YAZMIN LISBETH MACK VERGARA

Concrete water footprint: a streamlined methodology

São Paulo
2019

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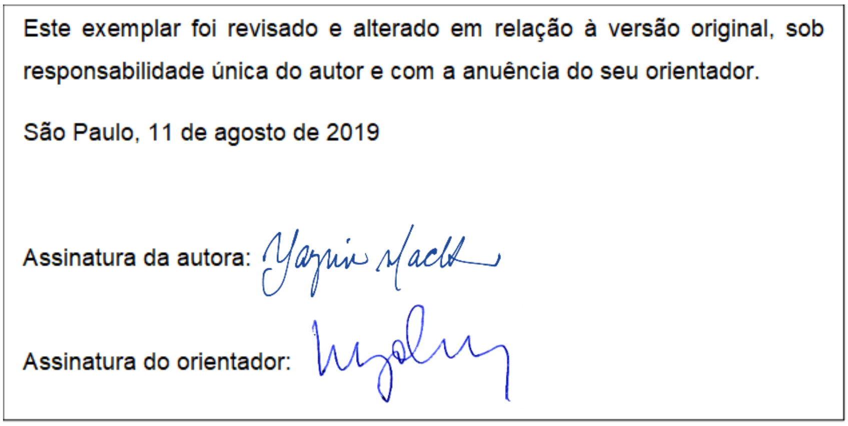
Revised version
(Original version is at the Graduate program unit)

Thesis submitted to the Polytechnic School of the University of São Paulo in fulfillment of the requirements for the degree of Doctor of Science in Civil Engineering.

Research area:
Civil and urban construction engineering

Doctoral advisor:
Prof. Vanderley Moacyr John, Dr. Sc.

São Paulo
2019



Este exemplar foi revisado e alterado em relação à versão original, sob responsabilidade única do autor e com a anuência do seu orientador.

São Paulo, 11 de agosto de 2019

Assinatura da autora: Yazmin Mack

Assinatura do orientador:

Catalogação-na-publicação

Mack-Vergara, Yazmin Lisbeth
Concrete water footprint: a streamlined methodology / Y. L. Mack Vergara -- versão corr. -- São Paulo, 2019.
163 p.

Tese (Doutorado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Construção Civil.

1.Cementitious materials 2.Construction materials 3.Water consumption 4.Life cycle assessment 5.Sustainable construction I.Universidade de São Paulo. Escola Politécnica. Departamento de Engenharia de Construção Civil
II.t.

Name: MACK VERGARA, Yazmin Lisbeth

Title: Concrete water footprint: a streamlined methodology.

Thesis submitted to the Polytechnic School of the University of São Paulo in fulfillment of the requirements for the degree of Doctor of Science in Civil Engineering.

Approved on: 17/06/2019

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Dedicado a:

Dios
Mamá, Papá, Franklin, Nidin, Jager y Polli
Abuelo Ulises, abuela Lidya, abuelo Ramón, abuela Zoila
Mi madrina Yiya y mi padrino Uli
Tía Luisa, tío Chino, Kathia y Camilo
Tía Noris, tío Erasmo, Rosy y Norisin
Tía Doris, tío Israel, Lourdes y Lorena
Elisa, José, Josecito y Andrea
Tías y tíos, primas y primos por parte de mi mamá y de mi papá
Missuly, Ana Patricia, Hannah, Linda, Keyra, Jilka, Wendy, Fer, Fore, Pablo, Omelsir
Francisco y Meli
A todas mis sobrinas amadas
Bruna y Jana
Ana Lídia y Nathi
Ricardo Jaime
LME & IBI
Prof. Vanderley
Prof. Pacca, prof. Kulay, prof. Sérgio, prof. Antonio, profa. Maria Alba. prof. Flávio, Diana, Marcia
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Carla, Engracia, Milton, Paulinho, Eliany, Wandrea, Patricia, Rogerio
Guillaume Habert
Vera, Alina, Deepika, Francesco, Gnanli, Isolda, Nikko, Sasha, Ana Spiroska
Sandra, Annete, Jacqueline, Roberta
Al personal de limpieza y seguridad de la USP

Este trabajo es de ustedes.

AKNOWLEDGEMENTS

This research is supported by the Technological University of Panama (UTP), the Institute for Training and Development of Human Resources (IFARHU) of the Republic of Panama (fellowship nº. 08-2014-42) and the Swiss Government Excellence Scholarship for Foreign Scholars 2017/2018.

“When you can measure what you are speaking about, and express it in numbers,
you know something about it..” (Kelvin 1891)

ABSTRACT

MACK-VERGARA, Yazmin L. **Concrete water footprint: a streamlined methodology.** Thesis for the degree of Doctor of Science in Civil Engineering, Escola Politécnica, Universidade de São Paulo, São Paulo, 2019.

Water is the most used substance in the world, followed by concrete. Water scarcity is nowadays more common due to concentrated population growth and climate change. Concrete demand is ~15 billion m^3 per year fulfilling the need for more and better housing and infrastructure for a growing and wealthier population. Since no other material could fulfil this demand, concrete needs to be produced in a sustainable way, minimizing environmental loads such as water consumption. The water footprint is a tool that measures water use over a products' life cycle and estimates its potential environmental impacts. Despite the growing concern on water, the existing water footprint methodologies are too complex and require large amounts of data. This study develops a streamlined water footprint methodology for concrete production, simple enough to be useful to the industry and robust enough to be environmentally meaningful. An extensive study on existing water footprint methodologies have been conducted. Then a streamlined methodology was proposed focused on the water flows that are more relevant in concrete production including water quantity and quality letting to meaningful results with less data. Typical water inventory includes the batch water (150–200 H kg/m^3), dust control (500–1500 H kg/day), truck washing (13–500 H kg/m^3), cement production (0.185–1.333 H kg/kg) and aggregates production (0.116–2.0 H kg/kg). Regarding water quality, the most critical flows - Zinc, Lead, Nitrate, Nitrogen oxides and Sulfur dioxide- were identified based on the contribution of these flows to the potential environmental impacts, the control or influence that the concrete producer has on the activities were these flows appear and the feasibility to measure these flows on site. Concrete water footprint varies due to mix design, technological routes, location and choice of impact assessment method. The results are of interest to the research community as well as to the stakeholders of the cement and concrete industries and a contribution to sustainable construction since study of water footprint is fundamental to improve water efficiency.

Keywords: Cementitious materials. Construction materials. Water consumption. Life cycle assessment. Sustainable construction.

RESUMO

MACK-VERGARA, Yazmin L. **Pegada hídrica do concreto: uma metodologia otimizada.** Tese para o grau de doutor em Ciências em Engenharia Civil, Escola Politécnica, Universidade de São Paulo, São Paulo, 2019.

A água é a substância mais utilizada no mundo, seguida pelo concreto. A escassez de água é hoje em dia mais comum devido ao crescimento populacional concentrado e às mudanças climáticas. A demanda de concreto é ~15 billion m^3 por ano que atende a demanda de mais e melhor moradia e infraestrutura para uma população crescente e mais prospera. Uma vez que nenhum outro material pode satisfazer essa demanda, o concreto precisa ser produzido de forma sustentável, minimizando as cargas ambientais, como o consumo de água. A pegada hídrica é uma ferramenta que mede o uso da água ao longo do ciclo de vida de um produto e estima seus potenciais impactos ambientais. Apesar da crescente preocupação com a água, as metodologias existentes de pegada hídrica são muito complexas e exigem grandes quantidades de dados. Este estudo desenvolve uma metodologia optimizada de pegada hídrica para produção de concreto, simples o suficiente para ser útil para a indústria e robusta o suficiente para ser ambientalmente significativa. Um estudo extensivo em metodologias existentes da pegada da água foi conduzido. Em seguida, uma metodologia optimizada foi proposta focada nos fluxos de água que são mais relevantes na produção de concreto, incluindo quantidade e qualidade, permitindo resultados significativos com menos dados. O inventário de água típica inclui a água de mistura (150–200 H kg/m^3), controle de poeira (500–1500 H kg/dia), lavagem de caminhões (13–500 H kg/m^3), produção de cimento (0.185–1.333 H kg/kg) e produção de agregados (0.116–2,0 H kg/kg). Em relação à qualidade da água, os fluxos mais críticos -Zinco, Chumbo, Nitrato, Óxidos de nitrogênio e Dióxido de enxofre-foram identificados com base na contribuição destes fluxos para os potenciais impactos ambientais, o controle ou a influência que o produtor de concreto tem sobre as atividades onde esses fluxos aparecem e a viabilidade para medir esses fluxos no local. A pegada de água de concreto varia devido à formulação, rotas tecnológicas, localização e escolha do método de avaliação de impacto. Os resultados são de interesse para a comunidade de pesquisa, bem como para as partes interessadas das indústrias de cimento e concreto e uma contribuição para a construção sustentável, uma vez que o estudo da pegada hídrica é fundamental para melhorar a eficiência da água.

Palavras-chave: Materiais cimentícios. Materiais de construção. Consumo de água. Avaliação do ciclo de vida. Construção sustentável.

RESUMEN

MACK-VERGARA, Yazmin L. **Huella hídrica del hormigón: una metodología optimizada.** Tesis para el grado de Doctor en Ciencias en Ingeniería Civilg, Escola Politécnica, Universidade de São Paulo, São Paulo, 2019.

El agua es la sustancia más utilizada en el mundo, seguida del hormigón. La escasez de agua es hoy en día más común debido al crecimiento concentrado de la población y al cambio climático. La demanda de hormigón es de ~15 millones de m^3 al año, satisfaciendo la demanda de más y mejor vivienda e infraestructura para una población creciente y más próspera. Dado que ningún otro material podría satisfacer esta demanda, el hormigón debe producirse de manera sostenible, minimizando las cargas ambientales como el consumo de agua. La huella hídrica es una herramienta que mide el uso del agua durante el ciclo de vida de un producto y estima sus posibles impactos ambientales. A pesar de la creciente preocupación por el agua, las metodologías de huella hídrica existentes son demasiado complejas y requieren grandes cantidades de datos. Este estudio desarrolla una metodología de huella hídrica optimizada para la producción de hormigón, lo suficientemente simple como para ser compatible con la industria y lo suficientemente robusta como para ser ambientalmente significativa. Se ha realizado un amplio estudio sobre las metodologías existentes de huella hídrica. Luego, se propuso una metodología optimizada centrada en los flujos de agua que son más relevantes en la producción de hormigón, incluyendo cantidad y calidad, lo que permite obtener resultados significativos con menos datos. El inventario típico de agua incluye agua de mezcla (150–200 H kg/m^3), el control de polvo (500–1500 H kg/día), el lavado de camiones (13–500 H kg/m^3), la producción de cemento (0,185–1,333 H kg/kg) y la producción de agregados (0,116–2,0 H kg/kg). En cuanto a la calidad del agua, los flujos más críticos -Zinc, Plomo, Nitrato, Óxidos de nitrógeno y Dióxido de azufre- se identificaron sobre la base de la contribución de estos flujos a los posibles impactos ambientales, el control o la influencia que el productor de hormigón tiene en las actividades en que aparecen estos flujos y la viabilidad de medir estos flujos in situ. La huella hídrica de hormigón varía debido al diseño de mezcla, rutas tecnológicas, ubicación y elección del método de evaluación de impacto. Los resultados son de interés para la comunidad investigadora, así como para las partes interesadas de la industria de cemento y hormigón y una contribución a la construcción sostenible, ya que el estudio de la huella hídrica es fundamental para mejorar la eficiencia del agua.

Palabras clave: Materiales cementicios. Materiales de construcción. Consumo de agua. Evaluación del ciclo de vida. Construcción sostenible.

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1. INTRODUCTION

Concrete is the most used material in the world and is second only to water in terms of consumption (Flower and Sanjayan 2007; World Business Council for Sustainable Development 2009a; Chen et al. 2010a; Hasanbeigi et al. 2012; Scrivener et al. 2018). In 2018, more than 4 billion tons (t) of Portland cement were produced worldwide (USGS 2019), enough to produce about 30 billion t of concrete, representing almost 4 tonnes (t) of concrete per person per year.

The concrete industry is consuming large amounts of resources and energy (Mehta, P.K. 2002). It is expected that the world cement production, which represents the greatest environmental impact in the production of concrete, will increase 2.5 times between 2005 and 2050 with most of this growth in developing countries (World Business Council for Sustainable Development 2007; Nicolas Müller 2008). Approximately 50% of the cement production goes to concrete production the rest goes to cementitious materials such as mortar, concrete blocks, concrete tiles, etc.

Due to the broad global use of concrete, it is essential to properly assess the environmental impact of this material (Habert et al. 2010). Among the main environmental impacts in concrete production are high energy consumption, raw material consumption, water consumption, waste generation and CO_2 emissions (Worrell et al. 2001; Van Oss and Padovani 2003; Metz et al. 2007; World Business Council for Sustainable Development 2009a; US EPA 2010; Hasanbeigi et al. 2012; Amato 2013). However, most of the efforts are focused on energy and CO_2 emissions and almost nothing on water (Jefferies et al. 2012; Conselho Brasileiro de Construção Sustentável 2014; Petek Gursel et al. 2014a).

The world situation according to Water Facts and trends of the World Business Council for Sustainable Development (WBCSD) (World Business Council for Sustainable Development 2009b) is that less than 3% of the world's water is freshwater, the rest is mostly seawater. Of that 3%, 2.5% is frozen. Only 0.5% is left for all human’s freshwater needs.

As economies develop and the population grows concentrated in certain regions, water demand increases rapidly, for this reason many regions face water scarcity challenges (Bodley 2012). Besides, the impact of climate change will exacerbate water problems, because it will probably lead to greater variability in supply, floods and droughts in many countries (Intergovernmental Panel on Climate Change 2008). Since it is expected that water stress will worsen in many parts of the world as a result of urbanization and population growth, increasing food production, industrialization, water pollution and climate change (United Nations Global Compact 2011); water management systems need to be more effective in addressing the challenges of water scarcity and assessing water resources prudently and fairly.

To understand and reduce the environmental impacts of concrete requires a life cycle assessment (LCA) approach. Unlike cement production LCA, there are not many LCA on other raw materials for concrete production including aggregates, admixtures, supplementary cementitious materials (SCM), etc. In addition, the impacts of water consumption are not considered, mostly due to lack of life cycle inventory (LCI) data. Without a comprehensive assessment, it is not possible to understand the environmental implications of concrete and its raw materials, or to compare concrete to other construction materials (Petek Gursel et al. 2014b).

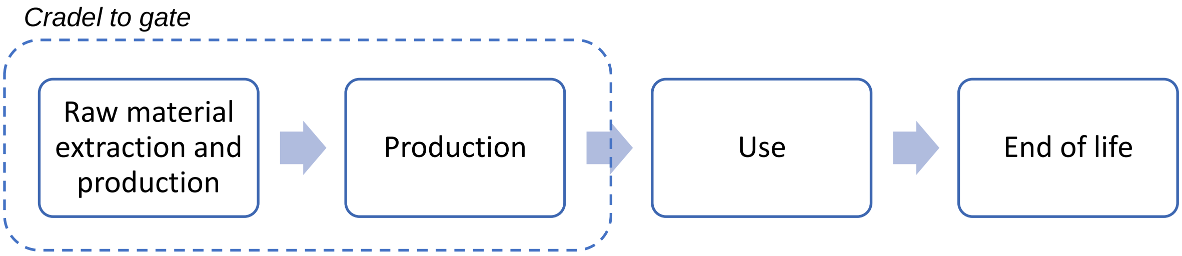
To identify opportunities to reduce potential impacts related to water and associated products and processes at different stages of the life cycle, the water footprint concept will be used. This concept applied to concrete production will be studied broadly for the proposed work.

1.1. AIM OF THE STUDY

The aim of this study is to develop a streamlined water footprint methodology for concrete production, simple enough to be compatible with the industry and robust enough to be environmentally meaningful. The development of tools in order to diagnose problems inherent to water footprint calculation in cementitious materials industry, and complemented by existing methodologies are established as an interesting contribution to a relatively new and little known topic (Gerbens-Leenes et al. 2018; Mahdi Hosseinian and Nezamoleslami 2019)

The concrete production represents the cradle to gate part of the life cycle of concrete. The other phases -use of the concrete and end of life of the concrete- are not included in this thesis. These phases might represent large amounts of water for activities such as curing, cleaning and dust control. However, these activities will be performed by many different parts that are not under the control or influence of the concrete producer. Acces to this kind of data would be more complex than access to cradle to gate data already is. It is expected that the variability of this data would be a lot higher than the variability that was found for cradle to gate data.

Figure 1-1 Concrete life cycle phases included in this study -cradle to gate approach.



Source: the author based on (Hauschild et al. 2017).

This research is composed by several manuscripts suitable for journal publication or already published. Each chapter consists of the content of a manuscript which has been published, submitted for publication, or which is being prepared to be submitted for publication in a scientific journal. An introductory chapter as well as the conclusion chapter are presented. The manuscript chapters include their own introduction, methodology, results, conclusions and appendices; however, they are related to each other as well as to the introduction and conclusion chapters.

1.2. CONTENTS OF THE THESIS

The thesis is divided in 8 chapters. The **first chapter** is the introduction to the topic where the importance and scale of research is demonstrated. Besides, the aim of the research is presented.

Chapter 2 presents an overview on concrete production and potential water impacts to provide a basic understanding of the general concepts related to this thesis. The water footprint concept is introduced, the water footprint assessment phases and the relation between water footprint and life cycle assessment as well as the gap that is water footprint in concrete production LCA are discussed. A review on water in concrete production that includes cement and aggregates production, has been carried out.

Chapter 3 evaluates existing water footprint methodologies based on life-cycle assessment, their concepts and difficulties, and link them to concrete industry.

Chapter 4 collects available water inventory data for concrete production, reviews 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.

Chapter 5 identifies the main contributors to water footprint of concrete production based on the contribution of the substances to the potential environmental impacts, their background or foreground classification and the feasibility to measure these flows on site. This chapter was conducted in exchange abroad at the Swiss Institute of Technology Zurich under the supervision of Prof. Dr. Guillaume Habert.

Chapter 6 consist of a cradle to gate water footprint study performed to estimate variability in concrete production water footprint including variability due to water use, location and choice of impact assessment method for a specific compressive strength.

Chapter 7 presents a simplified approach based on existing standards using primary data. The aim of this chapter is to define a streamlined water footprint methodology for concrete production including definitions, data requirements, life cycle inventory analysis and impact assessment. Concepts from existing water footprint methodologies are unified. In addition, the proposed methodology is applied to a water inventory case scenario. The results are compared to those from 7 other water footprint inventory methodologies.

Chapters 8 corresponds to the general conclusions.

The references for each chapter are integrated and presented as one final bibliography at the end of the thesis.

2. CONCRETE PRODUCTION: POTENTIAL WATER RELATED IMPACTS

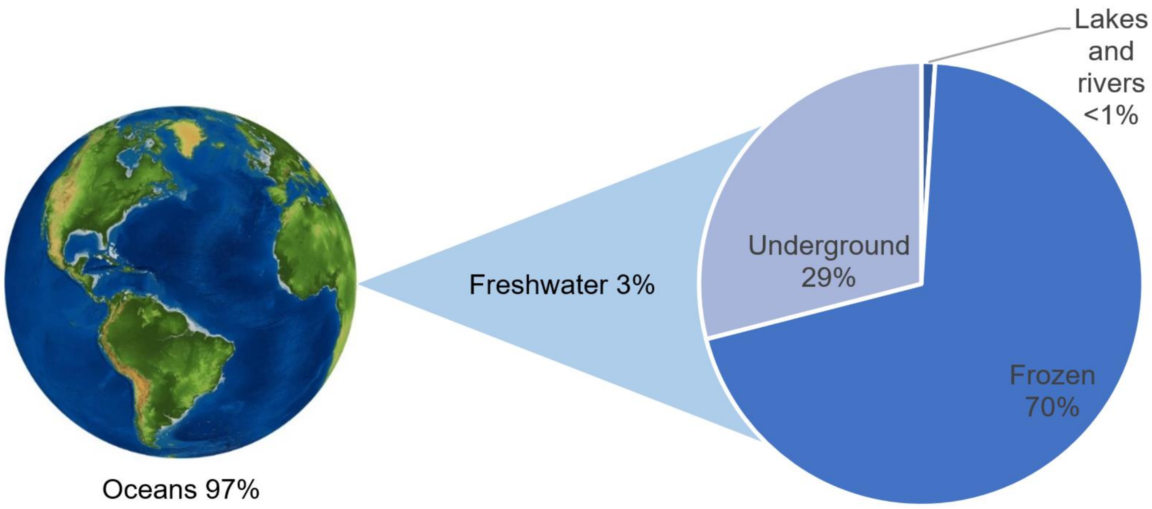
This chapter presents a concrete production and potential water impacts overview to provide a basic understanding of the general concerns and concepts in this thesis.

2.1. CHALLENGES REGARDING WATER RESOURCES

In 2010 the United Nations (UN) declared water access a human right through the resolution A/RES/64/292 (United Nations 2010). The problem with water is that it is unevenly distributed. In some regions there are large amounts of water and in others there is none. Furthermore, where there are large amounts of water, there could be other restrictions such as supply risk, environmental implications and vulnerability to supply restriction (Ioannidou et al. 2017).

Water constitutes ~70% of the earth's surface. However, oceans make up for 97% of the world's water and freshwater makes up for only 3% but only 0.5% is accessible (Gleick 1993; World Business Council for Sustainable Development 2009b; USGS 2016). Sea water has high content of salts; thus, it is a lot more complicated to be used as drinking water or as water for agriculture and industry uses due to its high salinity. The amount of water we have should be considered finite, and as population growth water demand will rise to produce more food and energy and to serve our communities.

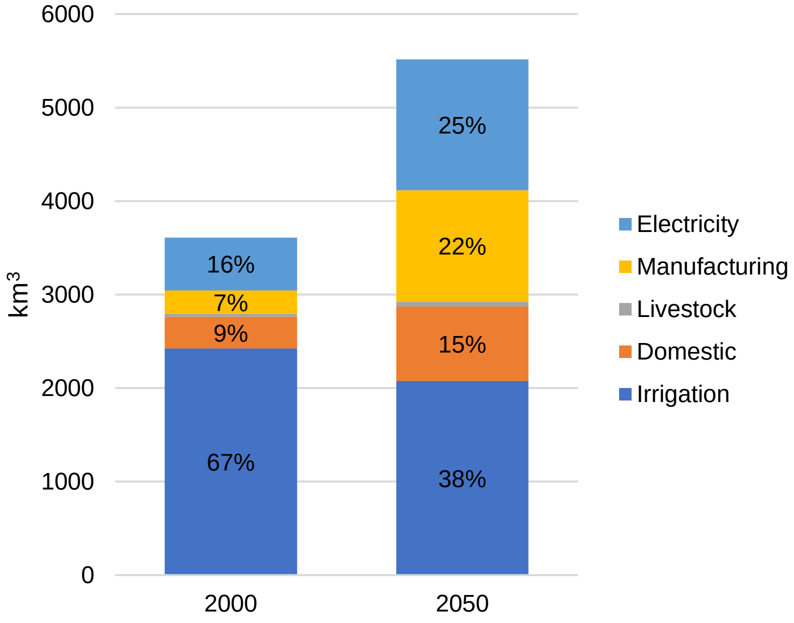
Figure 2-1 World water distribution. Most of the water is sea water or frozen and therefore its use is restricted.



Source: author with data from (Gleick 1993; World Business Council for Sustainable Development 2009b; USGS 2016).

Water is at the center of everything we do. In 2009, Rockström et al. (2009) proposed a planetary boundary of 4000 km^3 per year for freshwater use. By that time, the status was estimated in 2600 km^3 per year. According to the United Nations World Water Development Report 2015 (United Nations Educational, Scientific and Cultural Organization 2015), the global demand will increase from 3600 to 5500 km^3 approximately between 2000 and 2050, which would be crossing the proposed planetary boundary. The biggest increase will be in manufacturing (~5 times) follow by electricity and domestic water use.

Figure 2-2 Global water demand in 2000 and 2050. Water demand for manufacturing is expected to increase approximately 5 times, including water for concrete production.



Source: author with data from (United Nations Educational, Scientific and Cultural Organization 2015).

Access to clean freshwater is one of the biggest challenges that humanity faces. Both public and private sector entities need to think about water in the way that many think about other finite resources, such as oil and minerals. 2.1 billion people already lack access to clean water which causes diseases and other issues that impact economic and social growth (United Nations 2015a).

Even though we have large amounts of water, there are water scarcity issues due to low cost of the water and therefore people tend to use it when we should be conserving it. Climate change further increase these issues with dry regions becoming drier and other regions are flooding more often affecting specially the poorer and more vulnerable people.

The importance of water resources is reflected in many of the sustainable development goals adopted by the United Nation members in 2015 (United Nations 2015b). Clean water and sanitation and life below water are goals directly related to water availability and water quality. Zero hunger and good health and wellbeing are quite related to water as well. The decent work and economic growth and sustainable cities and communities' goals also depends on water efficiency. For this reason, research on industry innovation and infrastructure, responsible consumption and production and partnerships, will contribute to achieving sustainable development.

Figure 2-3 United Nations sustainable development goals for 2030. 9 (marked) out of 17 require action related to water efficiency to be achieved.

Source: (United Nations 2015b).

2.2. THE WATER FOOTPRINT CONCEPT

Allan (1998) introduced the virtual water concept, which states that each product requires a greater volume of water in their production process besides water that is incorporated. The concept refers to the hidden flow of water if food or other commodities are traded from one place to another.

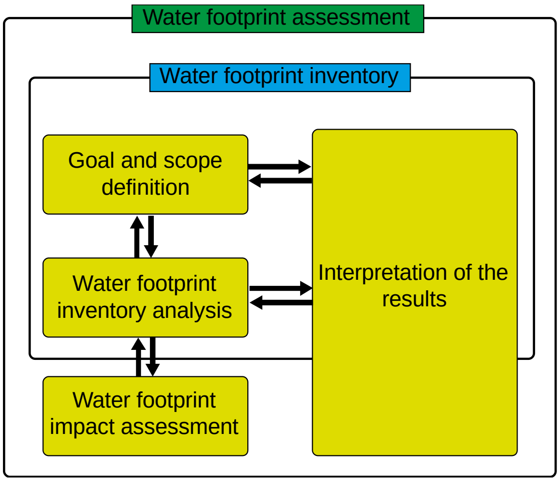
In 2002, Hoekstra (2003) introduces the concept of water footprint as the total fresh water used to produce goods and services consumed along the production and supply chain (Chapagain and Hoekstra 2004). Later, the ISO 14046 standard defines the water footprint as a parameter(s) that quantifies the potential environmental impacts related to water (International Organization for Standardization 2014). The water footprint is considered an extension of the LCA concept defined in the ISO 1400 and ISO 14044 (International Organization for Standardization 2006a, b).

The calculation of the water footprint ends up being a complementary indicator to assess the environmental impacts of natural resources used by people. This indicator includes all process data involving water, "where," "when" and "how much", consumed or contaminated, considering the whole supply chain. In addition, the water footprint specifies the use of the water and the source.

Because of the impending water crisis, it has been tried to apply the same measurement initiatives, mitigation, reduction and compensation designed for carbon emissions, but in the case of water related environmental impacts, location becomes crucial when making impact analysis. While global warming potential from CO_2 emissions is a global impact, water related impacts are local. Therefore, they need to be considered in different ways regarding mitigation, reduction and compensation.

The water footprint is extremely important worldwide due to the risks associated with future availability, scarcity and cost of water. The water footprint is a useful tool that helps identifying water reduction opportunities thus contributing to efficiency in water use for products as a response to the current water crisis in many regions of the world.

Figure 2-4 Water footprint assessment phases following ISO 14046 (International Organization for Standardization 2014).



Source: (International Organization for Standardization 2006a, b, 2014).

According to the ISO standard for Water Footprint (International Organization for Standardization 2014), the water footprint assessment phases consist of definition of goal and scope, water footprint inventory analysis, water footprint impact assessment and interpretation of the results. These phases are iterative, this means that once we are finished we may start the loop again or go back and forth between phases in order to refine the results.

The definition of the goal includes reasons for the study, intended applications -for instance if a comparison between products is intended-, target audience, if it is a standalone study or a part of a LCA, and objective of the study.

The scope should state the system under study and system boundaries in addition to functional unit, time frame and location coverage, data and data quality, input and output cut-off criteria, unit processes and stages of the life cycle, impact assessment methodology and chosen impact categories. All relevant information that the analysis is expected to attend should be stated.

The water footprint inventory analysis phase consists of compilation and quantification of water inputs and outputs. The volumes of water used in the different stages of the life cycle of a product or process are described in the step of the inventory. The inventory includes water inputs and outputs per volume, source, and water quality throughout the life cycle. Water balances should be established as well.

There are two kinds of data for the water footprint inventory. Primary data that come directly from processes and installations of the organization and secondary data coming from literature, suppliers, life cycle inventory databases and other sources. Secondary data is often not representative. Data quality should be representative, accurate, and precise and uncertainty should be assessed.

The ISO standard for Water Footprint (International Organization for Standardization 2014) stresses that the water footprint is an impact and not a volume or an inventory. The total water volume is not enough to evaluate the water footprint, it is necessary to transform the water inventory into environmental impacts, so it can be reported as water footprint. As the water footprint is a local indicator, regional water scarcity and water stress should be determined. The potential impact of water use is then evaluated by water scarcity indices or with wider impact assessment methods.

During the water footprint impact assessment phase, for each impact category, characterization factors that are specific to each flow are applied in order to estimate their potential impacts. Changes in both water volume and water quality can lead to local water stress, which should be assessed.

There are multiple possibilities to represent and communicate the results -with a single impact indicator or as a group of them-. Interpretation of the results includes conclusions, assumptions and limitations for data and methodology, positive aspects and expert judgment by internal or external -independent of the water footprint assessment team- part or panel of interested parties.

LCA is a tool to measure the various environmental impacts caused by products along their lifespan (International Organization for Standardization 2006a). A water footprint is the fraction of those impacts which are related to water. The concept of water footprint is based on life cycle thinking, this means accounting water consumption from the extraction of raw materials, through production, use, final treatment and recycling to disposal.

In the case of products, the water footprint is environmental impact of the total volume of water used to produce the product, summed over the various steps of the production chain. The water footprint assessment according to the ISO 14046 standard may be conducted and reported as a stand-alone or as part of a LCA (International Organization for Standardization 2014).

