Master thesis

THE BLUE AND GREY WATER FOOTPRINT OF INDUSTRY AND DOMESTIC WATER SUPPLY

The blue and grey water footprint of all industrial sectors and domestic water supply for each country annually in the period 1960-2015

Ruben C. Herrebrugh

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UNIVERSITY OF TWENTE.

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Faculty of Engineering Technology
Department of Water Engineering and Management

Author:
Ruben C. Herrebrugh

Student number: s1235710
Email: R.c.herrebrugh@alumnus.utwente.nl

Graduation committee:
University of Twente, Department of Water Engineering and Management

Prof.dr.ir. A.Y. Hoekstra

Msc. H.J. Hogeboom

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I. Summary

At this moment, two-thirds of the global population live under conditions of severe water scarcity at least 1 month a year and half a billion people in the world face severe water scarcity all year round. Increasing knowledge of freshwater abstraction and consumption could contribute to awareness, change, or a solution to the increasing freshwater abstraction and consumption worldwide. An indicator of the direct and indirect freshwater consumption of a consumer or producer is the water footprint. The water footprint is defined as the total volume of freshwater consumed to produce goods or services. Water consumption is defined as the blue water footprint and water pollution as the grey water footprint. The blue and grey water footprint of all industrial commodities and domestic water supply are treated as two whole sectors for a ten-year period in current literature. These sectors contribute approximately 8% of the total water footprint. It does not show annual variations or trends in time. However, the grey water footprint of the industry is grossly underestimated because of conservative assumptions that were made due to the lack of appropriate data on the pollutants discharged in industrial effluents.

The objective of this research is to estimate the blue and grey water footprint of industrial sectors and the domestic water supply sector per country annually for the period 1960-2015. The industry is classified in different industrial sectors and divisions - Mining and quarrying, manufacturing, electricity, and construction. The domestic water supply sector is defined and treated as a whole.

The blue water footprint is estimated by estimating the water consumption per current US dollar of an industrial sector and multiply it by its gross added value per country and year. For the missing data, interpolation and extrapolation based on the GDP of that country are used to complete the data for the whole period. The blue water footprint of the electricity sector is estimated by using a water consumption to MWh ratio. It turned out this sector has the largest blue water footprint and therefore the blue water footprint of the divisions within this sector are also estimated. The domestic water supply sectors are estimated by multiplying the water consumption to withdrawal ratio of 15% with the water withdrawal in this sector per country and year.

The grey water footprint of both industrial and domestic sectors is estimated by multiplying new estimated dilution factors with the effluent of the sectors. These estimations are based on contaminants found in effluents of the sectors or environment around these sectors. The new dilution factors can be up to five times larger than the conservative dilution factor 1 used in other literature, which results in higher grey water footprint.

The total industry had a global blue water footprint of $3.86 * 10^{10}$ m^3 in 1960 which increased to $3.02 * 10^{11}$ m^3 in 2015. The construction sector had a global blue water footprint of $5.07 * 10^6$ m^3 in 1960 and $2.97 * 10^8$ m^3 in 2015. The global blue water footprint of the manufacturing industry increased from $1.22 * 10^8$ m^3 in 1960 to $3.70 * 10^{10}$ m^3 in 2015. The mining and quarrying sector had a global blue water footprint of $4.23 * 10^8$ m^3 in 1960 and increased to $1.92 * 10^{10}$ m^3 in 2015. The electricity generation sector has the largest global blue water footprint every year, it was $3.72 * 10^{10}$ m^3 in 1960 and increased to $2.42 * 10^{11}$ m^3 in 2015 which is by far the largest blue water footprint of all industrial sectors.

The global grey water footprint of the industry was $1.56 * 10^{12}$ m^3 in 1960 and increased to $3.18 * 10^{13}$ m^3 in 2015. The construction sector had the smallest global grey water footprint with $1.60 * 10^9$ m^3 in 1960 which increased to $7.87 * 10^{10}$ m^3 in 2015. The global grey water footprint of manufacturing industry increased from $9.18 * 10^9$ m^3 to $3.97 * 10^{11}$ m^3 in 2015. In 1960 the mining and quarrying industry had a global grey water footprint of $4.39 * 10^{11}$ m^3 which increased and became the largest global grey water footprint in 1975 and eventually in 2015 it was $1.99 * 10^{13}$ m^3. The global grey water footprint of the electricity sector was $5.52 * 10^{11}$ m^3 in 1960 which was $5.69 * 10^{12}$ m^3 in 2015.

The domestic water supply sector had a global blue water footprint of $5.92*10^9$ m^3. This is increased to $1.10*10^{11}$ m^3. The global grey water footprint of the domestic water supply is $1.53*10^{13}$ m^3 in 1960 and $4.24*10^{13}$ m^3 in 2015.

This study contributes to science by making a distinction between blue and grey water footprint of sectors within the industry for a long period. It contributes to the discussion about the share per industrial sector to the total blue and grey water. The quantities per industrial sector and differences between industrial sectors can be seen for the first time. The method used in this study results in larger global blue and grey water footprint of the industry than other literature. The blue and grey water footprint is specified per country, industrial sector, and domestic water supply and, per year since 1960. The hydroelectricity division is according to this study responsible for a significant blue water footprint but is often not accounted for in other research. It can be concluded that this study used a more detailed analysis than before in quantifying the water footprint of different industrial sectors and the domestic water supply per country for a longer period and gives an insight in differences between industrial sectors, countries and years.

II.Preface

This report is the end result of the master's degree Civil Engineering and Management at the University of Twente. It took approximately one year to finish this research besides a part-time job at the Water risk Training Expertise center of the Dutch Army Corps of Engineers. Besides it was refreshing to work on two different objectives, it required discipline to switch topics between my job and the master thesis and to stay motivated for both.

This report will also mark the end of my life as a student at the University of Twente which I have always enjoyed. I am very grateful for having a lot of new friends in Enschede during my study period. I would like to thank them all for making my period in Enschede great and unforgettable. Luckily, these friendships will continue after graduating.

During the last year, I received help doing research and writing this thesis. I would like to thank Arjen Hoekstra and Rick Hogeboom as my supervisors during my research and also as the members of the graduation committee. I also want to thank my friends who helped me by discussing methods, results, layout and reviewing my thesis.

I hope you enjoy reading my thesis!

Ruben Herrebrugh

Enschede, February 2018

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1. Introduction

The demand for water increases across the globe and the availability of fresh water in many regions is likely to decrease because of climate change according to the United Nations' World Water Development Report (United Nations, World Water Assessment Programme, 2012). Water abstraction is increasing almost two times as fast as the population in the past several decades. Freshwater consumption grew at a rate of around 80 percent between 1980 and 2000 (Somlyódy and Varis, 2006). Inadequate access, inappropriate management of freshwater resources and over-consumption of resources can result in problems on ecosystems and on the society, it can even result in regional or international conflicts (Gleick, 1998). Water scarcity already affects every continent and the United Nations estimates that by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity (Reig, Shiao, and Gassert, 2013). At this moment, two-thirds of the global population live under conditions of severe water scarcity at least 1 month a year (Somlyódy & Varis, 2006) and half a billion people in the world face severe water scarcity all year round (Mekonnen & Hoekstra, 2016). Water scarcity is likely to limit opportunities for economic growth and the creation of decent jobs in the upcoming years and decades (United Nations, World Water Assessment Programme, 2016b). Increasing knowledge of freshwater abstraction and consumption could contribute to awareness, change, or a solution to the increasing freshwater abstraction and consumption worldwide.

The water footprint is an indicator of the direct and indirect freshwater consumption of a consumer or producer. The water footprint is defined as the total volume of freshwater consumed to produce the goods or services (Hoekstra, Chapagain, Aldaya, and Mekonnen, 2011). The water footprints of nations from both a production and consumption perspective are estimated by Mekonnen and Hoekstra (2011a). The green, blue and grey water footprints are quantified and mapped within countries associated with agricultural production, industrial production and domestic water supply at a high spatial resolution. Finally, they quantified and mapped the water footprint for all countries of the world distinguishing for each country between the internal and external water footprint of national consumption.

The global water footprint related to agricultural and industrial production and domestic water supply is according to Mekonnen and Hoekstra (2011a) $9087*10^{12}$ m^3y^{-1} for the period 1996-2005. Agricultural production takes the largest share, accounting for 92%. The water footprint of different sectors of agricultural production like crop production, pasture and water supply in animal raising is estimated.

The water footprint of a large amount of different agricultural commodities are considered separately, the industrial commodities and domestic water supply are treated as two whole sectors for a ten-year period. It does not show annual variations, variations within these sectors or trends in time. For estimating the grey water footprint of both sectors a dilution factor of 1 has been applied for all untreated return flows (Hoekstra and Mekonnen, 2011a). There is not as much detail as in the agricultural sector within the estimation of the water footprint of production and consumption of industrial products and domestic water supply. These sectors contribute approximately 8% of the total water footprint. However, the grey water footprint of the industry is grossly underestimated because of conservative assumptions that were made due to the lack of appropriate data on the pollutants discharged, treatment percentages, and qualities of treated and untreated industrial effluents (Zhang, Hoekstra, and Mathews, 2013). Because the sectors are lumped, it is not clear what the water footprint per specific industrial sector is. It makes it difficult to indicate where improvement is possible in the efficiency of the water abstraction and the water consumption reduction.

The hypothesis of this research is that there are large sectoral differences in blue and grey water footprint in the different sectors of industry and domestic water supply. Increasing the knowledge

about the water footprints of these sectors will provide more significant inputs for more comprehensive estimations of the total water footprint of humanity. Second, the method of quantifying and allocating the water footprints for each country and year could contribute to the call for more awareness about the efficiency of freshwater abstraction.

The objective of this research is to estimate the blue and grey water footprint of industrial sectors and the domestic water supply sector per country annually for the period 1960-2015. The industry is classified in different industrial sectors and divisions. The domestic water supply sector is defined and treated as a whole.

1.1 Research question
What is the blue and grey water footprint of the industrial sectors and domestic water supply sector on a global scale?

This main research question is split into the following sub-questions,

1. How can the industrial sectors and the domestic water supply sectors be classified?
2. What is the blue water footprint of the industrial sectors and domestic water supply sector per country annually in the time period 1960-2015 for each country?
3. What is the grey water footprint of the industrial sectors and the domestic water supply sector in the time period 1960-2015 for each country?
4. How can natural water footprints be downscaled to a 5 by 5 arc minute grid level in time?

1.2 Scope
The scope of this research is the blue and grey water footprint of classified industrial sectors, in case of electricity generation even the classified divisions, and domestic water supply on a national scale for each country. The blue and grey water footprint is estimated for the operating phase of the industries and domestic water supply and excluding the construction phase. The green water footprint measures consumption of rainwater which is relevant to the agricultural and forestry sector but not relevant to the sectors in this research.

Data about the gross added value of the industrial sectors of each country is required, with the exception of electricity generation, to estimate the blue and grey water footprint. Without any data, interpolation and extrapolation cannot generate missing data and therefore these countries are excluded. For most countries data is not complete for all years in the period 1960-2015, missing values are interpolated or extrapolated.

1.3 Glossary
The terminology used in this research.

Blue water footprint–Volume of surface and groundwater consumed as a result of the production of a good or service. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. It also includes water abstracted from surface or groundwater in a catchment and returned to another catchment or the sea. It is the amount of water abstracted from groundwater or surface water that does not return to the catchment from which it was withdrawn.
Consumption to withdrawal ratio– A percentage of the amount of water withdrawn which will be consumed during the production or process.
Division–The second largest form of classification. Several divisions can form a sector.
Effluent–The part of the water withdrawn for an agricultural, industrial or domestic purpose that returns to the groundwater or surface water in the same catchment as where it was abstracted. This

water can potentially be withdrawn and used again.

Grey water footprint— The grey water footprint of a product is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of water remains above agreed water quality standards.

Return flow – See 'Effluent'.

Water abstraction – The volume of freshwater abstraction from surface or groundwater. Part of the freshwater withdrawal will evaporate, another part will return to the catchment where it was withdrawn and yet another part may return to another catchment or the sea.

Water consumption – Refers to both the 'consumption of freshwater for human activities (green and blue water footprint) and the 'pollution' of freshwater by human activities (grey water footprint).

Water withdrawal – See 'Water abstraction'.

Sector– The largest form of classification in industry.

2. Method and data

This chapter provides the classification of the main industry and domestic water supply, the methodology of estimating the blue and grey water footprint per sector and in some cases per division of an industrial sector.

2.1 Classification

According to the hypothesis of this research, there are differences in water footprint between industrial sectors. A certain classification is needed for the main industrial sectors and domestic water supply to make different water footprints comparable within the industry.

The United Nations (2016c) designed an international standard industrial classification of all economic activities (ISIC). This classification contains a broad hierarchical structure of 21 sectors each consists of several divisions. These divisions consist of several groups and so on. The Organisation for Economic Co-operation and Development (OECD) and the database of UNdata (United Nations, Statistics Division, 2016a) use this classification and provide the gross added value per sector for most of the countries and years (OECD, 2017). The gross added value per sector is relevant for estimating the water consumption per country according to the method presented in chapter 2.2.

The water withdrawal of four industrial sectors is estimated for several countries and available at the database of Eurostat (Förster, 2016). Eurostat uses the NACE Rev.2 statistical classification of economic activities in the European community. NACE REV.2 classification is a derived classification from ISIC on EU-level. Several types of data, like water withdrawal, and gross added value for the main industrial sectors, are available and collected by Eurostat for the following industries:

- Mining and quarrying
- Manufacturing
- Electricity
- Construction

The definition of these specific sectors is abstracted from ISIC revision 4. These four sectors contain several divisions. The water consumed in these divisions together is the water footprint of a sector.

2.1.1 Mining and quarrying

Mining and quarrying include the extraction of minerals occurring naturally as solids (coal and ores), liquids (petroleum) or gases (natural gas). Extraction can be achieved by different methods such as underground or surface mining, well operation, seabed mining (United Nations, Department of Economic and Social Affairs, 2008). Mining and quarrying also include supplementary activities aimed at preparing the crude materials for marketing, for example crushing, grinding, cleaning, drying, sorting, concentrating ores, liquefaction of natural gas and agglomeration of solid fuels (United Nations, Department of Economic and Social Affairs, 2008).

This sector does not include the processing of the extracted materials which also covers the bottling of natural spring and mineral waters at springs and wells or the crushing, grinding or otherwise treating different kind of earth, rocks and minerals not carried out in conjunction with mining and quarrying. This is part of the section manufacturing (United Nations, Department of Economic and Social Affairs, 2008).

Mining and quarrying abstract water primarily for mineral processing, dust suppression, slurry transport and employees' needs. In most mining operations, water is sought from groundwater, streams, rivers, lakes, or through commercial water service suppliers (Vella, 2013). Mining and quarrying occur across the full spectrum of hydrological contexts; from the arid regions of central

Australia through the tropics and to the sub-arctic conditions of Canada and Finland (Northey, Mudd, Saarivuori, Wessman-Jääskeläinen, & Haque, 2016). Mining could be considered one of the most diverse industries with respect to how it interacts with water resources (Younger, Banwart, & Hedin, 2002).

The mineral raw materials which can be produced by mining and quarrying is arranged in five divisions based on their chemical characteristics by the International Organizing Committee for the World Mining Congresses and is presented in *Table 1* (Reichl, Schatz, & Zsak, World Mining Data, 2017).

Iron and Ferro-Alloy Metals	*Non- Ferrous Metals*	*Precious Metals*	*Industrial Minerals*	*Mineral Fuels*
Iron Chromium Cobalt Manganese Nickel Niobium Tantalum Titanium Tungsten Vanadium	Aluminum Antimony Arsenic Bauxite bismuth Cadmium Copper Gallium Germanium Lead Lithium mercury Rare earth minerals Rhenium Selenium Tellurium Tin Zinc	Gold, Platinum-group metals (palladium, platinum, rhodium) Silver	Asbestos Baryte, Bentonite Boron minerals Diamond(gem/industrial) Diatomite Feldspar Fluorspar Graphite Gypsum Anhydrite Kaolin (China-clay) Magnesite Perlite Phosphates (incl. guano) Potash Salt Sulfur Talc (incl. steatite and pyrophyllite) Vermiculite Zircon	Steam coal (incl. anthracite and sub-bituminous coal) Coking coal Lignite Natural gas Petroleum Oil Sands Oil Shales Uranium

Table 1 Five divisions in the mining and quarrying sector and the materials per sector.

Figure 1 (Reichl, Schatz, & Zsak, World Mining Data, 2016) shows a distribution with a significant part of mineral fuels which dominates the world mining production.
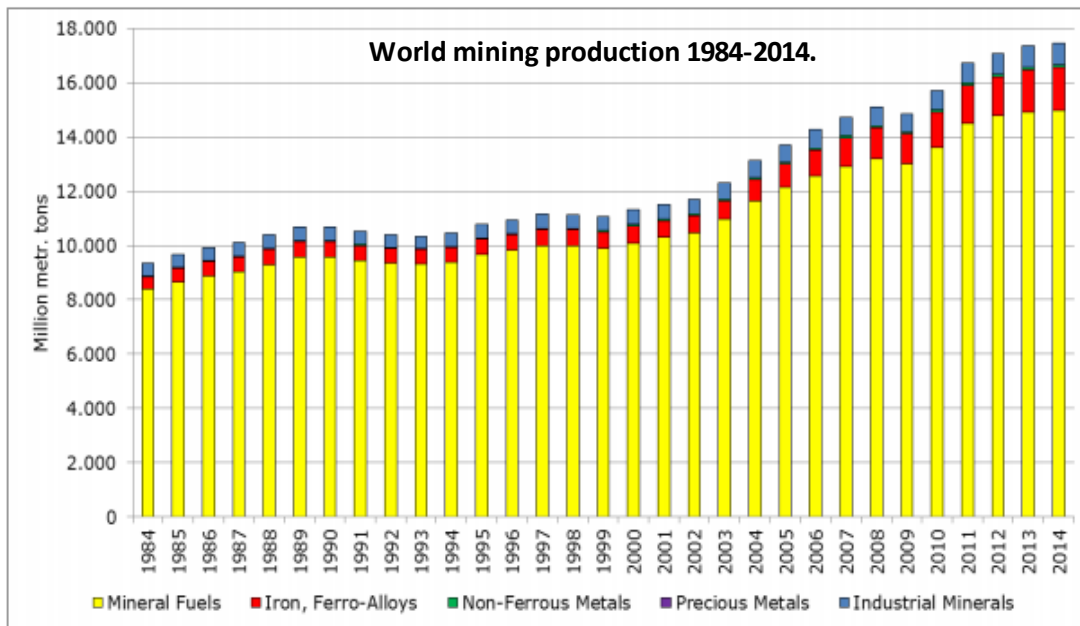

Figure 1 World mining production 1984-2014 by groups of minerals Reichl et al. *(2016)*.

