Sustainable Water Consumption in Building Industry: A Review Focusing on Building Water Footprint

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Abstract Sustainable water consumption has become a primary concern of the building industry. The water footprinting assesses the freshwater use and associated effects on local and global freshwater resources plus ecosystems therein. This review elaborates two extensively adopted water footprinting approaches, Water Footprint Network (WFN) and ISO 14046 Life Cycle Assessment (LCA), discussing their methodologies and perspectives of analyses with special regard to the building industry. An appraisal of water footprints of common building materials is presented in this study with glimpses of the hotspots of freshwater consumption along their supply chains. Further, it advances its water footprints appraisal into the use phase/case study level referring to the real-world applications of the building industry. The importance of comprehensive water footprint analysis covering the complete life cycle of buildings, the inclusion of allied environmental impacts into analyses, influence of building type/structural design/site-specific variables were highlighted under this discussion in support of the dependable judgment of freshwater appropriation performances. Ultimately, the review dedicated a segment to set a futuristic view into the matter featuring sustainable freshwater consumption, economic and developmental interests, challenges faced by the industry, prioritization and compromise of freshwater uses of the building industry.

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1 Introduction

Freshwater sustains the life on earth and reinforces the course of civilization accompanying agriculture, industrial processes, urban development and almost all human-induced activities [27]. Sustainable management of freshwater resources stands to satisfy the changing demands placed on water resources, at present and on into the future without system degradation [14]. The water footprint (WF) is a concept developed within the water resources research community by way of an assessment tool of sustainability of freshwater appropriation [9].

Water footprinting appraises freshwater use and its related effects from the consumption of goods and services [9, 20]. The assessment of water consumption is of paramount importance as freshwater resources are currently under greater pressure worldwide. Climate change, speeded-up industrialization, extensive urbanization, population growth and associated higher standards of lifestyle dynamics are aggravating the crisis of freshwater resources [2]. During the twentieth century, the growth of global water consumption was twice as the population growth and at this juncture, many of the comprehensive policy agendas focused on increasing the limited availability of freshwater to meet ever-growing and competing demands [28].

The constructions sector, especially the building industry's contribution to the total freshwater withdrawal is sizable as per the accounts documented. The World Bank [25] reports that around 19% of total water is withdrawn by the industrial sector in which the construction industry is among the top water consumers [7]. Abd El-Hameed et al. [1] report that the built environment globally consumes 20% of water and the green buildings can possibly reduce usage by almost 40%. Along the value chains, the water consumption profiles of different materials vary greatly during raw material extraction, processing, manufacturing, transportation and construction. Besides, both direct and indirect water uses have to be accounted for along their supply chains to explore the critical points of water efficiency's interests [17]. As the building construction is supported by complex supply chains involving many a manufacturing sector, comprehensive quantification of water footprints is difficult and intricate [5, 18]. Therefore, the need for metric(s) with methodical protocols to quantify the volumetric water use and/or potential environmental impacts related to the water use was of prime importance, and the international consensus for such metric(s) was well appreciated in facilitation of comparative analyses of water consumption performance assessments of products or processes in the sphere of building industry.

This review bids to present a landscape analysis of water footprinting discussing the developments and salient points with regard to sustainable freshwater consumption in the building industry. The literature was surveyed in Google Scholar by the keywords and the resourceful articles were pooled perusing the abstracts of the

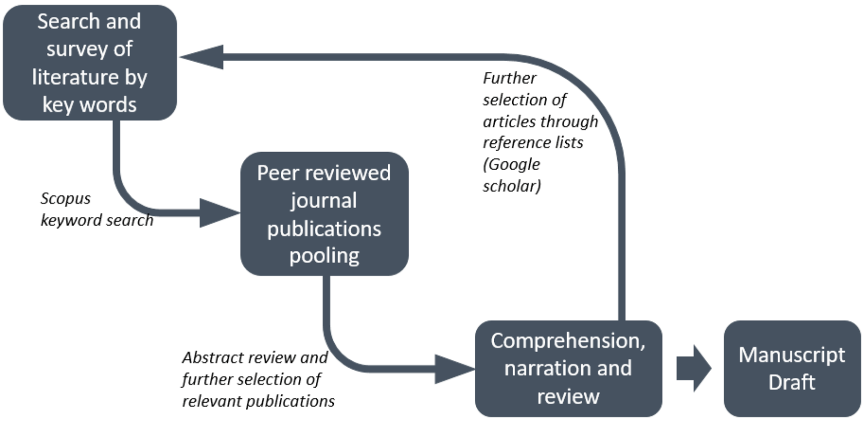

Fig. 1 The iterative operationalization of developing this review study

search results. Thereby, twenty-nine articles were selected as the primary reservoir of information for this review. This process was iterated as the narration of the review develops. Figure 1 illustrates the operationalization of this work.