In most LCA studies not related to agriculture, water consumption has been traditionally omitted (Canals et al. 2008; Cooney 2009). Until a few years ago, water consumption was not considered as a major problem by LCA community. Today, water conservation, water footprint, and water management are taking an increasing importance in the sustainability agenda of many companies (Holcim 2012; Lafarge 2012a; BASF 2014; Lafarge 2014).

LCA as well as water footprint seeks for “hot spots” –activities with a significant contribution to the total potential impact attributed to the product - along the life cycle of the product. In the case of water footprint, it specifically seeks for activities where the water demand is high, and the water availability is low. Once this “hot spots” are identified, companies can implement water reduction strategies. Potential synergies exist between water footprint and LCA, since they rely on the same data for water accounting and impact assessment (Jefferies et al. 2012).

2.3. CONCRETE PRODUCTION AND ITS ACCELERATED DEMAND: REASONS WHY

Due to current environmental issues such as climate change, engineers have the challenge of developing and working with more sustainable materials. Sustainability considers environmental, social and economic aspects of a product or service and is focused on allowing present generations to meet their needs without compromising the ability of next generations to meet their own needs (Bruntland, G. 1987).

Concrete is the largest manufactured material in the world and, is the second most consumed substance, after water. It is made by simple components including aggregates, cement, water and small amounts of chemical admixtures.

Figure 2-5 Massive concrete structures and cities. a. The Panama Canal expansion (Hydraulics pneumatics 2018). b. Sao Paulo city. c. The Hoover Dam (Mariordo 2017). d. Burj Khalifa (Luxe adventure traveler 2012). e. Christ the Redeemer.

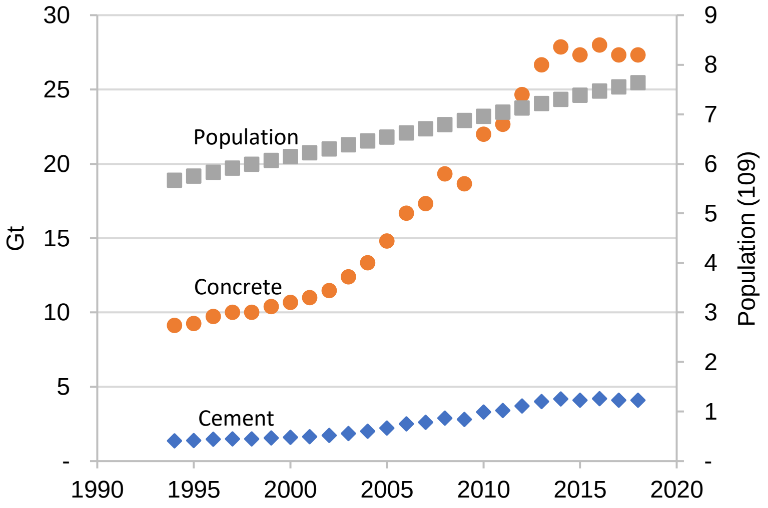
Source: (Luxe adventure traveler 2012; Mariordo 2017; Hydraulics pneumatics 2018) and the author.

Its large demand is made possible because it is based on abundant raw materials; has as low cost - a liter of concrete is cheaper than a liter of mineral water - making it affordable for billions of people in quantities large enough to make houses; it is easy to use which allows untrained people to produce large, cast-in-place monolithic 3D strong and durable structures of any shape, just mixing small particles without expensive equipment, and let it harden in the open environment; has a streamlined logistic because water and aggregates, its main constituents, can be locally produced. These gives concrete and enormous advantage over other building materials.

Concrete allows to build a wide variety of structures. From single family houses easy and fast to build to large skyscrapers such as the Burj Khalifa in Dubai. Regarding infrastructure, concrete allows the construction of impressive dams such as the Hoover dam. The Panama Canal expansion is a great example of what can be done with concrete: an amazing 5 million m^3 concrete structure that allows the passage of the biggest chips between the Atlantic to the Pacific. Even more important than impressive structures, concrete allows the construction of hospitals, schools and social housing.

Concrete demand have increase almost 34 times in the last 65 year and is expected to increase until 2050. The production of cement -one of concrete's main constituents- was of 4,6 billion ton in 2015 this is equivalent to a per capita consumption higher than that of human food, 626 kg of cement per capita (Food and Agriculture Organization of the United Nations 2013). Furthermore, the growing demand for larger and better built environment, may cause future production to surpass these values (Scrivener et al. 2018). From the cement production, it is estimated that approximately 50% goes to concrete production and the rest is divided into mortar production and other cementitious materials such as concrete blocks, tiles, etc.

Figure 2-6 Cementitious materials production, population growth. The production of concrete is growing faster than population which means in average the humans are living in a better built environment.



Source: data from (USGS 2019). Concrete production was calculated using a reference concrete mix design of 320 kg o cement, 1880 kg of aggregates and 162 kg of water.

The world population is expected to grow from 7 to 9 billion people between 2015 and 2050 (United Nations 2015c). The need of housing and infrastructure will increase as well. Figure 2-6 presents the increase of cement and concrete production compare to the increase in population growth. It is observed that the increase rate is higher than that of the world population. This increase in population is happening mostly in urban areas where access to resources is already limited.

Concrete have been the foundation of the built environment and will continue to play the main role in meeting the demand for housing and infrastructure in order to have a more sustainable world. In Europe, most of the housing and infrastructure that is needed is already built contrary to emerging and developing countries such as Brazil, India and China. These countries are characterized for an expected population growth and a current deficit in housing and infrastructure in terms of quantity and quality. The World Bank states that 65% of the urban population in low-income lives in slums, >60% do not have access to sanitation, and 35% do not have a safe water supply (DataBank 2019). Therefore concrete demand growth is and will continue to be concentrated in emerging and developing countries as the result of better quality of life requirements (Scrivener et al. 2018).

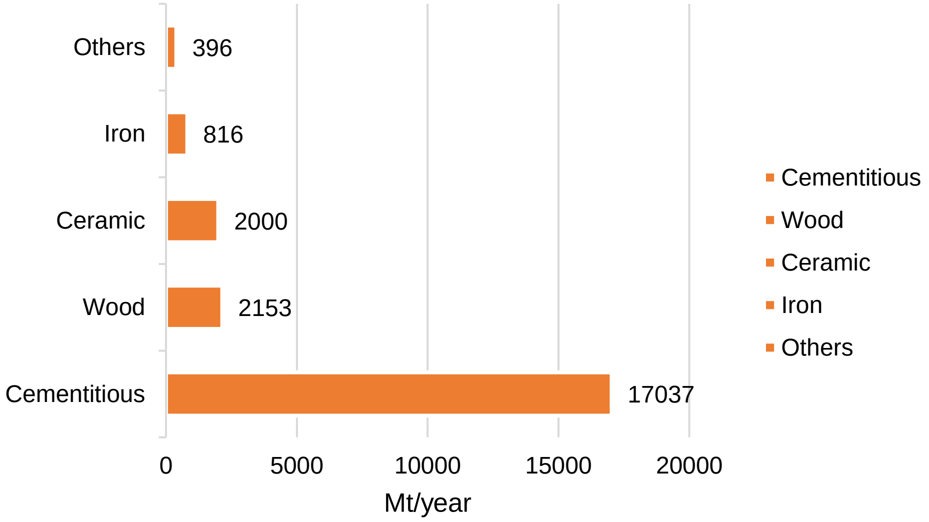
Figure 2-7 Before and after housing and infrastructure renovation at Curundu, Panama (Loo Pinzón 2016).

Source: (Loo Pinzón 2016).

It is important to work on solutions to the global challenges that the increase in urban population poses. It is a fact that there are no other materials that could replace all concrete, due the large amount that is needed. Neither other materials can be casted and easily molded in 3D shape by unequipped and almost untrained people. Figure

2-8 presents the production of common building materials such as iron, wood and others. It could be observed that the production of concrete amply surpasses the production of other building materials.

Figure 2-8 Production of common building materials (Scrivener et al. 2018).



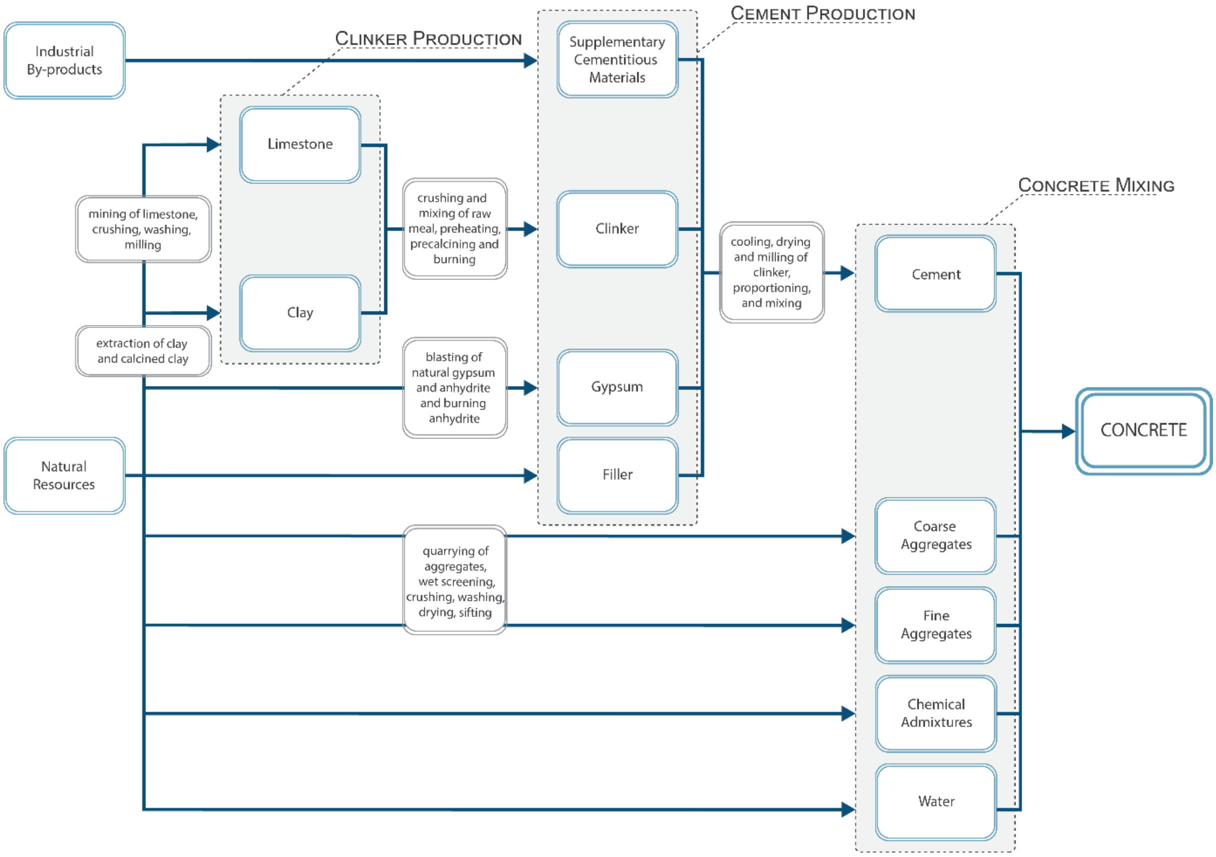
Source: adapted from (Scrivener et al. 2018).

Since we cannot replace it, it is crucial to develop more sustainable ways to produce and use concrete, allowing to meet the social needs meanwhile reducing environmental impacts. To reduce environmental impact of concrete, it is essential to quantitatively measure them. In this study, a streamlined methodology for the assessment of the concrete water footprint have been developed with the collaboration of an international group of academic and industry experts with various perspectives. With this work, we also aim to attract attention for future policy making that will lead and allow the concrete industry which provides space and infrastructure for many people.

2.4. CONCRETE LCA AND WATER FOOTPRINT: THE GAP

Most of the activities within the concrete life cycle, demand significant amounts of water. However, usually only water for mixing the concrete is measured. Sometimes even this water is not accurately measured since part of it comes from the aggregates, but the producers do not know the exact amount. In the mixing, water is added until concrete gets the desire slump, as a result not always is the water for mixing the same as the water in the concrete formulation since part of the water needed according to the mix design, come as humidity in the aggregates.

Figure 2-9 Cradle to gate system boundaries of concrete LCA including aggregates and cement production.



Source: (Spiroska et al. 2019).

There are other activities that demand water for concrete production such as washing the trucks, washing the yard, etc. as well as to produce cement and the aggregates. There is also water for curing the concrete which is not estimated in this work but is also important.

The cementitious materials industry already has some practices and available definitions regarding water footprint. Members of The Cement Sustainability Initiative (CSI) collect and disseminates primary data (World Business Council for Sustainable Development 2014a). However, there are still difficulties with these figures (Cemex 2015; Holcim 2015).

For the cementitious materials industry, measuring the water footprint is quite complex. There are many uncertainties, for example, there is no information on the origin of the water that comes with the aggregates, which can be from the quarry, or due to precipitation during transport and storage. Another challenge for instance is to measure water for curing concrete that depends on the environmental conditions and the type of application.

Water obtained from the public network is measured but the water losses in the public network are usually not considered and this could represent up to 30% of the water. However, the amounts of water extracted by companies from river, lakes or underground aquifers often are not as accurate.

It is also important to record and quantify the treatment and reuse of wastewater. This record is not only for the consolidation of the mass balance and environmental practices of rational use of water but also helps explaining the variation of the water footprint.

The concrete blocks modular life-cycle assessment project of the Brazilian Council for Sustainable Construction (CBCS) (John et al. 2014) was an interesting experience, where it was observed that almost no company measures its water consumption. Only the public water supply and water to the composition of the products are known.

A simplified water footprint is necessary to obtain more data. To measure what is not known a solution would be to measure systematically at different points of the production process and even the wastewater generation (equipment, management structure, etc.). A recommended practice is to install measuring devices as they did in Lafarge installations (Lafarge 2012b).

In order to assess the level of information and knowledge on the problem of water footprint in concrete and its constituents, a comprehensive survey of the literature focused on concrete related LCA survey was carried out searching for the ones including water related aspects. The review was done on studies published from 2013 to 2018 on in order to include the most recent references (i.e. most recent life cycle assessment methods and data). Furthermore, the focus of this study being water footprint, the review's objective was not only to evaluate if water was considered in the LCA, but to what extent. The peer-reviewed research literature databases scopus and google scholar were used for the search. The keywords include: cement, concrete, cementitious material, water use, water consumption, water footprint and life cycle assessment.

The studies were analyzed in two steps. First, the subject of analysis and the respective system boundaries shown in Table 2-1. The second step of the analysis was the one that focused on discerning the extension of water inclusion in the LCA.

Many of the studied papers, includes or excludes the same processes in most studies as seen in Table 2-1. For example, the transport of various components although not directly included in most of the inventory, it was calculated and analyzed after the fact with either a range of scenarios or a sensitivity analysis. This was especially important in studies on concrete with recycled aggregates where the distance of transport of the recycled aggregates is a key factor, which decides whether they lower the impact of the product or have the opposite effect.

Another characteristic of these studies was the end of life management and not all of them included it. Obviously, it was defined since the recycled aggregates have to come from another system, but it was not always included in the system boundaries, which suggests they were to be allocated as waste products on the originating system.

As shown in Table 2-2 most of the papers consider water in one way or another, which is encouraging. However, water is mostly considered as another inevitable component of the concrete mixing inventory. Scarcely is it discussed for any other function apart from direct use of batch water.

It is also not highlighted as water incorporated in constituent elements (e.g. in aggregates). Since all analyses were carried out using an LCA software and mostly secondary data from databases, we can say with some certainty that water withdrawal and consumption by upstream processes to the actual concrete production are taken into consideration.

All the 27 studies that made part of the final review centered around the system boundary of concrete production, and not cement or aggregates as separates. However, the fact that the focus of the studies is on either clinker replacement or aggregates replacement is quite telling. The former mainly focus on various SCM that can be used to decrease the clinker content in cement and the consequent change in the environmental impact compared to ordinary Portland cement use. Most of the latter instead propose the use of recycled aggregates to replace a portion of first-grade aggregates and the related impact change.

Table 2-1 System boundaries considered in the 27 LCA cementitious materials studies reviewed.

		Concrete and raw materials production								Concrete products				
Author	Region	Cement production	Fine aggregates production	Coarse aggregates production	Admixtures production	Water use	Concrete plant operations	Transportation	End of life: demolition / recycle	Concrete mix with 100% PC	Concrete mix with varying % slag	Concrete mix with varying % of FA	Other	Note
(Marinković et al. 2017)	Serbia	*	*	*	*	*	*	*			*	*	*	*recycled concrete (aggregates) **alkali activated fly ash concrete
(Tait and Cheung 2016)	UK	*	*	*		*	*	*		*	*	*		3 concrete designs
(Ingrao et al. 2014)	Italy	*	*	*	*	*	*	*		*			*	Basalt aggregates
(Nikbin et al. 2018)	Iran	*	*	*	*	*	*	*		*			*	Bauxite residue (red mud waste)
(Teixeira et al. 2016)	Portugal	*	*	*	*	*	*	*		*		*	*	Biomass fly ashes
(Ruan and Unluer 2017)	Singapore	*		*		*	*	*		*	*	*	*	Calcined magnesite cement concrete
(Gursel and Ostertag 2017)	Singapore	*	*	*		*	*	*		*				Concrete
(Kim and Chae 2016)	S. Korea	*						*		*	*		*	Industrial waste additive to BFS of titanium gypsum, sludge and limestone
(Kim et al. 2016a)	S. korea	*	*	*	*	*	*	*		*	*	*	*	OPC + GGBS + FA
(Mohammadi and South 2017)	Australia	*	*	*	*	*	*	*			*	*	*	Other cement-based materials: mortar, grout and render
(Knoeri et al. 2013)	Switzerland	*	*	*	*	*	*	*	*	*		*	*	Recycled concrete (aggregates)
(de Schepper et al. 2014)	Switzerland	*	*	*		*	*	*	*	*	*		*	
(Jiménez et al. 2015)	Spain	*	*	*	*	*	*	*		*	*	*	*	
(Turk et al. 2015)	Slovenia	*	*	*		*	*	*	*	*	*	*	*	
(Serres et al. 2016)	France	*	*	*	*	*	*	*		*			*	
(Ding et al. 2016)	China	*		*			*	*	*	*			*	
(Kim et al. 2016b)	S. Korea	*	*	*	*	*	*	*		*	*		*	
(Braga et al. 2017)		*	*	*	*	*	*	*		*	*		*	
(Fraj and Idir 2017)	France	*		*	*	*	*	*			*	*	*	
(Kleijer et al. 2017)	Switzerland	*		*	*	*	*	*		*			*	
(Yazdanbakhsh et al. 2018)	New York, US	*	*	*		*		*		*			*	
(Colangelo et al. 2018b)	Italy	*	*	*		*	*	*	*	*			*	
(Napolano et al. 2016)	Italy	*	*	*	*	*	*	*		*			*	Recycled lightweight concrete (lightweight aggregates)
(Gursel et al. 2016)	California, US	*	*	*	*	*	*	*		*		*	*	Rice husk ash concrete (pozzolana)
(Vieira et al. 2018)	Brazil	*	*	*	*	*	*	*		*	*	*	*	Self-compacting concretes
(Soleimani and Shahandashti 2017)	US	*	*	*		*	*	*		*			*	Sludge (bio)concrete & cement kiln dust / rice husk ash concrete
(Singh et al. 2017)	India	*	*	*		*	*		*	*			*	Waste marble powder as cement and sand substitute

Source: (Spiroska et al. 2019).

Table 2-2 Consideration of water uses, water sources and destinations in the 27 LCA studies reviewed.

Author	Water origin	Water use	Water destination	Note
(Marinković et al. 2017)	Tap water*	Concrete mixing	Incorporated water*	
(Tait and Cheung 2016)	Tap water*	Concrete mixing	Incorporated water*	
(Ingrao et al. 2014)	Tap water	Concrete mixing	Incorporated water*	
(Nikbin et al. 2018)	-	All processes [a]	-	Concrete mixing
(Teixeira et al. 2016)	Tap water*	Concrete mixing	Incorporated water*	
(Ruan and Unluer 2017)	Tap water*	Concrete mixing	Incorporated water*	
(Gursel and Ostertag 2017)	Tap water*	Aggregates production Concrete mixing	Incorporated water*	
(Kim and Chae 2016)	Industrial water Waste water	Hydropower water GBFS production Concrete mixing	Incorporated water* Waste water*	
(Kim et al. 2016a)	-	-	-	
(Mohammadi and South 2017)	Ground water Lake water River water Rain water	Hydropower water Cement production Aggregates production Concrete mixing Washing water	Incorporated water* Waste water* Evaporated water*	
(Knoeri et al. 2013)	Tap water	Concrete mixing	Incorporated water*	
(de Schepper et al. 2014)	Tap water	Concrete mixing	Incorporated water*	
(Jiménez et al. 2015)	Tap water	Concrete mixing	Incorporated water*	
(Turk et al. 2015)	Tap water	Concrete mixing Mixer cleaning	Incorporated water* Waste water	
(Serres et al. 2016)	Tap water*	Concrete mixing Aggregates production	Incorporated water*	
(Ding et al. 2016)	Tap water*	Concrete mixing	Incorporated water* Waste water*	
(Kim et al. 2016b)	Industrial water Waste water	Hydropower water Cement production Aggregates production GBFS production Concrete mixing	Incorporated water* Waste water*	
(Braga et al. 2017)	Tap water*	Concrete mixing	Incorporated water*	
(Fraj and Idir 2017)	Tap water	Aggregates production Concrete mixing	Incorporated water*	
(Kleijer et al. 2017)	Tap water*	Aggregates production Concrete mixing	Incorporated water*	
(Yazdanbakhsh et al. 2018)	Tap water*	Concrete mixing	Incorporated water*	
(Colangelo et al. 2018b)	Tap water*	Concrete mixing	Incorporated water*	
(Napolano et al. 2016)	Tap water	Aggregates production Concrete mixing	Incorporated water*	
(Gursel et al. 2016)	-	All processes [a]	-	Concrete mixing
(Vieira et al. 2018)	Lake water	Aggregates production Concrete mixing	Incorporated water*	
(Soleimani and Shahandashti 2017)	Tap water*	Aggregates production Concrete mixing	Incorporated water*	
(Singh et al. 2017)	Tap water*	Concrete mixing	Incorporated water*	

* implicated but not defined specifically

[A] not specified which processes

Source: (Spiroska et al. 2019).

Table 2-3 Water - related environmental impact categories considered in the 27 LCA studies reviewed.

	Midpoint impact categories									
Author	Water acidification	Freshwater eutrophication	Marine eutrophication	Freshwater ecotoxicity	Marine ecotoxicity	Water consumption	Water depletion	Ecotoxicity	Emissions to surface water	Emissions to ground water
(Knoeri et al. 2013)		*						*	*	*
(de Schepper et al. 2014)	*	*		*	*					
(Ingrao et al. 2014)										
(Jiménez et al. 2015)	*	*		*	*					
(Turk et al. 2015)	*	*								
(Serres et al. 2016)	*	*		*		*				
(Teixeira et al. 2016)	*	*								
(Gursel et al. 2016)	*									
(Ding et al. 2016)										
(Kim et al. 2016a)	*	*								
(Kim and Chae 2016)	*	*								
(Kim et al. 2016b)	*	*								
(Napolano et al. 2016)										
(Tait and Cheung 2016)	*	*						*		
(Gursel and Ostertag 2017)	*		*	*	*					
(Braga et al. 2017)	*	*								
(Fraj and Idir 2017)	*	*		*		*				
(Kleijer et al. 2017)										
(Marinković et al. 2017)	*	*								
(Mohammadi and South 2017)	*	*								
(Ruan and Unluer 2017)		*						*		
(Singh et al. 2017)							*			
(Soleimani and Shahandashti 2017)	*	*				*		*		
(Vieira et al. 2018)										
(Yazdanbakhsh et al. 2018)	*	*								
(Colangelo et al. 2018b)	*	*								
(Nikbin et al. 2018)										

Source: (Spiroska et al. 2019).

This review demonstrates the discussion of how water related impacts are usually neglected. There is clearly a gap in the concrete life cycle water impacts assessment since no thorough publication on the water footprint area in concrete was found.

The papers analyzed, showed a great variety in terms of methods used for the analysis and indicators considered. Understandably, since the range of available methods is wide and ever changing with methods being updated ever more often. Furthermore, most studies have a local connotation, whether based on local industry data, a local database or a local adaptation of database information, and thus they also use methods prevalently used in their region. Such an example is the North American TRACI method, which has been used by only 2 studies (Soleimani and Shahandashti 2017; Yazdanbakhsh et al. 2018), both focusing on US territory results. Often, different versions of the same base method are used, whether it is because of the time when the study was carried out or because of indicators that are more convenient. Such is the case of the CML method in de Schepper et al. (2014) and Braga et al. (2017) which use the CML 2 baseline 2000 whereas Jiménez et al. (2015); Marinković et al. (2017); Mohammadi and South (2017) use the CML IA baseline and Turk et al. (2015) uses the CML l 2001 method. This is also the case with the eco-indicator 95 and eco-indicator 99 (Knoeri et al. 2013; Tait and Cheung 2016; Ruan and Unluer 2017). Even when the same method and version of it were used in more papers, different indicators were considered as relevant for discussion. For instance, the CML IA baseline method was used in three papers in the same version. However, Jiménez et al. (2015) considers the full range of indicators because it focuses on an overall evaluation of the environmental impacts of recycled and conventional concrete. It would be better if the papers presented flow data information as a rule, but his is hardly the case. The impact categories concerning the water footprint considered are: freshwater aquatic ecotoxicity (FAE), marine aquatic ecotoxicity (MAE), acidification potential (AP), and eutrophication potential (EP). This is not the case for the other two papers. Marinković et al. (2017) deals with the comparison of “green” concretes with regular OPC concrete and considers only about half of the above listed indicators – EP, AP – mostly excluding those related to toxicity. Mohammadi and South (2017) studies the impact of typical standard concrete products and considers the same impact categories as the previously described paper. This shows, that because of the large range, the choice of impact categories is less dependent on the focus of the study and more dependent on a subjective choice of the researcher and what they consider important. This can also be influenced by many other factors that focus on the lowering of certain impacts of the industry.

Regarding water-related impact considerations shown in Table 2-3, many of the studies also have an indicator in the final results that is related to water quality, such as acidification, eutrophication and, very rarely, ecotoxicity, but only four have an indicator concerning quantity of water (Serres et al. 2016; Soleimani and Shahandashti 2017; Singh et al. 2017; Fraj and Idir 2017). Moreover, Singh et al. (2017) considers a water depletion indicator, whereas the rest consider it as water consumption. The details of these considerations are however up to the methods with which they were calculated. Finally, only a handful of the studies specified the origin of the water used, which was mostly tap water since it is what is mostly used for concrete mixing due to unwillingness to risk quality for a less critical water source. The destination of the wastewater is not specified in any study.

This shows that their water footprint, both in terms of quality and especially quantity, have not been a priority to the LCA studies. Since it is an issue of high importance, especially for regions that deal with water shortage and frequent draughts, it demonstrates the need to study water footprint of concrete production and its constituents.

3. CONCRETE WATER FOOTPRINT ASSESSMENT METHODOLOGIES

3.1. ABSTRACT

Concrete is the single most widely used material in the world and is only surpassed by water in terms of consumption. By 2013, 4 billion tonnes of Portland cement were produced worldwide, enough to produce about 30 billion tonnes of cementitious materials, which represents more than 4 tonnes per person per year. The high-water consumption and large amount of wastewater generated in the concrete industry has become a very important environmental issue. Due to the large global use of concrete, it is essential to correctly assess the environmental impacts of this material including impacts related to water consumption. Life cycle perspective is important because it allows identifying and reducing water related potential environmental impacts associated with products. In concrete life cycle assessment, these impacts are not considered mostly because of lack of data. There are several methodologies for water footprint assessment, as the water footprint assessment tool and the ISO 14046:2014 standard -that is based on life cycle assessment (ISO 14044)-, as well as sustainable reporting guidelines, which include water assessment for organizations. The aim of this chapter is to evaluate existing water footprint methodologies based on life-cycle assessment, their concepts and difficulties, and link them to concrete industry. Out of at least eighteen existing water footprint initiatives, it was found that four of them are feasible for cement-based materials industry, however there are differences between the definitions and criteria adopted by each methodology.

Keywords: Concrete water footprint. Cement based materials. Sustainability. Life cycle assessment.

3.2. INTRODUCTION

Concrete is the single most widely used material in the world (Flower and Sanjayan 2007) and is only surpassed by water in terms of consumption. In 2018, more than 4 billion tonnes of Portland cement were produced worldwide (USGS 2019), enough to produce about 30 billion tonnes of concrete, which represents almost 4 tons of concrete per person per year.

Due to the large global use of concrete, it is essential to correctly assess its environmental impact. Among the main environmental impacts in concrete production are: energy consumption, raw material consumption, waste generation and CO_2 emissions (Meyer 2009). Water consumption is an important impact that has been relatively ignored.

As economies develop and population grows concentrated in certain regions, water demand increases rapidly, for this reason many regions face scarcity challenges (Bodley 2012). Moreover the impact of climate change will aggravate water problems, as it will probably lead to greater variability in supply in many countries (Intergovernmental Panel on Climate Change 2008). In response, water management systems must be more efficient in addressing the challenges of water scarcity and assessing water resources.

The aim of this study is to evaluate existing water footprint methodologies, their concepts and difficulties, and link them to concrete industry. The study of water footprint methodologies for cement-based materials and their challenges, improvement on existing methodologies and development of new ones that could be adapted to the different realities of many companies, represents a major contribution to a subject that has been little studied. The measurement of the water footprint in different cement-based materials production will later serve to perform better life cycle analysis related to these products.

3.3. IMPORTANCE OF LIFE CYCLE PERSPECTIVE

To understand and reduce concrete environmental impacts during the different stages of the product´s life, a life cycle assessment (LCA) approach is needed. Regarding water consumption aspect, the ISO 14046 water footprint standard (International Organization for Standardization 2014) was published as a complement for the ISO

14040 and ISO 14044 life cycle assessment standard (International Organization for Standardization 2006a, b).

In concrete production LCAs found in literature, inventory analysis data availability and quality are identified as a severe problem (Petek Gursel et al. 2014a). Current concrete LCA literature focuses on energy use, greenhouse gases emissions and impacts of using waste as raw materials. Most of the time, water consumption impacts are not considered. As a result, water consumption uncertainty is evident in all life-cycle phases. In addition, location should be taken into account when assessing water sources and extraction for the many production processes (Cicas et al. 2007).