2.1.2   Manufacturing

Manufacturing includes the physical or chemical transformation of materials, substances, or components into new products, although this cannot be used as the single universal criterion for defining manufacturing. The materials, substances, or components transformed are raw materials that are products of other manufacturing activities. Substantial alteration, renovation or reconstruction of goods is generally considered to be manufacturing (United Nations, Department of Economic and Social Affairs, 2008).

According to UN Department of Economic and Social Affairs (2008), "Units engaged in manufacturing are often described as plants, factories or mills and characteristically use power-driven machines and materials-handling equipment. However, units that transform materials or substances into new products by hand or in the worker's home and those engaged in selling to the general public of products made on the same premises from which they are sold, such as bakeries and custom tailors, are also included in this section. Manufacturing units may process materials or may contract with other units to process their materials for them. Both types of units are included in manufacturing."

2.1.3   Electricity generation

The electricity generation sector abstracts the most freshwater of all sectors in the industry in most countries (Shiklomanov, 2003). *Figure 2* (Förster, 2016) shows the major contribution of the water abstraction by the production of electricity-cooling in Europe (Förster, 2016). Energy production requires significant volumes of fresh water and has significant impacts on water resources through thermal and chemical pollution. The largest water footprint is produced by hydropower and bioelectricity (Mekonnen, Gerbens-Leenes, & Hoekstra, 2015). Thermal power generation is responsible for a significant part of water abstraction in the electricity sector. For the USA 76% of the total water abstracted was needed for thermal power generation. In thermal power production, 0.5-3.0% of the water abstraction is consumed. (Shiklomanov, 2003). Besides thermal power, there are

different sources of electricity generation. A classification, used by US Energy Information Administration (EIA), will be used in this research (U.S. Energy Information Administration, 2014). The divisions used by the US EIA for the electricity generation sector are:

- Fossil fuels
- Biomass and waste
- Geothermal energy
- Hydroelectricity
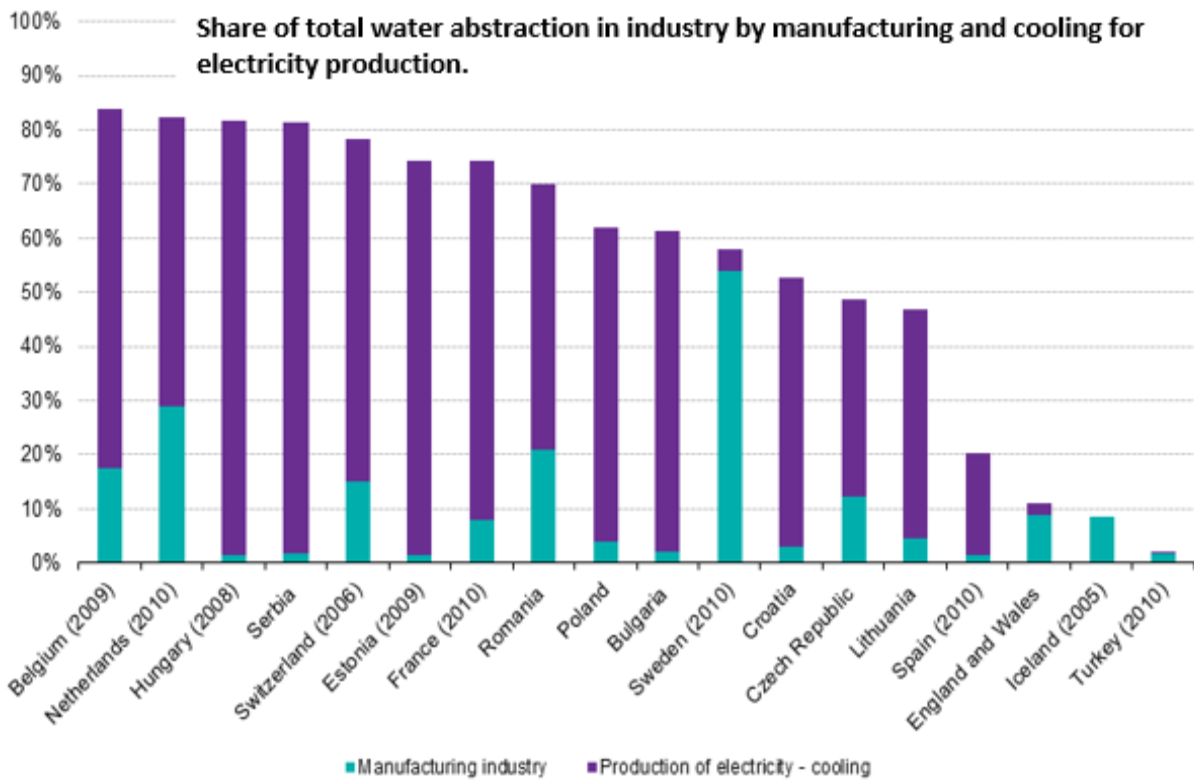- Nuclear power
- Solar power
- Wind energy

Figure 2 Share of total abstraction in the industry for the manufacturing industry and production of electricity (mainly cooling), 2011 (%) *(Förster, 2016)*.

Electricity from fossil fuel, biomass, nuclear power

It is estimated how much water different kinds of power plants withdraws and how much water will be consumed in the process. The Food and Agriculture Organization of the United Nations (FAO) provide these indicators for different power plants which are shown in *Table 2* (Kohli & Frenken, 2011).

Power plant and cooling system type	Withdrawal (m³MWh⁻¹)	Consumption (m³MWh⁻¹)
Fossil fuel, biomass, waste once-through cooling	76-190	1.0
Fossil fuel, biomass, waste closed-loop cooling	2.0-2.3	2.0
Nuclear steam once-through cooling	95-230	1.5
Nuclear steam closed-loop cooling	3.0-4.0	3.0

Table 2 Water withdrawal indicators for different sort of power plant cooling systems according to the FAO *(Kohli & Frenken, 2011)*.

Averages from *Table 2* are used when estimating the water abstraction and consumption of the division electricity from fossil fuel, biomass and waste, and electricity from nuclear power.

Biomass and waste consume more water per megawatt-hour (MWh). According to the US EIA biomass is defined as organic materials of biological origin constituting a renewable energy source such as biodiesel, biofuels, biomass waste, densified biomass, fuel ethanol, wood, and wood-derived fuels (U.S. Energy Information Administration, 2014). It is estimated that this division consumes 20.016 m^3MWh^{-1} (Gerben-Leenes et al., 2008a).

Hydroelectricity

There was a lot questioning about the water abstraction and consumption of hydropower generation (Mekonnen & Hoekstra, 2011c), (Bakken, Killingtveit, England, Alfredsen, & Harby, 2013). Hydroelectricity has historically been considered as a non-consumptive water user however, the study of 35 sites finds that, in contrary, hydropower is a large consumptive user of water (Mekonnen & Hoekstra, 2011a). A range between 1.08 m^3MWh^{-1} to 3045.6 m^3MWh^{-1} with an average of 244.8 m^3MWh^{-1} is estimated as water consumption by Mekonnen and Hoekstra (2012). In a more recent research, 54.35 m^3MWh^{-1} is estimated (Mekonnen et al., 2015). To estimate the total amount of consumed water the 54.35 m^3MWh^{-1} can be multiplied by the amount of generated electricity in MWh. The large range of consumption depends on the surface of the lake, the depth and the climate where the power is generated. In recent research the water consumption per country caused by hydropower is determined (Hogeboom, Knook, & Hoekstra, 2017). The water consumption per MWh of the corresponding country is used in this research, if not the average of 54.35 m^3MWh^{-1} is used.

Geothermal

Geothermal electricity generation is projected to upcoming besides other renewable power generation sources (Clark, Harto, Sullivan, & Wang, 2010). It could grow even more if enhanced geothermal systems (EGS) technology, which can effectively operate on more broadly available lower-temperature geofluids, proves to be a good cost and environmental performer. Also, geothermal plants tend to run trouble-free at or near full capacity for most of their lifetimes (Clark et al., 2010). Geothermal power plants consume relatively less water per MWh energy output than other electric power generation technologies. The water footprint is estimated at 1.206 m^3MWh^{-1} (Mekonnen et al., 2015). However geothermal power plants can require (withdraw) around 7.6 m^3MWh^{-1} of water for cooling purposes (Clark et al, 2010).

Solar energy

Solar energy can be utilized in three ways according to Gerben-Leenes et al.(2008a). Heat production, electricity production through photovoltaic (PV) cells, and electricity production through solar thermal power plants. It is estimated that on average 1.08 m^3MWh^{-1} is consumed by using solar energy to generate electricity (Mekonnen et al., 2015).

Wind energy

Wind energy utilizes the kinetic energy in the air to generate electricity. In wind farms, the average, annual energy generated varies between 0.05 and 0.25 GJm^{-2}(Gerben-Leenes et al., 2008a). Wind energy consumes a very small amount of water, it is estimated that utilities that generated power due to the wind consumes an average of $7.1*10^{-4}$ m^3MWh^{-1}(Mekonnen et al., 2015).

2.1.4 Construction

This sector includes general construction and specialized construction activities for buildings and civil engineering works. "It includes new work, repair, additions and alterations, the erection of prefabricated buildings or structures on the site and also the construction of a temporary nature. General construction is the construction of entire dwellings, office buildings, stores and other public and utility buildings, farm buildings or the construction of civil engineering works" (United Nations, Department of Economic and Social Affairs, 2008).

In the construction sector, the direct water footprint is small compared with the indirect water footprint related to the mining and manufacturing of materials used in construction (Hoekstra A. Y., 2015). The direct water abstraction in the construction process is maximally $1\,m^3$ per square meter of gross floor area. It has to be noted that the figures cited here refer to gross blue water abstraction, not net water consumption (McCormack, Treloar, Palmowski, & Crawford, 2007).

For Great Britain, the average water consumption at the construction site is estimated for the year 2008. In their research, they found that the average tap water consumption is $148m^3$ per £ million contractors output at a constant price according to the Strategic Forum Water Subgroup. (Waylen, Thornback, & Garett, 2011).

2.1.5 Classification Domestic water supply

Domestic water supply means the source and infrastructure that provides water to households and public, commercial and municipal needs (Perlman, 2017). Municipal water abstraction includes abstraction of water and its treatment and distribution mostly for domestic purposes to cities and towns and to public and private enterprises (Shiklomanov, 2003). The public water supply also includes water for industry, which consumes high-quality fresh water from the city water supply systems. A significant part of the domestic water consumption is used for watering lawns and gardens in certain countries (Shiklomanov, 2003).

Domestic or municipal water supply is also defined by Aquastat (2017) in their glossary as "the annual quantity of water withdrawn primarily for the direct use by the population. It includes water from primary renewable and secondary freshwater resources, as well as water from over-abstraction of renewable groundwater or withdrawal from fossil groundwater, direct use of agricultural drainage water, direct use of (treated) wastewater, and desalinated water. It is usually computed as the total water withdrawn by the public distribution network. It can include that part of the industries and urban agriculture, which is connected to the municipal network." (Food and Agriculture Organization of the United Nations, Aquastat, 2017)

For the domestic water supply sector, a consumptive portion of 10% is used in previous research (Mekonnen & Hoekstra, 2011a). A consumptive portion of 10-20% is estimated in the World Water Report (United Nations, 2009).

Different purposes of the water abstraction in the domestic water supply leads to a classification in sectors. In the Eurostat databases the domestic water supply is classified in the following sectors (Eurostat, 2017):

- Water abstraction for private households
- Water abstraction for public water supply and services

Private households can be defined as the water abstracted by the population at home. The volume of the water abstraction depends on the number of people and the degree which they are equipped with services and utilities (Shiklomanov, 2003). A large part of the water consumed consists of water losses

due to evaporation, leakage in water supply and sewer systems, and water used for gardening, cleaning streets, for recreational areas, and allotments. These causes of water consumption are not part of the sector private households.

Figure 3 shows that households constitute a significant part of the abstraction from the public water supply. The industrial sectors are responsible for the other part of the water abstraction (Eurostat, 2015). Public supply refers to water withdrawn by public and private water suppliers that provide water at least 25 people or have a minimum of 15 connections (U.S. Geological Survey, 2009). All other activities from the 21 derived sectors of ISIC with commercial purposes which uses public water supply fall within this sector. Small industries and services who abstracts tap water are part of this sector. According to *Figure 3*, these industries and services abstract a relatively small volume of tap water compared to households. Therefore, industries, services public (ISIC activities) and municipal which abstracts from tap water can be classified as one sector.
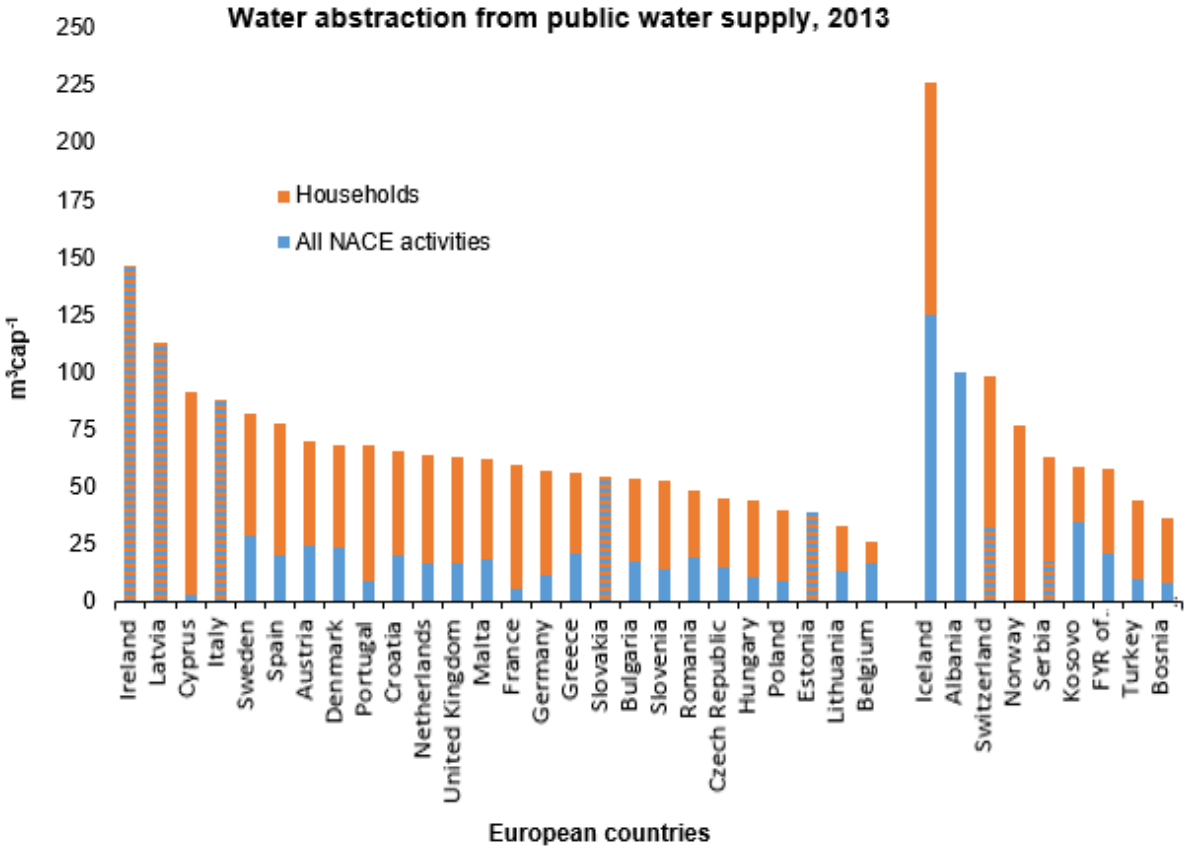

Figure 3 Water abstraction from the public water supply in m³ per inhabitant for European countries, NACE activities are the EU equivalent of the ISIC classification 2013 *(Eurostat, 2015).*

Eurostat is the only database who distinguished different divisions in the domestic water supply. Besides, Eurostat provides a low amount of annual data for both divisions. In addition, it is only data about abstraction for a marginal amount of countries and years. Due to this lack of data and literature, the domestic water supply sector will be considered as one sector in this research. The distinction between private households and public water supply and services is not been made.