2 Water Footprint Analysis in the Building Industry

At the outset, it is worth briefly review the two widely applied water footprinting approaches proposed by two different communities, the Water Footprint Network (WFN) and the Life Cycle Assessment (LCA). Both these methods are broadly similar standing for the computation of freshwater use and its impact. The WFN considers water footprinting as a volumetric approach (total volume of freshwater used by an individual/community/business activity), focusing on water productivity. It views freshwater as a limited global resource, and the environmental relevance of both consumptive (green and blue waters) and degradative (gray water) freshwater uses are accounted referring to the sustainability limits, environmental needs, efficiency of use and equitability of global freshwater resources [9]. Berger and Finkbeiner [4] define this approach as a volumetric water footprinting method since it determines the freshwater appropriation on an inventory level.

On the other hand, the LCA quantifies potential environmental impacts related to a particular freshwater appropriation going beyond the primary reporting of the volumetric water use [20]. The LCA approach extends the freshwater use assessment to the consequences resulting from water consumption (impact-based water footprinting) through weighting and characterization pertinent to the case of interest. Moving beyond the volumetric water use accounting (inventory level/LCI—life cycle inventorying), the LCA approach works on life cycle impact assessment (LCIA) based on freshwater scarcity/water quality/vulnerability of ecosystems/sensitivity of the population to human health damages [4]. This integration of freshwater use into life cycle assessments by the LCA community has formulated the international standard on water footprinting in ISO 14046.

Although the WFN and LCA approach manifest differences in their terminologies and communications, they share common fundamental principles in freshwater accounting. Both approaches intend for water efficiency, water productivity and environmental well-being giving complementary inputs to the system improvements. Further, both methods account for volumetric water use following the life cycle approach with nearly similar steps. Still, in contrast to the WFN's viewpoint (freshwater is deemed as a limited global resource), the LCIA of LCA approach adopts a damage-oriented analysis of local freshwater use [20]. Having all in mind, the WFN and LCA approaches should be regarded not as competing water footprinting tools, but as complementary methods. Thus, the approach/es should be fittingly adapted for the intended purpose.

The establishment of a transparent and replicable approach to quantify freshwater use in building industry entirely depends on the quality of available data. The embodied water demand of a particular product/process of the building industry is the overall freshwater need of manufacture/delivery covering both direct and indirect water uses. Though the direct water component of a product/process is straightforwardly assessed, the indirect water accounting is a hard task as it involves the freshwater use of all the processes along the upstream supply chain in which the main product moved through utilizing resources and raw materials [1]. The supply chain dispersion of the building industry moves across the national borders. Even though it observes variations of international building WFs among different countries, the supply chains of the building industry is highly dispersed going beyond country borders [21]. Therefore, the higher degree of sector disaggregation and the availability of corresponding fine resolution data throughout the supply chain nexuses become key determinants over the dependable quantification of water use in the building industry.

The process boundary of the water footprint analysis is another principal aspect in the evaluation of the material, technology and structural design alternatives in the field of the building industry. For instance, the water use performance of a building construction should be appraised referring to its practical applications of durability, water footprints of maintenance, repair, demolition/treatment/disposal (end-of-life), post-construction use phase water footprints, water footprints of material transportations, water footprints of compatible and complementary materials (e.g., stainless steel/glass fiber reinforcements for concretes with seawater and/or marine aggregates), gray water footprints related to effluents [2, 8, 23]. Thus, the establishment of comprehensive reasoning for a particular water-efficient alternative will only be rationalized by cradle-to-grave water footprint analyses. Moreover, the case-specific interests have to be duly inventoried and the associated water footprints should be well accounted for to secure the interpretational accuracy of individual case analyses. The case-specific water footprints of raw material extraction and processing, sources of energy used, mode of labor employed, soil characteristics of the construction site (influencing the load resisting structures of buildings), technologies adopted in different unit operations should be carefully surveyed throughout the supply chain network [1, 5, 11].

3 Appraisal of Water Footprints at the Construction Materials Level

In this section, a review on appraising water footprints of common building materials is presented based on the published work. A water footprint analysis of blue and gray waters for most common types of steel, cement and glass has been reported by [8] adopting a combined approach of LCA and WFN, and their findings are shown in Fig. 2.

Among the materials studied, steel records the top WF values with leading figures in both blue and gray WF components. In a cradle-to-grave LCA analysis of Ultra-High-Performance Concrete (UHPC) in comparison to Conventional Concrete (CC), [23] also have reiterated the predominance of steel's WF. The alloyed steel leaves the highest WF with a predominant blue WF for energy used. This is attributed to the relatively large electricity demand for ferronickel melting in the alloying process [8]. Further, the substantial gray WF values of steels and Portland cement are caused by the heavy metal (Cd, Hg, Cu) laden effluents of their manufacturing processes. Specifically, Cd is the critical pollutant responsible for the gray WFs of alloyed steel, unalloyed steel and Portland cement. These WF estimations at the material level are supported by a study [3] that has reported embodied water volume of building materials per unit floor area basis. Those estimations are comparable to the data presented above recording values for steel, cement and bricks as 25, 0.5 and 0.1 kl/m^2, respectively. Moreover, [3] has assessed both water use during the construction phase and embodied water use of building materials as 2 and 25.6 kl/m^2, respectively.