In order to understand the environmental implications of cement based materials and compare it to other building materials, a comprehensive assessment and reliable and complete data are needed (Petek Gursel et al. 2014b). Regarding lack of data, filling these gaps will require thorough measuring (Reap et al. 2008; Van den Heede and De Belie 2012).

3.4. THE WATER FOOTPRINT CONCEPT

The water footprint concept was introduced in by prof. Hoekstra in 2002 (Hoekstra 2003). The water footprint of a person, group or nation is defined as the total fresh water used to produce the goods and services consumed by that person, group or country along the production and supply chain (Chapagain and Hoekstra 2004). It is generally measured in units of volume of water (Casado et al. 2008). More recently, the ISO 14046 standard defines the water footprint as a parameter (s) that quantifies the potential environmental impacts related to water (International Organization for Standardization 2014). The calculation of the water footprint ends up being a complementary indicator in assessing the environmental impacts of natural resources used by humanity.

3.5. WATER CONSUMPTION IN CONCRETE PRODUCTION

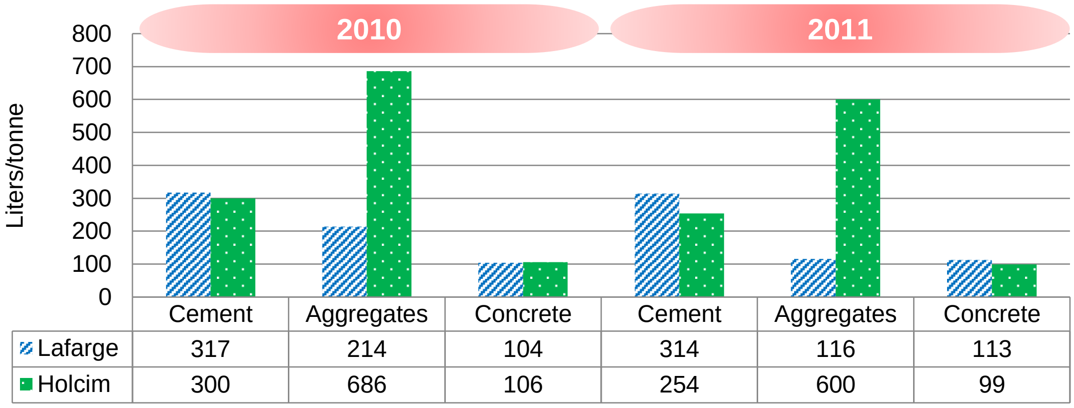
The available data on water consumption in concrete production shows diverse ranges for each application (Nisbet et al. 2002). When we consider the global volumes of cement based materials production, the magnitude of emissions and water use become significant (Petek Gursel et al. 2014a). For instance, a typical ready-mix plant may produce 500 m^3 of concrete per day. Based on 200 liters/m^3 of concrete, the plant consumes 10 000 liters of water per day only for concrete mixing. It must be noted that after concrete being placed there is water evaporation and water integrated into the product.

According to Marceau et al. (2006), water consumption during quarrying is about 60% of the total use. For quarrying, it must be considered that there is also water consumption in washing the aggregates, water integrated into the aggregates because of their origin and water gained during transportation and material storage due to precipitation, humidity, etc. The drainage of the quarry can impact the river basin with high temperatures, altered acidity or the presence of solids depending on the discharge point (World Business Council for Sustainable Development 2012).

In its 2012 Sustainability Report, Holcim states that in general the use of water increased in 2012 by 16%. Reported values of water consumption have increased as more concrete plants accurately reported their water consumption in 2012 when the water management strategy at group level started (Holcim 2013). In 2012, the extraction of water measured and reported by Lafarge also increased. The installation of measurement devices in several locations allowed to correct previous underestimation (Lafarge 2012b). Both, Holcim and Lafarge's cases demonstrate the growing concern with water assessment tools for proper water management.

Figure 3-1 shows the comparison between Lafarge and Holcim in terms of water consumption in the production of cement, aggregates and concrete for 2010 and 2011. Overall, similar values are observed. Regarding aggregates, Holcim presents values above 600 liters/ton, a value 3 times higher than Lafarge. As global averages of a commodity with quite homogeneous production technology, such discrepancy may be the result of differences on the inventory method.

Figure 3-1 Comparison of Lafarge´s (Lafarge 2012a) and Holcim´s (Holcim 2012) water consumption for 2010 and 2011.



	Cement	Aggregates	Concrete	Cement	Aggregates	Concrete
▨ Lafarge	317	214	104	314	116	113
🟩 Holcim	300	686	106	254	600	99

Source: (Mack-Vergara et al. 2015).

Literature reports 500-750 liters of water are used for washing out a 8 m^3 truck after every deliver (Paolini and Khurana 1998; Chini et al. 2001; Nisbet et al. 2002; Ekolu and Dawneerangen 2010) which represents water consumption of 60-90 liters/m^3 of concrete. Washing the concrete plant yard (Sealey et al. 2001), sprayed water to control dust during quarrying, cement production and concrete production (Ekolu and Dawneerangen 2010) and water consumption in buildings and offices in concrete production plants (Holcim 2013) must also be considered. During the use phase of the concrete there is water used to moisture the forms before placing the concrete and water for concrete curing after the concrete has been placed. However, we found almost no data on those aspects.

Part of this water becomes wastewater in a cement plant. When water used for the different production processes is combined with storm water run-off, significantly large quantities of waste water are generated (Ekolu and Dawneerangen 2010). The total amount of wastewater depends on the amount of precipitation. Literature reports total waste water disposed of 35 liters/m^3 (Marceau et al. 2007). However, this value is lower than truck wash water alone mentioned before.

Since ready-mix concrete waste has a pH of typically 11.5 or higher it is classified as hazardous waste from European Environmental Agency's Special Waste Regulations (Sealey et al. 2001) and US Environmental Protection Agency legislation (Paolini and Khurana 1998; Chini et al. 2001; Ružinski et al. 2011).

3.6. METHODOLOGY

A literature review was conducted in order to contextualize the study, describing the environmental impact of water consumption in concrete production, the water footprint concept and importance of life cycle analysis perspective. The peer-reviewed research literature databases scopus and google scholar were used for the search. The keywords include: cement, concrete, cementitious material, water use, water consumption, water footprint and life cycle assessment. Evaluation of available water footprint methodologies was also performed. From these existing methodologies, four methodologies that have compatibility with the cement-based materials sector and are considered robust were selected. Many of the water footprint related methodologies that were found, had specific interests such as agriculture products. Therefore, only methodologies that could be applied to any product or that was focused in cementitious materials were included. These four methods were evaluated and compared based on their main characteristics and considerations regarding water sources, water uses, level of application, approach, geographical focus and sectoral focus.

3.7. WATER FOOTPRINT ASSESSMENT METHODOLOGIES

Based on the Water for Business report (World Business Council for Sustainable 2012), eighteen initiatives supporting the sustainable use of water were studied in order to find water assessment methodologies compatible with LCA and the cement based materials sector. Four methodologies were selected to be evaluated and compared. Two of them, -The Water Footprint Assessment Tool and the ISO 14046 Standard- are methodologies that can be applied to a wide range of products, services or companies, while the two other methodologies –The Global Environmental Management Initiative and the Concrete Product Category Rules- are focused in cement-based materials industry.

3.7.1. WATER FOOTPRINT ASSESSMENT TOOL

In this approach, the water is classified as blue, green (mainly rainwater) and grey (polluted water). All water that only passes through the system, not being diverted or has not altered its composition, is not considered in the water footprint.

The Water Footprint Assessment Tool (The water footprint network 2014) is available in the The Water Footprint Network website and has many features such as quantifying and mapping the operational and supply chain water footprint of a product, assessing sustainability of the product water footprint, identifying ways to reduce the product water footprint, etc.

3.7.2. GLOBAL ENVIRONMENTAL MANAGEMENT INITIATIVE (GEMI) GLOBAL WATER TOOL FOR THE CEMENT SECTOR

The WBCSD Global Water Tool (GWT) allows companies and organizations to allocate water use and assess risks relating to its global operations and supply chains. A customized version of GWT for the Cement Sector was developed in 2013 (World Business Council for Sustainable Development 2014b) which integrates global data on groundwater, surface water, precipitation, etc. This water footprint assessment tool consists of an excel data sheet where water inventories for cement, aggregates and ready-mix concrete are inputted each one by site, country and region and by water types of resources and water uses. As an output, this tool presents important indicators such as Cement Sustainability Initiative (CSI) and GRI Water sustainability reporting indicator.

3.7.3. PRODUCT CATEGORY RULES FOR CONCRETE

The Product Category Rules (PCR) are the guides to produce an Environmental Product Declaration (EPD) which is an example of environmental seal Type III, defined in ISO 14025: 2006, Environmental Labels and Declarations standard (International Organization for Standardization 2006c). The Concrete PCR (World Business Council for Sustainable Development 2013a) defines parameters such as environmental impact indicators and inventory indicators to be declared and the way in which they must be declared and reported. An important feature found is that it describes the stages of the life cycle of a specific product, including the rules for this calculation and defines the conditions under which construction products can be compared.

3.7.4. ISO 14046:2014 ENVIRONMENTAL MANAGEMENT – WATER FOOTPRINT

The ISO 14046:2014 standard (International Organization for Standardization 2014) defines the water footprint as a parameter(s) that quantifies the potential environmental impacts related to water. This methodology is the new international standard that specifies the principles, requirements and guidelines for assessment and information about water footprints. It applies to products, processes and organizations based on life-cycle assessment. Among the benefits of using this standard are to identify ways to reduce the environmental impacts of water consumption, improve efficiency in the product and production processes and meet the expectations regarding greater environmental responsibility. This international standard also intends to provide consistency and credibility in the results of studies water footprint studies.

3.8. COMPARISON OF AVAILABLE WATER FOOTPRINT ASSESSMENT METHODOLOGIES

A comparison of four selected methodologies was performed. The classification adopted is based on the ISO 14044 standard and the idea is to find methodologies that are compatible with cement-based materials LCA. Table 3-1 shows a comparison of different available water footprint assessment methodologies. Significant differences were found mainly regarding type of resource and water use. For the purposes of this study, concrete PCR methodology seems more complete. Further research is needed to create and implement a complete life-cycle based methodology that comprises all approaches.

Table 3-1 Comparison of available water footprint assessment methodologies for cement-based materials.

Item	WFAT	GEMI-CSI	PCR concrete	ISO 14046
Level of application				
Products	x	x	x	x
Processes	x		x	x
Organizations	x	x		x
Approach				
Goal and scope	x		x	x
Accounting	x	x	x	x
Impact assessment	x		x	x
Interpretation	x		x	x
Geographical focus				
Global	x	x		x
Watershed distinctions	x	x	x	x
Sectoral focus				
Global	x			x
Cement based materials sector		x	x	
Resource				
Precipitation	green	x	x	x
Surface water	blue	x	x	x
Sea water		x	x	x
Soil water content	green			x
Groundwater	blue	x	x	x
Fossil water	blue	x	x	x
Brackish water		x	x	x
Effluents (includes effluents from other organization)	grey	x	x	
Public water supply		x	x	
Recycled or reused water		x	x	
Water use				
Evaporation, evapotranspiration	x	x	x	x
Water integrated into products	x	x	x	x
Discharge into different watershed or sea	x	x	x	x
Water displacement, from a water source to another within a watershed	x			x
Water quality change - pollution, purification	x		x	x
Other forms - use in continuous flow water to drive turbines, lost via transmission		x		x

Source: (Mack-Vergara et al. 2015).

The two methodologies that are focused in cement-based materials do not take into account the soil water content item, the reason is because this item is more related to agriculture. Another important difference found is that the methodologies focused in cement-based materials are more worried about recycling and reusing water which are very interesting practices for the cement-based materials industry.

3.9. CONCLUSIONS

When considering the overall production of cement-based materials, ignoring values because they are considered insignificant or due to lack of information may result in loss of important environmental impacts in LCA results. This is the case of water consumption in concrete production.

Despite the annual production of more than 4 billion tons of cement, the literature on environmental management of cement-based materials is limited and inconclusive, focusing mostly on input energy and associated CO_2 emissions.

In order to asses cement based materials water footprint, water consumption data per source and activity is needed, however little information is currently available.

Out of at least eighteen existing water footprint methodologies, it was found that four of them are feasible for concrete industry. However, there are differences between the definitions and criteria adopted by each methodology. Further research is needed to create and implement a complete life cycle-based methodology, which comprises all approaches.

4. LIFE CYCLE WATER INVENTORY IN CONCRETE PRODUCTION – A REVIEW

4.1. 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 since they have been calculated using different approaches. 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 chapter 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.

Keywords: Cementitious materials production. Water consumption. Water use. Water footprint. Life cycle assessment.

4.2. INTRODUCTION

The water footprint 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 (Intergovernmental Panel on Climate Change 2008; World Business Council for Sustainable Development 2009b, 2012, 2014b; Holcim 2010; United Nations Global Compact 2011). Water conservation, water footprints, and water management are nowadays of increasing importance in the sustainability agenda of many organizations (Holcim 2012; Lafarge 2012a, 2014; BASF 2014; Hu et al. 2016).

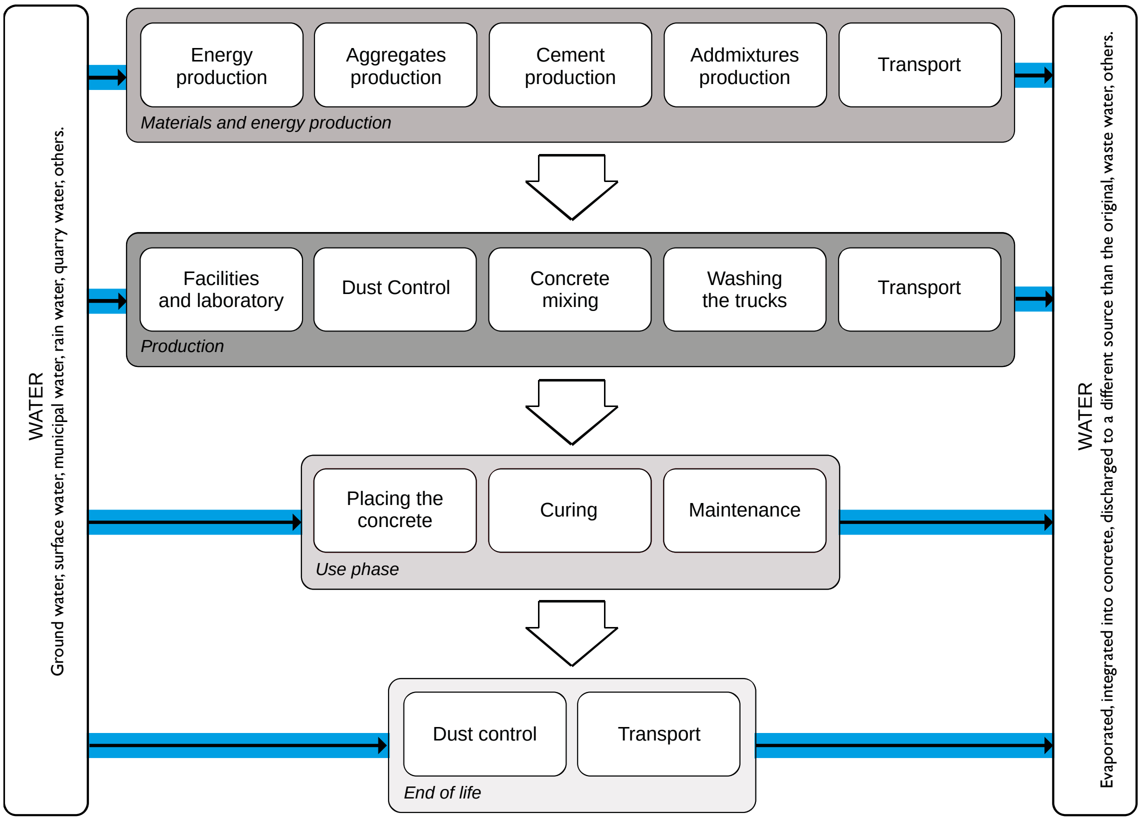
Water use can be classified as consumptive –water that is withdrawn from one source and discharged into a different source or not returned, such as water integrated into a product or evaporated- or degradative which entails changes in water quality (Ridoutt and Pfister 2012; Pfister et al. 2015). Water 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 (O’Brien et al. 2009; Pfister et al. 2009; World Business Council for Sustainable Development 2012; International Organization for Standardization 2014). 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 (Worrell et al. 2001; Van Oss and Padovani 2003; World Business Council for Sustainable Development 2009a; US EPA 2010; Hasanbeigi et al. 2012; Amato 2013). For these aspects, large worldwide datasets are available (World Business Council for Sustainable Development 2009a). 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 2012, 2013, 2015; Holcim 2012, 2013, 2014, 2015; Lafarge 2012a) 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 2014b) 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.

Figure 4-1 Concrete's life cycle including four phases: materials and energy production, concrete production, use and end of life.



Source: (Mack-Vergara and John 2017).

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 Figure 4-1. 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 study 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.

4.3. METHODOLOGY

In Figure 4-1 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 Figure 4-1 there is water in the production of admixtures which is one of the components of concrete. In a more specific study and where 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 (Scown et al. 2011; Lampert et al. 2015; Simons 2016). Water for energy is considered indirect water use as can be seen in Figure A. 1 to Figure A. 5 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 4.5) 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 study 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 study, 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 (Rudolf et al. 2013; World Business Council for Sustainable Development 2013a; International Organization for Standardization 2014), 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 (European Commission 2010a; Hoekstra et al. 2011; Rudolf et al. 2013; World Business Council for Sustainable Development 2013b, a; Ecoinvent 2014; International Organization for Standardization 2014). 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 study.

The concepts and definitions from seven water inventory methodologies that are applicable to cement and concrete materials were summarized in Table 4-1. The implications of the various methodologies on water inventory figures were tested in a hypothetical concrete production scenario. The water requirement for the hypothetical scenario of 1 m3 concrete production is presented in Table 4-3. Figure 4-8 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.

Table 4-3 and Figure 4-8 represent a hypothetical scenario based on figures from the literature and 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 enough detail and/or including all water sources.

4.4. RESULTS

4.4.1. 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. (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 (World Business Council for Sustainable Development 2013b) 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 (Lafarge 2012a; Cemex 2015). 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.

4.4.2. WATER INVENTORY TERMINOLOGY

Seven water inventory methodologies were selected to be evaluated and compared. The water footprint assessment manual by 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 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 2013a) and the Global Water Tool (GWT) for the Cement Sector (World Business Council for Sustainable Development 2013b) focus on the concrete and cement industry. Even though the Concrete PCR (World Business Council for Sustainable Development 2013a) 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 (European Commission 2010a; Hoekstra et al. 2011; Rudolf et al. 2013; World Business Council for Sustainable Development 2013b, a; Ecoinvent 2014; International Organization for Standardization 2014) are inconsistent since they have different considerations for water sources and water uses. Table 4-1 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 (Rudolf et al. 2013; World Business Council for Sustainable Development 2013a; International Organization for Standardization 2014).

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 2013a). In-stream water use refers to surface water resources, used directly in the watercourse. Examples of in-stream water use are in-stream aggregates mining, transport of raw materials through navigation and hydropower. Off-stream water use is water removed from its source during a product's life cycle. All methodologies 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 2013a) and Ecoinvent (Ecoinvent 2014) consider in-stream water use.

Table 4-1 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	GaBi	GWT cement	ILCD	ISO 14046	PCR Concrete	Ecoinvent
		(Hoekstra et al. 2011)	(Rudolf et al. 2013)	(World Business Council for Sustainable Development 2013b)	(European Commission 2010a)	(International Organization for Standardization 2014)	(World Business Council for Sustainable Development 2013a)	(Ecoinvent 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.

Source: (Mack-Vergara and John 2017).

Next, the water withdrawal approaches are reviewed. The water footprint assessment manual by 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 (World Business Council for Sustainable Development 2013b) 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 4-2 presents the water sources considered by the seven methodologies.

Table 4-2 Comparison of water sources considered by each methodology. Only PCR Concrete is consistent with ISO 14046.

	Hoekstra	GaBi	GWT cement	ILCD	ISO 14046	PCR Concrete	Ecoinvent
Water sources	(Hoekstra et al. 2011)	(Rudolf et al. 2013)	(World Business Council for Sustainable Development 2013b)	(European Commission 2010a)	(International Organization for Standardization 2014)	(World Business Council for Sustainable Development 2013a)	(Ecoinvent 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.

Source: (Mack-Vergara and John 2017).

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. (2011) considers as water 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 (World Business Council for Sustainable Development 2013b), 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 2013a) and the Ecoinvent database (Ecoinvent 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.

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 (World Business Council for Sustainable Development 2013b) only consider water used as water consumption. The rest of the methodologies (European Commission 2010a; Hoekstra et al. 2011; Rudolf et al. 2013; World Business Council for Sustainable Development 2013b) 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.

4.5. 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 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.

4.5.1. WATER INVENTORY FIGURES FOR CEMENT PRODUCTION

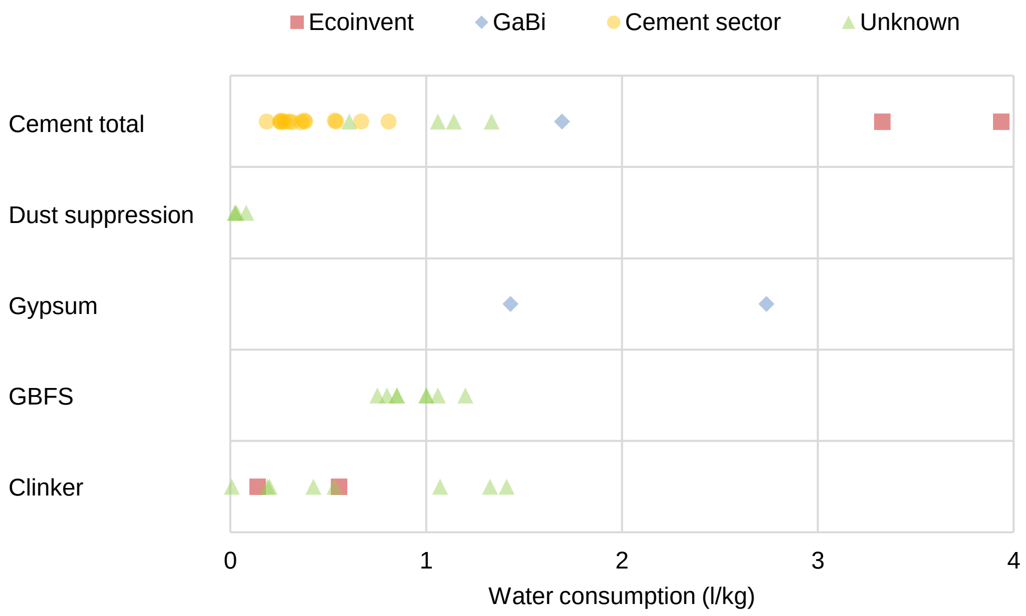
Figure 4-2 reports data from cement production, including different cement components. In addition, water figures for site dust suppression were also reported.

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 (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 strategies 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. (2010b) gave figures of 0.200 H kg/kg for a French cement clinker production. 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 are from the European reference Life-Cycle Database (European Commission 2006).

Figure 4-2 Water inventory figures for cement production. a. Cement as total; b. Dust suppression; c. Gypsum; d. GBFS; e. Clinker.



Source: (Mack-Vergara and John 2017).

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 ($CaSO_4$-2.H_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 (Cemex 2011, 2013, 2015; Holcim 2012, 2013, 2014, 2015; Lafarge 2012a; Argos 2014) 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 Bribián et al. (2011) presented figures above 3 H kg/kg for European cement production, values that are outliers.

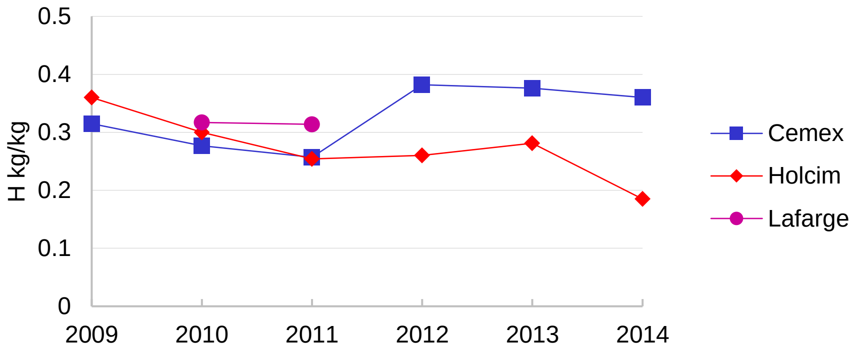
Chemically bounded water data were not found and is clearly a limitation in water inventory, however it has to be included for water balance (Pfister et al. 2015). In the case of cement production, considering the chemically bounded water in clay that is released during clinker production is interesting. For a raw estimation, considering 300 kg of clay per ton of clinker and 10% water content, 30 H l/ton 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) and/or pre-calciner (0.023 H kg/kg) (Marceau et al. 2006).

Figure 4-3 presents global data from Cemex, Holcim and Lafarge for the total direct water consumption in cement production (Cemex 2010, 2011, 2012, 2013, 2014, 2015; Holcim 2010, 2011, 2012, 2013, 2014, 2015; Lafarge 2012a). These data do not include water consumption by industrial operations 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 methodology and estimation of water consumption or even changes in the companies' water related policies.

Figure 4-3 Water consumption in cement production, global averages data from Cemex, Holcim and Lafarge.

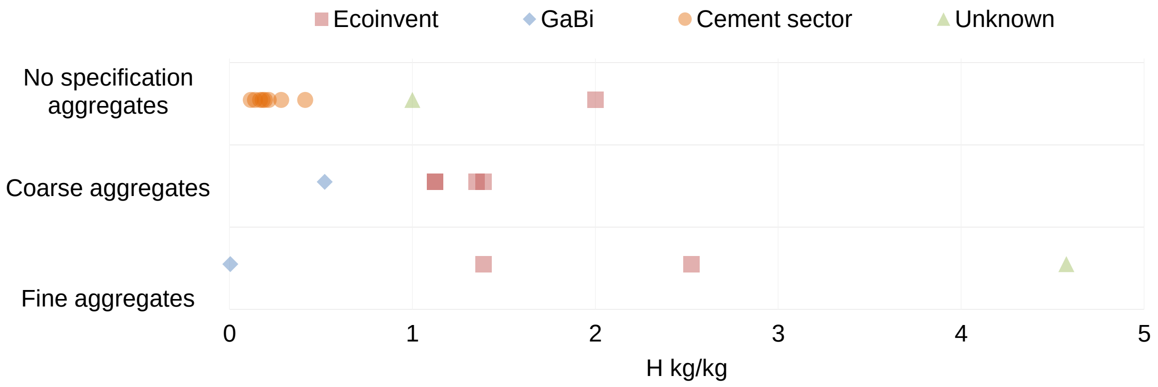


Source: (Mack-Vergara and John 2017).

4.5.2. WATER INVENTORY FIGURES FOR AGGREGATES PRODUCTION

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

Figure 4-4 Water inventory figures for aggregates production. a. Fine aggregates; b. Coarse aggregates; c. No specification aggregates. Cement Sector are global averages from various companies.



Source: (Mack-Vergara and John 2017).

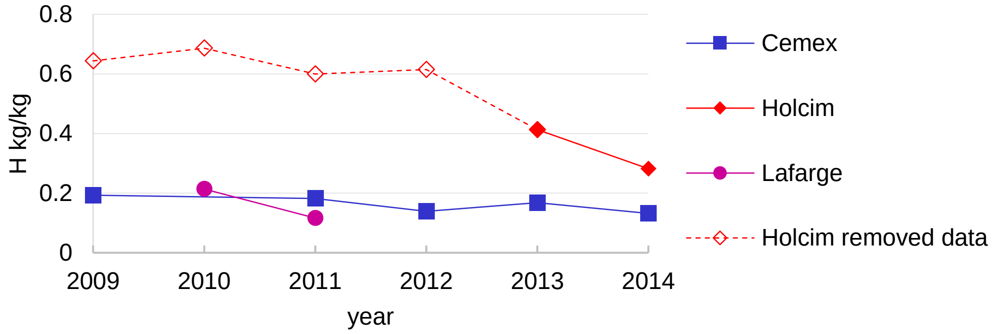
Dispersion seems to be high even when considering the global average figures generated with the same methodology; for example, the data produced by Cemex, Holcim and Lafarge varies between 0.116 and 0.413 H kg/kg (Cemex 2012, 2013, 2015; Lafarge 2012a; Holcim 2014, 2015).

The differences are probably a combination of the companies' water management practices as well as the production process setups (e.g., aggregates washing reported by Cemex). 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 2012, 2013) were updated. Holcim declared in their 2014 Sustainability Report that before 2013 (Holcim 2015) they only measured water withdrawal for aggregates and not water consumption. They had published water withdrawal data as water consumption. The impact of the revisions is significant, as presented in Figure 4-5 where it can be observed data calculated with the same methodology for different companies. Some companies that participate of the CSI project 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.

Quarry water is also 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 models 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 aggregates 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.

Figure 4-5 Original and reviewed water consumption in aggregates production, global average data for Cemex, Holcim and Lafarge.

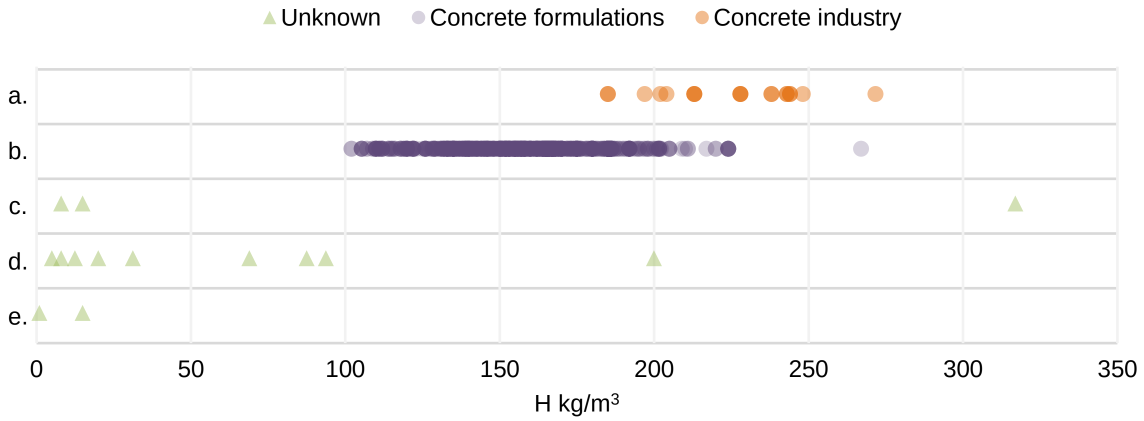


Source: (Mack-Vergara and John 2017).