2.1.6   Overview classification
All sectors and divisions whose water footprint is estimated or used to estimate a water footprint or water consumption to withdrawal ratio are presented in *Figure 4*. It should be noted that the water footprint of the following sectors is estimated, the mining and quarrying, manufacturing, construction,

and electricity generation sector. Also, the water footprint of electricity generation is estimated. And only the water footprint of the main sector domestic water supply is estimated instead of its sectors.
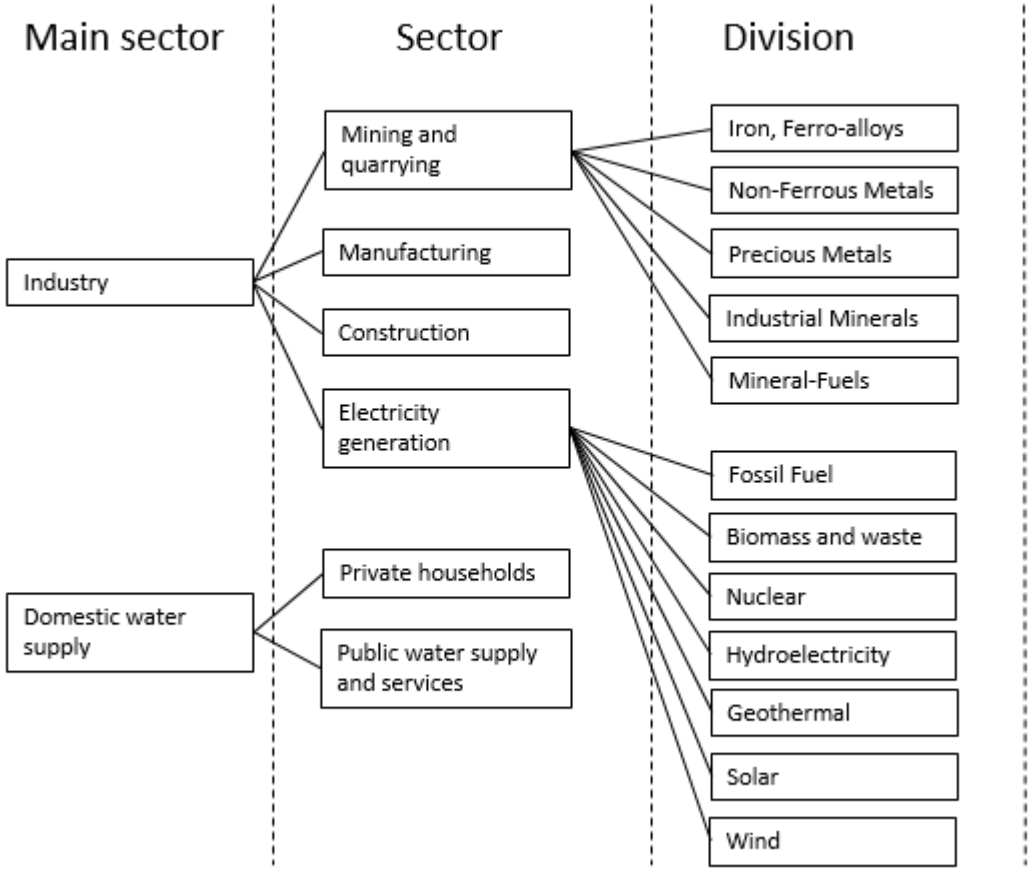

Figure 4 Overview of the sectors and divisions relevant for the estimation of the water footprints in this research.

2.2 The blue water footprint

This section provides the method of estimating the blue water footprint per country of each industrial sector and the domestic water supply sector annually for the period 1960-2015. Each sector, classified in section 2.1, consists of several divisions with each its own blue water footprint. The total blue water footprint of a sector is a combination of blue water footprints of the divisions. If possible, a weighted average of water consumption is obtained per sector by using available data about the quantities produced in the divisions. Some sectors have a significantly large part in water consumption in the industry. For the electricity generation sector, the water footprint is therefore estimated per division.

The average water consumption per division is obtained by estimating the average water footprint of the groups who form a division together in m^3t^{-1} in the industrial sector. Otherwise, an estimation is made by looking at the worldwide distribution to obtain a weighted average of water consumption of the divisions, like the mining and quarrying industry.

For the mining and quarrying, construction, electricity generation and manufacturing industry a bottom-up approach is used. It means that the blue water footprint is estimated by converting the gross added value (GAV) of the sectors per country per year into the water footprint. The United Nations Statistical Division (2016a) provides the gross added value for each industrial sector for most

countries. It is annual data for as long as it is available in the period 1960-2015. The gross added value measures the contribution to an economy of an individual producer, industry, sector or region (Financial Times, 2017). This data is first converted to current US dollars if it has not been done yet. Therefore, several steps are done to convert these yearly values to the blue water footprint.

While estimating the averages for each sector several assumptions are made, depending on the data availability, on different detail level. Assumptions cause rougher estimates of the water footprints of some of the industrial sectors. It is unavoidable on this scale of research. Accepting these assumptions, a rough estimate of the water consumption in the smaller divisions and groups is applicable to estimate the water footprint per country per sector and year.

Figure 5 shows the flow diagram of the method which is followed while estimating the blue water footprint per sector. However, this flowchart forms the basis of estimating the blue water footprint but it can differ per sector. This method is used to estimate the blue water footprint of the mining and quarrying sector and the construction sector. Step one and two are skipped when the blue water footprint of the manufacturing industry was estimated. The blue water footprint of the electricity generation divisions is estimated only using step four and not with a water consumption ratio per current US dollar but with a water consumption ratio per MWh.

The flowchart starts with indicating the blue water footprint per current US dollar and eventually estimating the blue water footprint for a sector per year per country.

Step 1: The gross added value from the UN Statistical Division is given in the local currency of the corresponding country for most of the sectors. This currency is converted to United States Dollars (US dollar). The World Bank (2017) maintains a databank which contains official exchange rates for countries for most of the years in the period 1960-2015. Accordingly, all values are converted to US dollars.

Step 2: The data is given in US dollars but needs to be converted to current US dollars. The present value is estimated by using the inflation rate for each country and each year which is abstracted from The World Bank (2016). The present value is calculated by the present value formula (Averkamp, 2017). This formula is used in finance and calculates the present day value of an amount that is received at a future or past date.

$$Present\ Value = \frac{Value}{(1+i)^n} \tag{1}$$

Where *Value* is gross added value provided by UN statistics division, *i* is inflation rate from the world databank, *n* is the number of years in the time since 2015.

Flowchart blue water footprint

Step 1
- Gross added value in national currency.
- Convert to US dollars with official exchange rate.
- Gross added value in US dollars.

Step 2
- Convert to present values with inflation rate.
- Current gross added value in US dollars.

Step 3
- Inter- and extrapolation values for missing years. Extrapolation by using GDP.
- Current gross added value, current US dollars, all years.
- Estimation water consumption to production ratio per sector or division.

Step 4
- Multiply with the amount of water consumption per current US dollar.
- Water consumption per country for all years.
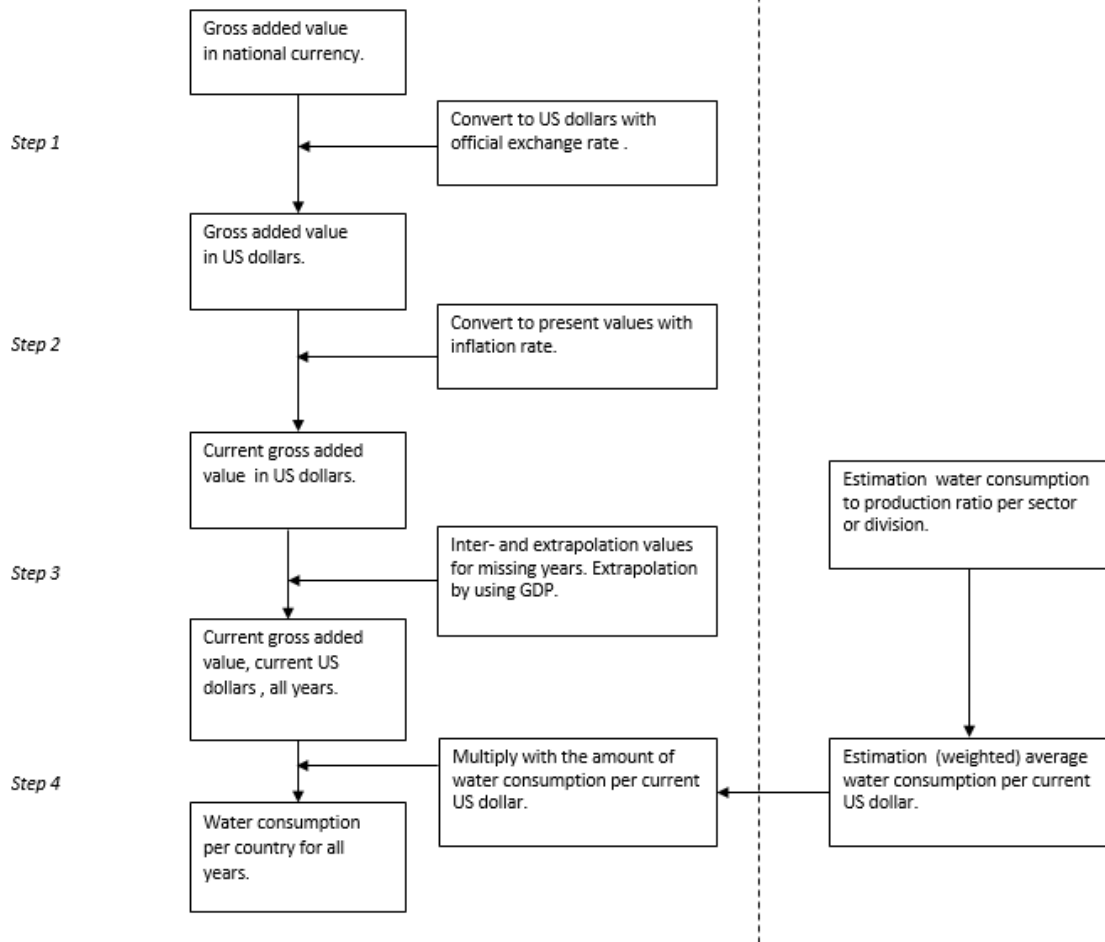- Estimation (weighted) average water consumption per current US dollar.

Figure 5 Flow chart of the bottom-up approach to estimating the blue water footprint of a sector.

Step 3: The United Nations Statistical Division and the US Energy Information Administration does not have data for each particular year for the mining and quarrying, construction, manufacturing, and electricity generation industry. Missing values are interpolated or extrapolated after step two. Linear interpolation is used between two known values. The Gross Domestic Product (GDP) extracted from the World Bank (2017) of the corresponding country is used to extrapolate missing GAV values. The growth factor of the GDP between two consecutive years is estimated for each country. When GDP data is not available for a country the growth factor is used of the worldwide GDP. For recently formed countries the GDP is used of the former country like the former USSR countries and Yugoslavia.

Step 4: The GAV in current US dollars is at this step multiplied by the water consumption per current US dollar of the corresponding industrial sector. The water consumption per current US dollar is estimated in different ways. It is sector dependent how the water consumption per current US dollar is estimated. This can be seen in the following sections about the sectors.

For the manufacturing industry firstly another approach is used for several European countries to estimate a water consumption per US dollar. Water abstraction data for the manufacturing industry for several countries are available and the corresponding gross added value. Both are downscaled to estimate the water abstraction per current US dollar.

2.2.1 Mining and Quarrying

The United Nations Statistics Division provides data about the gross value added for most of the countries for each industrial sector according to the ISIC rev.4 classification. This data spans the whole mining and quarrying sector. With this data, the flowchart in *Figure 5* is followed. The economical share of the different mining and quarrying divisions is extracted from World Mining Data, for the year 2015 (Reichl et al., 2017). It is estimated how much, in tons and in value, of a mining and quarrying division is produced. After estimating the water consumption per mining group per current US dollar, the weighted average water consumption per division is estimated, continued by the estimation of the weighted average water consumption of the mining and quarrying sector. In the flowchart, the estimation of the water consumption per US dollar is seen on the right side of the diagram and leads to step four.

The distribution of the mining and quarrying sector is obtained for the year 2015 in the report of the world mining data (2017). Distribution is defined as the composition, based on economic value or weight in tons, of the mining and quarrying sector by different mining and quarrying divisions. *Table 3* shows the distribution, and just like in *Figure 1* it can be concluded that the mineral-fuels have the largest contribution.

Country	Iron, ferro-alloys	Non-ferrous metals	Precious metals	Industrial minerals	Mineral-fuels
Share of production in tons	9.2%	0.5%	0.0%	4.4%	84.1%
Share of value in US dollars	7.7%	6.9%	3.9%	2.4%	75.2%

Table 3 Distribution of the mining products in percentages of the production in metric tons and in the value of US dollars (Reichl et al., 2017).

According to the world mining report the six biggest producers, China, USA, Russia, Australia, India, and Saudi Arabia are responsible for of 60% of the total world production. They are also responsible for 50% of the value of the total mining production in 2015 (Reichl et al., 2017). For that reason, the water footprint of the six largest producers is estimated for each division of the mining and quarrying sector.

It can be justified by the fact that the water footprint of a single division of one of the six largest producers can be larger than the total production of many other countries. Besides, the distribution of one of the six biggest producers differs compared to the average distribution of the world mining production. This will results in a larger margin of error when estimating the water footprint by using the distribution of the world mining and quarrying production instead of the distribution of the country itself.

For the year 2015, it is known how much in tons are produced per mining and quarrying division (Reichl et al., 2017). The report of the world mining data (2017) also provides the revenues of the mining productions for the year 2015. Therefore the value of one ton of a division of mining is estimated. Vice versa it is estimated how much tons needs to be produced for one million US dollars. This is shown in *Table 4* for the six biggest producers and for the total world.

Country	Total (tons mill US dollar^{-1})	Iron, ferro-alloys	Non-ferrous metals	Precious metals	Industrial minerals	Mineral-fuels
China	$7.05*10^3$	$1.18*10^4$	$5.13*10^2$	0.22	$1.056*10^4$	$8.39*10^3$
United States	$5.40*10^3$	$1.06*10^4$	$3.31*10^2$	0.15	$1.14*10^4$	$5.54*10^3$
Russia	$4.85*10^3$	$4.26*10^3$	$4.60*10^1$	0.15	$2.13*10^3$	$5.28*10^3$
Australia	$6.89*10^3$	$1.18*10^4$	$4.03*10^4$	0.15	$9.14*10^3$	$8.06*10^3$
India	$7.65*10^3$	$5.51*10^3$	$5.65*10^2$	1.62	$1.07*10^4$	$9.54*10^3$
Saudi Arabia	$2.87*10^3$	$1.82*10^4$	$5.24*10^2$	0.06	$5.00*10^4$	$2.86*10^3$
total world	$3.27*10^3$	$4.30*10^3$	$3.29*10^2$	0.20	$9.14*10^4$	$3.40*10^3$

Table 4 the amount of ton of a mining and quarrying product in 2015 to be produced for a value of 1 million US dollars for the six biggest producers in mining and for the world (Reichl et al., 2017). The first column represents the average of all mining products in tons per country to produce for a value of 1 million US dollars.

The amount of tons produced for a certain mining product is multiplied with the consumption to production ratio. The amount of water consumed to produce several mining and quarrying products are given in *Table 5*. These are products and minerals in the mining and quarrying sector, the values are gained from several reports; bauxite, nickel, zinc, lead, silver, gold non-refractory (Hoekstra 2015), oil conventional, steam EOR (Clark et al.,2010), copper pyrometallurgy and hydrometallurgy, cement and sulfuric acid (Northey et al., 2016). The products in *Table 5* are subdivided into the mining and quarrying divisions distinguished by the report of the world mining data (Reichl et al., 2017).

Mineral/metal/fuel	Water consumption per unit in m³
Bauxite[1], 1 ton of ore	1.09
Copper pyrometallurgy[3], 1 ton of ore	0.62
Copper hydrometallurgy[3], 1 ton of ore	0.32
Gold non-refractory[1], 1 ton of ore	1.96
Nickel [1], 1 ton of ore	1.01
Zinc, lead, silver[1], 1 ton of ore	2.67
Black Coal[1], 1 ton of ore	0.30
Oil conventional[2], 1 m³	$7.57*10^{-4}$
Steam EOR[2], 1 m³	$2.00*10^{-2}$
Steel[3], 1 ton of ore	4.21
Cement[3], 1 ton of ore	3.29
Sulfuric acid[3], 1 ton of ore	2.68

Table 5 Consumption to production ratio for mining products.

1. (Hoekstra A. Y., The water footprint of industry, 2015) 2. Clark, Harto, Sullivan & Wang, 2010) 3. (Northey, Mudd, Saarivuori, Wessman-Jääskeläinen & Haque, 2016).

For the six most producing countries in this sector, the corresponding distribution of the divisions is used for estimating the blue water footprint per division, based on the distribution of the year 2015.

The distribution of the economic shares per division of the total economic value of mining and quarrying is given in *Table 6*. This share is multiplied by the average value in current US dollars per m³ consumed per mining and quarrying group. The value is summed and represents the weighted average water consumption for the whole mining and quarrying sector, by using the amount of water consumed per current US dollar and the share of the mining product and mining group worldwide based on mining data of 2015 (Reichl et al., 2017). According to *Table 6*, an average of $2.91*10^{-3}$ m³ is consumed per current US dollar in the mining and quarrying sector. This amount is constantly used for each year and country.

Mining divisions and products	Water consumption m^3ton^{-1} ore	Average m3 ton^{-1}	Average \$ m^{-3} 2015	Average m3 $\$^{-1}$ 2015	The share of total value in %	The share of \$ contribute to total average
Iron and ferro-alloy metals		4.21	$4.09*10^1$	$2.45*10^{-2}$	7.7%	$1.89*10^{-3}$
Steel	4.21					
Nickel	1.01					
Non-ferrous metals		1.12	$2.28*10^3$	$4.38*10^{-4}$	6.9%	$3.00*10^{-8}$
Bauxite	1.09					
Copper pyrometallurgy	0.62					
Copper hydrometallurgy	0.32					
Zinc	2.67					
Precious metals		2.60	$1.74*10^6$	$5.76*10^{-3}$	3.9%	$2.26*10^{-8}$
Gold non-refractory	1.96					
Silver	2.67					
Industrial minerals		$8.84*10^{-1}$	$1.22*10^2$	$8.21*10^{-3}$	2.4%	$1.95*10^{-4}$
Gypsum	0.14					
Sulfuric acid	2.68					
Mineral fuels		$1.91*10^{-1}$	$9.53*10^2$	$1.05*10^{-3}$	75.2%	$7.89*10^{-4}$
Black coal	0.30					
Oil conventional	$7.57*10^{-4}$					
Water consumption, weighted average per US dollar						$2.91*10^{-3}$

Table 6 Weighted average water consumption per US dollar for Mining and quarrying divisions.

2.2.2 Manufacturing

The manufacturing industry is a very diverse industry with 23 varying divisions. Consequently, the method presented in the flowchart in *Figure 5* is more difficult to use in this case because averaging the water consumption per ton of all these products together will be less representative of this sector.

A different approach is used for this sector to estimate the water abstraction, not to be confused with water consumption, per current US dollar. Eurostat (2017) provides data about water abstraction in the manufacturing industry for several countries for several years. The World Bank (2016) provides for this sector the gross added value for each country and years in current US dollar. Accordingly, the water abstraction per current US dollar is estimated for these countries. All these values are averaged and give a water abstraction of $3.67*10^{-2}$ m^3 per current US dollar.

