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The blue and grey water footprint of construction materials: Steel, cement and glass

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ABSTRACT

Numerous studies have been published on water footprints (WFs) of agricultural products, but much less on WFs of industrial products. The latter are often composed of various basic materials. Already the basic materials follow from a chain of processes, each with its specific water consumption (blue WF) and pollution (grey WF). We assess blue and grey WFs of five construction materials: chromium-nickel unalloyed steel, unalloyed steel, Portland cement (CEM I), Portland composite cement (CEM II/B) and soda-lime glass. Blue and grey WFs are added up along production chains, following life cycle inventory and WF accounting procedures. Steel, cement and glass have WFs dominated by grey WFs, that are 20–220 times larger than the blue WFs. For steel, critical pollutants are cadmium, copper and mercury; for cement, these are mercury or cadmium; for glass, suspended solids. Blue WFs of steel, cement and glass are mostly related to electricity use.

1. Introduction

Societies depend on freshwater for drinking, washing and cleaning and for the production of food, materials and energy. It is expected that between 2000 and 2050, global water abstractions from groundwater and surface water will increase by 55%, particularly due to a growing water demand from manufacturing and thermal electricity generation [32]. This will lead to unsustainable conditions in places where water is scarce and poorly managed [40]. Already today, 3.3 billion people live in areas that experience severe water scarcity during at least a quarter per year [28]. Human impacts on freshwater systems can ultimately be linked to human consumption, and water shortages and pollution can be better understood and addressed by considering water use along production and supply chains [15]. While it is still most common to consider only the direct water use by households, farmers, manufacturers or other water users, it is insightful to know water use of final products by summing up the water use in all steps of the supply chain, which enables an analysis of which steps contribute most to the overall water use in the production of a product. This enables further focus on how water use can best be reduced in the most critical steps of a supply chain.

The majority of previous studies to quantify the water use and pollution along the supply chain of specific products focussed on crop and animal products, which are responsible for the largest amount of water consumption in the world. The industrial sector is the second largest water user, but product-specific studies are still very scarce [16]. Steel, cement and glass, the focus of the current study, are construction materials produced in millions of tonnes globally per year [31,37,46]. In the production chain of steel, cement and glass, water is needed and polluted in several processes. Besides, water is required indirectly for producing the energy applied in

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the production chain. For example, electricity produced in a power plant and used to mine iron ore needs cooling water. In the production chain of construction materials, emissions of toxic substances cause water pollution. The water footprint of these materials is potentially large, but never quantified before. In general, steel, cement and glass industries do not consider their supply chain water use and limit their scope to their own operations. For example, the water reporting and accounting guidelines from the Cement Sustainability Initiative excludes the supply chain [42,43].

The objective of this research is to assess the blue and grey water footprint (WF) of the most commonly used types of steel, cement and glass in terms of water volume per unit of mass of the end product. The blue WF refers to the consumption of fresh groundwater or fresh surface water; the grey WF refers to the volume of freshwater required to assimilate pollutants discharged into freshwater bodies [18]. The following research questions are addressed: what is the blue WF of the most commonly produced types of steel, cement and flat glass, produced by the most commonly used production routes; what is the grey WF of these products, accounting for different types of pollutants; which processes give the largest contribution to the WFs of steel, cement and glass; and which substances determine the grey WF of steel, cement and glass? Since steel, cement and glass are basic construction materials, the results of this study will be helpful in water footprint assessments for infrastructure or products containing these materials.

The study is based on the accounting procedures as commonly employed in Life Cycle Assessment and following the Global Water Footprint Standard published by Water Footprint Network [18]. This paper is the first study that employs commonly used LCA software and databases to estimate the blue and grey WF of steel, cement and glass. While Life Cycle Assessment (LCA) and Water Footprint Assessment (WFA) have different roots, the current study shows that methods and tools from both fields can effectively be combined. The LCA research field focusses on the quantification of potential environmental impacts of products considering a range of environmental issues (e.g. climate change, emissions of pollutants). To do this, first an inventory is made of all processes in a production chain. Advanced software programmes like GaBi [13] and databases like Ecoinvent [7] have been developed to support the execution of LCA studies. The interest in applying LCA to water started to develop in 2009 [30], and in response to that water use has been better incorporated in the LCA databases. WFA is a research field that has evolved since 2002 to address the relation between the consumption of goods and services on the one hand and water use, scarcity and pollution on the other. It is based on four notions [17]. First, freshwater is a global resource, because people in one place use freshwater resources elsewhere. The constituents for construction materials, for example, are mined all over the world, transported, produced and then distributed again. The second notion is that freshwater renewal rates are limited: over a certain period of time, precipitation in an area, recharging groundwater and river flows, is always limited to a certain amount, putting a constraint to water consumption. If freshwater is consumed for the production of construction materials, it cannot be applied anymore for other purposes, hence the interest in where precisely scarce water resources are used for. The third notion is that to understand the impacts of water consumption, we need to consider complete production chains. The fourth notion is that we need to consider both water consumption and water pollution. LCA and WFA serve different purposes, but the inventory stage of LCA and accounting stage of WFA require the same sort of supply chain analysis and data [3]. The current study is innovative in showing how blue and grey WFs can be estimated employing LCA software and databases.

2. Production chains of steel, cement and glass

2.1. Steel

Iron and steel have played an important role in the development of human civilisation. In the 13th century BC, steel was first produced and the Iron Age began [45]. In modern society, iron and steel have many applications, such as for construction, the automotive industry, for tools and machinery. The construction industry is the largest steel using industry, accounting for more than 50% of the world steel production. In 2015, the total world steel production was 1622.8 Mt [46]. Steel is a product derived from iron with a small carbon content that is used for iron production. When other metals are added to steel, so termed alloys are produced. Stainless steel is an alloy that includes chromium, nickel and manganese. The majority of steel is unalloyed steel, also called carbon steel. Of the worldwide steel production, 89% is unalloyed steel and 11% is alloyed steel [38].

There are several steel production routes. The most common is the blast furnace (BF) / basic oxygen furnace (BOF) route. The BF is a furnace where oxygen is removed from iron ore by binding it to carbon. The BOF is a furnace where the carbon content in the iron is lowered by blowing pure oxygen onto the metal. In 2014, the BF/BOF route produces 74% of total steel [44]. Fig. 1 shows the six steps of the steel production chain: (1) mining of raw materials; (2) processing of raw materials (beneficiation, calcination and coking); (3) iron ore reduction; (4) air separation; (5) ferroalloy production and (5) steel production. Every step needs the input of energy (red arrows) and water (blue arrows) and results in the output of products (black arrows).

In the first step, the raw materials, mainly consisting of iron ore, limestone ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), coal and other ores for alloyed steel, such as chromite and laterite, are mined. In the second step, the properties of the raw materials are improved by the following processes:

a. Beneficiation, the process where the ore concentration is increased and fine ore particles are bound to form pellets or sinter. Fine coke is the main energy source for sinter production [35]. Water is used for dust emission control, sorting material, cleaning, cooling and gas treatment [41].
b. Calcination, the process to produce lime (CaO) and calcined dolomite ($CaO.MgO$) from limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Lime and dolomite remove impurities from steel [2]. Sometimes water is used to wash limestone. Mostly gas and solid fossil fuels are used for calcination [37].
c. Coking, the process that improves coal properties. Coal enters a coke oven resulting in cokes. Cokes have a higher carbon purity

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