4.5.3. WATER INVENTORY FIGURES FOR CONCRETE PRODUCTION

Figure 4-6 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 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 than the formulation water.

Figure 4-6 Water inventory figures for concrete production. a. Concrete total b. Concrete mix water; c. Washing trucks out; d. Washing trucks off; e. Cleaning the yard. Data do not include water used for raw materials.



Source: (Mack-Vergara and John 2017).

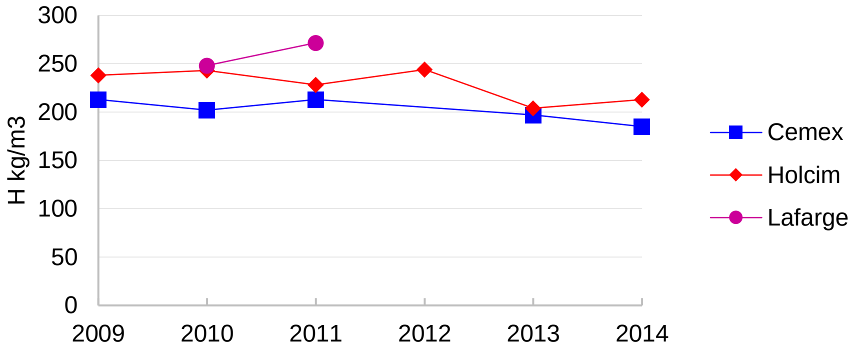
Concrete total in Figure 4-6 -which includes all the water consumption for concrete production as reported by Holcim, Cemex and Lafarge-, does not differ significantly from the formulation water and in some cases is even smaller. This result may be due to the high-water recycling rate of these companies 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.

Figure 4-7 presents the data published by Cemex, Holcim and Lafarge concerning the direct total water consumption for concrete production between 2009 and 2014 (Cemex 2010, 2011, 2012, 2013, 2014, 2015; Holcim 2010, 2011, 2012, 2013, 2014, 2015; Lafarge 2012a). 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.

Figure 4-7 Water consumption in concrete production, global average data for Cemex, Holcim and Lafarge.



Source: (Mack-Vergara and John 2017).

4.6. 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. In addition, 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 (World Business Council for Sustainable Development 2013b) 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 (Qadir et al. 2007; Junjie et al. 2007; Peñate and García-Rodríguez 2012; Zhao et al. 2012; McGinnis et al. 2013; González-Bravo et al. 2015) 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 aggregates 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 (Nebot et al. 2007; Junjie et al. 2007; Constant et al. 2010) 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; Wahidul K. Biswas 2009; Elimelech and

Phillip 2011). 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 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 (World Business Council for Sustainable Development 2013b) and the Concrete PCR (World Business Council for Sustainable Development 2013a). 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. (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 (World Business Council for Sustainable Development 2013b). 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 (World Business Council for Sustainable Development 2013b) and the Concrete Product Category Rules (PCR) (World Business Council for Sustainable Development 2013a); however, in the GaBi Database and Modelling Principles (Rudolf et al. 2013) and the Ecoinvent database (Ecoinvent 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 study, 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. 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.

4.7. 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 4-3. Figure 4-8 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.

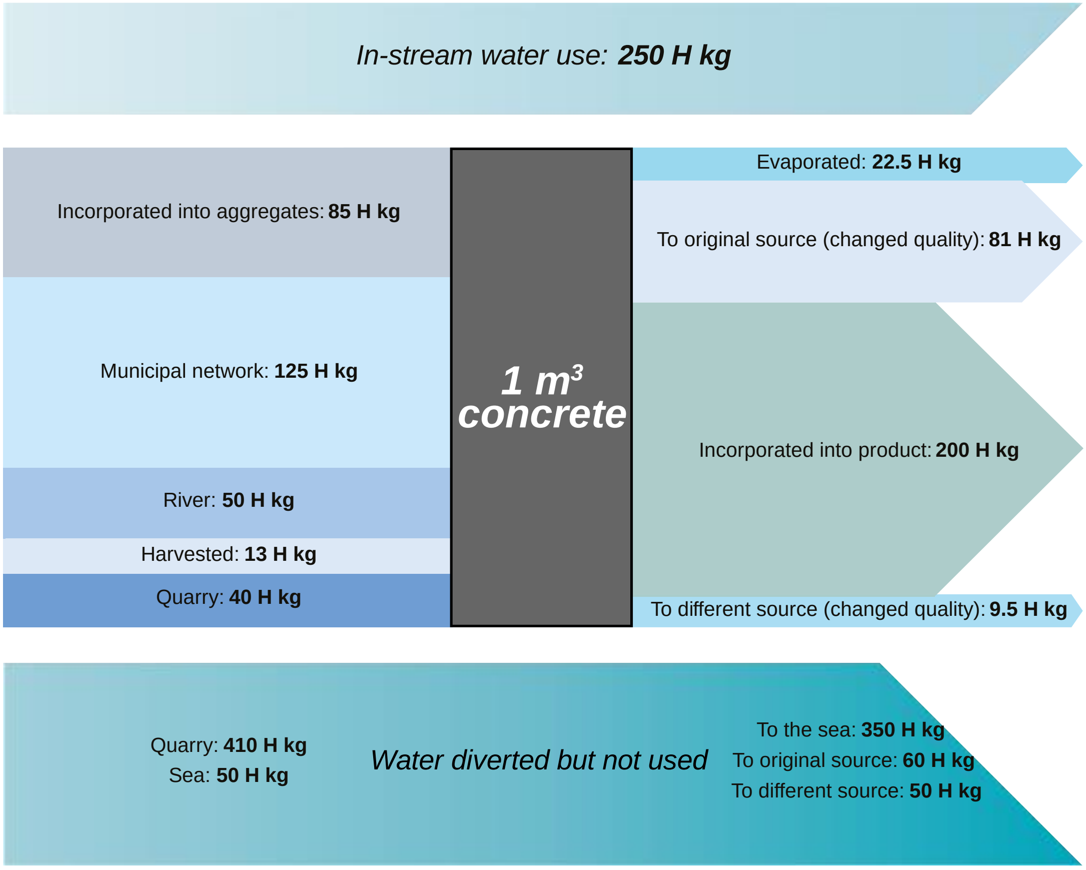
Table 4-3 Hypothetical scenario of water requirement per activity for concrete production.

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

Source: (Mack-Vergara and John 2017).

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 (Marceau et al. 2007; Cemex 2015) * 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 plant's 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.

Figure 4-8 Hypothetical scenario of the water balance for 1 m^3 concrete production.



Source: (Mack-Vergara and John 2017).

Table 4-4 summarizes the results of various water inventory methodologies applied to the scenario presented in Table 4-3 and Figure 4-8.

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 formulation, approximately 200 kg/m^3. GWT for the Cement Sector (World Business Council for

Sustainable Development 2013b) 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 results from Hoekstra et al. (2011) are 2.2 times higher than GWT for the Cement Sector (World Business Council for Sustainable Development 2013b) 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 (World Business Council for Sustainable Development 2013b), 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 (World Business Council for Sustainable Development 2013b) 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.

Table 4-4 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.

	Hoekstra	GaBi	GWT cement	ILCD	ISO 14046	PCR Concrete	Ecoinvent
(H kg/m^3)	(Hoekstra et al. 2011)	(Rudolf et al. 2013)	(World Business Council for Sustainable Development 2013b)	(European Commission 2010a)	(International Organization for Standardization 2014)	(World Business Council for Sustainable Development 2013a)	(Ecoinvent 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

Source: (Mack-Vergara and John 2017).

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.

4.8. CONCLUSIONS

The aim of this study 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 aggregates 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 are 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.

5. CRITICAL FLOWS FOR WATER QUALITY ASSESSMENT IN CONCRETE PRODUCTION

5.1. ABSTRACT

The aim of this chapter is to propose and test a streamlined water footprint methodology for concrete production regarding water quality through identification of critical flows. In this study, the reduction of flows for the streamlined methodology is performed based on the contribution of the substances to the potential environmental impacts related to water and the feasibility to measure these flows on site. The results limit the amounts of flows to be measured from 1580 to 5: Zinc, Lead, Nitrate, Nitrogen oxides and Sulfur dioxide. These substances are among the most important contributors to the potential environmental impacts related to water, are under the control of the concrete producer and are easy to measure in the cement and concrete production plants. In addition, these substances represent at least 80% of the variance of the complete inventory. A comparison between a complete water footprint of concrete production and a streamlined water footprint based on the results from this study shows that 34% for human non-carcinogenic toxicity in clinker production, 96% for aquatic acidification in clinker production and 100% for marine eutrophication in concrete wastewater are covered by the streamlined methodology. The rest of the impacts ar controlled by processes where the company has no influence. The results from this study will allow companies to measure and assess their water footprint including quality. This is quite relevant in times of increasing concrete demand and on the other hand increasing water scarcity in many regions of the world.

Keywords: Foreground processes. Cementitious materials production. Streamlined life cycle assessment. Sustainable construction.

5.2. INTRODUCTION

Water related environmental impacts are of great concern and both diminishing quality issues and scarcity are a perceivable reality in various places such as California, São Paulo, Cape Town and Panama (du Plessis 2017; Agência Nacional de Águas 2018; Flint et al. 2018; Ministry of Foreign Affairs 2018). These impacts are expected to worsen in many regions of the world due to urban population growth, industrialization, and climate change (Veldkamp et al. 2017; Mukherjee et al. 2018).

The production of cement based products is approximately 15 billion m^3 (Scrivener et al. 2018). The increase in concrete production is expected due to population growth and consequential housing and infrastructure demand. Abundant literature on environmental impact of concrete production mostly report energy consumption, and CO_2 emissions. Despite concrete consuming water, few LCA studies report water related impacts. The lack of a suitable life cycle assessment (LCA) methodology for water is a more evident reason. It is usually believed that water for concrete production consist only of the mixing water. The fact is that concrete production water use goes beyond mixing water and includes activities such as dust control, truck cleaning, yard cleaning in addition to water used for raw materials production -aggregates and cement (Mack-Vergara and John 2017; Miller et al. 2018). It is interesting that industry was the first to promote water efficiency through measurements in their plants. The Water Tool from CSI (World Business Council for Sustainable Development 2013b) clearly demonstrates that they are more advanced than the LCA community in this regard.

It is important to identify opportunities for impact reduction through LCA and water footprint tools and measuring is fundamental for this purpose (International Organization for Standardization 2014). However, there are many limitations for a complete LCA such as lack of data transparency and data availability, complexity and associated cost and time (Agis et al. 1999; Hochschorner and Finnveden 2003; Hanes et al. 2013). In the case of water related impacts, life cycle impact assessment (LCIA) methods with different impact categories require inventorying many flows (not only going to water, but also to air and soil), some of them very hard to measure. These limitations represent a great obstacle for LCA. As a result, although very extensive LCAs have been performed, a complete LCA has never been performed with primary data since data from background processes which are usually modelled using lifa cycle inventory databases (Hauschild et al. 2017). Another consequence is the lack of reliability of these LCA. All these limitations prevent LCA from becoming more prevalent (Rampuria 2012).

Thus, many authors agree that there is a need for simplification (Hochschorner and Finnveden 2003; Wangel 2018; Guérin-Schneider et al. 2018) to make it more feasible and more immediately relevant without losing the key features of a life-cycle approach (Agis et al. 1999). For instance, Lasvaux et al. (2016) demonstrates the possibility of a reduction of impact assessment indicators for construction materials without losing relevant information. The aim of this study is to propose and test a streamlined water footprint methodology for concrete production regarding water quality through identification of critical flows. This methodology will support decision making based on relevant primary data enabling them to accurately identify water impacts reduction opportunities resulting in benefits for the environment, the economy and society.

5.3. METHODOLOGY

Figure 5-1 presents the flowchart of the methodology used in this study.

The water quality impact assessment includes: ionizing radiation (IR), freshwater eutrophication (FWE), marine eutrophication (ME), freshwater ecotoxicity (FWET), marine ecotoxicity (MET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), aquatic acidification (AA), freshwater sedimentation ecotoxicity (FWSET) and marine sedimentation ecotoxicity (MSET).

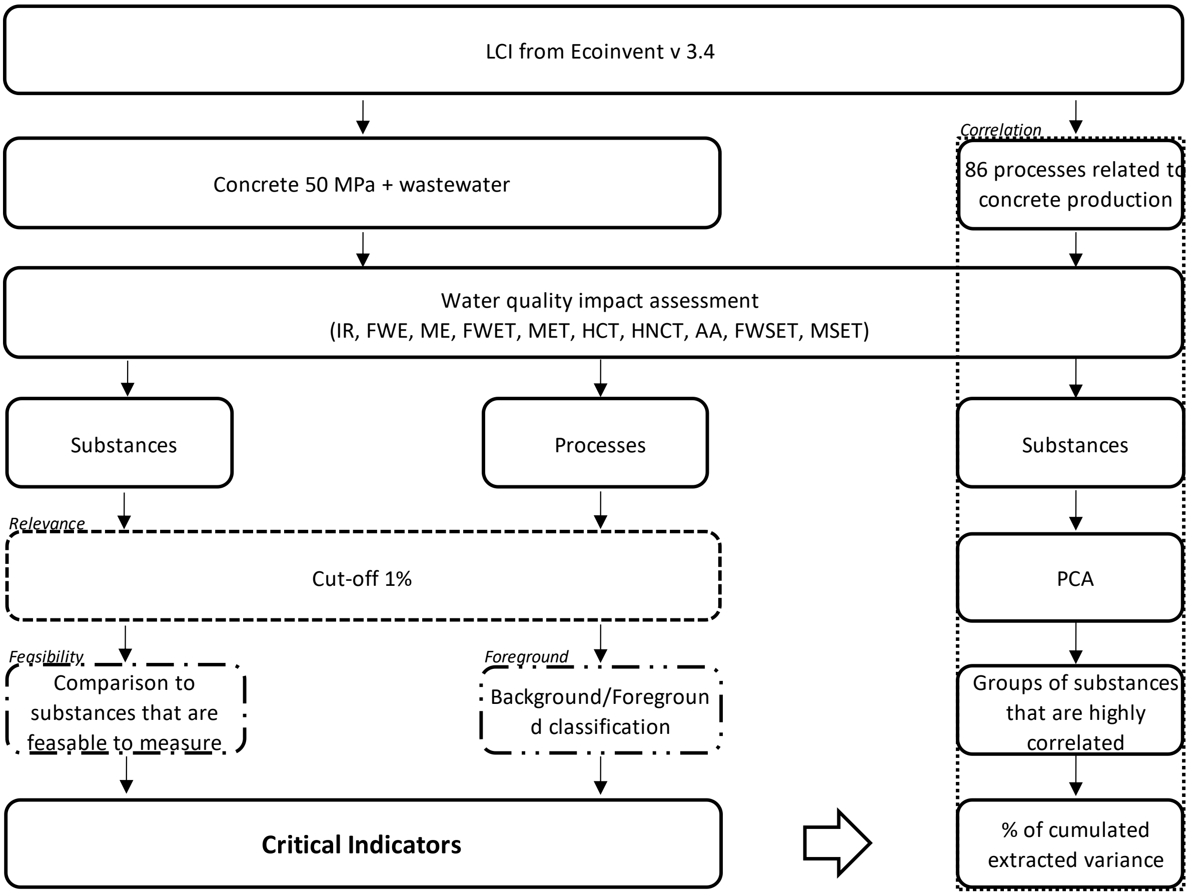
The identification of critical flows in this study was done based on the relevance of the flows to the potential environmental impacts, the influence that the concrete industry has on the processes that control these flows and the feasibility to measure these flows. Afterwards, each step is explained.

5.3.1. WATER FOOTPRINT INVENTORIES AND IMPACT CATEGORIES

This study is based on a cradle to gate analysis –water footprint of the production of concrete. 86 processes from specific regions such as Switzerland (CH), United States (US), Germany (DE) and Canada (CA) - unit process, cut-off approach were selected from the life cycle inventory database Ecoinvent version 3.4 (see Appendix E Table E. 0-1). Mixed inventories i.e. rest of the world (RoW) and global (GLO) were avoided since GLO consists of average data from different regions covered ecoinvent while RoW is generated as an exact copy of the GLO dataset with uncertainty adjusted

(Ecoinvent 2014). Therefore, these datasets contains higher uncertainties. However, for some processes, this was the only option available (fly ash, silica fume, kaolin, inert filler, chemical admixtures and blasting). The process with higher environmental impact from this list is concrete 50 MPa since it includes all other processes and therefore was chosen for a detailed study.

Figure 5-1 Summary of the methodology used in this study including impact categories applied to ecoinvent processes. The critical indicators are the results of the relevance, applicability and foreground approaches applied to the impact assessment results of the concrete 50 MPa production + wastewater and PCA + varimax applied to 86 processes related to concrete production.



Source: the author.

The impact categories that should be included in a water footprint profile were identified from the main standards and references for water footprint including the ISO Standard 14046 for Water Footprint (International Organization for Standardization 2014), the ISO Technical Report 14073 on how to apply the ISO 14046 Standard (International Organization for Standardization 2017a), scientific papers on water footprint and available water related impact assessment methods and categories within methods from SimaPro version 8.5.

The impact categories that are usually considered in cement and concrete LCA were identified from 27 of the most recent scientific papers on life cycle assessment of concrete and/or cement that were reviewed. For the latter, not only substances but also parameters such as color, conductivity, odor, pH, taste, temperature, turbidity, etc. were identified. However, these types of parameters are not included in life cycle inventory databases since they are not flows. The ISO 14046 Water Footprint standard states that the impacts related to water can be represented by the water footprint profile which comprises several indicators results (International Organization for Standardization 2014). These impact categories can be expressed at midpoint or endpoint level. An endpoint indicator considers the environmental impact at the end of the cause-effect chain i.e. damage to human health, ecosystems and resources. These indicators are the result of many assumptions and considerations after the characterization factor have been applied to the life cycle inventory. A midpoint indicator is calculated by applying the characterization factor directly to the life cycle inventory this means they consider the impact earlier in the cause-effect chain. In this study, the impacts were assessed to a midpoint level since endpoint indicators entails higher uncertainty in their calculation.

Table 5-1 Water related environmental impacts identified from the ISO standard 14046 (International Organization for Standardization 2014), the ISO technical report 14037 (International Organization for Standardization 2017a) and cited literature on water footprint assessment.

Impact category	Reference
Water scarcity	(International Organization for Standardization 2014, 2017a)
Aquatic eutrophication	(Ridoutt and Pfister 2012; International Organization for Standardization 2014, 2017a; Pradinaud et al. 2018)
Aquatic ecotoxicity	(Ridoutt and Pfister 2012; International Organization for Standardization 2014, 2017a; Pradinaud et al. 2018)
Aquatic acidification	(Ridoutt and Pfister 2012; International Organization for Standardization 2014, 2017a; Pradinaud et al. 2018)
Thermal pollution	(International Organization for Standardization 2014, 2017a)
Human toxicity due to water pollution	(Ridoutt and Pfister 2012; International Organization for Standardization 2014, 2017a; Pradinaud et al. 2018)
Ionizing radiation (impact on freshwater ecosystem)	(International Organization for Standardization 2017a)
Ionizing radiation (impact on marine ecosystem)	(International Organization for Standardization 2017a)
Ionizing radiation (impact on human health)	(International Organization for Standardization 2017a)
Sedimentation	(Ridoutt and Pfister 2012)

Source: the author.

According to Pradinaud et al. (2018), emission-related impacts to assess water degradation include aquatic ecotoxicity, eutrophication, acidification and human toxicity. Ridoutt and Pfister (2012) states that water degradation assessment commonly includes freshwater eutrophication, freshwater ecotoxicity, impacts related to human health, marine eutrophication, marine ecotoxicity and sedimentation.

Three impact assessment methods were chosen from the list of available methods in the LCA software SimaPro version 8.5 - ReCiPe 2016 Hierarchist (H) midpoint, IMPACT 2002 and, CML – IA non-baseline. The criteria for selection of these methods was that they should have indicators related to water quantity and/or water quality. The water footprint methods available in SimaPro were not used since they either are focused on freshwater consumption or are results of water consumption and water degradation assessment whilst this study is focused on each water footprint impact category separately.

The ReCiPe 2016 (H) midpoint method was chosen since is an updated method that includes most of the impact categories related to water quality and water quantity. However, since it does not include all the water related impact categories that should be assessed for water footprint, it was complemented with other methods.

A “mixed method” with 10 water quality impact categories was created in SimaPro including the water related impact categories in the ReCiPe 2016 (H) midpoint method, the aquatic acidification impact category from IMPACT 2002 and the freshwater and marine sediment ecotoxicity 100a from the CML – IA non-baseline method (see Table 5-2).

Table 5-2 Life cycle impact assessment methods and categories included in this study (available in SimaPro).

Method	Impact category	Unit
ReCiPe 2016 (H) midpoint	Ionizing radiation	kBq Co-60 eq.
	Freshwater eutrophication	kg P eq.
	Marine eutrophication	kg N eq.
	Freshwater ecotoxicity	kg 1,4-DCB eq.
	Marine ecotoxicity	
	Human carcinogenic toxicity	
	Human non-carcinogenic toxicity	
IMPACT 2002	Aquatic acidification	kg SO_2 eq
CML-IA non-baseline	Freshwater sediment ecotox. 100a	kg 1,4-DB eq
	Marine sediment ecotox. 100a	

Source: the author.

5.3.2. APPLICATION OF IMPACT CATEGORIES

This “mixed method” was applied to the 86 processes using the “compare” tool in SimaPro. The results of the impact assessment where extracted as inventories with the characterization and skip unused options from SimaPro (Supplementary material Table A1). This gives a list of substances, the compartment (air, soil or water) where they are emitted and the total amount (cumulative amount) for each process that is compared in the unit of the respective impact category. This is done for each impact category. The results of the impact assessment were also extracted as process contribution with the characterization option from SimaPro (Supplementary material Table A2). This gives a list of processes and the total amount (cumulative amount) for each process that is compared in the unit of the respective impact category. This is done for each impact category.

The impact assessment methods and categories presented in Table 5-2 where applied to 1 m^3 Concrete, 50 MPa {CA-QC} + 0.09 m^3 of wastewater from concrete production {CH}| concrete production 50MPa, RNA only | Cut-off, U which gathers all other materials that are part of cement-based materials. This process was created using Ecoinvent to include wastewater from washing the trucks. The amount of wastewater for washing the trucks was considered 0.09 m^3 based on a value of 90 l/m^3 for washing the trucks (Maranhão 2015).

The results of the impact assessment were extracted as inventories with the characterization and skip unused options from SimaPro. This gives a list of substances, the compartment where they are emitted and the amount for each process within the concrete production (non-cumulative amount) in the unit of the respective impact category (Supplementary Material Table A3). This is done for each impact category. The results of the impact assessment were also extracted as process contribution with the characterization option from SimaPro. This gives the list of processes and the amount for each process within the concrete production (non-cumulative amount) in the unit of the respective impact category (Supplementary material Table A4).

5.3.3. RELEVANCE APPROACH: LEVEL OF ENVIRONMENTAL SIGNIFICANCE

A cut-off of 1% (i.e. the contribution is more than 1% of the total contribution for a specific impact category) is applied to the results extracted as inventories and process contribution (International Organization for Standardization 2017b). This gives the substances and processes that contribute more than 1%. This was done for the 86 processes compare results and for the 1 m^3 Concrete, 50 MPa {CA-QC} + 0.09 m^3 of wastewater from concrete production {CH}| concrete production 50MPa, RNA only | Cut-off, U process.

5.3.4. APLICABILITY APPROACH

A literature review focused on indexed articles on life cycle assessment in cement and concrete was done to identify water related environmental impacts that are usually included in cement and concrete LCA and which impact assessment methods are usually used. 27 papers from the main scientific papers databases were reviewed. This are the results for the most recent papers in the area from 2013 in order to gather the most recent impact assessment methods and avoid superseded methods. In addition, a list of substances that are commonly measured and controlled in aggregates, cement and concrete production were identified from the industry sustainability and operational reports. This was done in order to categorize the applicability of the results from the relevance and influence approaches, i.e. if the substances that resulted from these analyses could be measured and controlled on site.

The list of substances included by each impact category was extracted from SimaPro including the compartment (air, soil and water) where the substances are emitted and their characterization factors (Supplementary Material Table A5). This was done to compare to the substances that are usually measured by the industry. This resulted in another reduction of substances to be inventoried for a streamlined concrete water footprint.

5.3.5. FOREGROUND APPROACH

The processes that are foreground where identified and analyzed separately. This was done for each impact category for the 1 m^3 Concrete, 50 MPa {CA-QC} + 0.09 m^3 of wastewater from concrete production {CH}| concrete production 50MPa, RNA only | Cut-off, U process. Foreground processes are the ones where the concrete industry could control or influence, according to the foreground definition by ILCD (European Commission 2010a). The main substances were identified, the processes where they happen and the impact category that they influence.

5.3.6. CRITICAL INDICATORS AND APPLICATION

A new impact assessment method was created in SimaPro including the impact categories and flows that were determined to be critical for concrete production. This new impact assessment method was applied to the foreground processes that were identified as critical in concrete production. A comparison of the impact assessment results from a complete water footprint and a streamlined water footprint applied to concrete production was performed. A comparison between the number of flows that should be included in the inventory for a complete water footprint according to the ecoinvent datasets to the number of flows that should be included for the streamlined concrete water footprint was also performed.

5.3.7. PRINCIPAL COMPONENTS ANALYSIS

The statistical method principal components analysis (PCA) with varimax rotation was applied to the inventory of substances extracted from the SimaPro analysis (Jolliffe 2002). This statistical method uses an orthogonal transformation to translate a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components transforming a large set of variables into a smaller one that still contains most of the information in the large set. The PCA demonstrates cluster of correlated substances but not which substances are more important in terms of impacts. Only substances going to water or air were considered. Substances going to soil are not considered since only substances emitted to water or air resulted from the application of the impact categories in Table 5-2 to the processes in Appendix E Table E. 0-1. The raw data used for the PCA includes the substances contribution to different impact categories for the 86 materials (results extracted from SimaPro and tabulated in excel, see Supplementary material Table A6). The PCA was focused on water quality since water consumption will anyway be included. Calculations were conducted using the statistical software SPSS version 24.

5.4. RESULTS AND DISCUSSION

In this section, the results for each step are presented and finally the critical indicators for a streamlined water footprint methodology for concrete production water quality.

5.4.1. RELEVANCE: MAIN SUBSTANCES, ACTIVITIES AND WATER RELATED ENVIRONMENTAL IMPACTS TO CONSIDER IN CONCRETE PRODUCTION

From 1580 flows, the result of the relevance approach -substances that contribute with more than 1% of the impact- limits the amount of substances to 19. It should also be noticed that these substances could result in water related environmental impacts after being emitted to water but also after being emitted to air because they precipitate afterwards.

5.4.2. APPLICABILITY: LITERATURE REVIEW ON CONCRETE WATER FOOTPRINT

27 scientific papers on life cycle assessment of concrete and/or cement were reviewed. From these studies, 9 impact categories related to water quality and 1 impact category related to water quantity were identified. Table 2-3 presents the impact categories for each study.

Water degradation could be the result of pollutants discharge to water, soil or to air. In the case of pollutants discharge to the soil, these could infiltrate until reaching an underground watercourse or reservoir or it could also be transported to other watercourses by rain.

For emissions to air, these could settle onto a watercourse or reservoir causing it to degenerate. Among the substances that could cause water degradation, heavy metals such as Cadmium (Cd), Lead (Pb), Manganese (Mn), Copper (Cu), Zinc (Zn), Chromium (Cr), Mercury (Hg), Arsenic (As), Iron (Fe), Cobalt (Co), Antimony (Sb), Tin (Sn), Titanium (Ti), Vanadium (V), and Nickel (Ni) are one of the main causes of water pollution (Baysal and Akman 2013).

Kim and Chae (2016) present the main substances emitted in concrete production from cradle to gate that cause acidification and eutrophication. These substances include Ammonia (NH_3) and Sulfur dioxide (SO_2) for acidification potential and NH_3 and Phosphate (PO_4^{3-}) for eutrophication potential. The substances are emitted to the air, settle by precipitation and therefore end up in surface water or even in ground water if they infiltrate the soil. Kim and Chae (2016) states that the emissions come mainly from clinker production and waste water from the concrete plant but also from energy production for the activities included in the concrete production life cycle including transportation.

According to Sharma et al. (2013), storm water flowing through material stockpiles in a cement plant could cause contamination with sulphate in soil, zinc, lead and chromium in dust and high total dissolved solids (TDS) in groundwater. Ipeaiyeda and Obaje (2017) studies the impact of cement effluent on a case study of water quality in rivers where they found that the cement effluent significantly contributed to the levels of Zn (0.045 ± 0.003 mg/l) and Pb (0.016 ± 0.001 mg/l) downstream such that they exceeded the criteria set by the United States Environmental Protection Agency (USEPA) and the World Health Organization (WHO) respectively, this was in the Onyi river at Obajana, Nigeria. The sustainable reports from CSI companies report dust, Nitrogen oxides (NO_x), Sulfure oxides (SO_x), Carbon monoxide (CO), Volatile organic compounds VOC/THC, PCDD/F, Hydrogen chloride (HCl), Hydrogen fluoride (HF), Hg, Cd, Ti, As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V. These emissions to air are monitored in the cement kilns reported per ton of clinker.

Other sources of dust from cement production are handling raw materials, grinding clinker, and packaging or loading finished cement. Other air pollution emissions from cement and concrete production such as Pb, Cd, Hg, etc. result from fossil fuel burning for process and transportation uses (Achternbosch et al.; Nriagu 1990).

Concrete wastewater results from washing of the concrete yard, trucks and other equipment. The wastewater from washing activities is alkaline and contains high levels of chromium. Concrete process water is caustic and typically has a high pH value ranging between 11 and 12. It contains dissolved solids including sulfates and hydroxides from cement and derivatives from chemical admixtures. Concerning aggregates production, the drainage of the quarry can impact the river basin depending on the discharge point (Paolini and Khurana 1998; Chini et al. 2001; Sealey et al. 2001; Ružinski et al. 2011; World Business Council for Sustainable Development 2012).

Background processes are the ones where the producer has no control or influence on. For instance, energy production and end of life related processes.