The water abstraction per current US dollar is multiplied by the water consumption to withdrawal ratio. This can differ per country. Unfortunately, only for one country, the estimation of the water consumption to withdrawal ratio is known. In Canada, it is estimated that the water consumption of the manufacturing industry in 2008 is 355.6 million cubic meters or 9.3% of the total water intake of 3,806.2 million cubic meters (Statistics Canada, 2009). The 9.3% of water consumption in the

manufacturing industry of Canada is used as a representative water consumption to withdrawal ratio to estimate the blue water footprint for other countries and for each year.

Step 1 and 2 of the flowchart is excluded from this sector because the GAV is already in current US dollar provided by the World Bank (2016). After interpolation and extrapolation in step 3, and estimating the water consumption per current US dollar, step 4 is completed.

2.2.3 Electricity generation

The electricity generation sector use a slightly different method as presented in the flowchart in *Figure 5*.

Due to large water abstraction in the electricity generation sector, the water footprint for different sources of electricity is estimated. This sub-classification of electricity sources is used by the US Energy Information Administration (2014) and are treated as divisions in this research. The amount of consumption per MWh per source is shown in *Table 7*.

Source	Consumption M^3MWh^{-1}
Fossil fuel[1]	1.50
Biomass and waste[3]	20.02
Nuclear[1]	2.25
Hydroelectricity[2]	54.35 (Averaged)
Geothermal[2]	1.21
Solar[2]	1.08
Wind[2]	$7.2*10^{-4}$

Table 7 Amount of water consumed to generate 1 MWh per energy source.
1: (Kohli & Frenken, 2011) 2: (Mekonnen, Gerbens-Leenes, & Hoekstra, 2015) 3: (Gerbens-Leenes, Hoekstra, & Van der Meer, 2008b).

For almost every country, the US EIA provides data from 1980 to 2014 about the amount of Mega Watthour (MWh) generated per source. The blue water footprint is therefore estimated in a different way than the other sectors. For the period 1960-1980, there is no data available from the US EIA. Missing data is extrapolated by using the GDP.

Eventually, the blue water footprint is estimated by multiplying the water consumption per MWh of the corresponding source, instead of current US dollar. For Hydroelectricity, the water footprint per MWh is estimated for a significant amount of the countries (Hogeboom et al., 2017). Therefore the corresponding water footprint per MWh is used, if not the average of 54 m^3 per MWh is used (Mekonnen et al., 2015).

2.2.4 Construction

Similarly, as for the mining and quarrying sector, the United Nations Statistics Division (2016a) provides the gross added value for almost every country for multiple years for this specific industrial sector. The blue water footprint is estimated by using exactly the flowchart in *Figure 5*.

For Great Britain, it is estimated what the average tap water consumption on site is. As tap water is mostly used in construction, these values are used in this research. 2008 Is used as a baseline in the report: WATER: An Action Plan for reducing water usage on construction sites (2011). In this report, they found that the average tap water consumption is 148m^3 per £ million contractors output at a constant price according to the Strategic Forum Water Subgroup in 2008 (Waylen, Thornback, & Garett, 2011). With the exchange rate of 2008 (The World Bank, 2017) the water consumption is 80.51 m^3 per million US dollars contractors output at a constant price or $8.05*10^{-5}$ m^3 per current US dollar.

2.2.5 Domestic water supply

The domestic water supply is considered as one sector and will be estimated by a different method as shown in *Figure 4*.

The United Nations quoted in their World Water Development Report 2016: Water and Jobs (2016b) an estimate of the consumptive factor which is between 10% and 20% for domestic use (Margat & Andréassian, 2008). The average, 15%, is used to estimate the water consumption of all countries and years, this fraction is also used in other literature by Vandecasteele, Bianchi, Basitta e Silva, Lavelle, and Batelaan (2014).

The total water abstraction in the domestic water supply is available in the database of the FAO, (Food and Agriculture Organization of the United Nations, Aquastat, 2017). Although missing values are linearly interpolated and extrapolated by using GDP to gain values for the whole period and for each country. These values are multiplied by the water consumption to withdrawal ratio and provide the estimated water footprint of domestic water supply.

2.3 The grey water footprint

The grey water footprint is an indicator of the water volume needed to assimilate a pollutant load that reaches a water body. The grey water footprint is based on the tier-1 level. Tier 1 simply uses a leaching-runoff fraction to translate data on the amount of a chemical substance applied to the soil to an estimate of the amount of the substance entering the groundwater or surface water system (Franke, Boyacioglu, & Hoekstra, 2013).

The part of the return flow which is disposed into the environment without prior treatment can be taken as a measure of the grey water footprint. The so-called dilution factor represents the number of times that the effluent volume has to be diluted with ambient water in order to arrive at the maximum acceptable concentration level (Hoekstra et al., 2011). The dilution factor 1 is a very conservative factor to be applied for all untreated return flows of the industry and domestic water supply. Based on literature and the equation below a new dilution factor is estimated per sector if possible.

A simplified equation of the grey water footprint is the following (Hoekstra et al., 2011):

$$WF_{grey} = \frac{c_{effl} - c_{act}}{c_{max} - c_{nat}} \times Effl_{c,t} \tag{2}$$

Where $\frac{c_{effl} - c_{act}}{c_{max} - c_{nat}}$ is the dilution factor.

c_{effl} is the concentration of the contaminant in the effluent in mg l^{-1}.
c_{act} is the concentration of the contaminant in the current stream, before abstraction in mg l^{-1}.
c_{max} is the maximum allowable concentration of the contaminant in the surface water in mg l^{-1}.
c_{nat} is the natural concentration of the contaminant in surface waters in mg l^{-1}.
$Effl$ is the part of the abstracted water returning to the surface water in m^{3}y^{-1} where c is country and t is time in years.

In this research, c_{act} is equal to c_{nat} because characteristics of individual streams and surface water will not be used and therefore only the natural concentration worldwide.

2.3.1 Mining and Quarrying

Mining and quarrying of metals and minerals, separated in divisions in section 1.1, results in pollution by various amounts of contaminants in varying concentrations. Chemical pollutions with toxic metals and organics affect the aquatic environment and are the result of oil and gas industries according to Elosta (2016). The quality of groundwater and surface water can decrease near mining areas where

open cast, as well as underground coal, is mined according to Prasad, Kumari P, Shamima and Kumari S (2013). Metal mines in the surrounding of streams can cause heavy metal contamination of surface water (Schaider, Senn, Estes, Brabander, & Shine, 2014). Most frequently substances that pollute water are caused by different mining divisions. These substances are arsenic, lead, cadmium, copper, zinc, chromium, manganese, iron, and sulphates. Concentrations of these substances are found in varying degrees in ground and surface water nearby mines in different cases. The maximum allowable concentrations and natural concentrations of these contaminants are given in the Canadian Environmental Quality Guidelines by CCME (2013). In *Table 8* the substances are given with maximum, natural and found concentrations nearby mining areas in ground and surface water (Prasad et al.,2013), (Schaider et al., 2014), (Razo, Carrizales, Castro, Diaz-Barriga, & Monroy, 2003). In this research the scope lies on the grey water footprint of a sector, therefore an average of all maximum, natural and found concentrations are made to estimate an average dilution factor for the mining and quarrying industry, also shown *Table 8*.

The dilution factor is estimated by the following calculation (Mekonnen & Hoekstra, 2011a):

$$Dilution\ factor = \frac{C_{effl} - C_{act}}{C_{max} - C_{nat}} \hspace{3cm} (3)$$

Contaminants	Maximum concentration (μgL^{-1})	Natural background concentration (μgL^{-1})	Found concentrations near mines (μgL^{-1})	Dilution factor(-)
Arsenic (As)[1]	50	8.0	$2.1*10^2$	4.76
Lead (Pb)[2]	2.5	$4.0*10^{-2}$	2.6	1.04
Lead(Pb)[3]	2.5	$4.0*10^{-2}$	3.8	1.53
Cadmium (Cd)[2]	$8.0*10^{-2}$	$1.0*10^{-3}$	0.88	11.1
Cadmium (Cd)[3]	$8.0*10^{-2}$	$1.0*10^{-3}$	0.41	5.18
Copper (Cu)[3]	2.0	1.4	8.4	11.7
Zinc (Zn)[3]	30	0.2	$2.1*10^2$	7.09
Chromium (Cr)[3]	8.9	0.1	7.2	0.81
Manganese (Mn)[2]	$1.0*10^2$	10	$2.6*10^2$	2.78
Manganese (Mn)[3]	$1.0*10^2$	10	166.2	1.74
Iron (Fe)[2]	$3.0*10^2$	50	$1.6*10^3$	6.20
Iron (Fe)[3]	$3.0*10^2$	50	$5.4*10^3$	1.97
Sulphate (So4)[3]	$5.0*10^4$	$4.8*10^3$	$1.4*10^3$	n/a
Average concentration of c_{max}, c_{nat} c_{effl} and average dilution factor	74.7	10.82	$2.51*10^2$	4.65

Table 8 Nine substances who pollutes surface and groundwater near mining areas according to several types of research. The average dilution factor is estimated. Found concentrations near mines are abstracted from the following research: 1. Razo, Carrizales, Castro, Diaz-Barriga, and Monroy, (2003) 2. Schaider, Senn, Estes, Brabander, & Shine (2014) 3. Prasad et al. (2013).

The grey water footprint is estimated by multiplying the dilution factor with the annual water abstraction for each country. The water consumption per country is already estimated as the blue water footprint. The water abstraction minus the water consumption is the effluent which is needed to estimate the grey water footprint.

The water abstraction from groundwater, surface water, and public water is estimated based on water abstraction data of European countries for several years from (Eurostat, 2017). For the years where water abstraction data in the mining and quarrying sector is known, water abstraction per current US dollar is estimated by using the GAV of the corresponding country and year. This results in an average water abstraction per current US dollar. Total water abstraction per country and year is estimated with

the average water abstraction per current US dollar times the gross added value of the mining and quarrying industry.

The grey water footprint is estimated by:

$$Grey\ WF = DF \times (total\ water\ abstraction_{c,t} - total\ water\ consumption_{c,t}) \qquad (4)$$

Where DF is dilution factor, c is country and, t is time in years. The grey water footprint for the six most producing countries in this sector is estimated by the same method as other countries. The grey water footprint cannot be estimated per division of the mining and quarrying sector because it is not clear in literature in what kind of mining and quarrying division which contaminants occur and the quantities of those contaminants. Therefore, the averaged dilution factor 5 will be used for the top six producing countries in this sector.

2.3.2   Manufacturing

As stated in section 1.2, the manufacturing industry is a very diverse industry with 23 varying divisions. Wastewater from manufacturing processes released into streams, rivers, and lakes adds pollutants to the water. Other water pollution occurs when tanks storing chemicals leak and leach into the groundwater. Paper and textile manufacturing, which use chemicals such as chlorine and benzene, are among the processes that can contribute to water pollution (Myers, 2016). A weighted average as a dilution factor will, because of the diversity of this sector, not be representative of the manufacturing industry. Besides, the load of the effluent of manufacturing industries is not known in the literature. The conservative dilution factor of 1 is used for the industrial (Mekonnen & Hoekstra, 2011a). Therefore the grey water footprint is estimated by multiplying the effluent of the manufacturing sector with this dilution factor 1 for each year and country.

2.3.3   Electricity generation

The electricity generation divisions, which includes thermal and nuclear power plants, are by far the divisions which abstract the most water. Those divisions generate electricity by fossil fuels, nuclear power and biomass and waste. It is estimated how much water is abstracted in these divisions per MWh in chapter 1.3.   These divisions pollute the water by the effluent with a different, higher, temperature. The thermal difference of the effluent water is the biggest form of pollution within these divisions. This results in a grey water footprint with a corresponding dilution factor.

Thermal and nuclear power plants discharge into rivers and lakes which are 8-12 degrees Celsius above ambient water temperature (Shiklomanov, 2003). To sustain the quality of fresh water, water temperature may increase with maximal three degrees Celsius (EU, 2006). With the following formula, the dilution factor can be calculated and thereby the grey water footprint (Hoekstra et al., 2011).

$$WF_{grey} = \frac{T_{effl} - T_{act}}{T_{max} - T_{nat}} \times Effl_{c,t} \qquad (5)$$

Where $\frac{T_{effl} - T_{act}}{T_{max} - T_{nat}}$ is the dilution factor.

$T_{effl} - T_{act}$ is difference between the temperature in degrees Celsius of an effluent flow and the receiving water body.
$T_{max} - T_{nat}$ is the maximum temperature rise in degrees Celsius.

$Effl_{c,t}$ is the volume of the effluent or wastewater flow in m^3 per country and year. The effluent will be estimated by multiplying the specific water abstraction per MWh per division minus the blue water footprint.

For power plants, the dilution factor is an average of 10 degrees Celcius divided by a maximum increase of 3 degrees. $\frac{10}{3} = 3,3$ is a rough estimation of the dilution factor for the thermal power plants by fossil fuels and biomass and waste and nuclear power plants.

Geothermal power plants can have impacts on the quality of water. Hot water pumped from underground reservoirs often contains high levels of sulfur, salt, and other minerals (Union of Concerned Scientists, 2016). The geothermal exploitation causes the drifting of contaminants such as mercury, antimony, boron, arsenic, and hydrogen sulfide (Manzo, Salvini, Guastaldi, Nicolardi, & Giuseppe, 2013). Concentrations of contaminants in the effluent are not quantified in literature. Therefore, the conservative approach of the dilution factor 1 is used to estimate the grey water footprint. The effluent per country and year of this division is multiplied by the dilution factor. Currently, there is no evidence in literature of pollution in fresh surface or ground water by solar electricity, wind-driven electricity and hydroelectricity generation. A contaminant load of their effluent is zero which results in no grey water footprint. It must be noticed the grey water footprint is only zero for operation phase. The construction phase of these different electricity generators could have a different grey water footprint but is not relevant to this research.

2.3.4 Construction

Sources of water pollution on building sites include diesel and oil, paints, solvents, cleaners and other harmful chemicals like construction debris, dirt, and cement (Gray, 2017). Due to a lack of literature about a load of water pollution caused by the construction industry, a conservative dilution factor of 1 is used for the effluent in the construction industry for all countries and years. This dilution factor is used for the industrial sector in the report of Mekonnen and Hoekstra (2011b).

2.3.5 Domestic water supply

Human emission in wastewater consists of the pollutant substances nitrogen (N) and phosphates (P). For estimating the grey water footprint, a load of these emissions needs to be estimated. The load divided by the difference between the ambient water quality standard for N or P (the maximum acceptable concentration c_{max} mgL^{-1}) and the natural concentration of N or P in the receiving water body (c_{nat} in mgL^{-1}) results in the grey water footprint. These concentrations are respectively 2.9 mgL^{-1} or 0.4mgL^{-1} for N (Mekonnen & Hoekstra, 2015) and respectively 0.024 mgL^{-1} and 0.01 mgL^{-1} for P (Franke, Boyacioglu, & Hoekstra, 2013).

$$Grey\ water\ footprint = \frac{Load}{C_{max} - C_{nat}} \tag{6}$$

The load can be estimated by the following formula for nitrogen or phosphorus:

$$Load = \left(E_{sw} \times D_{(c,t)} * TP_{(c,t)} \right) + \left(E_{hum} \times \left(1 - D_{(c,t)}\right) \times TP_{(c,t)}\right)f_{sw} \tag{7}$$

Where E_{sw} is emission in N or P from the sewage for a country and year in kg^{-1}cap^{-1}y^{-1} , E_{hum} is de emission per from humans in kg^{-1}cap^{-1}y^{-1}, $D_{(c,t)}$ is the fraction connected to sewerage system per country and year, $TP_{(c,t)}$ is total population of a country and year (United Nations, 2017). Where f_{sw} is the non-sewered human waste that enter the surface water through dumping of human waste in open water or through surface runoff. This is assumed 10% (Mekonnen & Hoekstra, 2017). In total, this is the load of the emission which comes via the sewerage, the left the side of the formula, or direct from humans to surface water for each year and country, the right side of the formula. The total emission of N from sewerage is estimated with the following equation:

$$E_{sw}^N = E_{hum}^N D(1 - R^N) \tag{8}$$

Where E_{sw}^N is the nitrogen emission to surface water in kg^{-1}cap^{-1}y^{-1}, E_{hum}^N is the human nitrogen emission per country and year in kg^{-1}cap^{-1}y^{-1}, D is the fraction of the total population that is connected to public sewerage systems (no dimension), and R^N is the overall removal of nitrogen through wastewater treatment (no dimension). These variables vary per world region and year and are provided in the research of Van Drecht, Bouwman, Harrison, and Knoop, (2009).

If available, country specific values are used for some years. The total population per country per year is obtained (United Nations, 2017). The nitrogen emission is estimated per year and per country and is based on the dietary per capita protein consumption which is abstracted from FAOSTAT (2018). The N intake through food is estimated by assuming an average of 16% N content in the protein consumed. About 97% of the N intake is assumed to be excreted in the form of urine and faeces and the remainder 3% is lost via sweat, skin, hair, blood, and miscellaneous (Mekonnen & Hoekstra, 2015). The percentage of population connected to public sewerage systems for several countries is abstracted from Eurostat (2016). Three wastewater treatment types with differing N removal efficiencies are based on the work of (Van Drecht et al., 2009). They distinguish primary treatment (10% N removal), secondary treatment (35% N removal) and tertiary treatment (80% N removal). Data on the distribution of these different treatment types are given by Van Drecht et al. (2009) on a regional scale and for several countries on a national scale (OECD, 2015). If data is available for these variables, but not for every year in the period 1960-2015, interpolation or extrapolation is used based on the world region data (Van Drecht et al., 2009).

