefined	0.317	(Lafarge, 2012)	2010	Sustainability report	France	Worldwide
		0.314		2011	Sustainability report	France	Worldwide
Cement	Wet	1.059	(Marceau et al., 2006)	2006	Report	Canada/USA	Canada/USA
	Dry	1.333					
	Pre-heater	1.141					
	Pre-calciner	0.606					
Portland cement (CEM I)	CEMBUREAU technology mix, production mix, at plant (en)	1.693	(European Commission, 2006)	2006	LCI database	Europe	CEMBUREAU member countries

Table D8
Water inventory figures for dust suppression in cement production.

Product	Process	H kg/kg	Reference	Year	Reference type	Reference region	Data region
Cement	Wet	0.024	(Marceau et al., 2006)	2006	Report	Canada/USA	Canada/USA
	Dry	0.032					
	Pre-heater	0.080					
	Pre-calciner	0.023					

Table D9
Water inventory figures for cleaning the concrete plant yard.

Product	H kg/day	Reference	Year	Reference type	Reference region	Data region
Concrete	500	(Jaques R., 2001)	2001	Report	New Zealand	New Zealand
	1500					

Table D10
Water inventory figures for washing of the concrete trucks (trucks wash out).

Product	H kg/m^3	Reference	Year	Reference type	Reference region	Data region
Concrete	20.000	(Chini et al., 2001)	2001	Paper	USA	n/d
	5.000	(Nisbet et al., 2002)	2002	Report	USA/Canada	USA/Canada
	69.000	(Nisbet et al., 2002)	2002	Report	USA/Canada	USA/Canada
	31.250	(Ekolu and Dawneerangen, 2010)	2010	Paper	South Africa	–
	93.750	(Paolini and Khurana, 1998)	1998	Paper	Italy	–
	8.000	(Jaques R., 2001)	2001	Report	New Zealand	New Zealand
	12.500	(Jaques R., 2001)	2001	Report	New Zealand	n/d
	200.000	(Concretos del Sol, 2015)	2015	Personal communication	Panama	Panama
	87.500	(Maranhão, 2015)	2015	Personal communication	Brazil	Rio de Janeiro

Table D11
Water inventory figures for washing of the concrete trucks (truck wash off).

Product	H kg/m^3	Reference	Year	Reference type	Reference region	Data region
Concrete	15.000	(Nisbet et al., 2002)	2002	Report	USA/Canada	USA/Canada
	317.000	(Nisbet et al., 2002)	2002	Report	USA/Canada	USA/Canada
	8.000	(Jaques R., 2001)	2001	Report	New Zealand	New Zealand

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