5.4.1. FOREGROUND PROCESSES: BACKGROUND AND FOREGROUND CLASSIFICATION

For the substances that end up being in the background system, an efficiency approach is recommended i.e. reducing the amount of the product flow to which these elementary flows belong. For instance, even though the industry cannot control energy production processes, could still work on energy efficiency in their plants. Thus, reducing the impacts from the company due to these background processes.

The results show that most of the impacts related to water occur in background processes where the concrete industry does not have any influence. For instance, the treatment of hard coal ash (residual material), treatment of spoil from hard coil mining, treatment of spoil from lignite mining and treatment of sulfidic tailing -all background processes- are responsible for 73% of freshwater ecotoxicity, 99% of freshwater eutrophication, 65% of freshwater sediment ecotoxicity, 70% of marine ecotoxicity and 67% of marine sediment ecotoxicity. These processes are also responsible for 40% of human carcinogenic toxicity. In the case of ionizing radiation, only the treatment of tailing from uranium milling already causes 81% of this impact.

Table 5-3 Main substances, activities and water related environmental impacts to consider in concrete production.

Substance (cut-off 1%) for Concrete 50 MPa +wastewater	Unit	Emissions to	Process (cut-off 1%) for Concrete 50 MPa +wastewater	Impact category
Ammonia	kg SO_2 eq	Air	Clinker production	Aquatic acidification
Hydrogen chloride		Air		
Nitrogen oxides		Air		
Sulfur dioxide		Air		
Lead	kg 1,4-DCB	Air		Human non-carcinogenic toxicity
Zinc		Air		
Zinc		Water		
Ammonium, ion	kg N eq	Water	Wastewater from concrete production	Marine eutrophication
Nitrate		Water		
Carbon-14	kBq Co-60 eq	Air	Background	Ionizing radiation
Radon-222		Air		
Phosphate	kg P eq	Water		Freshwater eutrophication
Chromium VI	kg 1,4-DCB	Water		Freshwater ecotoxicity
Copper		Water		
Nickel		Water		
Vanadium		Water		
Zinc		Water		
Chromium VI	kg 1,4-DCB	Water		Marine ecotoxicity
Copper		Air		
Copper		Water		
Nickel		Water		
Vanadium		Water		
Zinc		Water		
Chromium VI	kg 1,4-DCB	Air		Human carcinogenic toxicity
Chromium VI		Water		
Nickel		Water		
Barium	kg 1,4-DB eq	Water		Freshwater sediment ecotox. 100a
Beryllium		Water		
Cobalt		Water		
Copper		Water		
Cypermethrin		Soil		
Nickel		Water		
Vanadium		Water		
Zinc		Water		
Barium	kg 1,4-DB eq	Water		Marine sediment ecotox. 100a
Beryllium		Water		
Cobalt		Water		
Copper		Air		
Copper		Water		
Nickel		Air		
Nickel		Water		
Vanadium		Water		
Zinc		Water		

The complete list of substances required to be inventoried by each impact assessment method is present in Supplementary Material Table A5.

Source: the author.

Table 5-4 Background processes with high fraction of the potential environmental impacts. This group of background processes make up for at least 40% of freshwater ecotoxicity (FWET), freshwater eutrophication (FE), freshwater sedimentation ecotoxicity (FWSET), human carcinogenic toxicity (HCT), marine ecotoxicity (MET) and marine sedimentation ecotoxicity (MSET).

Processes	FWET	FWE	FWSET	HCT	MET	MSET
Hard coal ash {RoW}| treatment of, residual material landfill | Cut-off, U	2%	1%	11%	9%	2%	11%
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	19%	56%	29%	22%	18%	30%
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	7%	22%	11%	7%	6%	11%
Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	45%	19%	14%	5%	44%	15%
Total	73%	99%	65%	43%	70%	67%

Source: the author.

From 10 impact categories only 3 happen in foreground processes and from 1580 substances in the inventory only 19 contribute to more than 1 % of the impact of a certain category and only 5 belong to foreground processes. Results also show that not only substances emitted to water could cause water related environmental impacts but also substances emitted to air that afterwards settle and produces water related impacts. Such is the case of Sulfure dioxide (SO_2) and Nitrogen dioxide (NO_2) emitted during clinker production that could cause water acidification. Most of the impacts occur in background processes were the concrete industry does not have any influence. For instance, ionizing radiation due to energy production.

5.4.2. CRITICAL INDICATORS AND APPLICATION

After the three steps approach -relevance, applicability and foreground- 5 critical indicators (flows) are proposed in order to calculate a streamlined concrete water quality footprint from cradle to gate. Table 5-5 presents the 5 indicators, the processes where they happen, the compartment (air, soil or water) where the emissions go and the main impact categories that these indicators influence. All these processes are considered foreground for the concrete industry and feasible to measure by the industry.

Table 5-5 Critical indicators for a streamlined water footprint methodology for concrete production.

Impact category	Emissions to	Unit	Substance (cut-off 1%) for Concrete 50 MPa +wastewater	Process (cut-off 1%) for Concrete 50 MPa +wastewater
Human non-carcinogenic toxicity	Water	mg/kg	Zinc	Clinker production
	Air	µg/kg	Lead	
Marine eutrophication	Water	g/m^3	Nitrate	Wastewater from concrete production
Aquatic acidification	Air	g/kg	Nitrogen oxides	Clinker production
	Air	g/kg	Sulfur dioxide	

Source: the author.

Table 5-6 Reduction of flows through the identification of relevance, feasibility to measure and foreground processes.

Impact category	Number of flows	Cut-off 1%	Feasible to measure	Foreground	Complete WF (all substances)	Streamlined WF (critical indicators)	%
Ionizing radiation	28	2	n/a	n/a			
Freshwater eutrophication	3	3	1	n/a			
Freshwater ecotoxicity	405	5	3	n/a			
Marine ecotoxicity	405	6	4	n/a			
Marine eutrophication	2	2	1	1	0,000807	0,000807	99%
Human non-carcinogenic toxicity	270	3	2	2	0,005453	0,001871	34%
Aquatic acidification	14	4	2	2	0,001204	0,001156	96%
Human carcinogenic toxicity	99	3	2	n/a			
Freshwater sediment ecotox. 100a	177	8	n/a	n/a			
Marine sediment ecotox. 100a	177	9	n/a	n/a			
Total of flows	1580	45	15	5			

Source: the author.

From Table 5-5, only marine eutrophication and aquatic acidification impacts are considered in current concrete LCA. However, most of the substance that resulted as critical indicators, have been measured in the cement and concrete industry i.e. Zn, Pb, NO_x and SO_2 in clinker production and nitrate (NO_{3^-}) in concrete production wastewater. Therefore, it should be possible to measure these flows in the cement and concrete production plants.

The streamlined methodology was applied to concrete production. The impact assessment resulted in 34% for human non-carcinogenic toxicity, 96% for aquatic acidification and 100% for wastewater.

5.4.3. PRINCIPAL COMPONENTS ANALYSIS

The PCA demonstrates cluster of correlated substances but not which substances are more important in terms of impact. The substances with higher contribution to the impacts were identified. From the 86 materials, concrete processes presented higher amounts of these substances. Thus, the main substances were traced in the processes within concrete production chain. The PCA results were reduced to substances that contribute to more than 1% of the impacts. All these substances belong to the first component of the PCA, which controls 80% of the total variance (see Table 5-7).

The results of the PCA, show that the substances that contribute the most to the potential environmental impacts, are highly correlated and belong to the first component of the PCA except for Cypermethrin to soil, Ammonia to air, Cadmium to water and Ammonium, ion to water. These substances do not pass the influence and applicability cut-off anyway, since they do not happen in foreground processes neither are commonly measured.

Table 5-7 PCA results for substances that contribute more than 1% to the environmental impacts for Concrete 50 MPa + wastewater.

Impact category	Substance	Compartment	Unit	1	2	3	4	5	6	7	8	9	10
Ionizing radiation	Carbon	Air	kBq Co-60 eq	0,964	0,161	0,075	0,013	-0,126	0,038	0,131	0,038	0,003	0,028
Marine sediment ecotox. 100a	Beryllium	Water	kg 1,4-DB eq	0,927	0,346	0,093	0,017	-0,036	0,043	0,069	0,054	0,013	0,023
Freshwater sediment ecotox. 100a	Beryllium	Water	kg 1,4-DB eq	0,927	0,346	0,093	0,017	-0,036	0,043	0,069	0,054	0,013	0,023
Ionizing radiation	Radon	Air	kBq Co-60 eq	0,908	-0,200	0,052	0,003	-0,301	0,023	0,182	0,014	-0,004	0,051
Marine sediment ecotox. 100a	Cobalt	Water	kg 1,4-DB eq	0,883	0,443	0,097	0,018	0,029	0,047	0,084	0,062	0,012	0,009
Freshwater sediment ecotox. 100a	Cobalt	Water	kg 1,4-DB eq	0,883	0,443	0,097	0,018	0,029	0,047	0,084	0,062	0,012	0,009
Freshwater eutrophication	Phosphate	Water	kg P eq	0,881	0,432	0,092	0,018	0,020	0,102	0,102	0,058	0,011	0,010
Marine ecotoxicity	Copper	Air	kg 1,4-DCB	0,872	0,469	0,091	0,021	0,074	0,045	0,018	0,058	0,011	-0,002
Marine sediment ecotox. 100a	Copper	Air	kg 1,4-DB eq	0,871	0,470	0,089	0,021	0,076	0,045	0,017	0,059	0,011	-0,003
Human non-carcinogenic toxicity	Zinc	Air	kg 1,4-DCB	0,870	0,468	0,094	0,020	0,069	0,046	0,054	0,064	0,021	-0,002
Freshwater sediment ecotox. 100a	Zinc	Water	kg 1,4-DB eq	0,869	0,473	0,100	0,020	0,058	0,046	0,050	0,058	0,015	0,003
Freshwater ecotoxicity	Zinc	Water	kg 1,4-DCB	0,869	0,473	0,100	0,020	0,058	0,046	0,050	0,058	0,015	0,003
Human non-carcinogenic toxicity	Zinc	Water	kg 1,4-DCB	0,869	0,473	0,100	0,020	0,058	0,046	0,050	0,058	0,015	0,003
Marine ecotoxicity	Zinc	Water	kg 1,4-DCB	0,868	0,474	0,100	0,020	0,059	0,046	0,050	0,058	0,015	0,003
Marine sediment ecotox. 100a	Zinc	Water	kg 1,4-DB eq	0,862	0,484	0,100	0,020	0,065	0,046	0,049	0,058	0,015	0,002
Human carcinogenic toxicity	Chromium VI	Air	kg 1,4-DCB	0,847	0,506	0,105	0,019	0,074	0,060	0,045	0,055	0,016	0,003
Human non-carcinogenic toxicity	Lead	Air	kg 1,4-DCB	0,831	0,532	0,096	0,021	0,097	0,047	0,023	0,065	0,014	-0,003
Marine sediment ecotox. 100a	Nickel	Air	kg 1,4-DB eq	0,822	0,541	0,113	0,020	0,105	0,047	0,033	0,061	0,019	-0,003
Human carcinogenic toxicity	Chromium VI	Water	kg 1,4-DCB	0,818	0,475	0,103	0,016	0,069	0,287	0,048	0,067	0,016	0,002
Freshwater ecotoxicity	Chromium VI	Water	kg 1,4-DCB	0,818	0,475	0,103	0,016	0,069	0,287	0,048	0,067	0,016	0,002
Marine ecotoxicity	Chromium VI	Water	kg 1,4-DCB	0,818	0,475	0,103	0,016	0,069	0,287	0,048	0,067	0,016	0,002
Marine eutrophication	Nitrate	Water	N eq	0,804	0,487	0,087	0,015	-0,018	0,289	0,100	0,049	0,009	0,010
Marine ecotoxicity	Copper	Water	kg 1,4-DCB	0,779	0,335	0,080	0,011	0,002	0,516	0,078	0,044	0,009	0,011
Marine sediment ecotox. 100a	Copper	Water	kg 1,4-DB eq	0,779	0,335	0,080	0,011	0,002	0,516	0,078	0,044	0,009	0,011
Freshwater sediment ecotox. 100a	Copper	Water	kg 1,4-DB eq	0,779	0,334	0,080	0,011	0,002	0,516	0,078	0,044	0,009	0,011
Freshwater ecotoxicity	Copper	Water	kg 1,4-DCB	0,779	0,334	0,080	0,011	0,002	0,516	0,078	0,044	0,009	0,011
Freshwater sediment ecotox. 100a	Barium	Water	kg 1,4-DB eq	0,775	0,601	0,093	0,021	0,128	0,047	0,066	0,060	0,014	-0,003
Marine sediment ecotox. 100a	Barium	Water	kg 1,4-DB eq	0,773	0,603	0,093	0,021	0,129	0,047	0,064	0,060	0,014	-0,003
Aquatic acidification	Nitrogen oxides	Air	SO2 eq	0,759	0,528	0,354	0,010	0,103	0,044	0,055	0,053	0,013	-0,004
Freshwater ecotoxicity	Vanadium	Water	kg 1,4-DCB	0,758	0,611	0,147	0,019	0,140	0,052	0,036	0,065	0,033	-0,005
Freshwater sediment ecotox. 100a	Vanadium	Water	kg 1,4-DB eq	0,758	0,611	0,147	0,019	0,140	0,052	0,036	0,065	0,033	-0,005
Marine ecotoxicity	Vanadium	Water	kg 1,4-DCB	0,758	0,611	0,147	0,019	0,140	0,052	0,036	0,065	0,033	-0,005
Marine sediment ecotox. 100a	Vanadium	Water	kg 1,4-DB eq	0,758	0,611	0,147	0,019	0,140	0,052	0,036	0,065	0,033	-0,005
Aquatic acidification	Sulfur dioxide	Air	SO2 eq	0,755	0,623	0,095	0,022	0,143	0,047	0,055	0,067	0,015	-0,006
Marine ecotoxicity	Nickel	Water	kg 1,4-DCB	0,714	0,352	0,066	0,010	0,022	0,592	0,088	0,044	0,007	0,007
Marine sediment ecotox. 100a	Nickel	Water	kg 1,4-DB eq	0,714	0,352	0,066	0,010	0,022	0,592	0,088	0,044	0,007	0,007
Human carcinogenic toxicity	Nickel	Nickel	kg 1,4-DCB	0,714	0,352	0,066	0,010	0,022	0,592	0,088	0,044	0,007	0,007
Freshwater ecotoxicity	Nickel	Water	kg 1,4-DCB	0,714	0,352	0,066	0,010	0,022	0,592	0,088	0,044	0,007	0,007
Freshwater sediment ecotox. 100a	Nickel	Water	kg 1,4-DB eq	0,714	0,352	0,066	0,010	0,022	0,592	0,088	0,044	0,007	0,007
Freshwater sediment ecotox. 100a	Cypermethrin	Soil	kg 1,4-DB eq	0,290	0,950	0,060	0,018	-0,071	0,042	0,015	0,034	0,017	-0,022
Aquatic acidification	Ammonia	Air	SO2 eq	0,439	0,038	0,886	-0,027	-0,085	0,019	0,079	0,012	0,020	0,019
Human non-carcinogenic toxicity	Cadmium	Water	kg 1,4-DCB	0,558	0,285	0,055	0,006	0,034	0,775	0,035	0,029	0,007	0,002
Marine eutrophication	Ammonium, ion	Water	N eq	0,033	0,027	0,032	-0,009	0,015	0,998	0,019	-0,006	0,008	-0,001

Source: the author.

5.5. CONCLUSIONS

A streamlined consistent methodology for the water footprint of concrete that may be based on existing standards and primary data when possible is needed for implementation and the decision-making process in small and medium enterprises as well as in large companies. The assessment should be complete and rigorous enough to be a guide to the industry, yet no so complex as to be difficult or impracticable to perform. This study proposes a streamlined methodology for water footprint in concrete production from cradle to gate. A significant reduction of flows to be inventoried was achieved from 1580 to 5 flows. This methodology is based on three approaches that consider the contribution of each flow to the potential environmental impacts, the influence that the industry has over these flows and the feasibility to measure these flows in the cement and concrete plants. The results show the possibility of reducing the inventories 99,7% and keeping at least 80% of the variance accomplishing the objective of streamlined LCA methodologies. This methodology will facilitate the estimation of water footprint for concrete production which will result in reduction of the environmental impacts of the industry.

5.6. SUPPLEMENTARY MATERIAL

Supplementary material Table A1. Compare inventory characterization skip unused
Supplementary material Table A2. Compare process contribution characterization skip unused
Supplementary material Table A3. Concrete 50 + wastewater impact assessment (inventory)
Supplementary material Table A4. Concrete 50 + wastewater impact assessment (process contribution)
Supplementary material Table A5. Substances and characterization factors for ReCiPe 2016, the IMPACT 2002 and the CML – IA nonbaseline methods
Supplementary material Table A6. Raw data for PCA

Supplementary material from this chapter could be find through the following link:

https://www.dropbox.com/sh/w2emxc3bxpnyba0/AACYbUdOv4bx-Mo2AiNlIG59a?dl=0

6. VARIABILITY IN CONCRETE PRODUCTION WATER FOOTPRINT

6.1. ABSTRACT

Concrete is the most used material in the world after water. However, impacts related to water use in its production have been neglected or at best inconsistently reported. In general, results on environmental indicators are presented as single value which hides variability and uncertainties from different sources. In this chapter, a cradle to gate water footprint study was performed to estimate variability in concrete production water footprint including variability due to water use, location and choice of impact assessment method for different concrete formulations. The assessment is done based on a sample of 25 MPa concrete formulations. The main sources of variability for concrete water inventory and water footprint are identified. Direct water use is usually a fixed value 196-249 l/m^3 which is less than 5% of the variability. Variability from indirect water use and energy production water use are in the range of 5 -10 % for specific regions. The choice of impact assessment method accounts for the biggest share, 80-99% of the variability. For the water use inventory, the energy production and aggregates production seem to be the most important contributors. The water footprint varies mainly depending on the location and method used for the assessment. Therefore, special attention should be paid to the choice of method.

Keywords: Cementitious materials. Variability. Water consumption. Life cycle assessment. Sustainable construction.

6.2. INTRODUCTION

Water is the most demanded substance in the world only followed by concrete (Scrivener et al. 2018). The annual concrete production is approximately 30 billion tonnes, with total mixing water of ~1 trillion liters (Monteiro et al. 2017). These two substances have a tight relationship since water is vital for cement hydration and corresponding concrete strength and workability (Damineli et al. 2016). On top of this water, there is water use in concrete production activities such as washing the trucks and washing the yard (Mack-Vergara and John 2017). Climate change and population growth, will worsen water availability (Larsen et al. 2016). Due to water crisis in different regions of the world and on the other hand increasing demand of concrete for housing and infrastructure, it is vital to assess water use in different activities (World Business Council for Sustainable 2012).

The life cycle assessment (LCA) approach is commonly used in order to assess potential environmental impacts from products, services, etc. (International Organization for Standardization 2006a, b). This methodology calculates the potential environmental impacts at different stages e.g. Raw material extraction, production, use, end of life phase. In the same line, the water footprint is a tool for calculating potential environmental impacts related to water use in the life cycle of a product (International Organization for Standardization 2014; Pfister and Ridoutt 2014). Even though, concrete demand represents a high share, few studies on water footprint have been performed. From 27 studies found between 2015 and 2017, only 3 include water consumption (Serres et al. 2016; Soleimani and Shahandashti 2017; Fraj and Idir 2017).

In general, results on water footprint or other environmental indicators are presented in databases, scientific publications and environmental product declarations (EPD) as single value which hides variability and uncertainties from the processes. A study of CO_2 emissions in concrete formulations from 29 countries has unveiled wide variability even for concretes with the same compressive strengths (Damineli et al. 2010). Another study on concrete blocks production, demonstrated important variability in CO_2 emissions and energy demand within manufactures of the same product (Oliveira et al. 2016). Significant variation is expected due to energy matrix, technological route, resources availability, cement type, location and characterization factors which vary according to the chosen impact assessment method. Therefore, it is relevant to assess this variability.

In this study we identify sources of variability and estimate ranges of water footprint results in concrete water footprint. The assessment is done based on a sample of 25 MPa concrete formulations with slump of 120 mm. The understanding of variability in the water use and water footprint of concrete production is relevant for decision making of the companies that are trying to reduce environmental loads and improve efficiency of their processes. In addition, the results of the contribution of different sources of variability allows to prioritize where to act.

6.3. UNDERSTANDING UNCERTAINTY AND VARIABILITY IN LCA

Uncertainty and variability often go hand in hand and are often interchangeably used. This is incorrect and may cause initial errors to stem from it. In Huijbregts (1998) variability is described as stemming from inherent variations in the real world, while uncertainty comes from inaccurate measurements, lack of data, model assumptions, etc. that are used to convert the real world into LCA outcomes. Lehmann and Rillig (2014) further explains that uncertainty can be unexplained or unknown variation and may be partly due to measurement errors or lack of understanding of cause and effect whereas variability is naturally present in time and space in the form of heterogeneity of responses. Which means that uncertainty may be decreased with each step toward more accurate, relevant, local and recent data use in the analysis, with more concrete understanding of the system and processes being analyzed and their careful and detailed modelling. Variability on the other hand, will not shrink with scientific progress.

Uncertainty and variability may be unwanted but unavoidable complications in the LCA analysis (Huijbregts 1998). They indeed are complications because they may overwhelm the already data-heavy analysis. By inserting an uncertainty or a variability range to each process of an already complex system means to further load the system with information. The issue is not only about the load of information, but the fact that it may jeopardize the results and the conclusions reached with a certain LCA. On the other hand, that is precisely why uncertainty and variability in LCA need to be evaluated in each system. Without their evaluation, strong claims in the performance and impact of products can be made without a necessarily solid base for them. If the uncertainty in some of the processes used in the analysis are high, the confidence in the results of the analysis is decreased and needs to be verified by other means. The same goes for variability, which means apart from evaluating these elements inside the LCA, decision makers have to be careful in the interpretation of the results and consideration of the context of the data used in the analysis. It does not necessarily mean that when uncertainties are evaluated the results will be disproved, but it is an integral element to be considered when decisions are made considering the choice of a product or process.

6.4. METHODOLOGY

This study consists of a cradle to gate water footprint assessment of concrete. Therefore, it includes activities happening in the concrete plant -direct water use- mixing the concrete, washing the trucks and washing the yard. Indirect water use is considered for cement production, slag treatment and aggregates production since these activities could be influenced by the concrete producer. The water footprint of the energy is also included.

Water use figures for direct and indirect water use where taken from (RMC Research & Education Foundation 2011; Mack-Vergara and John 2017) which include life cycle water inventory figures for concrete production. For the study of variability due to technological route, only ready-mix concrete is considered however different concrete formulations are used for the analysis. Concrete formulations produced in Brazil were used to estimate water consumption including the amount of each concrete constituent, compressive strength and slump. The functional unit is 1 m^3 of concrete of 25 MPa compressive strength with workability of 120 mm slump. This type of concrete was used since it was determined by industry production data thatit is a commonly used concrete.

Figure 6-1 water use scopes for inventory following the Greenhouse Gas Protocol for reporting emissions (Bhatia et al. 2011).

Direct water use	Indirect water use	Water use for energy production
• Mixing water • Washing the trucks • Washing the yard	• Cement production • Aggregates extraction/production	• Electricity • Fuels

Source: (Mack-Vergara et al. 2019).

This study is focused on water consumption which is defined as water that is not available anymore at the original source where it was extracted (International Organization for Standardization 2006b). Water quality is not included in this study.

For the study of variability due to environmental impact (water footprint), three methods are used: AWARE (Boulay et al. 2018), (Hoekstra et al. 2012) and ReCiPe 2016 (H) midpoint (Huijbregts et al. 2017). In addition, three regions were chosen to estimate variability due to location -Brazil (BR), Switzerland (CH) and rest of the world (RoW). Table 6-1 presents the characterization factors for the impact assessment in each region according to the three impact assessment methods. In the case of the recipe method, the values of 1 and -1 are not precisely characterization factors but only used to calculate the water consumption (Huijbregts et al. 2017).

Table 6-1 Characterization factors for water footprint (AWARE (Boulay et al. 2018), (Hoekstra et al. 2012) ReCiPe 2016 (H) midpoint (Huijbregts et al. 2017)).

	Unit	Water use (AWARE (Boulay et al. 2018))			Water scarcity index (Hoekstra et al. 2012))			Water consumption (ReCiPe 2016 (H) midpoint (Huijbregts et al. 2017))		
		BR	CH	RoW	BR	CH	RoW	BR	CH	RoW
Water withdrawal	m^3/m^3	2.17	1.34	44	0.05	0.12	1.39	1	1	1
Water returned to the same source	m^3/m^3	-2.17	-1.34	-44	-0.05	-0.12	-1.39	-1	-1	-1

Source: (Mack-Vergara et al. 2019).

The methods chosen for the water footprint impact analysis and comparison were the AWARE (Boulay et al. 2018) and Hoekstra et al. (2012), which are water footprint methods and the ReCiPe 2016 (H) midpoint method (Huijbregts et al. 2017), which is a general impact analysis but contains several impact categories. These methods have been extensively described by their developers and were chosen based on their wholesome considerations of water as a resource and the fact that they all focus on a midpoint result. They present some differences in their consideration of water availability, usage and indicator calculation.

The AWARE method which is based on a characterization factor 1/amd, which is the inverse of the difference between availability per area and demand per area, quantifies the potential of water deprivation, to either humans or ecosystems, and serves in calculating the impact score of water consumption or a water scarcity footprint. It is based on the available water remaining per unit of surface in a given watershed relative to the world average, after human and aquatic ecosystem demands have been met.

This method assumes that the potential to deprive another user of water is directly proportional to the amount of water consumed and inversely proportional to the available water remaining per unit surface and time (Boulay et al. 2018).

The Hoekstra 2012 method was developed by combining three innovations in measuring water use and availability: water is measured in terms of consumptive use rather than withdrawals, flows necessary to sustain critical ecological functions are considered and water use, and availability is compared on a monthly rather than annual level. The results are classified in 4 levels of scarcity – low (<100%), moderate (100-150%), significant (150-200%), severe (>200%) (Hoekstra et al. 2012).

The ReCiPe 2016 (H) midpoint considers all water impacts based on water consumption, is related to location and considers local water availability per watershed (or country). Different technologies and management of the watersheds, as well as the development index are considered. Screening assessment is made using the water stress index (WSI) which is the ratio of total annual freshwater withdrawals to hydrological availability (moderate > 20%, severe > 40%) and indicates the portion of consumptive water use that deprives other users of freshwater (Pfister et al. 2009).

Table 6-2 Comparison summary of three methods used for water footprint.

Method	AWARE	Hoekstra 2012	ReCiPe 2016 (H) midpoint
Characterization factor	1/amd	Not defined	Wsi = $m^3_{w,cons}/m^3_{w,ext}$
	0.1 - 100	-	0 (0.1) - 1
Unit of measurement	m^3	m^3	m^3
Availability	Actual run-off from watergap 2.2 model	Volume of water that can be consumed without expected adverse ecological impacts calculated as actual natural runoff minus environmental flow requirements	Watergap 2 model for hydrological availability on annual base modified for monthly and yearly variability
Demand	Watergap 2.2 method - human water consumption and environmental water requirements	Water footprint - volume of water consumed	Water consumption and flows given in terms of withdrawal are factored to account or water use efficiency (water requirement ratio)
Water consumption	Agriculture, industry, domestic, livestock, energy production	Agriculture - 2 scenarios, industrial - 5%, domestic - 10%	Agriculture - 44%, industrial - 10%, domestic - 10%
Water source	Blue water	Blue water	Blue water
Time reference	Not defined/monthly	Monthly	Factored yearly/monthly

Source: (Mack-Vergara et al. 2019).

Even though the three methods use m^3 units for their results and are considered water footprint methods, they should be used with caution and their results should be carefully interpreted since they are the consequences of different considerations.

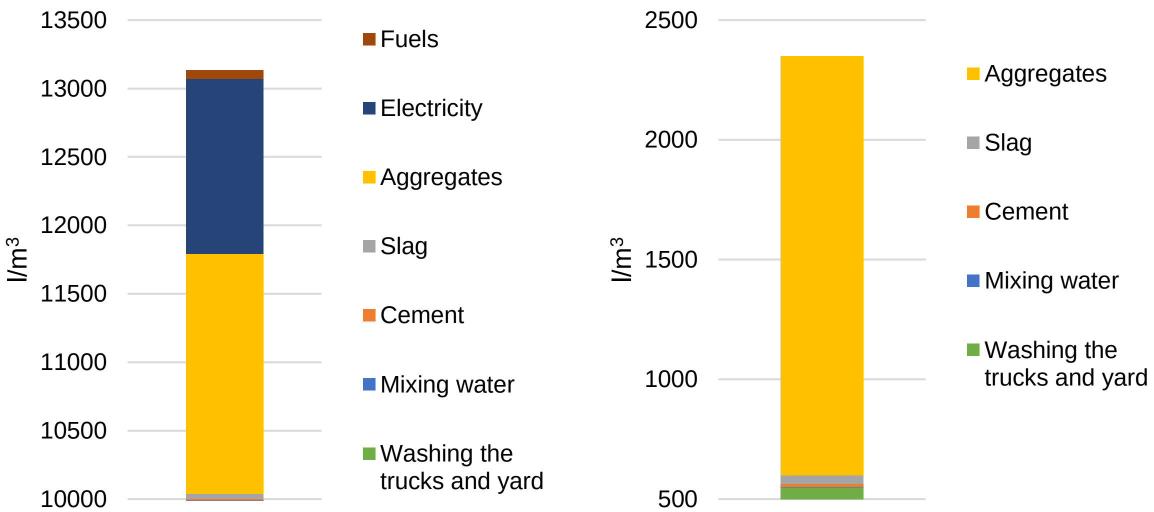
A final analysis was performed to compare the sources of variability and their importance.

6.5. RESULTS AND DISCUSSION

6.5.1. VARIABILITY IN THE WATER INVENTORY OF CONCRETE PRODUCTION

Water use for concrete production is divided according to the 3 scopes of the Greenhouse Gas Protocol (Bhatia et al. 2011). Direct water, used in the concrete production plant includes mixing water, water for washing of the truck and water for washing of the yard. Indirect water includes water to produce cement and aggregates. Finally, there is water for energy production -electricity and fuels.

Figure 6-2 Range of water inventory for concrete production (1 m^3, 25 MPa, 120 mm) for direct and indirect activities.



Source: (Mack-Vergara et al. 2019).