The total emission of P from sewage is estimated with the following equation:

$$E_{sw}^P = (E_{hum}^P + E_{Ldet}^P + E_{Ddet}^P / D)D(1 - R^P)$$ (9)

Where E_{sw}^P is the P emission to surface water in kg^{-1}cap^{-1}y^{-1}, E_{hum}^P is the human P emission in kg^{-1}cap^{-1}y^{-1}, E_{Ldet}^P is the P emission from laundry detergents in kg^{-1}cap^{-1}y^{-1}, E_{Ddet}^P the P emission from dishwasher detergents kg^{-1}cap^{-1}y^{-1}, D is the fraction of the total population that is connected to public sewerage systems (no dimension), and R^P is the overall removal of P through wastewater treatment (no dimension). These variables vary per world region and year (Van Drecht et al., 2009). The P emission is estimated by using a ratio of 10:1 between N and P (Mekonnen & Hoekstra, 2017). The overall removal is estimated as a weighted average of primary, secondary and tertiary sewerage systems in the specific region for N and P based on data of Van Drecht et al. (2009). The amount of total population and the percentage of the population connected to waste water treatment is already obtained when the load of N is estimated and stays the same.

The load and therefore the GWF, is estimated for N and P emission based on the regional data or national data if available. The highest GWF by N or P is determined and is responsible for each specific year and country.

3. Results

The results of this research are presented in this chapter. Section 3.1 shows the results of the blue water footprint per sector. Section 3.2 shows the results of the grey water footprint per sector. The last section is about allocating the water footprints geographically. Per sector, it is argued how the water footprint could be allocated.

3.1 The blue water footprint

In this section, the results of the blue water footprint are presented. The blue water footprint is estimated per country, the graphs in this chapter show the global blue water footprint per industrial sector. For the electricity generation sector, the blue water footprint per division is presented. Also, the blue water footprint of the domestic water supply is presented. All results are shown as global results, with the exception of countries which have a lack of data or inadequate data. Third world countries with an economic crisis in the past, military coups, other conflicts or wars can affect the inflation in that country. It can result in extreme inflation or deflation which results in unrealistic peaks in the gross added value and therefore the blue water footprint. These countries are excluded in the results. For the mining and quarrying industry, the six countries which are responsible for the majority of the production are treated separately. Per division of mining and quarrying sector, the blue water footprint is estimated. In subsection 3.1.6 the blue water footprint of industry and domestic water supply are compared. And in subsection 3.1.7 the comparison of water abstraction and consumption is made.

3.1.1 Mining and quarrying

For all countries, the blue water footprint is estimated based on weighted average water consumption per current US dollar of the divisions and added up in *Figure 6* with the exception of some small countries and islands and countries with a lack of data or inadequate data. Also, unrealistic peaks are removed and replaced with an average of surrounding years.
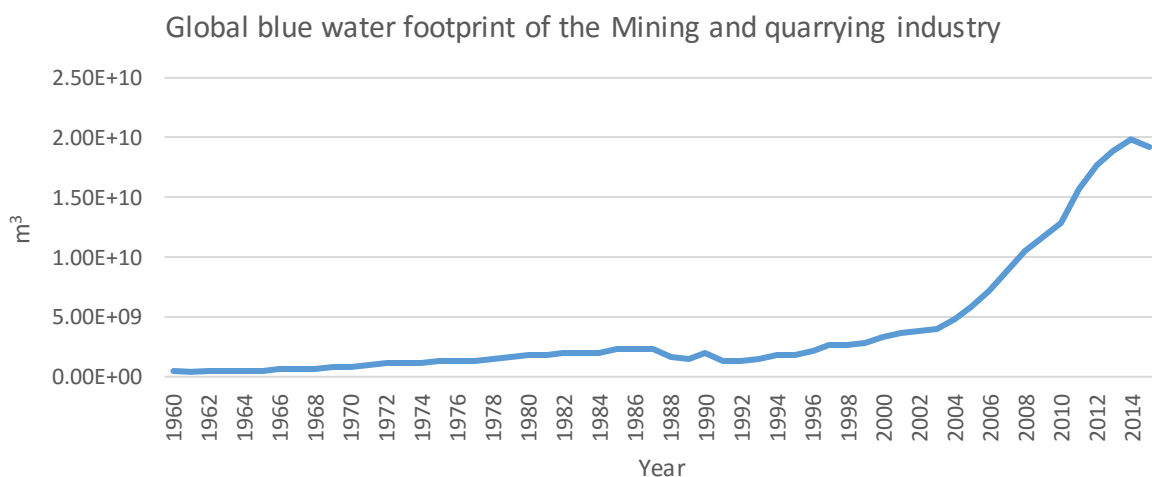

Figure 6 The blue water footprint of the mining and quarrying industry of the world.

The six biggest producers in the mining and quarrying sector, China, USA, Russia, Australia, India and Saudi Arabia are responsible for the majority of the production in this sector during the whole period. For these countries, the blue water footprint is estimated per division. These divisions are Iron, Ferro-alloy Metals, Precious Metals, Mineral Fuels, Non- Ferrous Metals and Industrial Minerals. It is based on the share of the specific division of the total mining and quarrying sector, depending on the country and on the year 2015.

According to *Figure 7* up to and including *Figure 12*, it can be seen that Mineral Fuels division is the largest division in all countries which. This is not surprising as it includes oil and coal. From the six biggest distributors in this sector, Australia has the most diverse composition of divisions because of the different metals they produce. During the economic crisis of 2008 the USA, Australia, Russia and Saudi Arabia shows a decrease in the blue water footprint. Since 1990 it can be seen in *Figure 7* that the production is increasing in China and eventually China is the biggest producers in this sector for all countries. The Mineral Fuels division is by far the biggest division in China and the other five countries. China's blue water footprint of the other four divisions is also larger than the other five countries.
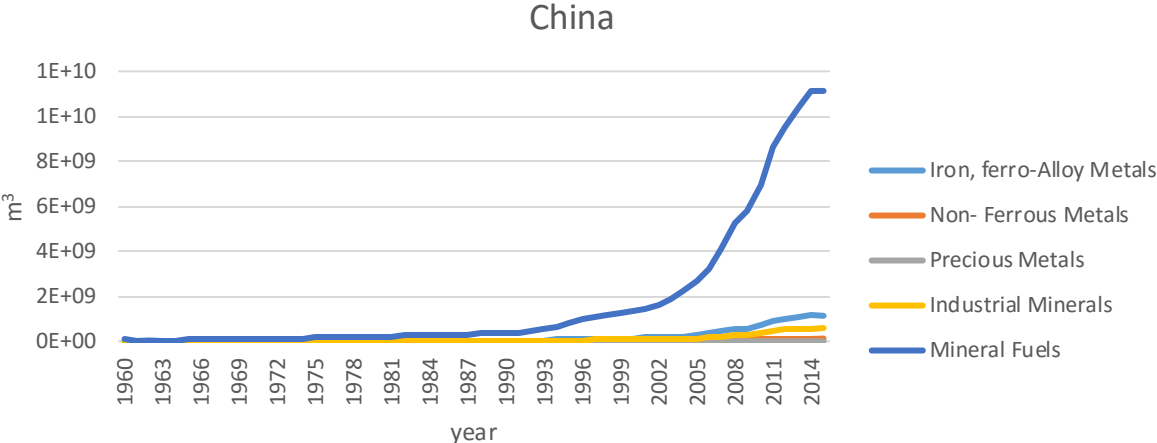
Figure 7 The blue water footprint of the mining and quarrying sector divided into five divisions for China during the period 1960-2015.
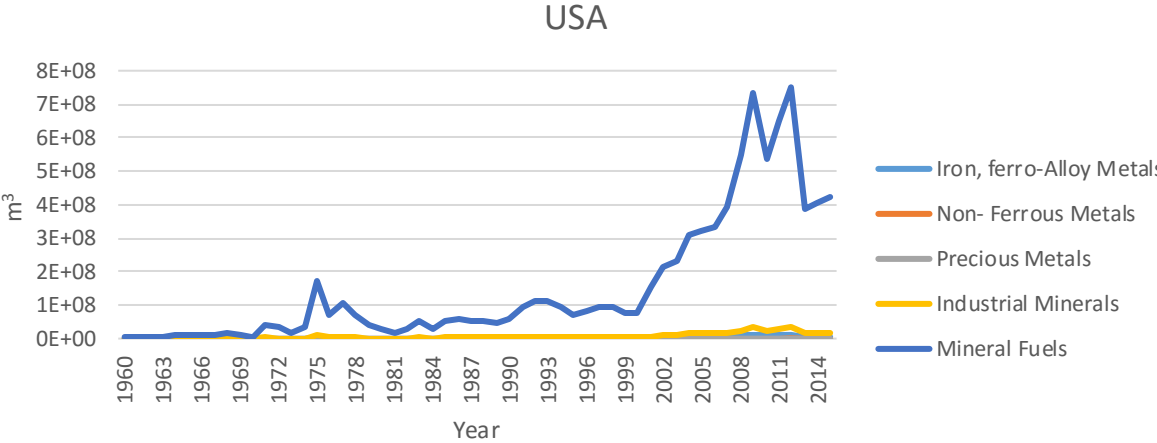
Figure 8 The blue water footprint of the mining and quarrying sector divided into five divisions for the USA during the period 1960-2015.

Figure 9 The blue water footprint of the mining and quarrying sector divided into five divisions for Russia during the period 1960-2015.
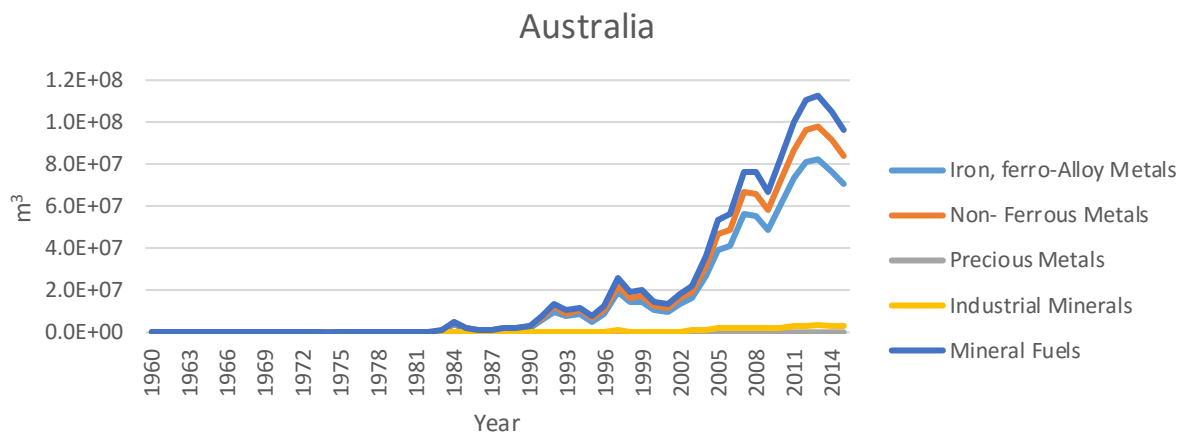

Figure 10 The blue water footprint of the mining and quarrying sector divided into five divisions for Australia during the period 1960-2015.
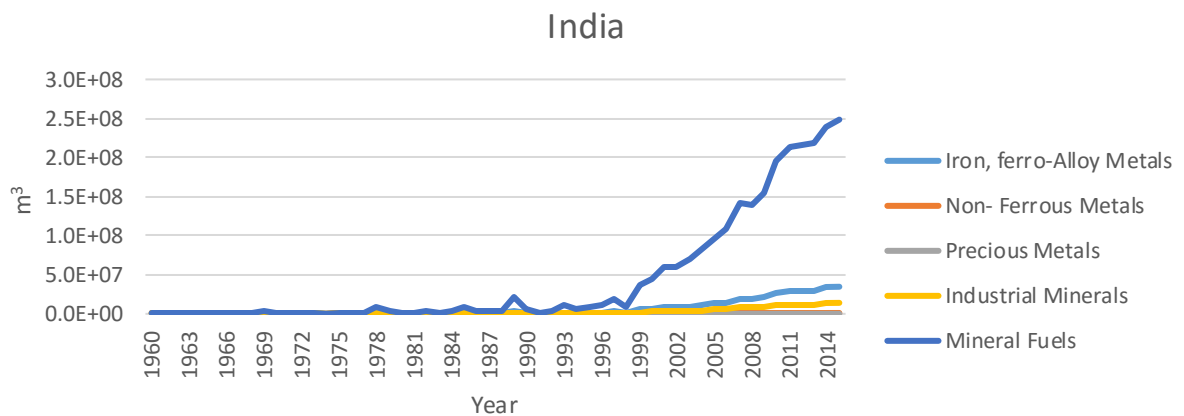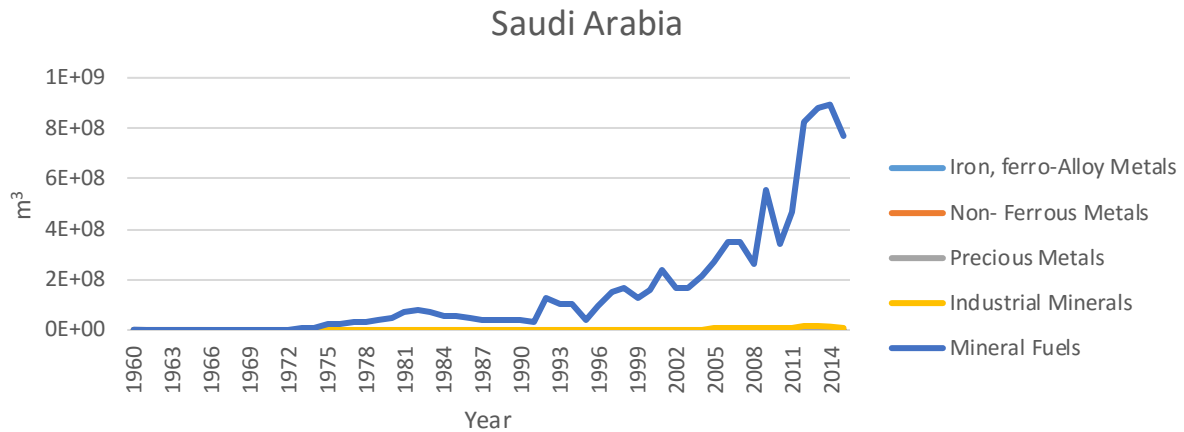

Figure 11 The blue water footprint of the mining and quarrying sector divided into five divisions for India during the period 1960-2015.

Figure 12 The blue water footprint of the mining and quarrying sector divided into five divisions for Saudi Arabia during the period 1960-2015.

3.1.2 Manufacturing

The blue water footprint is estimated based on the water abstraction per current US dollar and a water consumption to withdrawal ratio of 9.3%. Per year all values are added up in *Figure 13* with the exception of some small countries and islands because of inadequate data.
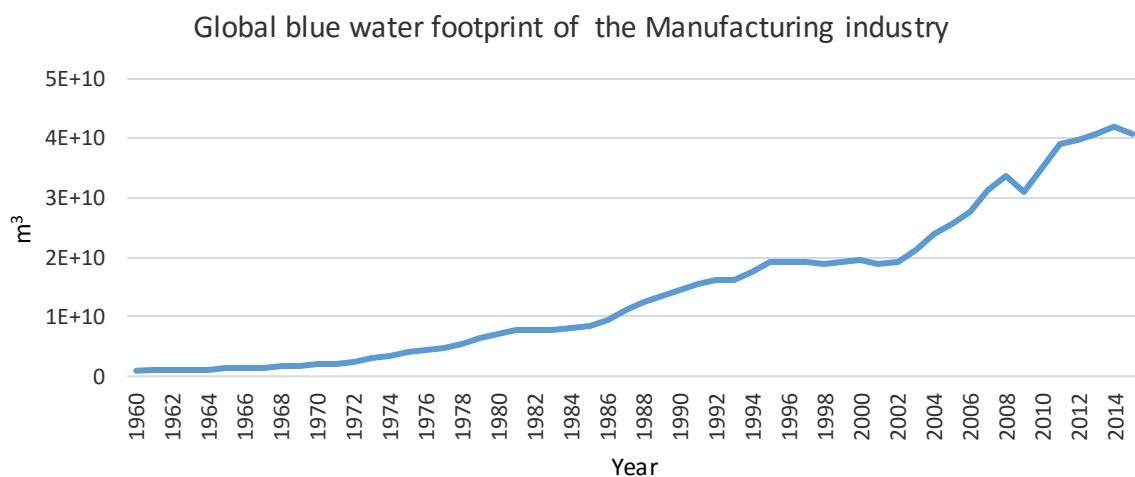

Figure 13 The blue water footprint of the manufacturing industry added up per year for all, known, countries for the period 1960-2015

3.1.3 Electricity generation

The electricity generation sector abstracts and consumes relatively much water compared to other industrial sectors. This is mainly due to the Hydroelectricity division which is responsible for 90% to 79% of the global water consumption in the electricity sector. This division is responsible for around 86% to 66% of the global blue water footprint of the total industry. The second largest water consumer in this sector is the electricity generation driven by fossil fuel. The blue water footprint of these and the other divisions of electricity generation is presented in *Figure 14*.
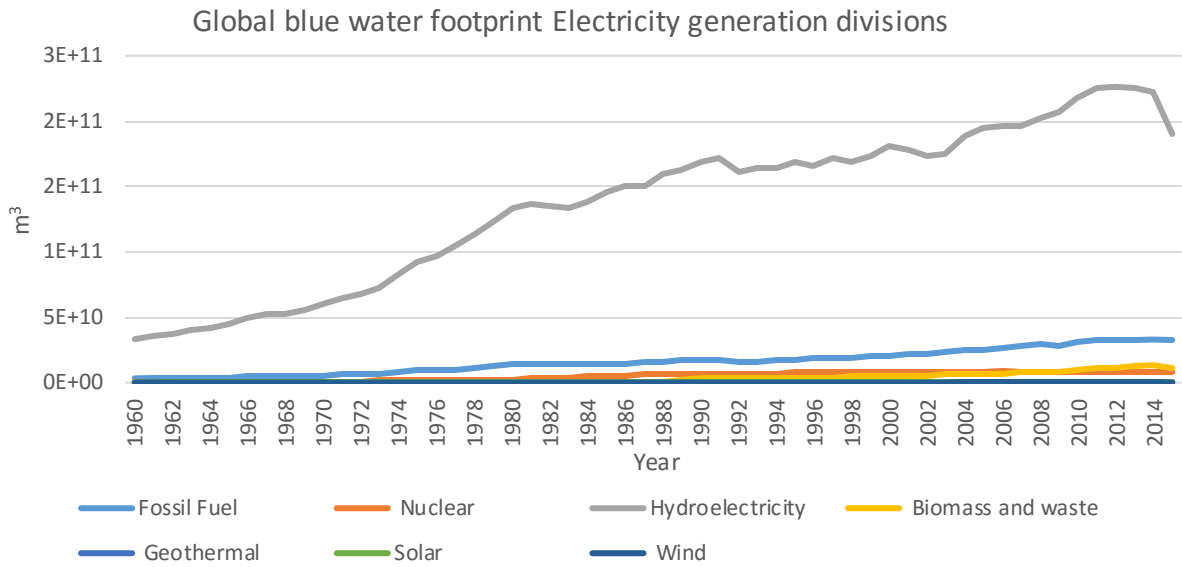
26

Figure 14 The total blue water footprint of the world per year for each division in the electricity generation sector.

3.1.4 Construction

The construction industry appears to be the sector that consumes the smallest amount of water in the total industry. A constant water consumption of 8.05×10^{-5} m^3 per current US dollar contributes to the small amount of blue water footprint together with a relatively low gross added value. Besides, not every country has data available to estimate the blue water footprint in this sector. The global blue water footprint is presented in *Figure 15*.
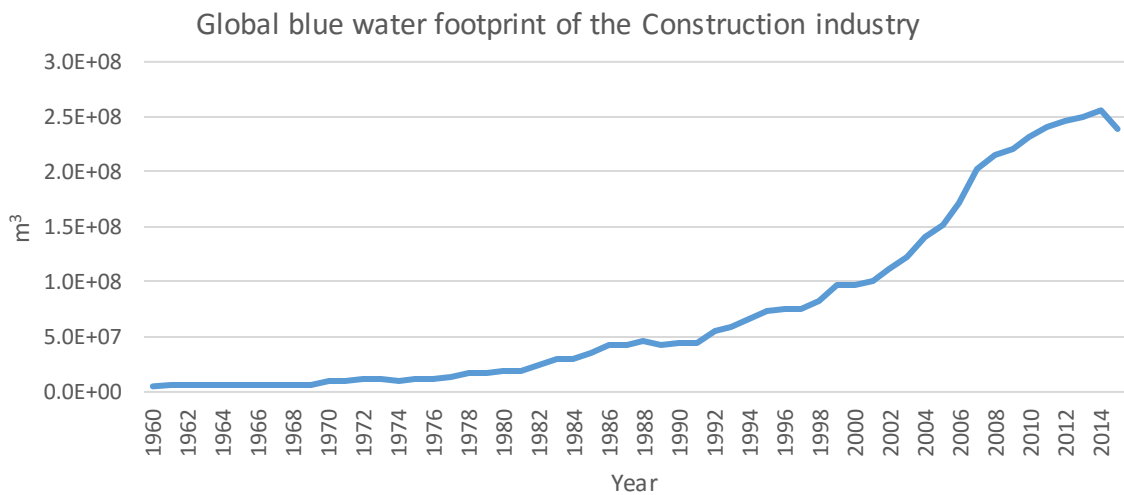

Figure 15 The total blue water footprint of the construction industries for all, available, countries per year.

3.1.5 Domestic water supply

The global blue water footprint for the domestic water supply is given in *Figure 16*. The blue water footprint is estimated by using a different method than was used for the industrial sectors. It is based on the data of Aquastat (2017) and an average consumption to withdrawal ratio of 15%. In 55 years the blue water footprint of this sector has almost constantly increased from around 5.92×10^9 m^3 to 1.07×10^{11} m^3 in 2015.

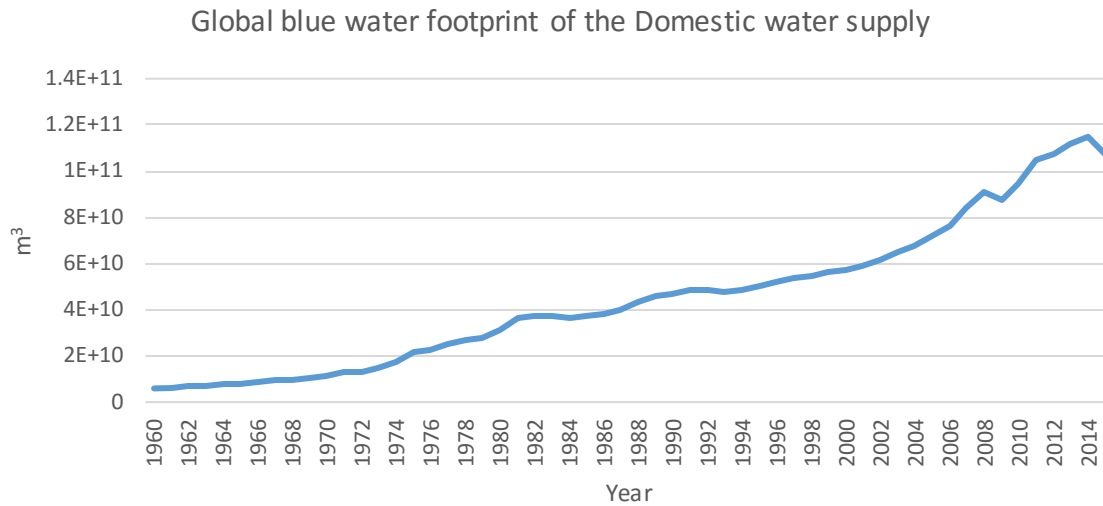Global blue water footprint of the Domestic water supply

Figure 16 Total blue water footprint of the domestic water supply per year for all countries.

3.1.6 Total blue water footprint of industry and domestic water supply

The global blue water footprint of the industry is for the whole period 1960-2015 larger than the global blue water footprint of domestic water supply. All industrial sectors are responsible for 87% of the global blue water footprint of industry and domestic water supply combined in 1960, in 2015 it was 74%. The results are shown in *Figure 17*.
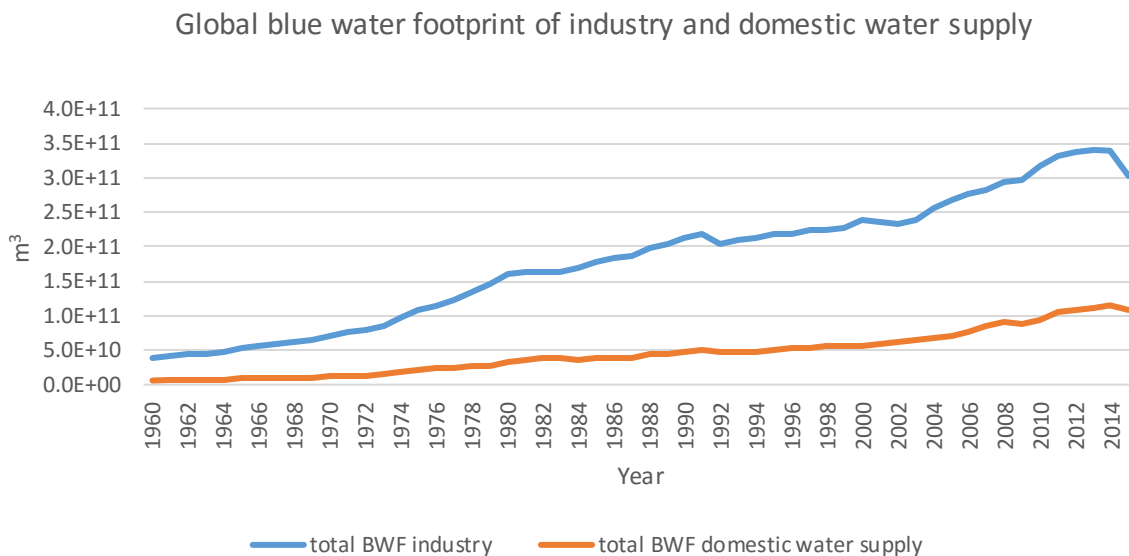

Global blue water footprint of industry and domestic water supply

Figure 17 Total blue water footprint of domestic water supply and industry for all countries each year for the period 1960-2015.

3.1.7 Global blue water footprint compared to global water abstraction

The global blue water footprint of the industrial sector can be compared with the global water abstraction of the industrial sector according to Aquastat (2017). Before this research, it was assumed that 5% of the water abstracted for industrial purposes is actual consumption and the remaining fraction is return flow (Mekonnen & Hoekstra, 2011a). The abstraction according to Aquastat and the consumption (blue water footprint) of the industry estimated in this report are compared. Aquastat (2017) excludes the water abstraction for hydroelectricity, therefore the blue water footprint of

hydroelectricity is also excluded in the comparison in *Figure 18*. The figure presents a water consumption to withdrawal ratio between the 4% and 8%.
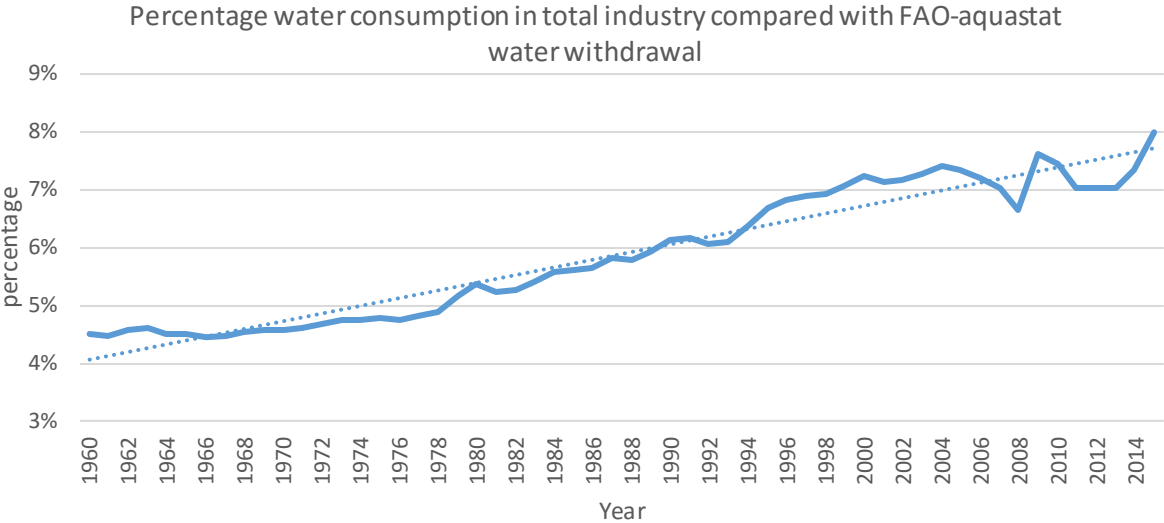
Percentage water consumption in total industry compared with FAO-aquastat water withdrawal

Figure 18 Percentage of water consumption of the total water withdrawal, according to Aquastat *(2017)* for the industry, hydropower excluded.

Figure 19 presents the quantification of the comparison of global blue water footprint and global water withdrawal of the total industrial sector for each year.
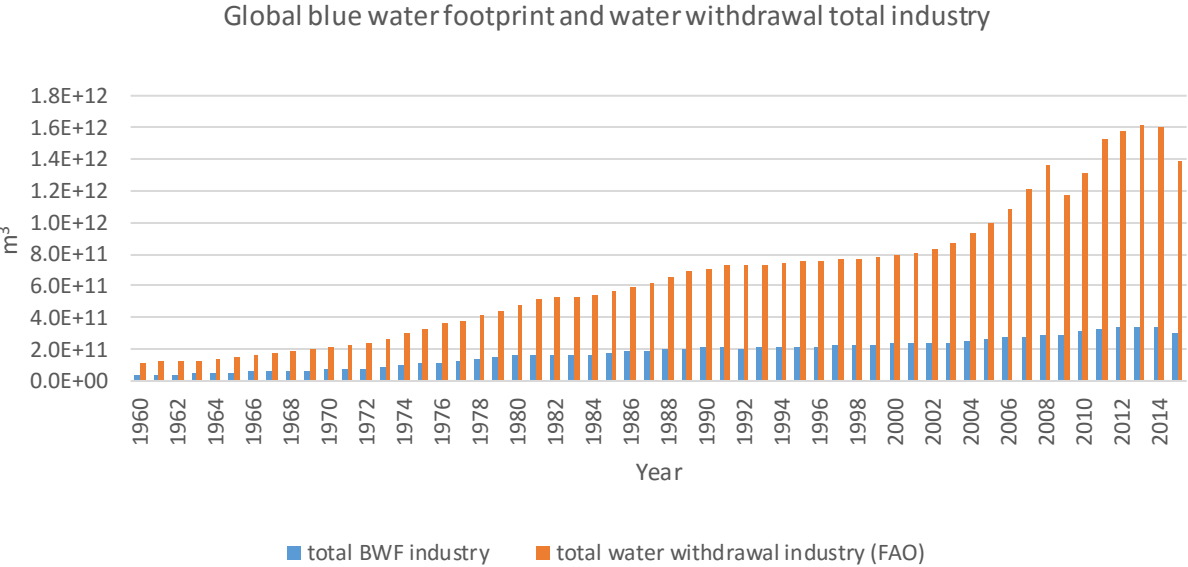
Global blue water footprint and water withdrawal total industry

Figure 19 Blue water footprint and water withdrawal in total industry sector compared.

3.2 The grey water footprint

This section shows the results of the global grey water footprint annually for all industrial sectors in the period 1960-2015. The results of all countries are added together in this chapter per sector or division. Same as the blue water footprint, the grey water footprint of the divisions of the electricity generation is also estimated. The conservative dilution factor 1 which is used in previous research (Mekonnen & Hoekstra, 2011a), is replaced with a new, mostly higher, dilution factor where possible.

This dilution factor is estimated in section 2.3. Mostly, the same countries which are missing in the results of the blue water footprint are also missing in the results in this section. This is caused by the same reason as these countries have a lack of data or inadequate data.

3.2.1   Mining and quarrying

In section 2.3, a new dilution factor estimated. The effluent per country and year is multiplied by the dilution factor 5. The global grey water footprint is presented in *Figure 20*. In *Figure 21*, the grey water footprint is presented of the six countries which are responsible for the largest part of the production in this sector. In 2015 China has a grey water footprint of almost $1.4*10^{13}$ m^3 and is, therefore, the major contributor to the global grey water footprint in the mining and quarrying industry. In 1960 China was responsible for approximately 20% of the global grey water footprint which increased to 69% in 2015 of the global water footprint in the mining and quarrying industry.
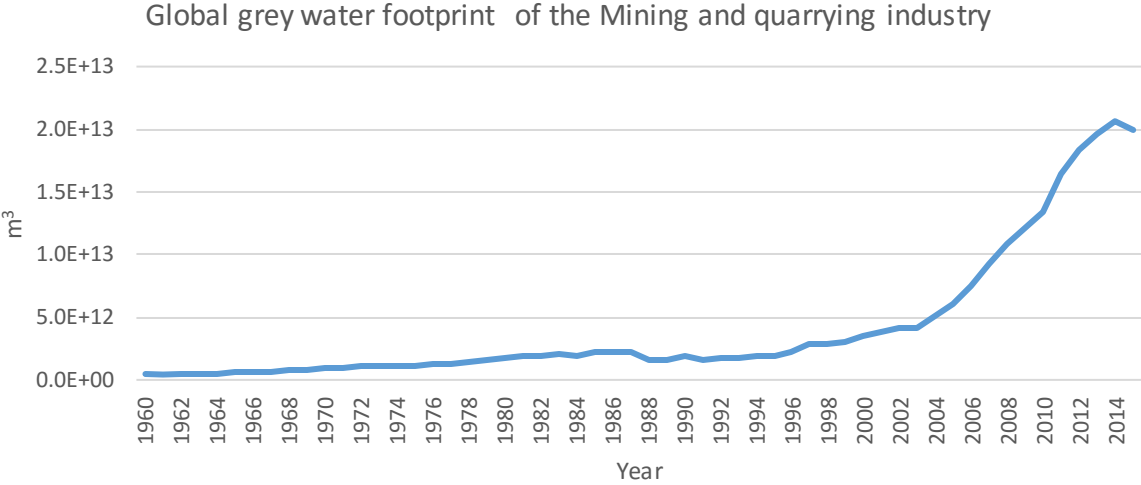

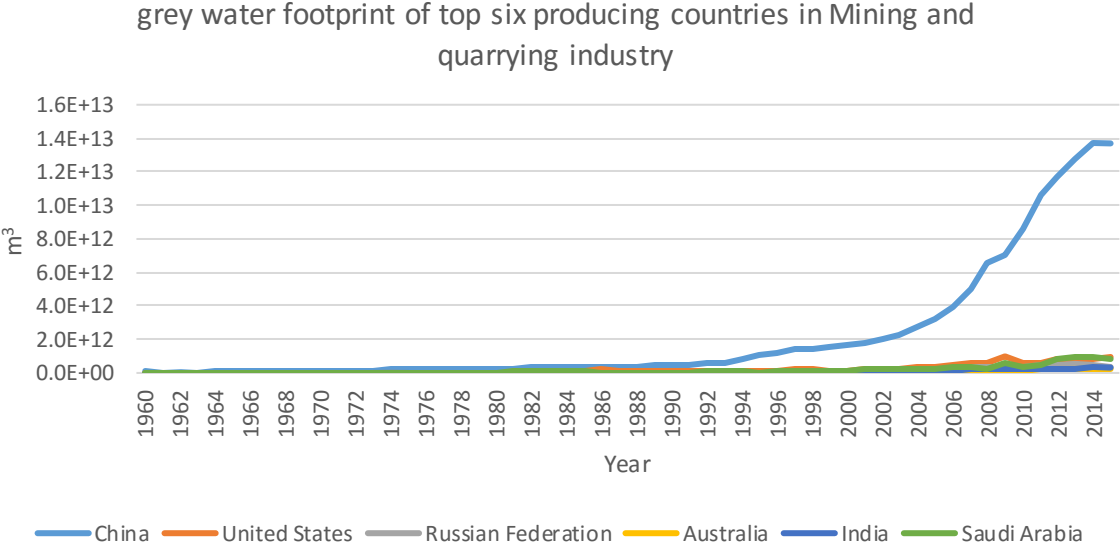Figure 20 Global grey water footprint of mining and quarrying annually.