Direct water use ranges from 196-249 l/m^3 including mixing water, water for washing the yard and washing the truck. The mixing water varies according to the workability and compressive strength requirements (Damineli et al. 2010) but compared to other water uses, this activity represents a small fraction ~180 l/m^3. The water for washing the yard and washing the trucks is considered constant in this study independently from the concrete design. However, there could be a difference in the amount of water used to wash the trucks since depending on the rheology of the mix (Vieira and Figueiredo 2016), more or less concrete would stay in the bottom of the truck to be washed. For water efficient companies -focused on reducing water use, water losses and implementing recycling/reuse practices- the water use for washing the trucks and yard could be considerably lower. Indirect water use varies from 302-2100 l/m^3 including water for cement production, water for slag treatment and water for aggregates production. From Figure 6-2 we can observe that the activity that presents highest variability is the aggregates production. This is probably because this activity is usually performed near superficial or underground water sources and the water withdrawal and consumption is not controlled as usually the company gets a permit to use this water sources and does not need to pay depending on the water use but only a fixed price that is very cheap. Also, the use of water in aggregates production depends on weather conditions (e.g. if it rains, it is not necessary to control dust or to wash the aggregates) but also on industry practices such as washing the aggregates for a better performance of the material. This means, without having a primary data inventory for aggregate production, we are not able to estimate water footprint without large uncertainty. Finally, water for energy varies from 9400-10785 l/m^3 including water for fuel production and for electricity production and represent the highest water consumption. The water use for energy production is high, this is after CO_2 emissions another reason to improve energy efficiency in concrete production.

To reduce the water consumption per activity, the direct water use could be target, the indirect water use even if is not controlled by the concrete producer could be somehow influenced in order to be more efficient since for these activities and products -cement and aggregates production- the concrete producer is their main client. Finally, for energy production, this would be a background activity since it is difficult to be influenced by the concrete producer. However, as mentioned before, the concrete producer would reduce its energy water consumption by being more efficient in terms of energy consumption.

6.5.2. VARIABILITY IN THE WATER FOOTPRINT OF CONCRETE PRODUCTION DUE TO LOCATION AND THE CHOICE OF IMPACT ASSESSMENT METHOD

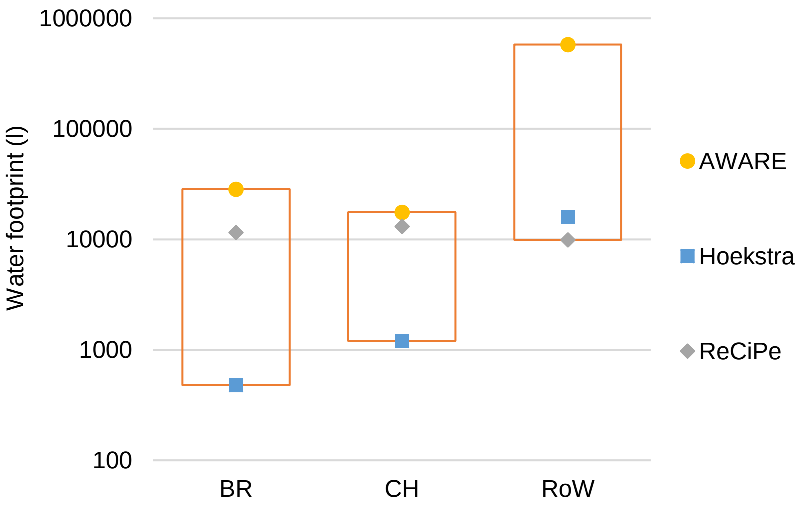
Water related impacts are local (Boulay et al. 2018) and for this reason the impact assessment characterization factors vary according to the region where the water is extracted and used. The characterization factors also vary according to the water footprint method (see Table 6-1). Figure 6-3 presents variability for concretes of 25

MPa (120 mm) for Brazil, Switzerland and rest of the world. The results vary up to 60 times depending on the method. The highest results correspond to the AWARE.

The characterization factors for each method were downloaded from the SimaPro software v 8.5. For ReCiPe 2016 (H) midpoint water consumption, the factor is 1 since they do not have characterization option in their last update of the method. For the AWARE method and Hoekstra method, the characterization factors are presented per country and type of water. Characterization factors should vary according to region, and in the case of Brazil for instance, the availability of water varies from places like Amazonia to São Paulo where water drought have affected (see Figure 6-4). On top of this variability there is the water demand in function of the population of the region. One number representing the potential impact of water consumption of a whole country is unacceptable, ever worse to represent the rest of the world.

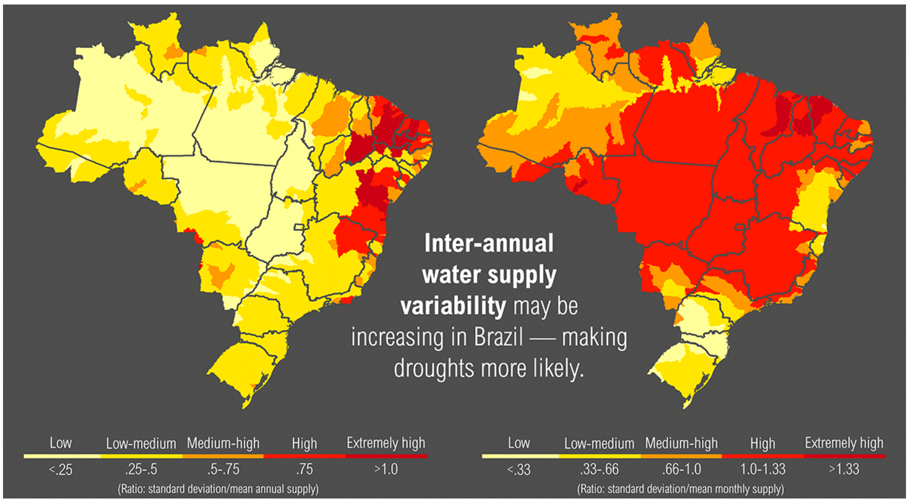
The choice of method is crucial. Moreover, the understanding of the method before it is used and for interpretation of results. The location is critical when performing a water footprint. It is important to understand that the "RoW" includes all countries without a local inventory in the Ecoinvent database. This option is commonly used but should be avoided since the results present the worse cases and not the reality of the region.

Figure 6-3 Impact of the region in total values and range concrete water footprint 1 m^3 of concrete, 25 MPa, 120 mm (the vertical scale was adjusted since RoW values are >100,000 m^3).



Source: (Mack-Vergara et al. 2019).

Figure 6-4 Annual variability (on the left) and seasonal variability (on the right) for water availability in Brazil.

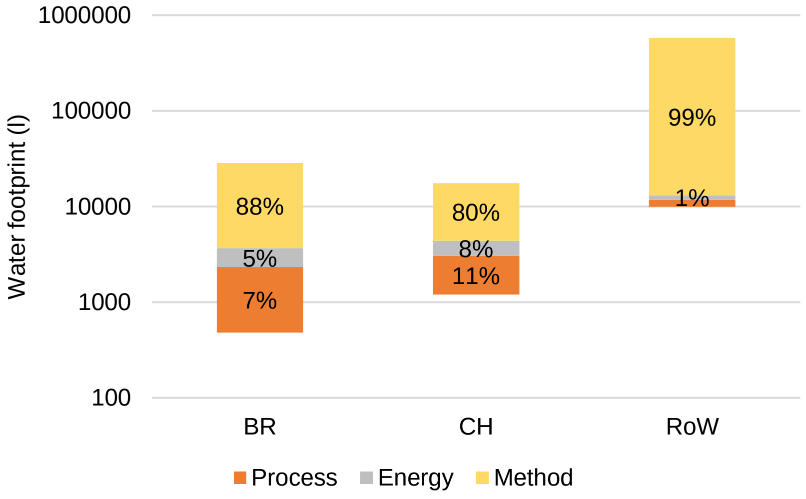


Source: www.wri.org (World Resources Institute 2014).

6.5.3. INFLUENCE OF EACH SOURCE OF VARIABILITY

The sources of variability were classified as direct, indirect and method. At the same time, we can observe variability depending on the region (BR, CH and RoW).

Figure 6-5 Contribution of variability due to direct water use, indirect water use and impact assessment method for 1 m^3 of concrete, 25 MPa, 120 mm (the vertical scale was adjusted since RoW values are >100,000 m^3).



Source: (Mack-Vergara et al. 2019).

Comparing the three regions in Figure 6-5, Switzerland (CH) has the lower variability. This happens because the Ecoinvent database is developed there, i.e. The Swiss inventory is the most complete and accurate available. It may be more homogeneous, being a small country. For the Brazilian case (BR) we can observe larger variability, but the results are still better than for the rest of the world (RoW) case. This is because Brazil has developed some inventories with local data but not all. This variability is underestimated since Brazil should have characterization factors per region or, even better, per watersheds. For RoW, the variability comes from the characterization factor that generalizes the worst-case scenario for all the regions without local information including regions where the water availability super exceeds the water demand.

Comparing the sources of variability, direct water use is low -this does not mean that the water use in the concrete plant should not be carefully assessed but is more or less a fixed value. After this, we can observe that variability from indirect water use and energy production water use are in the range of 5-10 % for Brazil and for Switzerland.

The difference is that the indirect activities could be influenced by the concrete producer in addition to be more efficient in terms of materials use while for energy production the only possible strategy in terms of reducing water consumption would be to increase efficiency in energy use. The highest variability comes from the choice of method. In the case of RoW, this source of variability represents almost 100%. Before performing a water footprint assessment, the impact assessment method should be carefully chosen, studied and understood in order to avoid misleading results.

6.6. CONCLUSIONS

A study of variability in concrete production was performed including variability due to water use, location and choice of impact assessment method. The highest water consumption is due to energy production. Therefore, it is important to continue with efforts to reduce energy demand not only because of CO_2 emissions but also because of its high-water footprint. The most important contributor in terms of water use after energy production is aggregates production. This activity is rarely controlled. Measurements to improve water efficiency in this activity should be considered. Aggregates production also represents the highest variability. Most of the variability comes from the choice of method which could influence the results by a factor of 60. The use of water footprint methods and interpretation of water footprint results should be carefully done since the methods have an important influence and represent different situations. Moreover, water footprint methods should converge to one universal method.

7. STREAMLINED CONCRETE WATER FOOTPRINT METHODOLOGY

7.1. ABSTRACT

Increasing concrete demand and less water availability represent quite a challenge in part due to the large amounts of water needed for concrete production and to produce its constituents but also due to inefficiency in concrete production. The study of concrete water footprint is needed to stablish actions to improve water efficiency in concrete production. Water footprint in cementitious materials is a complex subject, usually overlooked. A streamlined and standardized methodology for concrete water footprint should be easy to perform and therefore have better chances to become largely adopted by industry and researchers, helping to increase the efficiency of this resource. A simplified water footprint should be compatible preferentially on existing standards using primary data. In addition, since ready mix concrete plants are relatively small industrial operations, it should be practical for small and medium organizations as well as for large companies. The aim of this chapter is to develop a streamlined water footprint methodology for concrete water footprint including definitions, goal and scope definition, data requirements, life cycle inventory analysis, impact assessment and interpretation of the results. Concepts from existing water footprint methodologies are unified. In addition, the proposed methodology is applied to a water inventory case scenario. The results are compared to those from 7 other water footprint inventory methodologies.

Keywords: Cement. Water consumption. Simplified life cycle assessment. Sustainability.

7.2. INTRODUCTION

The cement and concrete industries not only demand large amounts of energy and generates CO_2 emissions but also requires large amounts of water in their processes and generates waste causing major impacts on the environment along their supply chain (Worrell et al. 2001; Van Oss and Padovani 2003; World Business Council for Sustainable Development 2009a; US EPA 2010; Hasanbeigi et al. 2012; Amato 2013; Conselho Brasileiro de Construção Sustentável 2014). These environmental aspects are quite complex by themselves. However, once these issues are assessed through primary data in a life cycle assessment (LCA) approach, it is possible to correctly estimate the actual impacts, identify reduction opportunities and monitor the results of mitigation measures allowing to compare products and producers, from their actual environmental performance and not only by economic or technical indicators.

LCA has been used in the building sector since 1990 (Fava 2006), and it is now a widely used methodology with the limitation of being based mainly on secondary data (Colangelo et al. 2018a; Röck et al. 2018). There are many limitations for a complete LCA such as lack of data transparency, few primary data, most of the inventories are based on secondary data, lack of benchmarks to motivate the industry, complexity, and associated cost and time despite the major streamlining that is the use of secondary data which is not always relevant data. For these reasons, many authors and organizations agree that there is a need for simplification (Graedel, T. E. 1998; Agis et al. 1999; Hochschorner and Finnveden 2003; Mourad et al. 2006; World Business Council for Sustainable Development 2007; Γεωργακέλλος 2007; Kellenberger and Althaus 2009; Zabalza Bribián et al. 2009; Rampuria 2012; Hanes et al. 2013; Brown 2014; Conselho Brasileiro de Construção Sustentável 2014). The water footprint (International Organization for Standardization 2014) is a LCA based tool, and as such, it shares these limitations. Therefore, a streamlined methodology is appropriate.

Even though, there are several methodologies to define water use metrics which can be used in the concrete industry case (European Commission 2010a; Hoekstra et al. 2011; Rudolf et al. 2013; World Business Council for Sustainable Development 2013b, a; Ecoinvent 2014; International Organization for Standardization 2014), there is not a complete and consistent water footprint methodology or inventory methodology for concrete production. This is despite the annual concrete production of 15 million m^3. Due to lack of data, water related impacts are usually neglected.

In practical terms water footprint may be difficult to estimate for concrete producers. If appropriate and justified, the water footprint assessment may be restricted to one or several life cycle stages. This chapter presents a streamlined water footprint methodology for concrete production including definitions, data requirements, life cycle inventory analysis and impact assessment. The goal of this water footprint methodology is to be used by the concrete industry to asses water related environmental impacts, identify water reduction opportunities and optimize processes in concrete production. This chapter is based on the water footprint challenges, limitations and studies for the concrete production case that have been considered along the previous chapters in this thesis.

7.3. METHODOLOGY

A structure of the methodology and definition of guidelines was prepared. A list of main definitions was developed based on water footprint standards. The methodology has a cradle to gate scope and a functional unit of 1 m^3 of concrete. The required principles and framework, data inventory and impact assessment considerations are presented. The data requirements are based on what is more relevant for the concrete production case. The flows needed for water quality assessment are the results from chapter 5. The methodology was applied to the case study scenario from chapter 4. Finally, a discussion on the simplifications and main concerns is presented.

7.4. RESULTS AND DISCUSSION

In this study, a streamlined LCA based methodology for concrete water footprint is proposed, including relevant definitions and steps to be followed. The methodology is built in compliance with ISO standards and based on ISO standards definitions and other water footprint definitions from documented methodologies.

The system boundaries of the study include all the inputs and outputs associated with producing concrete. Concrete production consists of aggregates extraction, cement production and concrete production –mixing of the concrete and other activities in the concrete plant. The methodology can be used as stand-alone water assessment intended or as part of a LCA, comparative assertions between processes and products in the concrete industry are intended as well (i.e. benchmarks).

7.4.1. DEFINITIONS

Existing definitions related to water and life cycle from different methodologies were unified for a consistent methodology. In some cases, these definitions were modified in order to fit the cementitious materials case.

1. Brackish water: water containing dissolved solids at a concentration less than that of seawater, but in amounts that exceed normally acceptable standards for municipal, domestic and irrigation uses -vary from1000 mg/l to 30000 mg/l- (International Organization for Standardization 2014).
2. Direct water footprint inventory water footprint inventory considering inputs and outputs resulting from activities within the established organizational boundaries (International Organization for Standardization 2014).
3. Drainage basin: area from which direct surface runoff from precipitation drains by gravity into a stream or other water body. (International Organization for Standardization 2014). Synonyms include: catchment, catchment area, drainage area, river basin and watershed.
4. Fossil water: groundwater that has a negligible rate of natural recharge on the human time-scale (International Organization for Standardization 2014).
5. Freshwater: the constituent content of freshwater should be defined by local regulations. In the absence of local regulations, a limit of 1000 mg/l of total dissolved solids (TDS) (the limit recommended by world health organization is considered (World Business Council for Sustainable Development 2013b; International Organization for Standardization 2014).
6. Functional unit quantified performance of a product system, process or organization for use as a reference unit (International Organization for Standardization 2014).
7. Groundwater: water in soil beneath the soil surface, under conditions where the pressure in the water is greater than the atmospheric pressure, and the soil voids are substantially filled with water (Kumar 2008; World Business Council for Sustainable Development 2013b).
8. Harvested rainwater: rainwater that is collected and used on the site (World Business Council for Sustainable Development 2014a).
9. Indirect water footprint inventory water footprint inventory considering inputs and outputs which are consequences of an organization’s activities but which arises from processes that are owned or controlled by other organizations (International Organization for Standardization 2014).
10. Municipal water supply: supply of potable water by a public organization (World Business Council for Sustainable Development 2013b).

11. Potable water: water that is suitable for drinking (World Business Council for Sustainable Development 2013b).
12. Primary data: quantified value of a unit process or an activity obtained from a direct measurement or a calculation based on direct measurements at its original source (International Organization for Standardization 2014).
13. Quarry dewatering: pumping water from a quarry to lower the water level in the quarry in order to obtain a dry area (World Business Council for Sustainable Development 2014a).
14. Quarry water: water that is extracted from the quarry (or quarry dewatering). It may be a combination of groundwater and/or surface water and/or precipitation (World Business Council for Sustainable Development 2013b).
15. Receiving body: destination of water discharges.
16. Recycled water: the amount of used water/wastewater employed through another cycle back in the same process or in a higher use in the process cycle before discharge for final treatment and/or discharge to the environment (World Business Council for Sustainable Development 2013b).
17. Reporting period: period in which the life cycle inventory was built.
18. Reused water: the amount of used water/wastewater employed in another function in a lower use in the process cycle before discharge for final treatment and/or discharge to the environment (World Business Council for Sustainable Development 2013b).
19. Seawater: water in a sea or an ocean with concentration of dissolved solids greater than or equal to 30 000 mg/l (International Organization for Standardization 2014).
20. Secondary data: data obtained from sources other than a direct measurement or a calculation based on direct measurements at the original source such sources can include databases and published literature validated by competent authorities (International Organization for Standardization 2014).
21. Surface water: water in overland flow and storage, such as rivers and lakes, excluding seawater (International Organization for Standardization 2014).
22. Uncertainty analysis systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty or data variability (International Organization for Standardization 2014).
23. Water body: entity of water with definite hydrological, hydrogeomorphological, physical, chemical and biological characteristics in a given geographical area (International Organization for Standardization 2014).
24. Water consumption: evaporation, transpiration, integration into a product, or with quality changed (for worse). Water that is not used in production processes but has to be managed within the system boundaries, is not considered consumed.
25. Water discharge: the sum of water discharged with the same quality (or improved) (World Business Council for Sustainable Development 2013b, 2014a).

26. Water footprint inventory: result of a water footprint inventory analysis, including elementary flows which are usable for subsequent water footprint impact assessment. (International Organization for Standardization 2014).
27. Water impact assessment: evaluating the magnitude and significance of the potential environmental impacts related to water of a product, process or organization (International Organization for Standardization 2014).
28. Water incorporated in raw material: water that is integrated as humidity or chemically bonded in raw materials.
29. Water quality: physical, chemical and biological characteristics of water with respect to its suitability for an intended use by humans or ecosystems (International Organization for Standardization 2014).
30. Water scarcity: extent to which demand for water compares to the replenishment of water in an area, e.g. a drainage basin, without taking into account the water quality (International Organization for Standardization 2014).
31. Water source: origin of water withdrawal (World Business Council for Sustainable Development 2013b). e.g. public water supply, superficial (ponds, rivers, lakes, etc.), underground (wells, etc.), rain, chemically bounded or integrated as humidity, effluent, recycled, reused, others.
32. Water stress: Water stress is commonly defined by the ratio of total annual freshwater withdrawals to hydrological availability (Pfister et al. 2009).
33. Water use: use of water by human activity (Rudolf et al. 2013; World Business Council for Sustainable Development 2013a; International Organization for Standardization 2014).
34. Water withdrawal: the sum of all water drawn into the boundaries of the organization from all sources and for any use (World Business Council for Sustainable Development 2013b).

7.4.2. WATER FOOTPRINT INVENTORY

The water inventory consists of all site water flows including sources where the water is withdrawn, sites where water is used, consumed, recycled and discharged. A process flow diagram is required to have a clear understanding of all water flows. The inventory should be direct, measured, primary data during at least 12 months. The following data related to water should be considered for data collection:

1. Inputs and outputs quantities of water used, by source.
2. Recycled and reused water.
3. Types of water resources used, including for water withdrawal and water receiving body (rainwater, surface water, seawater, brackish water, groundwater, fossil water, etc.).
4. Data describing water quality including for water withdrawal, release and water receiving body.
5. Forms of water use (evaporation, transpiration, product integration).

6. Geographical location of water used or affected including withdrawal and/or discharge.
7. Assumptions made in the collection.
8. Water losses.

The proposed streamlined water footprint methodology considers the amount of water withdrawn or captured by an organization to carry out a process, minus the amount of water that is returned to the hydrosphere with the same quality except for water vapor (equations 1 and 2).

$$\text{Water}_{\text{consumption}}=\text{Water}_{\text{withdrawal}}-\text{Water}_{\text{discharged with same or better quality}} \quad (1)$$

$$\text{Water}_{\text{consumption}} =\text{Water}_{\text{evaporated}}+\text{Water incorporated in the product}+\text{Water}_{\text{discharged with lower quality}} \quad (2)$$

The streamlined water footprint includes direct water use which considers the inputs and outputs from activities within established organizational boundaries. In addition, the indirect water use that considers the inputs and outputs that are not the result of the activities of the organization, but from the processes that are owned or controlled by other organizations. Water for energy production associated with the process in question is considered as indirect water use. Indirect and energetic use of water (Hirata 2019) could be based on secondary data, considering explicitly the uncertainty. Equation 1 and 2 shows the water balance in the concrete production process. The water that returns with the same quality, is not part of the water consumption. It is recorded only to estimate mass balance.

Water obtained from the public network is usually measured. Yet, the amounts of water extracted from natural water sources by companies often are not accurately measured, so it is difficult to estimate. In this case the different practices used by the company should be register in order to help in explaining the variation of the water footprint.

The water consumption should be accounted according to their destination and includes evaporation, water incorporated into the product and water with quality changed. Table 7-1 presents the flows to be inventoried for water quality assessment.

Appendix F presents the data that companies should collect in a systematic way. This includes, location, plant area, date, working hours, number of workers (in offices and operation), flowchart of the company’s operation, data on the products, data on water sources and destinations for water consumption calculation and data on water quality.

Table 7-1 Main flows to be inventoried for water quality assessment in concrete production.

Impact category	Emissions to	Unit	Substance	Process
Human non-carcinogenic toxicity	Water	mg/kg	Zinc	Clinker production
	Air	µg/kg	Lead	
Marine eutrophication	Water	g/m^3	Nitrate	Wastewater from concrete production
Aquatic acidification	Air	g/kg	Nitrogen oxides	Clinker production
	Air	g/kg	Sulfur dioxide	

Source: the author.

7.4.3. WATER FOOTPRINT IMPACT ASSESSMENT

Two main aspects related to water use are considered: quality and quantity. It has to be emphasized, that the ecological impact of water consumption varies by location where the water is obtained and the availability and local use rates (O'Brien et al. 2009; Pfister et al. 2009; World Business Council for Sustainable Development 2012).

For quality, water is considered polluted when certain substances or conditions are present to an extent that water cannot be used for a specific purpose. Changing its physical, chemical and biological characteristics with respect to their suitability for the intended use by humans or ecosystems is defined as water degradation (International Organization for Standardization 2014). Some effects of water pollution are: the progressive loss of lakes and rivers which results in the reduction of freshwater supplies, reducing the water available for consumption by humans and animals.

Concerning quantity, water scarcity is the lack of enough available water resources to meet the demands of a region. Water scarcity can be caused by climate change, such as altered climatic patterns including droughts and floods, increased pollution, increased human demand and excessive use of water (Hoekstra 2014; World Wildlife Fund 2019). Freshwater scarcity of is manifested as a decrease in groundwater levels, reduced river flows, reduction in polluted lakes, in addition to rising costs of supply and treatment, intermittent water supplies and the conflict water (Hoekstra 2014).

For the impact assessment, we recommend the comparison of the water consumption with the water stress that varies by location and could be found in public websites such as WRI[1]. However, many of these maps are not updated or do not consider the water stress indicator by watershed. In the case of the map in Figure 7-1, we can notice that most of the Brazilian region appears to be green which is the lowest water stress indicator. However, it is known that in many of the capitals there is water stress issues.

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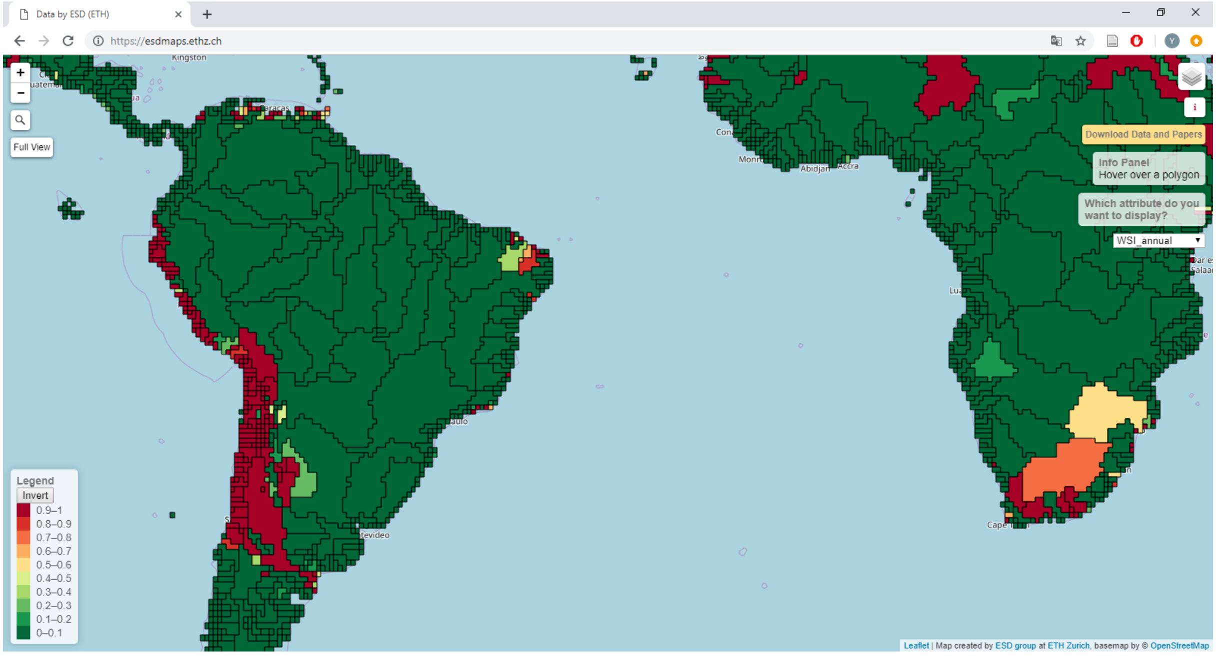
[1] http://www.wri.org/applications/maps/aqueduct-country-river-basin-rankings/

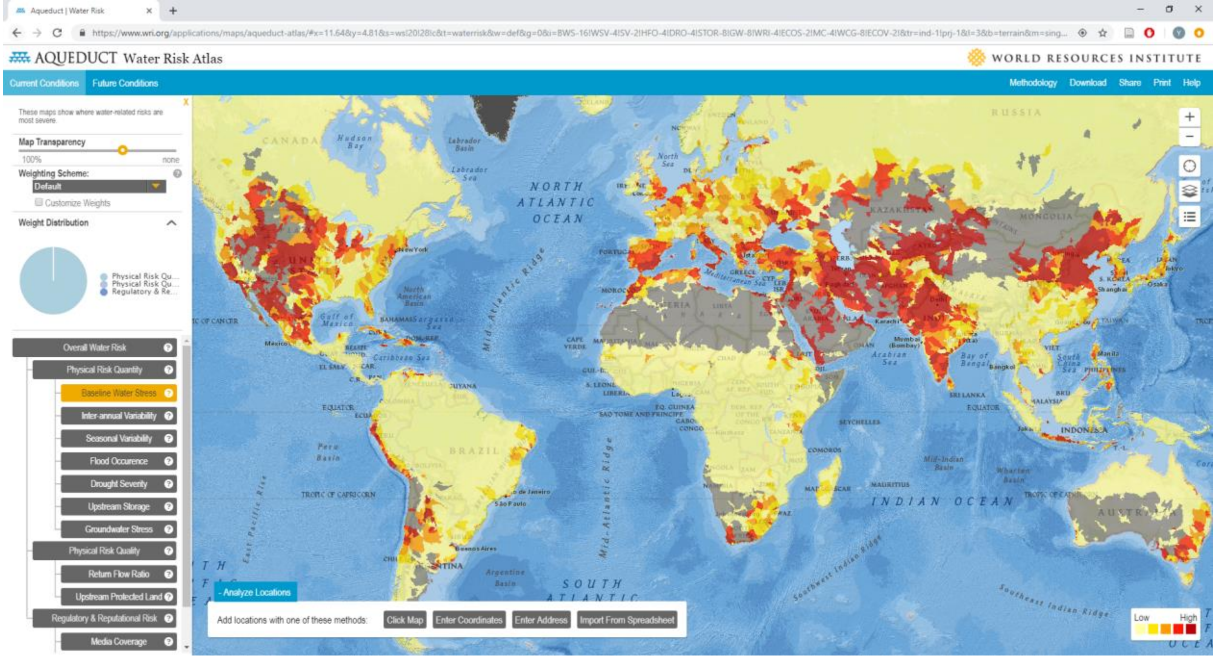
For instances in Porto Alegre, Rio de Janeiro and Sao Paulo as could be observed in the map in Figure 7-2. Hence, we recommend the use of the map in Figure 7-2 or a map with similar or better resolution. The information in the water stress map should be available at least at a watershed level.

Figure 7-1 Interactive geomap on water stress provided by the chair of Ecological system design of ETHZ.



Source: (ETH 2019).

Figure 7-2 Interactive geomap on water stress provided by Aqueduct water risk atlas.



Source: (Lehner et al. 2008).

7.5. SIMPLIFICATION AND COMPARISON TO OTHER METHODOLOGIES

Table 7-2 presents the water uses, water discharge deduction and water consumption considered by the proposed streamlined concrete water footprint methodology (SCWF) compared to other water footprint methodologies from chapter 4.

Table 7-2 Comparison of the definition of water use, water withdrawal and water discharged for each methodology.

		Hoekstra	GaBi	GWT cement	ILCD	ISO 14046	PCR Concrete	Ecoinvent	**SCWF**
		(Hoekstra et al. 2011)	(Rudolf et al. 2013)	(World Business Council for Sustainable Development 2013b)	(European Commission 2010a)	(International Organization for Standardization 2014)	(World Business Council for Sustainable Development 2013a)	(Ecoinvent 2014)	
Water use type									
In-stream			X			X	X	X	
Off-stream		X	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	X
Water withdrawal									
Used		X	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				X
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	X
Water consumption									
Water evaporated		X	X	X	X	X	X	X	X
Water integrated into product		X	X	X	X	X	X	X	X
Water discharged to a different source	Quality changed	X			X	X	X	X	X
	Same quality	X				X	X	X	
Water discharged to the same source from origin	Quality changed	X			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.

Source: the author.

Table 7-3 presents the water sources considered by the streamlined methodology for concrete water footprint compared to other methodologies studied in chapter 4.

Table 7-3 Comparison of water sources considered by each methodology. Only PCR Concrete is consistent with ISO 14046.

	Hoekstra	GaBi	GWT cement	ILCD	ISO 14046	PCR Concrete	Ecoinvent	**SCWF**
Water sources	(Hoekstra et al. 2011)	(Rudolf et al. 2013)	(World Business Council for Sustainable Development 2013b)	(European Commission 2010a)	(International Organization for Standardization 2014)	(World Business Council for Sustainable Development 2013a)	(Ecoinvent 2014)	
Ground water	X	X	X	X[2]	X	X	X	X
Surface water	X	X	X	X	X	X	X	X
Quarry water			X					X
Seawater			X	X	X	X	X	
Municipal water			X			X		X
Rain water	X[1]	X	X		X	X	X	X[3]
Soil water content and moisture	X[1]	X					X	X
External waste water			X					X
Chemically bounded in raw materials		X					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.

[3] Only rainwater collected and used by the company in their production processes should be accounted and not rainwater diversion from the plant.

Source: the author.

Table 7-4 presents the results from the application of the streamlined water footprint methodology for concrete production to the case study scenario presented in chapter 4.

Table 7-4 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.

	Hoekstra	GaBi	GWT cement	ILCD	ISO 14046	PCR Concrete	Ecoinvent	**SCWF**
(H kg/m^3)	(Hoekstra et al. 2011)	(Rudolf et al. 2013)	(World Business Council for Sustainable Development 2013b)	(European Commission 2010a)	(International Organization for Standardization 2014)	(World Business Council for Sustainable Development 2013a)	(Ecoinvent 2014)	
Water withdrawal	723	313	313	773	773	773	773	313
Water discharge	60	90.5	90.5	550.5	141	141	141	0
Water consumption	713	822.5	222.5	222.5	882	882	882	313
Water consumption (except in-stream)	713	572.5	222.5	222.5	632	632	632	313

Source: the author.

7.6. DISCUSSION

The proposed methodology presents the principles and framework to be followed by the concrete water footprint practitioner. The methodology is compatible with existing methodologies and focused on concrete production. There are different methodologies, including specific to cement and concrete production; however, due to their complexity the companies have problem using these methodologies.

Water footprint methodologies were developed from the beginning focused on agriculture, and therefore, these methodologies have some applications that may not be necessary or useful in the case of concrete production. Existing methodologies were reviewed to identify what is needed and useful for the concrete production to be more efficient in terms of water use.

The definitions gathered and presented in this chapter are important in order to be able to compare the results from different studies or companies. In the proposed methodology, the definitions come from the ISO 14046 standard and the Global Water Tool for Cement Sector. Therefore, this methodology is in accordance with the ISO 14046 standard but focused on the concrete production case.

The proposed methodology has a cradle to gate approach. The water footprint of concrete production consists of the activities from the extraction of raw material to the concrete mixing in the concrete trucks. However, as is not always that all the activities happen in the same place, a modular approach is considered including direct water use in the concrete plant, indirect water use in cement and aggregates production and water use for energy production. The water use at the concrete should be primary data directly measured at the plant. For the cement and aggregates, the same applies. Since the relation between the concrete industry and the construction aggregates and cement industry is dependent from each other, we believe that the exchange of primary data should be feasible. For the water use in energy production, this is an activity that is background i.e. could not be controlled by the concrete company in any way. Still, it is recommended to have control over the energy uses in the different processes and for transportation. This is commonly done since energy represents a high cost for companies and for this reason companies are motivated to reduce the energy consumption. A reduction in energy consumption is also recommended due to its high-water footprint. Primary data on energy use is needed in order to estimate the water footprint for the energy production and to be able to reduce the water footprint by being more efficient in terms of energy use as well.

The results are presented in units of volume of water per m^3 of concrete. However, in order to define a functional unit in LCA and water footprint assessment, the main function of the product should be considered. Damineli et al. (2010) proposes a functional unit for binder intensity and CO_2 intensity based on the mechanical strength of the concrete. In the case of water use in concrete production, an appropriate functional unit would also consider the slump to express the rheological behavior of the concrete since the main functions of the concrete are mechanical strength and workability. The mechanical strength will depend on the cement reaction with water and the rest of the water in the concrete mix would be used to assure workability. However, considering that the mixing water represents a small fraction of the total water used in concrete production, it is feasible to compare concrete production without knowing their compressive strength and or slump. This is in the case that this information is not available, but companies usually have this data.

The main characteristics of the water flows that are considered in the proposed methodology is that they should be water that is used and primary data. This is done in order to be able to identify water reduction opportunities based on what the companies actually uses. Regarding the primary data requirements, there is no reason for the companies not to collect their own data. And in order to have meaningful results, the very least that companies should do is to gather their own data. It is difficult to have any kind of improvement when the measures taken to reduce water consumption are based on assessment done from secondary data.

Water reuse and water recycling is highly encouraged. In the case of concrete production, water reuse and recycle will decrease the potable water requirement and it has been proven that is possible to use water treated from concrete production and even from other uses to produce concrete. In the case of aggregates production, the reuse of water could decrease the high-water consumption linked to this activity. Many quarries extract water from water pounds, rivers or lake when they could just reuse the water. For cement production, there is a large amount of water use for cooling purposes which could be reuse and recycled. In order to motivate these practices, it should be accounted separately in the water inventory. Figure F. 0-1, presents an example of water recycling scenario for 1 m^3 of concrete. However, water recycling and reusing is a very specific process and should be study in detailed based on the flowchart of each company. It is worth mentioning that many studies demonstrated promising results from the reuse of ready-mixed concrete waste water in several ratios with fresh water for concrete production (Borger et al. 1994; Sandrolini and Franzoni 2001; Su et al. 2002; Chatveera et al. 2006; Chatveera and Lertwattanaruk 2009; Ružinski et al. 2011; de Paula et al. 2014).

This methodology requires to include water losses. In the case of water from the public network, there should be a consensus on the amount of water that is loss through the network. This water would be a hidden flow that could represent large amounts. In the case of Sao Paulo, it is estimated that the public network has a loss of roughly 30%.

Another relevant water flow to be consider and discussed is the water integration in raw materials or in the final products. This can happen in two ways: humidity or water chemically bounded. For instance, there is humidity that comes in the aggregates. The origin of the water that comes in the aggregates is undefined. Could be water from the extraction, water due to washing of the aggregates, rainwater during stock or transportation, etc. The aggregates become a water source then. Regarding water chemically bounded, there is the water that comes in the clay and is release during clinker calcination for cement production and there is the water that becomes chemically bounded in the hardened concrete due to reaction with cement.

There are many specific cases that could happen. It is common for some companies to collect rainwater and only use part of it. In this case, the measurement of the water collected, extracted and used should be carefully performed. The water consumption depends on where the water is discharged.

The water footprint of a product should include water quality and water quantity aspects. Regarding water quantity, the flows to be inventoried are presented in Table 7-3 and the water consumption should be calculated according to equations 1 and 2. The impact assessment is recommended to be done based on the water stress. For this, a water stress map is needed. There are some available options of water stress maps, however, most of these options do not have the best resolution which should be water stress by watershed. Many of these maps present water stress per country or per region. Even characterization factors based on these maps are presented by country. All countries are divided by watersheds and therefore have different levels of water stress according to this resolution. Even more, Brazil which is a continental size country, and similar should not be considered to have the same level of water stress across the country. Water stress maps with better resolutions are needed for the water impact assessment of water consumption in concrete production and other products as well.

It could be helpful to add a characterization factor at the inventory level for the water from the public network to incentive the use of other water sources. However, further study is needed to define which would be the appropriate characterization factor. This characterization factor could include the water losses and/or a subjective value in order to increase the weight of this water flow since using water from the public network - which is already quite stressed in many cities- will directly affect the population.

For water quality aspects, the substances to be inventoried are presented in Table 7-1. From these flows, only nitrate form concrete wastewater should be inventoried. Lead, Nitrogen oxides, Sulfur dioxide to air and Zinc to water effluents should be inventoried during clinker production. Lead, Nitrogen oxides, Sulfur dioxide to air are usually controlled in clinker production. Regarding Zinc in water effluents, this have been done according to the review that was done in chapter 5 and is possible to control with basic equipments.

In this methodology, it is required to identify the geographical location and temporal dimension where the data is taken. This is done since water impacts are local, and in order to perform an impact assessment, this information is needed. However, this methodology is mostly focused on the water inventory, since this information will allow the companies to identify where they could be more efficient and to compare themselves to other companies through benchmarks. For instance, if we compare the water footprint of 1 m^3 of concrete in a water stressed region versus a region with high water availability, the chances of improving the production process will be hidden by the characterization factors of the impact assessment. Furthermore, benchmarks require local geographic influences to be minimized by comparing only water flows.

The water impact assessment might be useful if the reason for the study is to determine where to obtain or produce a product. However, in the concrete industry, the concrete demand is driven by the region. Therefore, the water footprint objective is to be more efficient rather than to choose a region to stablish the concrete production since this is already defined by the demand of concrete for housing and infrastructure.

In many cases the water footprint is used to decide where is better to produce a product i.e. where would the water related impacts be lower. In the case of concrete, the concrete plants are located based on the demand. Therefore, it would be counterproductive to decide to shut down a concrete plant because of its water footprint when the region where the concrete plant is located needs this product to build houses and infrastructure in order to improve quality of life of the people. The answer is in water management and measuring is fundamental for this. Without knowing the amount of water that is used and where it is used i.e. in which activities, it is not possible to identify water reduction opportunities or increase water efficiency. Water footprint measures are fundamental to inform water management and policy making.

Comparing water inventories has many advantages. For instance, it would be useful in the case of comparing technological routes and this is what companies participating in the former Cement Sustainability Initiative (CSI) (now transferred to the Global Cement and Concrete Association (GCCA)) are doing. These companies, account water withdrawal and water consumption for many of their plants and then they can be compared to their peers. Generating a benchmark in the form of a range of water use for each typical variation of the production processes could be used to promote more rational use of water. Regardless, the inventory has to be simple enough to be used by most organizations, including small and medium-sized enterprises.

Regarding water impact assessment, a complete water footprint should include water quality and water quantity aspects. This study is focused on water quantity at a midpoint level to stand out its importance without combining the potential environmental impacts of other water related issues such as freshwater ecotoxicity, freshwater eutrophication, etc. There are many water footprint definitions and methodologies (Mack-Vergara et al. 2015). The understanding of the methodology and characterization factors is fundamental when reporting our own water footprint results or when interpreting water footprint results from other sources.

The location where the concrete production happens is quite relevant for the water footprint assessment. For instance, is not the same to consume 500 liters of water in Zurich where there is plenty of water and a small stable population than to consume the same amount in Sao Paulo where there was a recent water crisis and where the population surpasses 20 million only in the metropolitan region and is expected to increase rapidly.

Season is as relevant for water footprint assessment as the location. In most countries, water is only available during some periods of the year. In developed countries they probably have some way of saving water for dry seasons, but this is hardly the case in other countries. The concrete demand though, do not match the wet seasons and could be severely affected leaving ongoing projects to slow down as well as economy.

The simplification that was achieved in this study consist of 5 out of 1580 flows for water quality assessment (chapter 5) and mainly water that is off-stream used. This allows the companies to gather their own inventories since there are no substances or flows that they do not have control on. Furthermore, this simplification will motivate companies to build their own water inventories knowing that the results they will get are based on what they do and representative data. Opposite from the case where secondary data is used and even if the water footprint is done with large amounts of data, the result will include impacts where the concrete manufacturer has no control at all and therefore there is not much the company could do to improve the situation. In this case, the results could mask the processes where the companies could actually improve leaving us with a ”complete water footprint assessment” that is not helpful for improving water efficiency of the company or the concrete industry at all.

7.7. CONCLUSIONS

In this work, a streamlined water footprint methodology was proposed for concrete production. The main water sources and uses were identified for the concrete production case. This methodology will allow more straightforward and meaningful water assessment in concrete production. This streamlined methodology could allow and incentivize the construction of a water figures benchmark. This streamlined methodology could be used by small, medium and large companies due to its simplicity but with relevant results.

This streamlined water footprint methodology represents a simplification of other water footprint methodologies based on the water sources and uses that are relevant for the concrete production case. The streamlined methodology allows to have meaningful results with less data by identifying what really matter in terms of water use in concrete production. Compared to other methodologies, the streamlined methodology reduces complexity and data requirement which in many cases prevent companies from performing water footprint of their products.

For a water footprint assessment to be performed, it is needed to consider the location and period when the processes are happening. However, in the case of concrete production, the water inventory alone, also has great importance since it allows to identify where exactly in the production process we can reduce water and which water sources are more critical.

The proposed methodology is simple for any company to use it but complete enough for companies to identify and assess the potential environmental impacts related to water in concrete production. This methodology will allow companies to identify water reduction opportunities, optimize their processes through water efficiency and report consistent and reliable information to the decision-makers in industry.

8. CONCLUSIONS

Water is a basic need for all human activities. Furthermore, we need mostly freshwater which is not that abundant. Due to population growth, the demand for water will increase. On the other hand, the availability of water is compromised due to factors such as climate change. Therefore, we need to be more efficient in terms of water use.

The annual production of concrete is ~15 million m^3 and is expected to increase until the year 2050. This means that approximately (8–40 billion m^3) are used for the global concrete production. The concrete demand will take place mostly in developing countries such as South Africa, India and China, where water scarcity is a major problem specially in large cities. Since there is no replacement for concrete, it needs to be produced in the most efficient and sustainable way possible.

Despite the large amount of concrete production and water used for its production, the literature on environmental assessment of cement-based materials is limited, focusing primarily on energy and CO_2 emissions. Concrete LCA usually lack water related impacts. This happen mainly because of complexity of existing methodologies.

The cement industry has started to measure and save water in their plants. However, the adoption by the cement industry of available water footprint methodologies, has been problematic. Such methodologies do not not fulfill the requirements of the industry, and probably will not be part of the industry management at large scale in the near future even by large, resourceful organizations such as the cement companies. Considering aggregates and ready-mix concrete plants are much smaller than cement plants, the development of a simplified methodology for the water inventory, allowing decisions to be made based on primary data, is desirable. Nevertheless, it is also desirable that such methodology would be consistent with ISO LCA standards.

In the cement value chain processes the variability of water use among producers is high. Since concrete cannot be replaced in large scale by other material, mitigation strategies require the select of the best supplier. Therefore, primary data measured at company level is needed otherwise it is impossible to identify best producers, produce industrywide benchmarks and identify opportunities of improvement at each company. To have large sets of primary data at company level, the methodology for measuring and collecting data should be easy to use even by small and medium enterprises.

The water inventory and footprint methodology are more complex than CO_2. For a water footprint assessment to be performed, it is needed to consider the location and period when the processes are happening. However, in the case of concrete production, the water inventory alone, also has great importance since it allows to identify where exactly in the production, we can reduce water and critical water sources.

An extensive study on water footprint methodologies was conducted in order to understand their implications on the water inventory figures in concrete’s life cycle from cradle-to-gate. The water use for different components and processes in concrete production cradle-to-gate were identified along with water inventory figures. The most critical flows in terms of water quality assessment were identified based on the contribution of the substances to the potential environmental impacts, the control or influence that the concrete producer has on the activities were these flows appear and the feasibility to measure these flows on site.

A streamlined water footprint methodology was proposed for concrete production. This streamlined water footprint methodology presents a simplification of other methodologies based on the water sources and uses that are relevant for concrete production. This methodology allows to have meaningful results with less data by identifying what really matter in terms of water use in concrete production. Compared to other methodologies, the streamlined methodology reduces complexity and data needs that usually prevent companies from performing water footprint of their products.

Water directly used in the concrete production plant is variable. Typical water inventory 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 aggregates production (0.116–2.0 H kg/kg).

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.

Study of concrete water footprint is fundamental to establish actions to improve water efficiency. 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. The development of tools to diagnose problems inherent to water footprint calculation in cementitious materials industry and complemented by existing methodologies represent an interesting contribution to sustainable construction.

8.1. RESEARCH PRODUCTION

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8.2. RECOMMENDED FUTURE WORK

1. Development of a common standard for water inventory in building materials, with a simplified method, to allow comparable data to be gathered by large fractions of the industry, building relevant benchmark for each sector.
2. Water figures benchmark based on primary data collection.
3. Practices, technologies and alternatives water sources that could be implemented to reduce water footprint in concrete production.
4. Further study on energy water footprint models.
5. Water footprint of other life cycle stages (use and disposal).
6. Water intensity index based on the concrete strength.
7. Water intensity index based on the concrete slump.
8. Automatization of the streamlined concrete water footprint methodology.
9. Impacts on water policy making of the concrete industry and government.
10. Water footprint of the new CICS building.

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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) (Pickering et al. 1985; American Concrete Institute 2000, 2003; C09 Committee 2004, 2010, 2014; O’Brien et al. 2009; Yang et al. 2014) that contribute to the properties of hardened concrete through hydraulic or pozzolanic activity.

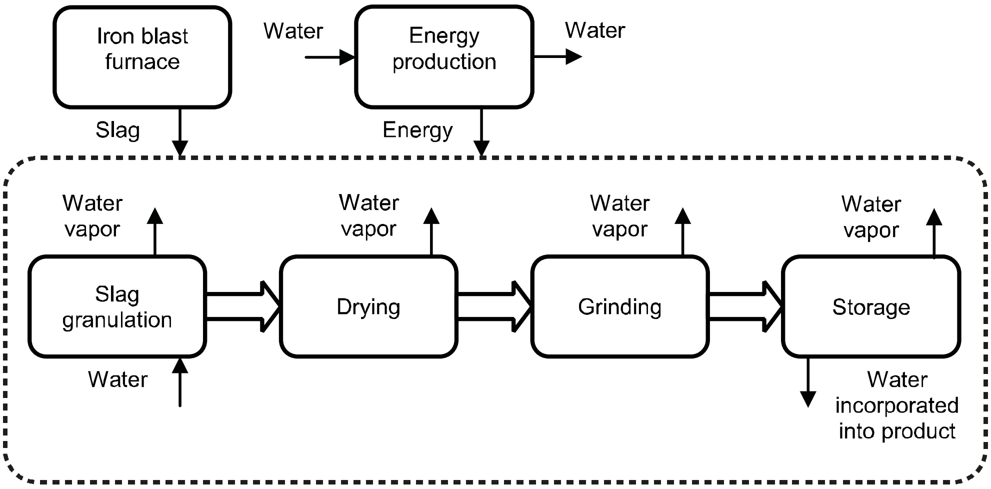
Each cement plant has a unique design due to technical decisions, climate variations, location, topography, available raw materials, fuels and dealers, environmental legislation and owners’ preferences. This design decisions frequently impact the water use.

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). Figure A. 1 presents the BFSG treatment process and related water use. Indirect water in the energy production is also associated with cement production (O’Brien et al. 2009) and treatment of other SCMs such as fly ash (FA) (Chen et al. 2010a).

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 (Yoshinaga et al. 1982; Mizuochi et al. 2002; Liu et al. 2011).

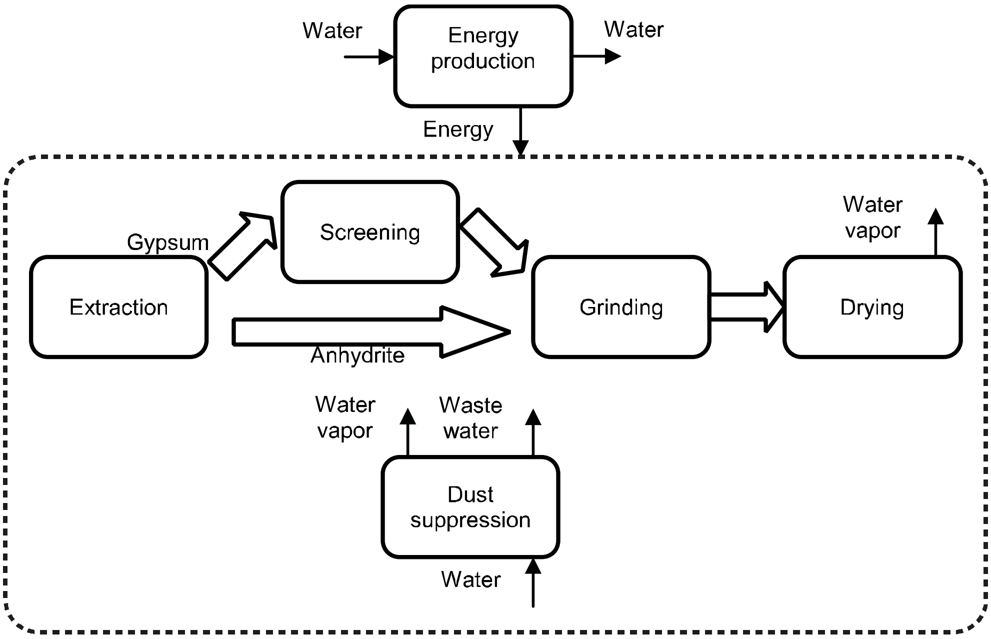
Figure A. 1 BFSG treatment process and related water use.



Source: (Mack-Vergara and John 2017).

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 (Eurogypsum 2011). Since these are waste products from another industrial process, none of the burdens process would be allocated to it. Figure A. 2 presents the process of gypsum production.

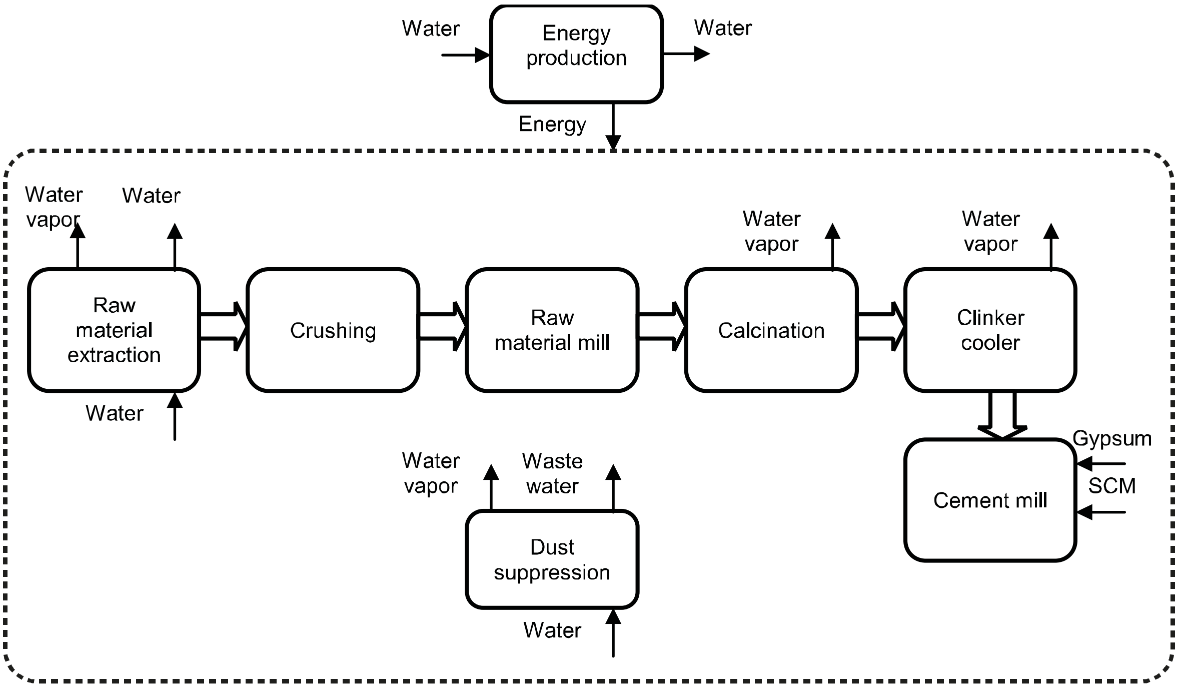
Figure A. 2 Gypsum process and related water use.



Source: (Mack-Vergara and John 2017).

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). Figure A. 3 presents the cement production process and water allocation for the different steps.

Figure A. 3 Cement production process and related water use.



Source: (Mack-Vergara and John 2017).

A.2 AGGREGATES PRODUCTION

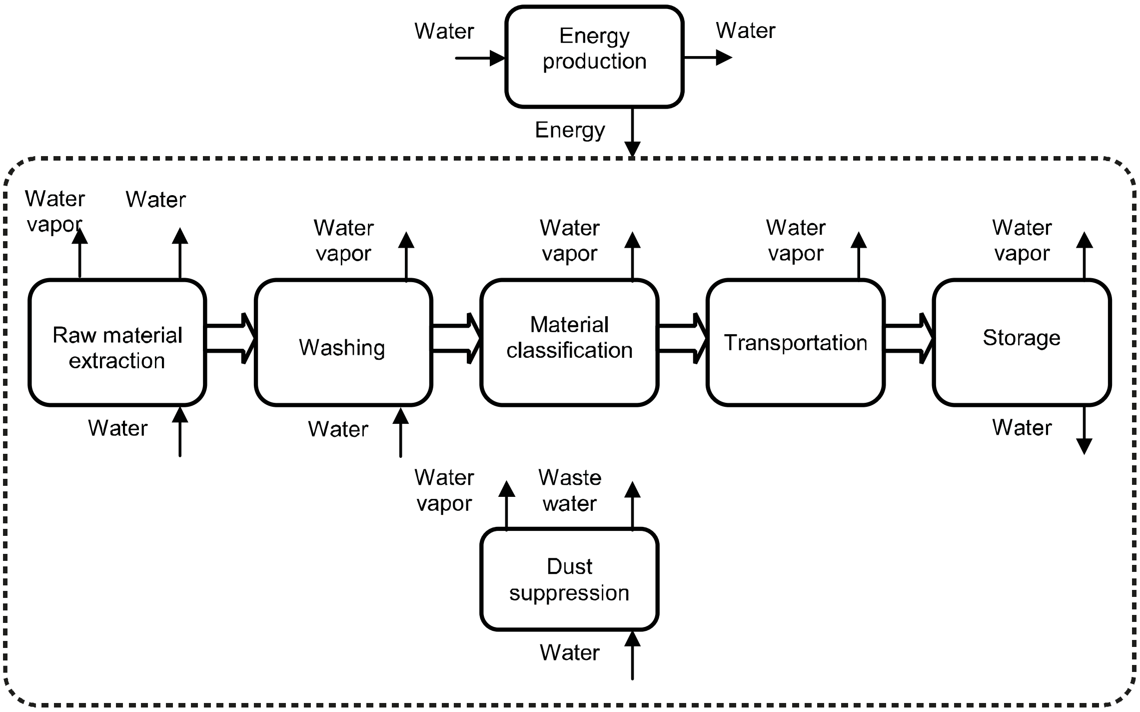
Aggregates extraction typically comprises mining and quarrying (Korre and Durucan 2009) including sand and coarse aggregates extraction from water courses, an in-stream water use. Extraction can involve the use of explosives and heavy machinery as well as hydro-excavation, which uses a high-pressure water system for digging (Gyori et al. 1994; Rajewski 2009).

The production of fine and coarse aggregates 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 aggregates 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 classification, 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 2014a). Figure A. 4 presents the aggregates production process and related water use.

Figure A. 4 Aggregates production process.



Source: (Mack-Vergara and John 2017).

A.3 CONCRETE PRODUCTION

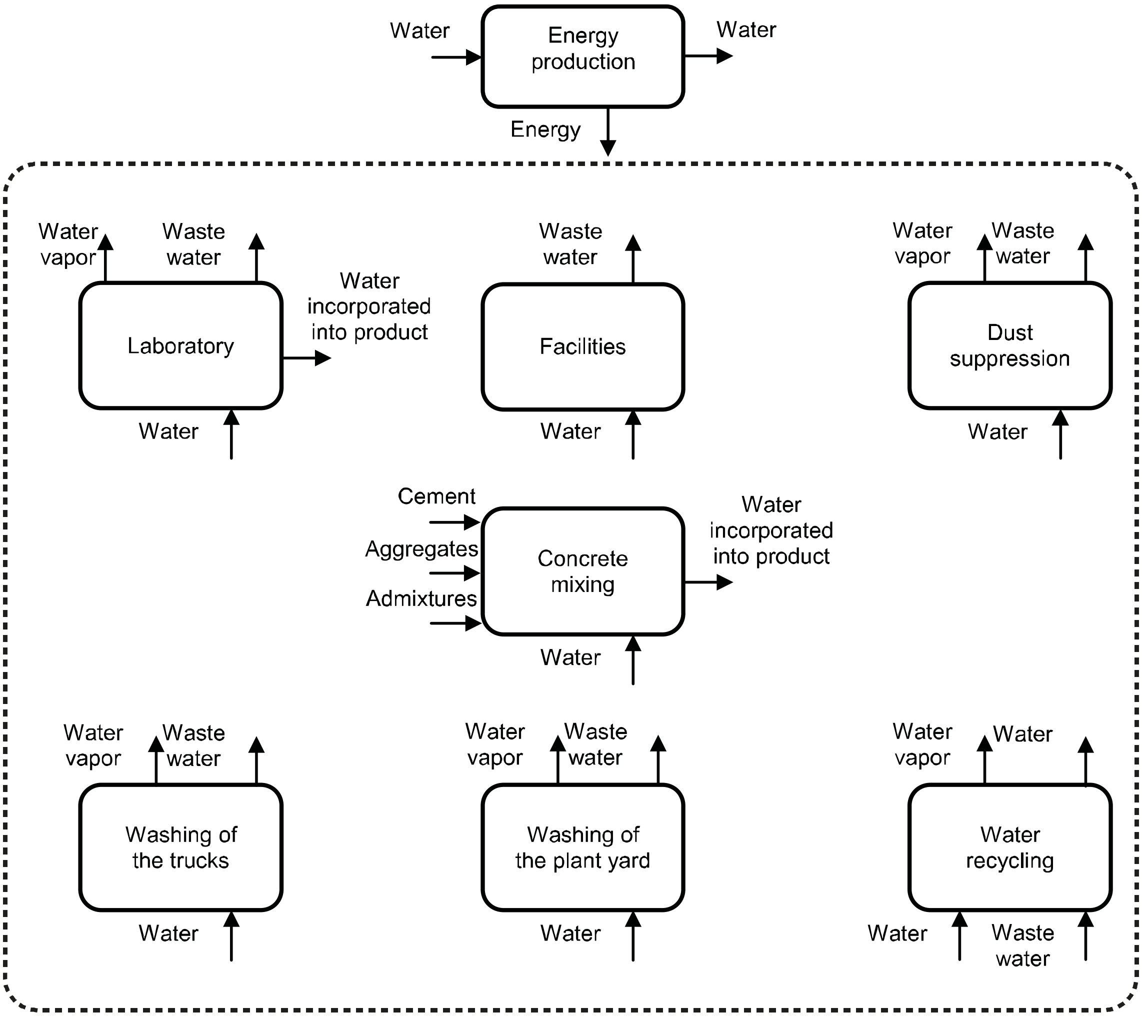
In its most simple form, concrete is a mixture of cement paste and aggregates. In addition, admixtures, which are solid or liquid substances added before or during mixing of the concrete that have multiple functions, may be used (C09 Committee 2013). Portland cement chemistry reactions starts in the 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) (Paolini and Khurana 1998; Chini et al. 2001; Nisbet et al. 2002; Ekolu and Dawneerangen 2010), 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 Figure A. 5.