Figure 21 The grey water footprint of the six countries which has the largest contribution in the mining and quarrying sector.

3.2.2 Manufacturing

The effluent in the manufacturing industry is multiplied with the conservative dilution factor 1 to estimate the grey water footprint for each country and year in the period 1960-2015. The results of all countries with available data is combined and presented in *Figure 22*. The grey water footprint is estimated for the same amount of countries as the blue water footprint.
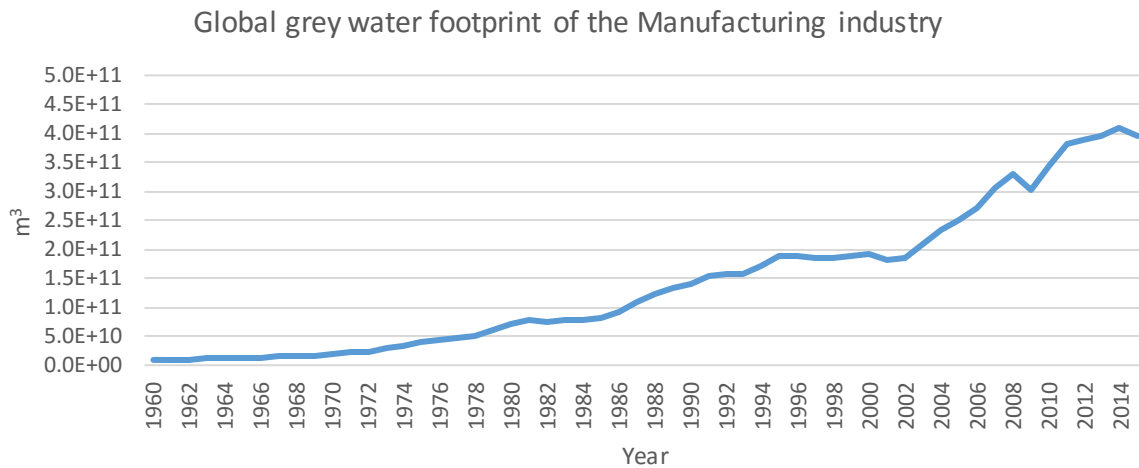
Global grey water footprint of the Manufacturing industry

Figure 22 The global grey water footprint of manufacturing in total per year.

3.2.3 Electricity generation

The electricity generation sector, consisting of several divisions, abstracts significant amounts of water. In most division water is used as cooling water. In subsection 2.3.2 a dilution factor of 3.3 is estimated when thermal contamination is the biggest pollution. Otherwise, the conservative dilution factor 1 is used. For wind-, solar- and hydroelectricity there is no kind of contamination in the operating stage. The results of the divisions with a grey water footprint are summed up for all countries each year and are presented in *Figure 23*. The three largest grey water footprints are those which use water for cooling purposes. Thermal power plants which use fossil fuels have the largest grey water footprint followed by nuclear power plants and thermal power plants driven by biomass and waste.
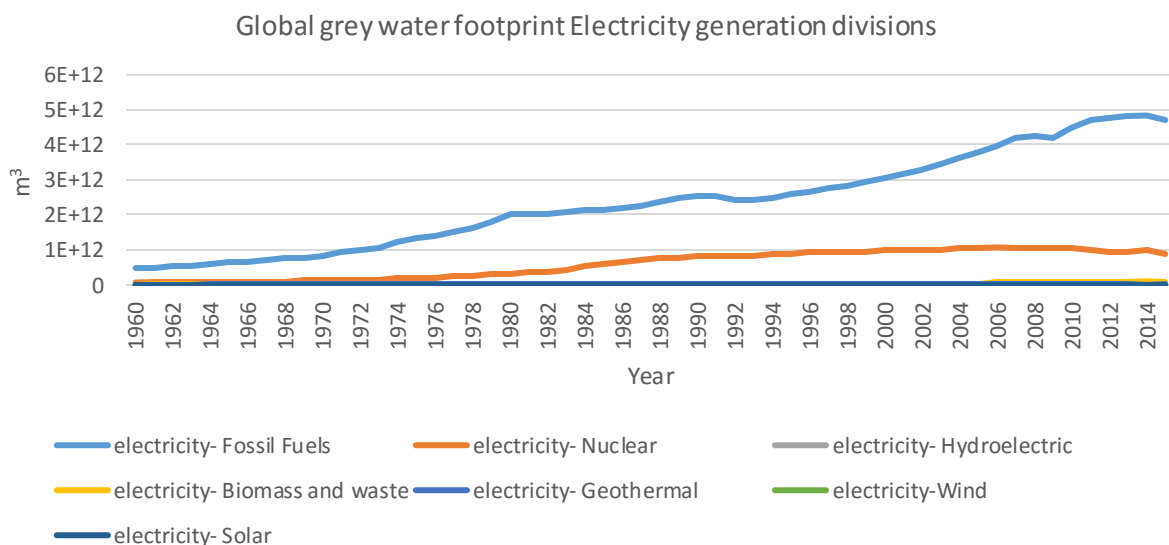
Global grey water footprint Electricity generation divisions

Figure 23 The grey water footprint of electricity generation divisions.

3.2.4 Construction

For the construction industry, a conservative dilution factor 1 is used to estimate the grey water footprint. The results are presented in *Figure 24* were the grey water footprint for all countries is added up together and forms the global grey water footprint.
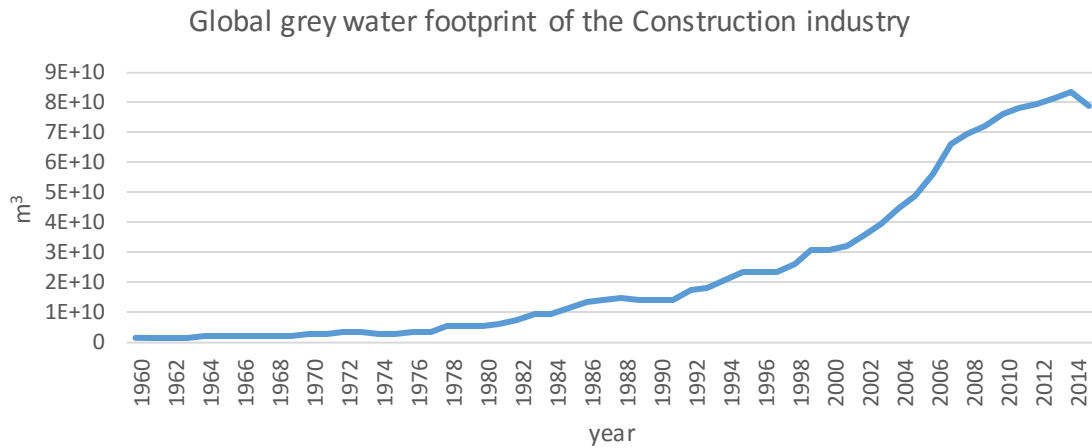
Global grey water footprint of the Construction industry

Figure 24 Grey water footprint of the construction industry.

3.2.5 Domestic water supply

The grey water footprint of domestic water supply is estimated for the contaminants nitrogen and phosphorus. The contaminant which causes the highest grey water footprint is responsible for the actual grey water footprint of domestic water supply per country and year. *Figure 25* presents the global grey water footprint of domestic water supply annually. *Figure 25* also shows both global grey water footprint caused by the nitrogen and phosphorus. The global grey water footprint by caused for the phosphorus contaminants is responsible for the grey water footprint of domestic water supply for most of the time and years.
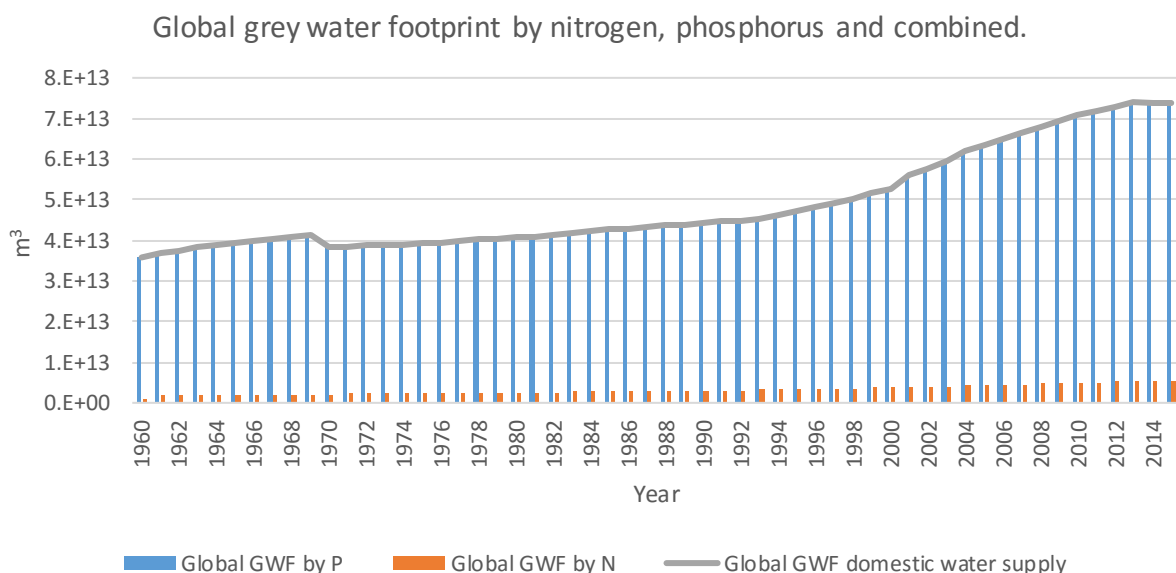
Global grey water footprint by nitrogen, phosphorus and combined.

Figure 25 Global grey water footprint of domestic water supply by the contaminants Nitrogen (N) and Phosphorus (P) and those contaminants combined.

3.2.6   Global grey water footprint of Industry and domestic water supply

The global grey water footprint of all sectors and division is summed in this section. In *Figure 26* also the global grey water footprint of domestic water supply is included. The global grey water footprint of domestic water supply is larger for every year until eventually, it is approximately two times larger than the global grey water footprint of the industry.
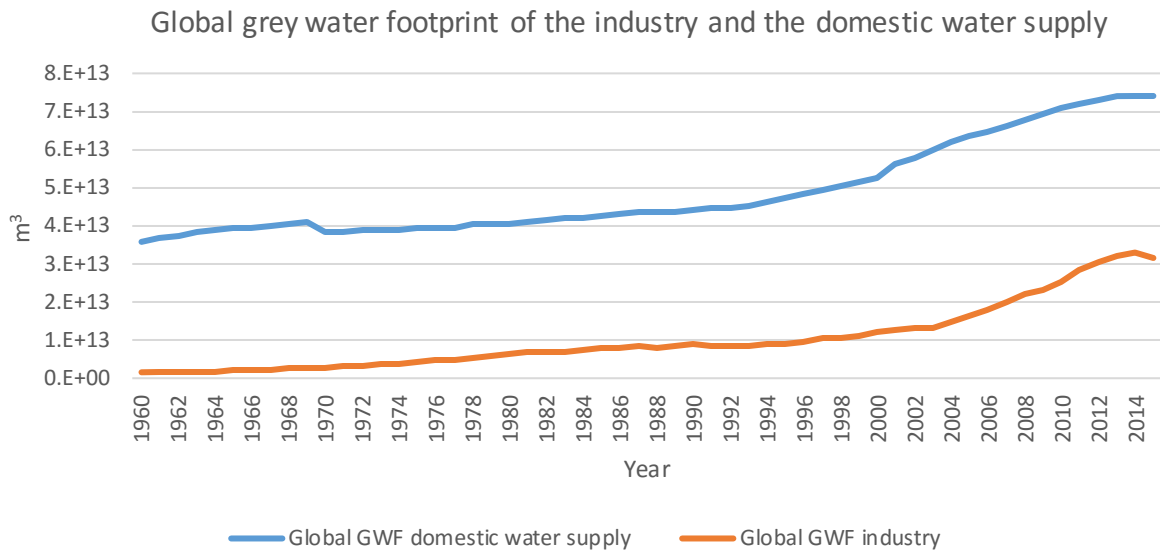

Figure 26 Total global grey water footprint of industry and domestic water supply.

3.3 Mapping the results

In this section, recommendations and suggestions are made which can be used to map the blue and grey water footprint of all sectors based on geographical locations of the industrial sectors. Existing maps of industrial sectors can be used to locate the blue and grey water footprint of those sectors.

3.3.1   Mining and quarrying

The blue and grey water footprint of the mining and quarrying sector is dependent on the location of resources in the earth's surface. Those resources are mostly coal, gas, oil, and iron. Petroleum fields and gas fields are presented for the world at the so-called website World Map established at Harvard (Center for Geographic Analysis, 2014). World Map is an open source database which provides the data in layers about several sectors in files such as .CSV. The layer which presents these fields is accessible and originally made by Päivi et al. (2007). The petroleum fields can correspond to the water footprint per country. Assuming that the place where the mining products are extracted is the same as where water is consumed. Suggesting that the blue and grey water footprint can be spread along the locations of the gas and oil fields which are presented, excluding areas in the sea.

3.3.2   Electricity generation

The water footprint for electricity generation is related to the location of the power plants nearby rivers or the location of windmill fields, solar panel fields, and electricity generating dams. The world map of the Center for Geographic Analysis of Harvard (2014) presents layers which shows the location of nuclear power plants, gas power plants, oil power plants and coal power plants. Also, layers of solar power plants and hydroelectric generating units are available.

Fossil fuels

The division fossil fuels contain electricity generated in power plants driven by coal, gas or oil. All those power plants are located in three layers in the world map of the Center for Geographic Analysis (2014). These layers are OSM Worldwide Oil Power Generating Units, OSM Worldwide Gas Power Generating Units, OSM Worldwide Coal Generating Units this is data from 2014 (Center for Geographic Analysis, 2014). These layers are extracted originally from OpenStreetMap (2018).

The blue water footprint of the fossil fuels division can equally be divided over the coal, gas and oil power plants per country when the generating capacity of all, or most, power plants are not known. Not every power plant will generate the same amount of MWh and power plants with a different kind of fuel will have a different water footprint. The majority of the abstracted locations of gas, oil and coal power plants in the world also presents the generating capacity in Megawatt (MW). The average blue and grey water footprint are estimated per MWh in section 2.2.3 and 2.3.3. As 1 MW is equal to 2,190 MWh, the corresponding water footprint can be allocated to the specific power plant in a country. Therefore, the blue water footprint can be estimated for a specific location of a power plant if the generating capacity is known. At these specific locations water is consumed, therefore these are the locations of the blue water footprint. If a certain country has multiple power plants but no or fewer data about the generating capacity, the water footprint should be allocated by dividing the blue water footprint by the number of power plants.

The grey water footprint is also located on the location of the power plants. Because of the current method, it is not possible to allocate the grey water footprint in the same way. The grey water footprint is not estimated per MWh, a dilution factor is used and the effluent of the power plants per country. Therefore, the grey water footprint needs to be divided by the number of power plants and an average grey water footprint will be allocated.

Nuclear electricity

Nuclear electricity is generated in nuclear power plants. Location of nuclear power plants worldwide are available and presented in a layer of the Socioeconomic Data and Applications Center (Center for International Earth Science Information Network - CIESIN -, 2017). The blue water footprint of the nuclear electricity sector in a country needs to be equally divided by the number of nuclear power plants per country if the generating capacity per nuclear power plant is not provided. Most nuclear power plants located on the map of Socioeconomic Data and Applications Center also includes data on the amount of power generated in MW for most years. The corresponding blue water footprint can be allocated to the specific nuclear power plant. The power plants without specific power generating data will be responsible for the remaining blue water footprint of the country. The grey water footprint needs to be allocated by dividing the grey water footprint by all nuclear power plants. Each power plant will have an averaged grey water footprint because it is not estimated what the grey water footprint is per MWh.

Geothermal electricity

The same as for the blue water footprint of the nuclear electricity division, the blue water footprint of the geothermal electricity division per country needs to be divided between the amounts of geothermal power plants per country. The generating capacity in MW for the major part of the geothermal power plant is known and presented in the map created by the National Renewable Energy Laboratory (2014). Data about the locations of geothermal power plants are also presented (National Renewable Energy Laboratory, 2014). CSV file is available to present locations of the geothermal power plants with the associated data. The blue water footprint can be allocated because it is estimated how

much water is consumed per MWh for grey and blue water footprints in section 2.2.3 and 2.3.3. If there is no generating capacity data available, the total blue and, in any case, the grey water footprint needs to be divided by the number of geothermal power plants in a country and year.

Solar electricity

A layer with solar power generating units is available on the World Map of Harvard (Center for Geographic Analysis, 2014) which is abstracted from OpenStreetMap (2018). A few locations where solar power is generated contains data about the quantity of electricity generated in kW. For these locations the blue water footprint can be assigned by the amount of water consumed per kW. 1 kW is $1*10^{-3}$ MWh and therefore the blue water footprint can be assigned to locations with known capacity generation as it is estimated how much water is consumed per MWh in section 2.2.3. For power generating units in countries without or less known power generating capacity, the amount of blue water footprint per country needs to be equally divided per location where solar power is used for generating electricity.

Wind electricity

Worldwide locations of electricity generating units by wind are given in a layer of OpenStreetMap presented by the Venter for Geographic Analysis (2014). Same as the solar electricity division the amount of blue water footprint in a country can be divided, by using the electricity generating capacity if available per location. Less than half of all locations contain data about the amount of electricity generating capacity in MW. In section 2.2.3 the water consumption per MWh is estimated and therefore the water footprint per location can be located based on the electricity generating capacity. The remaining water footprint should equally be divided between wind electricity generating units without further data. If the electricity generating capacity is not available, the water footprint of a country needs to be equally divided by the amount of wind electricity generating units.

3.3.3   Manufacturing

The widely varying divisions and groups which forms the manufacturing industry is spread within countries for various reasons. At this moment, there are no layers or maps available which presents locations of the manufacturing industries. However, it is logical to relate the density of the population to the productivity in the manufacturing sector. The population density can, therefore, be used to allocate the water footprint within countries. A gridded population of the world can be used (CIESIN and CIAT, 2015).

3.3.4   Construction

The construction sector is related to the density of buildings and constructions. In this research, it is assumed that the density of buildings and constructions is also related to population density. Therefore, the global population density is used to locate the grey and blue water footprint in this sector by using a gridded population of the world (CIESIN and CIAT, 2015).

3.3.5   Domestic water supply

Mapping the blue and grey water footprint of domestic water supply can be based on the global population density just like the construction industry. This method of mapping the water footprint of domestic water supply is already done by Mekonnen and Hoekstra (2011a). A new gridded population of the world, for the year 2015, is available on the World Map (CIESIN and CIAT, 2015).

4. Discussion

The research presented in this thesis provides a detailed analysis of blue and grey water footprints of industry and domestic water supply. The large number of details considered herein required a narrow focus of the work. Such a narrow focus unavoidably means that improvements can be made. In this chapter, several remarks concerning the described method, and the obtained results will be discussed. Thereby, any potential future work may aim to be broader applicable.

The water consumption ratios and dilution factors in this research are individually estimated per sector or division. However, the water consumption ratios and dilution factors are constant for all years. This will not be the case in practice, it could vary in time. Some production processes will have a decreasing water consumption or dilution factor in time which means eventually an overestimation in this research. The other way around there could be production processes which consume more water by evolving over time which means an underestimation in this study. Research to the evolving water consumption and water pollution in production processes in time can result in different water consumption ratios and water pollution per year. It could give a more accurate estimation of the blue and grey water footprint per year.

This study used water consumption ratios and dilution factors independently of location. Location of a certain production process in the industry can affect the amount of water consumption and water pollution. It is conceivable that the wealth, climate, and other variables in a country can be of influence on the water consumption and water pollution. Research on these variables can result in more insight on water consumption in production processes and the percentages of industry and households connected to the sewerage system. A more accurate blue and grey water footprint can be estimated if the water consumption and dilution factor are related to variables per location or country.

The grey water footprint of solar power, wind energy, and hydroelectricity is assumed zero in this research. It is imaginable that some pollution will occur in these electricity divisions during operating. The hydroelectricity division will also have a certain impact on the surrounding area. However, these divisions do not produce a contaminant load, or it is not known at this moment, and therefore the grey water footprint is assumed zero in this research. Research on the pollution of these divisions and if the pollution for these divisions could affect or merge with water can reveal whether a grey water footprint should be estimated or not.

Exchange rates and inflation rates are used to convert local currencies to current US dollars. Some unstable countries with unstable economies can have very fluctuating inflation or exchange rates. This results in relatively high or low gross added value in current US dollars compared to other years. It does not have to mean that the production and therefore the water footprint also fluctuates like that. These years are replaced by an average of surrounding years. Eventually, these cases result in a less accurate estimation of the water footprint of those years. For several countries where this happened, the cause was very clear, they are summed and a possible explanation is found. Iraq with several wars till 2003, Ghana 1967-1972 when there was a coup, Chile 1973 when there was a coup, Mexico 1982 debt crisis, Mozambique 1987 civil war, Azerbaijan and Armenia with a coup in 1993. The current method is less useful for the year in countries with this kind of situations. Some countries are excluded because of a lack of appropriate data. Research about the water consumption per division or product, if available, in a sector in m^3 per ton could present a more accurate estimation of the water footprint during these events.

In subsection 2.3.1, the mining and quarrying sector has a dilution factor of 5 to estimate the grey water footprint. The dilution factor is increased a lot compared to the conservative dilution factor of 1 (Mekonnen & Hoekstra, 2011a). It is based on contaminants found near mining areas in streams and

surface water. However, originally the dilution factor needs to be based on the contaminants and their concentrations in the effluent. It will cause a higher dilution factor than used in this research and will result in a larger grey water footprint. Unfortunately, concentrations of contaminants in mining and quarrying effluents is not found in current literature. More research about the concentration of contaminants in effluents which reaches surface water could increase the dilution factor and will cause a higher grey water footprint.

The blue water footprint of domestic water supply is based on the water consumption to withdrawal ratio of 15% which is found in the literature. Leakages through pipelines are not included as water consumption as the water flows to the groundwater and therefore stays in that catchment and can be used again. However, the percentage of leakage is not known and water from leakage can partially be consumed by evaporation or be polluted in the ground. Research about leakage and the consequences of water from leakage could refute this issue.

In section 3.3 it is explained how to map and spatially allocate the water footprint per sector or division. In practice, most power plants will not have the same amount of production and therefore not the same water footprint. Also, different mining areas will produce different products and amounts per mining area. However, this will be the case when there is no production data available besides the location of the power plants or mining areas. It will make this research stronger if the amount of generated power is known for all power plants and other power generating sources and is related to the associated water footprint. This is also the case for the production of mines in the mining and quarrying sector.

The grey water footprint of domestic water supply is based on the nitrogen and phosphorus loads. The highest grey water footprint of these two contaminants is decisive for the grey water footprint of domestic water supply per year and country. The estimation of the grey water footprint based on loads of nitrogen and phosphorus is based on the method of Van Drecht et al. (2009). These loads are based on variables such as the accounting for protein consumption, wastewater treatment coverage, and nitrogen and phosphorus removal ratios at sewerage systems. The variables differ per country, the values are given in world region and per year in the research of van Drecht et al. (2009). The nitrogen and phosphorus emission is based on the diet of the population per country and year. For several countries and years, the percentage of population connected to the sewerage and the removal ratios at sewerage systems are known. The result will be more accurate if all variables are estimated for every country and year. This method is mostly the same as the grey water footprint based on the nitrogen or phosphorus load by Mekonnen and Hoekstra (2015, 2017). Similarly, they used the same variables in their method but these are country specific and available for a smaller period.

Differences, presented in *Table 9*, can be explained by the fact that in this study the variables only vary per region if data of one of the variables for a specific country is missing. If that is the case, data from van Drecht et al. (2009) is used in this research because it covers the period 1970-2010 for the whole world. Extrapolation is used to cover the period 1960-2015 for all variables. Investigating a smaller and recent period allows more detailed and more recent data and therefore country-specific data is usable in the study of Mekonnen and Hoekstra (2015, 2017). This can result in difference per country and in total, presented in *Table 9*. Country-specific variables will cause a more accurate result such as the research of Mekonnen and Hoekstra (2015, 2017). However not for every variable data is available when going back in time.

Average grey WF (m³y⁻¹) based on phosphorus loads, 2002-2010.			Average grey WF (m³y⁻¹) based on nitrogen loads, 2002-2010.		
Country	Mekonnen and Hoekstra (2017)	Current result	Country	Mekonnen and Hoekstra (2015)	Current result
China	$2.23*10^{13}$	$1.04*10^{13}$	China	$8.91*10^{11}$	$4.17*10^{11}$
India	$4.81*10^{12}$	$3.63*10^{12}$	U.S.	$2.24*10^{11}$	$2.70*10^{11}$
U.S.	$7.10*10^{12}$	$7.25*10^{12}$	Russia	$1.07*10^{11}$	$1.26*10^{11}$
Spain	$1.01*10^{12}$	$1.23*10^{12}$	India	$1.92*10^{11}$	$1.45*10^{11}$
Brazil	$3.17*10^{12}$	$3.41*10^{12}$	Pakistan	$2.30*10^{10}$	$2.13*10^{10}$
Russia	$3.13*10^{12}$	$3.46*10^{12}$	Brazil	$1.02*10^{11}$	$1.02*10^{11}$
Japan	$2.84*10^{12}$	$2.50*10^{12}$	Egypt	$2.80*10^{10}$	$1.81*10^{10}$
Mexico	$2.02*10^{12}$	$1.40*10^{12}$	Japan	$1.14*10^{11}$	$9.60*10^{10}$
Turkey	$1.67*10^{12}$	$8.09*10^{11}$	Germany	$2.60*10^{10}$	$4.61*10^{10}$
France	$1.23*10^{12}$	$1.60*10^{12}$	Ukraine	$3.20*10^{10}$	$2.80*10^{10}$
World	$7.99*10^{13}$	$6.46*10^{13}$	World	$2.97*10^{12}$	$4.49*10^{12}$

Table 9 the average grey water footprint for the period 2002-2010 based on loads of nitrogen and phosphorus compared with the results of Mekonnen and Hoekstra (2015, 2017).

The water footprint in this research is estimated by using a different method compared to other literature such as Mekonnen and Hoekstra (2011a). In this research, the water footprint of the sectors and even divisions within the total industry are estimated. These are based on the water consumption per current US dollar per sector or division. Water consumption per MWh is used for the electricity generation sector. Also, different dilution factors are used per sector. Mekonnen and Hoekstra (2011b) estimated the water footprint of the industry by looking at it as one lumped sector and using a consumption factor of 5 percent. Treating all industrial sector seperately makes the estimated total blue and grey water footprint more accurate. Referring to *Table 10*, for the period 1996-2005, a larger blue and grey water footprint for both industry and domestic water supply according to this research compared to Mekonnen and Hoekstra (2011a) can be seen. Not accounting for the hydroelectricity division, the blue water footprint of the industry is 19% larger in this research.

The grey water footprint of the industry is more than 22 times larger than estimated by Mekonnen and Hoekstra (2011a). It can be explained by the fact that in the most industrial sectors has dilution factor which is three to five times larger than in the study of Mekonnen and Hoekstra (2011) who used the conservative dilution factor 1. Besides, a larger blue water footprint has often a larger water abstraction and therefore a larger effluent. Larger effluent with not a varying concentration of contaminants has a larger grey water footprint.

The blue water footprint of the domestic water supply sector is estimated almost by the same method. A higher water consumption to withdrawal ratio of 15 % is used instead of the 10% used by Mekonnen and Hoekstra (2011a). The grey water footprint is estimated by the methods of Van Drecht et al. (2009) instead of using a dilution factor of 1. Therefore, the result of this study of the grey water footprint is larger than the results of Mekonnen and Hoekstra (2011a). However, the results are in the same range as those of Mekonnen and Hoekstra (2015, 2017) but it has to be noticed the results of this study are dependent of the largest amount of grey water footprint of nitrogen or phosphorus per country and year. This is not estimated in the research of Mekonnen and Hoekstra (2015, 2017).

Global water footprint in m^3y^{-1} 1996-2005	Mekonnen and Hoekstra (2011a) industry	Results all industrial sectors excl. hydroelectricity	Results all industrial sectors	Mekonnen and Hoekstra (2011a) domestic water supply	Results domestic water supply
Blue water footprint	$3.80*10^{10}$	$5.94*10^{10}$	$2.36*10^{11}$	$4.20*10^{10}$	$5.99*10^{10}$
Grey water footprint	$3.63*10^{11}$	$8.20*10^{12}$	$8.20*10^{12}$	$2.82*10^{11}$	$5.51*10^{13}$

Table 10 The global averaged water footprint for industry and domestic water supply for the period 1996-2005.

In this research, it is clear that hydroelectricity division cannot be ignored when concerning water abstraction and consumption. Aquastat (2017) presents data about water abstraction per country for the total industry. Aquastat (2017) and Mekonnen and Hoekstra (2011a) excludes the water abstraction in the hydroelectricity sector when comparing the water abstraction of Aquastat (2017) with the water consumption in this research, the hydroelectricity sector is also excluded. In further research, including the hydroelectricity sector in the water footprint of the industry will cover the complete industrial sector.

5. Conclusion

In this study, the blue and grey water footprint for the industry and domestic water supply is estimated per country for the period 1960-2015. These estimations are done for several sectors and divisions in the total industry. The main research question is: What is the blue and grey water footprint of the industrial sectors and domestic supply sector on a global scale? This question is answered in this chapter. Besides, it is not possible to draw conclusions for each year, country and sector. Therefore, the conclusions are made on a global scale with several exceptions worth mentioning.

Reflecting on the first sub-question, the total industry can be classified into four sectors when estimating the water footprint. This classification is internationally used and therefore very suitable. The classified sectors are mining and quarrying, manufacturing, electricity generation and construction. According to this study, the water footprint of electricity generation sector appeared to be the largest of all sectors in the industry. This resulted in a classification within the electricity generation sector. The following divisions in this sector are classified: electricity generation by fossil fuels, nuclear energy, geothermal energy, biomass and waste, hydroelectricity, wind and solar power.

The domestic water supply sector can theoretically be classified in two other sectors: private households, and public water supply and services. However, the classification turns out not to be suitable when estimating the water footprint. The domestic water supply sector is therefore seen as a whole.

It can be concluded that the global blue water footprint of the total industrial sector is expanded since 1960. The global blue water footprint in 1960 was $3.86*10^{10}$ m^3 and became more than eight times larger in 2015 where it was $3.02*10^{11}$ m^3. It turns out that the global blue water footprint varies between 4% and 8% of the global water abstraction in the industry which is noted by Aquastat (2017). The sector with the smallest water footprint is the construction industry with a global blue water footprint of $5.07*10^6$ m^3 in 1960 and $2.97*10^8$ m^3 in 2015. The global blue water footprint of the manufacturing industry increased from $1.22*10^8$ m^3 in 1960 to $3.70*10^{10}$ m^3 in 2015. The mining and quarrying sector had a global blue water footprint of $4.23*10^8$ m^3 in 1960 and increased to $1.92*10^{10}$ m^3 in 2015. The electricity generation sector has the largest global blue water footprint every year, it was $3.72*10^{10}$ m^3 in 1960 and increased to $2.42*10^{11}$ m^3 in 2015 which is by far the largest blue water footprint of all industrial sectors.

The reason for the large global blue water footprint is mainly caused by the hydroelectricity division which was $3.32*10^{10}$ m^3 in 1960 and increased to $3.97*10^{11}$ m^3 in 2015. In 1960 the hydroelectricity division was responsible for approximately 86% of the global blue water footprint of the electricity generation sector and in 2015 approximately 66%. Fossil fuels and biomass and waste have respectively the second and third largest global water footprint in this sector in 2015. It should be mentioned that in 1960 nuclear energy was third instead of biomass and waste. Wind energy had the smallest global water footprint in 1960 which was zero and $4.22*10^6$ m^3 in 2015.

The global grey water footprint of the industry was $1.56*10^{12}$ m^3 in 1960 and increased to $3.18*10^{13}$ m^3 in 2015. It is for each year larger than the blue water footprint for all industrial sectors. Similar to the global blue water footprint, the construction sector had the smallest global grey water footprint with $1.60*10^9$ m^3 in 1960 which increased to $7.87*10^{10}$ m^3 in 2015. The global grey water footprint of manufacturing industry increased from $9.18*10^9$ m^3 to $3.97*10^{11}$ m^3 in 2015. In 1960 the mining and quarrying industry had the second largest global grey water footprint with $4.39*10^{11}$ m^3 which increased and became the largest global grey water footprint in 1975 and eventually in 2015 it was $1.99*10^{13}$ m^3. The electricity generation sector had the largest global grey water footprint until 1975. This is mainly caused by the large effluents of cooling water from fossil fuel, nuclear and biomass and

waste power plants. On the other hand, the global grey water footprint of hydroelectricity is zero just like the wind and solar power division. The global grey water footprint of this sector was $5.52*10^{11}$ m^3 in 1960 which was $5.69*10^{12}$ m^3 in 2015.

The domestic water supply sector had a global blue water footprint of $5.92*10^9$ m^3 in 1960. This is increased to $1.10*10^{11}$ m^3 in 2015. These volumes are only 13% in 1960 to 27% in 2015 of the global blue water footprint of the industry. The global grey water footprint of the domestic water supply is $1.53*10^{13}$ m^3 in 1960 and $4.24*10^{13}$ m^3 in 2015.

Since this study, a distinction can be made in the blue and grey water footprint between sectors within the industry for a longer period than before. This study can contribute to the discussion about the contribution per industrial sector to the total blue and grey water footprint of the industry and the volume of the water footprint per industrial sector. This study caused a higher level of detail of the water footprint of the industry and presents a larger global water footprint per year than estimated before. The water footprint can also be specified per country, sector and year since 1960. In this study, water consumption to withdrawal ratio is estimated per industrial sector which replaced the conservative water consumption to withdrawal ratio of 5%. The conservative dilution factor of the total industry, used for estimating the grey water footprint, is replaced and can differ per sector in the industry. The quantities per industrial sector and differences between industrial sectors can be seen for the first time. The hydroelectricity division is according to this study responsible for a significant blue water footprint but is often not accounted for in other research. The water footprint of this division should be taken into account in further research on the blue water footprint of the industry. Currently, it is not possible to classify the domestic water supply sector when estimating the water footprint with current literature. However, a renewed and higher consumption to withdrawal ratio is estimated and the blue and grey water footprint per country are estimated for a longer period than before just like the industry from 1960 to 2015. Suggestions are made on how the water footprint of each industrial sector can be spatially mapped in countries based on several recommended industrial maps.

The global grey water footprint of the industry is estimated larger than other studies. Conclusions only about the grey water footprint do not reckon with the complete view of the effect on the environment. If, for example, the grey water footprint of power plants is lower than the discharge of the river where the effluent of the power plant will merge, the ecology of the river and environment will not be damaged. Conclusions about the degree of the damage can only be made if the water pollution level is estimated. Therefore, it can be recommended to estimate the water pollution levels when conclusions about the effect of the grey water footprint need to be made.

The blue and grey water footprint in this research are based on an economic variable, the gross added value. An increasing gross added value in time will cause an increasing water footprint. However, it is possible that products in the sectors could have a changing value. When values increase, the water footprint also increases in this case. But the production in tons could be equal or even less which should result in an equal or a decreased water footprint. Research can be recommended about the value of products could avoid this insecurity. The accuracy of the water footprint can increase when dividing the current results with the ratio of change of the values of products per sector if these are available for all products within the industrials sectors per year.

The results of this study give the possibility to observe the behavior of an individual industrial sector and the possibility to compare water footprints of industrial sectors separately per country for the period 1960-2015. The detailed analysis in this study resulted in a higher and renewed global blue and grey water footprint of the industry and domestic water supply. Since this study, it is clear which

industrial sectors have a large or small share in the total water footprint of industry per country and globally. Large sectoral differences, trends and variations in time have been made visible.

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