Figure A. 5 Concrete production process and related water use.



Source: (Mack-Vergara and John 2017).

APPENDIX B. WATER INVENTORY FOR CONCRETE PRODUCTION PROPOSED SCENARIO

Table B. 1 Water inventory for concrete production proposed scenario.

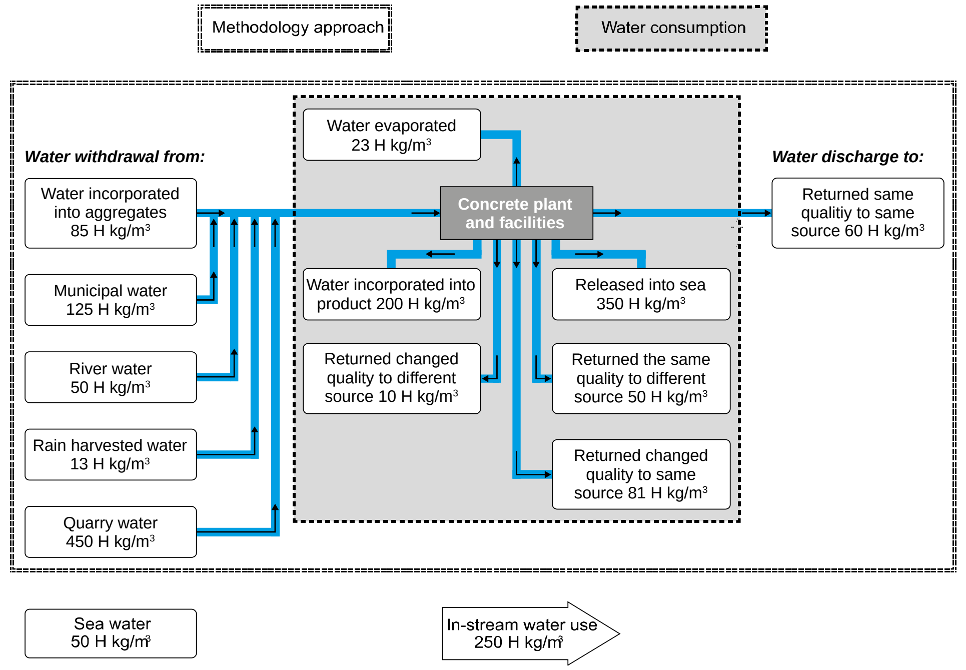
Water withdrawal per source (H kg/m^3)		Use (H kg/m^3)		Evaporated (H kg/m^3)	Incorporated into product (H kg/m^3)	Release into sea (H kg/m^3)	Returned changed quality to different source (H kg/m^3)	Returned the same quality to different source (H kg/m^3)	Returned changed quality to same source (H kg/m^3)	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[1]	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

[1] 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 (Marceau et al. 2007; Cemex 2015) * 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 plant's 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.

Source: (Mack-Vergara and John 2017).

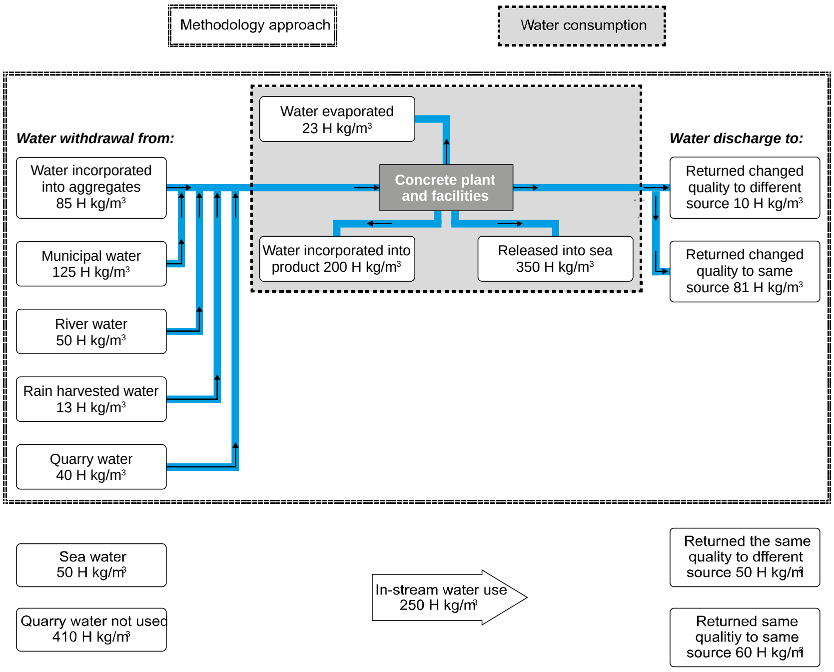
APPENDIX C. WATER CONSUMPTION FOR CONCRETE PRODUCTION PROPOSED SCENARIO ACCORDING TO THE DIFFERENT METHODOLOGIES

Figure C. 1 Water consumption scenario for concrete production according to The water footprint assessment manual by (Hoekstra et al. 2011).



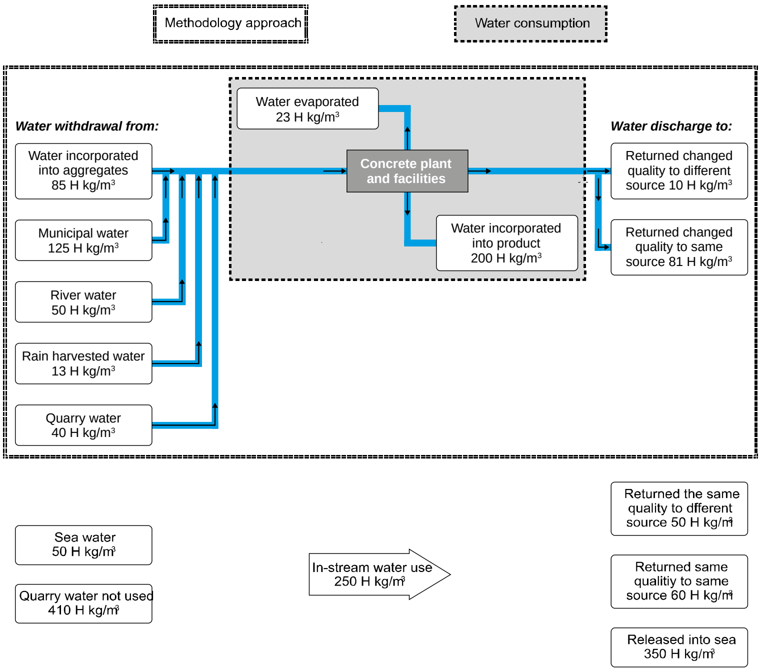
Source: (Mack-Vergara and John 2017).

Figure C. 2 Water consumption scenario for concrete production according to the GaBi Database and Modelling Principles (Rudolf et al. 2013).



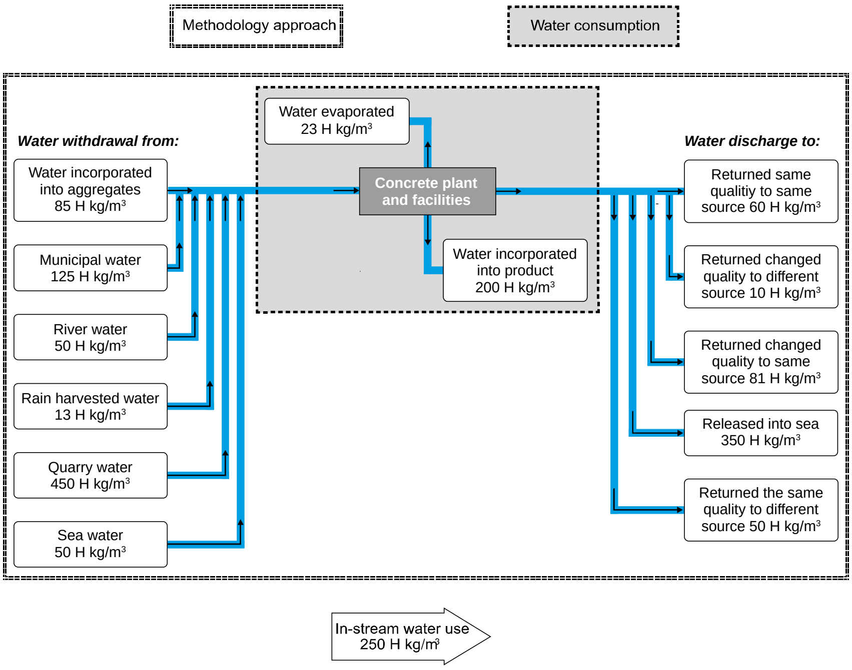
Source: (Mack-Vergara and John 2017).

Figure C. 3 Water consumption scenario for concrete production according to GWT for Cement Sector (World Business Council for Sustainable Development 2013b).



Source: (Mack-Vergara and John 2017).

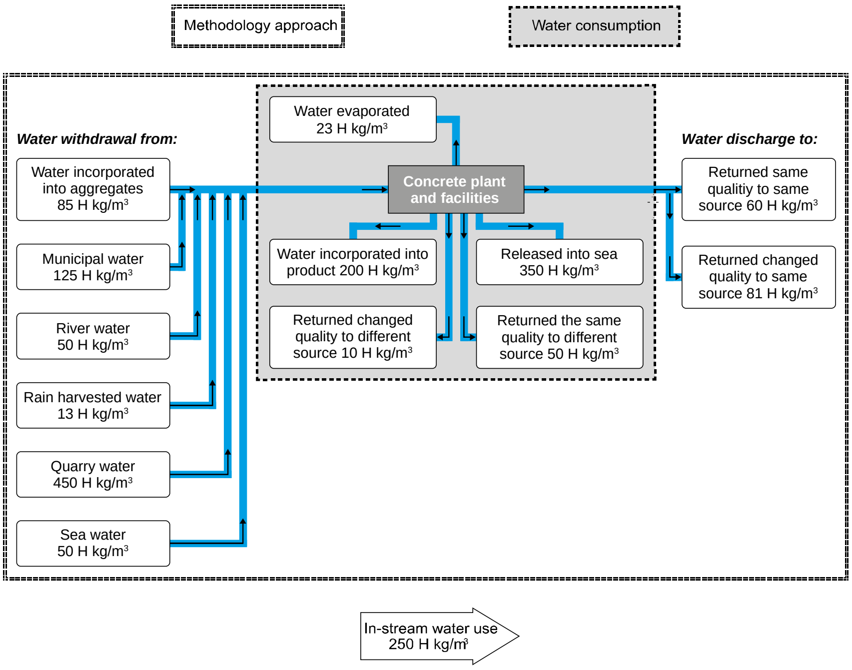
Figure C. 4 Water consumption scenario for concrete production according to the ILCD Handbook for LCI (European Commission 2010a).



Source: (Mack-Vergara and John 2017).

Figure C. 5 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 2013a) and the Ecoinvent database (Ecoinvent 2014).



Source: (Mack-Vergara and John 2017).

APPENDIX D. WATER INVENTORY FIGURES FOR AGGREGATES, CEMENT AND CONCRETE PRODUCTION

Table D. 1 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 2014)	2014	LCI database	Switzerland	Switzerland
Sand - RoW	Undefined	2.526	(Ecoinvent 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

Source: (Mack-Vergara and John 2017).

Table D. 2 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 2014)	2014	LCI database	Switzerland	Switzerland
Gravel, crushed - RoW	Undefined	1.124	(Ecoinvent 2014)	2014	LCI database	Switzerland	Worldwide
Gravel, round - CH	Undefined	1.390	(Ecoinvent 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

Source: (Mack-Vergara and John 2017).

Table D. 3 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 2015)	2012	Sustainability report	Mexico	Worldwide
Aggregates	Production includes washing	0.168	(Cemex 2015)	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 2012a)	2010	Sustainability report	France	Worldwide
Aggregates	Undefined	0.116	(Lafarge 2012a)	2011	Sustainability report	France	Worldwide
Sand or gravel	Undefined	2.000	(O'Brien et al. 2009)	2009	Paper	Australia	n/d

Source: (Mack-Vergara and John 2017).

Table D. 4 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. 2010b)	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	

Source: (Mack-Vergara and John 2017).

Table D. 5 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 vapor condensation	0.750	(Schweitzer 2015)	2015	Personal communication	Luxembourg	Worldwide
		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

Source: (Mack-Vergara and John 2017).

Table D. 6 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

Source: (Mack-Vergara and John 2017).

Table D. 7 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 2015)	2012	Sustainability report	Mexico	Worldwide
		0.376		2013	Sustainability report	Mexico	Worldwide
Cement	Undefined	0.360	(Holcim 2012)	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 2012a)	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

Source: (Mack-Vergara and John 2017).

Table D. 8 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					

Source: (Mack-Vergara and John 2017).

Table D. 9 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					

Source: (Mack-Vergara and John 2017).

Table D. 10 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

Source: (Mack-Vergara and John 2017).

Table D. 11 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

Source: (Mack-Vergara and John 2017).

APPENDIX E CONCRETE RELATED PROCESSES FROM ECOINVENT V 3.4 USED FOR THE IDENTIFICATION OF CRITICAL FLOWS

Table E. 0-1 presents 86 processes including production of cement constituents, concrete constituents, different types of cements and concretes, cement-based products and other processes related to concrete production. This materials and processes were used to estimate the relevance, sensitivity and applicability of the proposed streamlined water footprint for concrete production.

Table E. 0-1 Complete list of processes from Ecoinvent v 3.4 (allocation, cut off by classification, unit processes).

Cement constituents	Concrete constituents	Cements	Concretes	Cement based products	Others
1 kg Blast furnace slag {US}| ground granulated production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Chemical, inorganic {GLO}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement mortar {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, 20 MPa {CA-QC}| concrete production 20MPa, RNA only | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Autoclaved aerated concrete block {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Blasting {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Blast furnace slag {US}| treatment of, to inert waste | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Gravel, crushed {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, alternative constituents 21-35% {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, 25 MPa {CA-QC}| concrete production 25MPa, RNA only | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Concrete block {DE}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Blasting {RoW}| processing | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Calcareous marl {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Gravel, crushed {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, alternative constituents 6-20% {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, 30-32 MPa {CA-QC}| concrete production 30-32 MPa, RNA only | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Concrete roof tile {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Wastewater from ceramic production {CH}| treatment of, capacity 5E9l/year | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Clay {CH}| clay pit operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Gravel, round {CH}| gravel and sand quarry operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, alternative constituents 6-20% {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, 35 MPa {CA-QC}| concrete production 35 MPa, RNA only | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Light mortar {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Wastewater from concrete production {CH}| treatment of, capacity 5E9l/year | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Clinker {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, blast furnace slag 18-30% and 18-30% other alternative constituents {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, 50 MPa {CA-QC}| concrete production 50 MPa + wastewater truck washing, RNA only | Cut-off, U (of project SLCA)		1 m^3 Wastewater from ground granulated blast furnace slag production {US}| treatment of | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Clinker {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, blast furnace slag 25-70%, US only {US}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, 50 MPa {CA-QC}| concrete production 50 MPa, RNA only | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 m^3 Wastewater from pig iron production {CH}| treatment of, capacity 5E9l/year | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Clinker {US}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Sand {CH}| gravel and quarry operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, blast furnace slag 31-50% and 31-50% other alternative constituents {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, for de-icing salt contact {CH}| concrete production, for drilled piles, with cement CEM I | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 m^3 Wastewater from wafer fabrication {CH}| treatment of, capacity 1.1E10l/year | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Fly ash and scrubber sludge {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Silica sand {DE}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg Cement, blast furnace slag 36-65%, non-US {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, for de-icing salt contact {CH}| concrete production, for drilled piles, with cement CEM II/A | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		
1 kg Ground granulated blast furnace slag {US}| production | Cut-off, U (of		1 kg Cement, blast furnace slag 5-25%, US only {US}| production |	1 m^3 Concrete, for de-icing salt contact {CH}| concrete production, for		

project Ecoinvent 3 - allocation, cut-off by classification - unit)		Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	drilled piles, with cement CEM II/B | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Gypsum, mineral {CH}| gypsum quarry operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, blast furnace slag 70-100%, non-US {US}| cement production, blast furnace slag 70-100%, US only | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, high exacting requirements {CH}| concrete production, for building construction, with cement CEM II/A | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Gypsum, mineral {CN}| citric acid production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, blast furnace slag 81-95%, non-US {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, high exacting requirements {CH}| concrete production, for building construction, with cement CEM II/B | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Inert filler {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, blast furnace slag, 66-80%, non-US {CH}| cement production, blast furnace slag 66-80%, non-US | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, normal {CH}| unreinforced concrete production, with cement CEM II/A | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Inert filler {GLO}| sand to generic market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, Portland {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Concrete, normal {CH}| unreinforced concrete production, with cement CEM II/B | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Kaolin {RoW}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, Portland {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Lean concrete {CH}| production, with cement CEM II/A | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Lime {CA-QC}| lime production, milled, loose | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, Portland {US}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 m^3 Lean concrete {CH}| production, with cement CEM II/B | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Lime {CH}| production, milled, loose | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, pozzolana and fly ash 11-35%, non-US {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	
1 kg Lime, hydrated, loose weight {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, pozzolana and fly ash 15-40%, US only {US}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	
1 kg Lime, hydrated, loose weight {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, pozzolana and fly ash 36-55%,non-US {CH}| cement production, pozzolana and fly ash 36-55%, non-US | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	
1 kg Lime, hydrated, packed {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)		1 kg Cement, pozzolana and fly ash 5-15%, US only {US}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	
1 kg Lime, hydraulic {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)			
1 kg Lime, packed {CH}| lime production, milled, packed | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)			
1 kg Limestone, crushed, for mill {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)			

1 kg Limestone, crushed, for mill {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Limestone, crushed, washed {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Limestone, crushed, washed {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Limestone, unprocessed {CA-QC}| limestone quarry operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Limestone, unprocessed {CH}| limestone quarry operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Quicklime, in pieces, loose {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Quicklime, in pieces, loose {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Quicklime, milled, loose {CA-QC}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Quicklime, milled, loose {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Quicklime, milled, packed {CH}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
1 kg Silica fume, densified {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)

Source: (Ecoinvent 2014).

APPENDIX F EXAMPLES OF WATER DATA FORMS FOR AGGREGATES, CEMENT AND CONCRETE

The next forms are example of water data forms for collection of water data in aggregates, cement and concrete production. These forms are a proposal and should be adjusted based on feedback from the industry.

Table F. 0-1 Company's general data on the extraction/production of aggregates for civil construction.

Date of completion of the form:				
Plant name and company:				
Plant location:				
Plant area (m^2):				
Person filling out the form:				
Position in the company:				
Phone:				
Email:				
Number of company employees:	In office		In the field	
Operating hours[1]:	Hours per shift		Shifts per day	
	Days per month		Months per year	
Period of data (12 months):	Beginning		End	
Environmental standards or initiatives of the company:				
Observations:				
[1]How many shifts and how many hours.				

Source: the author.

Table F. 0-2 Plant’s flow chart data on the use of water in extraction/production of aggregates for civil construction.

Indicate inputs and outputs of raw materials including water and energy, products, by-product and losses.
Are the data obtained by measurement or estimation?
How often are the data collected?

Source: the author.

Table F. 0-3 Products’ data on the use of water in extraction/production of aggregates for civil construction.

Product or by-product		Origin[2]	Rock type	Production process	Through sieve x mm	Retained in sieve y mm	Monthly min production[3] (t)	Monthly max production[3] (t)	Annual production[3]	Loss index range (%)	Measurement or estimation?
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											

[2] Natural, artificial, recycled, other (specify).
[3] Including losses.

Source: the author.

Table F. 0-4 Data on the use of water in extraction/production of aggregates for civil construction.

Unit (liter/kg)	Source									Unit (liter/kg)	Destination									Effluent quality control				
	Public water supply	Superficial (ponds, rivers, etc.)	Underground (well, etc.)	Rain	Chemically Integrated or as humidity	Effluent (specify if it comes from another organization)	Recycled	Reused	Other sources (specify which ones)		Evaporated	Discharged to the sea	Chemically Integrated or as humidity	To a different source of the original. Has altered Quality (-)	To a different source of the original. Has the same quality	Returns to the same source with altered quality (-)	Returns to the same source with the same quality	Other uses (specify which ones)	Passes through WWTP before discharged to the environment (yes/NO)	pH	DBO	DQO	Suspended Solids	Others
Gravel 0										**Gravel 0**														
Extraction and production										Extraction and production														
Washing										Washing														
Water from transport or storage										Water from transport or storage														
Gravel 1										**Gravel 1**														
Extraction and production										Extraction and production														
Washing										Washing														
Water from transport or storage										Water from transport or storage														
Sand										**Sand**														
Extraction and production										Extraction and production														
Washing										Washing														
Water from transport or storage										Water from transport or storage														
Dust suppression										**Dust suppression**														
Extraction and production										Extraction and production														
Storage										Storage														
On the roads										On the roads														
Plant use										**Plant use**														
Yard cleaning										Yard cleaning														
Truck cleaning (external)										Truck cleaning (external)														
Equipment cleaning (other than trucks)										Equipment cleaning (other than trucks)														
Use of administration										**Use of administration**														
General cleaning										General cleaning														
Water use of employees (office)										Water use of employees (office)														
Facility water use (field)										Facility water use (field)														
Other										**Other**														

Source: the author.

Table F. 0-5 Company’s general data on the production of cement.

Date of completion of the form:				
Plant name and company:				
Plant location:				
Plant area (m^2):				
Person filling out the form:				
Position in the company:				
Phone:				
Email:				
Number of company employees:	In office		In the field	
Operating hours[1]:	Hours per shift		Shifts per day	
	Days per month		Months per year	
Period of data (12 months):	Beginning		End	
Environmental standards or initiatives of the company:				
Observations:				
[1] How many shifts and how many hours.				

Source: the author.

Table F. 0-6 Plant’s flowchart data on water use in cement production.

Indicate inputs and outputs of raw materials including water and energy, products, by-product and losses.
Are the data obtained by measurement or estimation?
How often are the data collected?

Source: the author.

Table F. 0-7 Products’ data on water use in cement production.

Product or by-product		Monthly min production[3] (t)	Monthly max production[3] (t)	Annual production[3]
1	Clinker			
2	CPI			
3	CPI-S			
4	CPII-E			
5	CPII-Z			
6	CPII-F			
7	CPIII			
8	CPIV			
9	CPV			
10	Others			
11				
12				

Source: the author.

Table F. 0-8 Data on water use in cement production.

Unit (liter/kg)	**Source**									**Unit (liter/kg)**	**Destination**									**effluent quality control**				
	Public water supply	Superficial (ponds, rivers, etc.)	Underground (well, etc.)	Rain	Chemically Integrated or as humidity	Effluent (specify if it comes from another organization)	Recycled	Reused	Other sources (specify which ones)		Evaporated	Discharged to the sea	Chemically Integrated or as humidity	To a different source of the original. Has altered Quality (-)	To a different source of the original. Has the same quality	Returns to the same source with altered quality (-)	Returns to the same source with the same quality	Other uses (specify which ones)	Passes through WWTP before being discharged to the environment (yes/no)	Zinc to water	Lead to air	Nitrogen oxides to air	Sulfur dioxe to air	Other
Clay										**Clay**														
Extraction and production										Extraction and production														
Limestone										**Limestone**														
Extraction and production										Extraction and production														
Clinker calcination										**Clinker calcination**														
Clinker cooling										Clinker cooling														
Dust suppression										**Dust suppression**														
On the roads										On the roads														
Plant use										**Plant use**														
Yard cleaning										Yard cleaning														
Equipment cleaning										Equipment cleaning														
Use of administration										**Use of administration**														
General cleaning										General cleaning														
Water use of employees (office)										Water use of employees (office)														
Water use of employees (field)										Water use of employees (field)														
Other										**Other**														

Source: the author.

Table F. 0-9 Company’s general data on the production of ready mix concrete.

Date of completion of the form:				
Plant name and company:				
Plant location:				
Plant area (m^2):				
Person filling out the form:				
Position in the company:				
Phone:				
Email:				
Number of company employees:	In office		In the field	
Operating hours[1]:	Hours per shift		Shifts per day	
	Days per month		Months per year	
Period of data (12 months):	Beginning		End	
Environmental standards or initiatives of the company:				
Observations:				
[1] How many shifts and how many hours.				

Source: the author.

Table F. 0-10 Plant’s flowchart on the use of water in ready mix concrete production.

Indicate inputs and outputs of raw materials including water and energy, products, by-product and losses.
Are the data obtained by measurement or estimation?
How often are the data collected?

Source: the author.

Table F. 0-11 Products’ data on the use of water in ready mix concrete production.

Strength		Water	Cement type	Cement	Fine aggregates	Coarse aggregates	Admixtures	Monthly min production[3] (t)	Monthly max production[3] (t)	Annual production[3]	Loss index range (%)	Measurement or estimation?
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												

Source: the author.

Table F. 0-12 Water data on the use of water in ready mix concrete production.

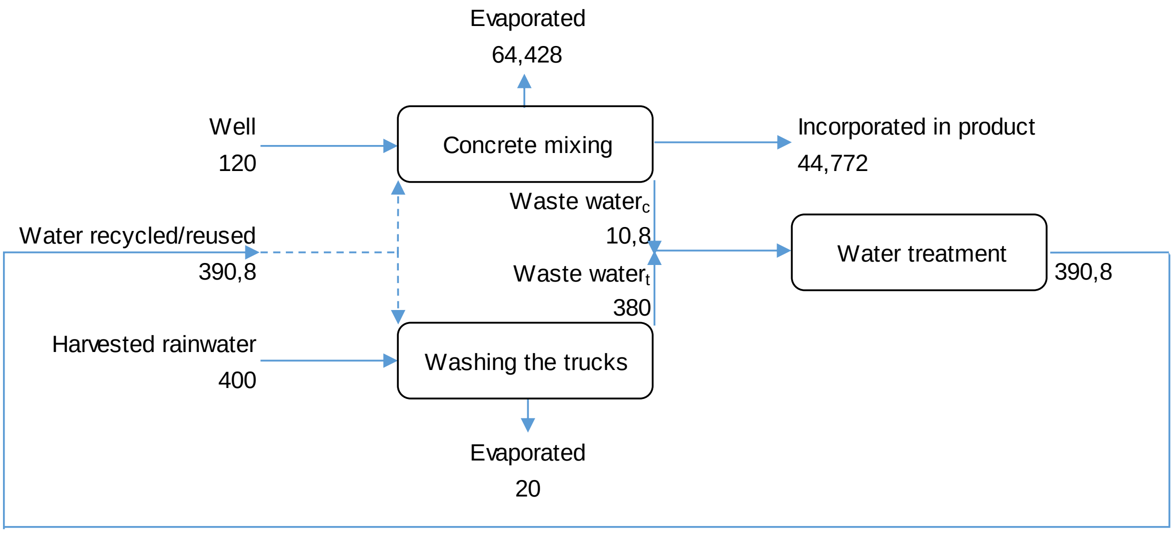
Unit (liter/kg)	**Source**									**Unit (liter/kg)**	**Destination**									**Effluent quality control**	
	Public water supply	Superficial (ponds, rivers, etc.)	Underground (well, etc.)	Rain	Chemically Integrated or as humidity	Effluent (specify if it comes from another organization)	Recycled	Reused	Other sources (specify which ones)		Evaporated	Discharged to the sea	Chemically Integrated or as humidity	To a different source of the original. Has altered Quality (-)	To a different source of the original. Has the same quality	Returns to the same source with altered quality (-)	Returns to the same source with the same quality	Other uses (specify which ones)	Passes through WWTP before being discharged to the environment (yes/NO)	Nitrate in waste water	Other
Dust Suppression										**Dust Suppression**											
On the roads										On the roads											
Plant Use										**Plant Use**											
Yard cleaning										Yard cleaning											
Truck cleaning (external)										Truck cleaning (external)											
Equipment cleaning (other than trucks)										Equipment cleaning (other than trucks)											
Use of Administration										**Use of Administration**											
General cleaning										General cleaning											
Water use of employees (office)										Water use of employees (office)											
Water use of employees (field)										Water use of employees (field)											
Other										**Other**											

Source: the author.

APPENDIX G EXAMPLE OF WATER RECYCLING IN CONCRETE PRODUCTION

Water reuse or recycle should be inventory and this water is deduced from the water withdrawal. In the example presented in Figure F. 0-1, the water withdrawal consists of the water extracted from the well plus the harvested rainwater, the water consumption consists of the water evaporated and incorporated in the product. In this case, the water recycled is deducted from the water withdrawal and therefore is not part of the water consumption.

Figure F. 0-1 Water recycling scenario for 1 m³ of concrete in l/m³.



Source: the author.