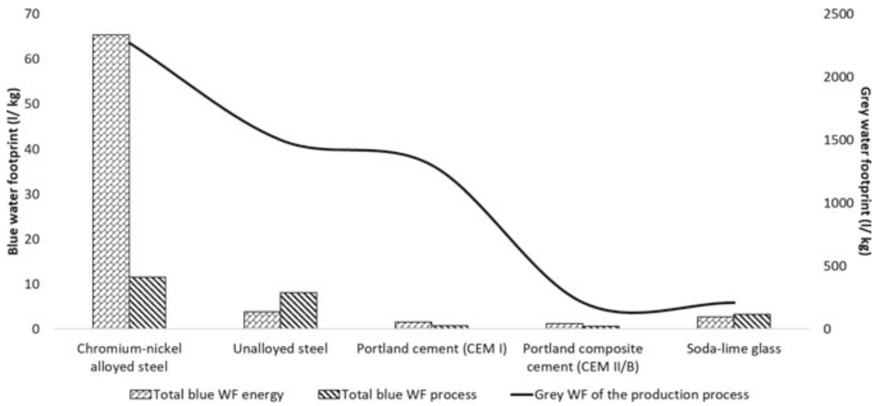

Fig. 2 Blue and gray WFs of common building materials pertaining to the direct production process, energy inputs of the production process and pollutant effluent of wastewaters [8]

This assessment stands with the study of [11] as they have recorded the extents of direct water consumption of on-site constructions and indirect water consumption of off-site processes (energy use, material production, transportation, food, water use for equipment and machinery, etc.) as 2.26% and 97.74%, respectively. Therefore, it can be deduced that the building industry exerts comparatively less pressure on local freshwater resources while its greatest impact is on national water resources or beyond (Fig. 3). This matter would be very much insightful in the determination of the water footprinting approach for case studies. To be specific, for the off-site freshwater use quantifications of the building industry, the WFN approach can be generally recommended whereas LCA water footprinting fits most for the on-site operations of building constructions.

In [8], the total blue WF of the process represents the direct blue water use by the material excluding water use for transportation. The blue WF of energy is a sizable predictor of the water use performance of each material as it ranges from 32 to 85% of the total blue WFs. Thus, the WF of the energy source of material manufacturing becomes a critical determinant of the overall blue WF of construction materials. The WFs of energy sources corresponding to this study have been tabulated below (Table 1), and the relative variation of blue WF ranges implies the significance of the choice of energy source over the total blue WF of the material. This claim is further supported by [11] as they have weighted >50% of the total WF of building

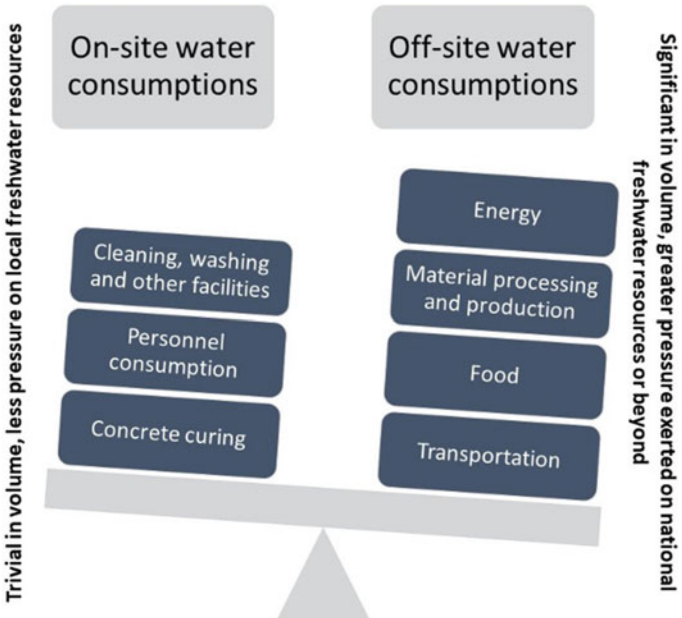

Fig. 3 On-site and off-site water consumptions of building industry and their relative pressure exerted on freshwater resources

Table 1 Ranges and median values of blue WFs of energy sources reported by [8]

Energy source	Blue WF range (l/GJ)	Blue WF median value (l/GJ)
Diesel	28–376	80
Light fuel oil	19–259	55
Heavy fuel oil	10–133	28
Natural gas	0.6–18	2.2
Coal	6.6–228	15–39
Hard coal cokes	42–321	52–82
Electricity	4241	

construction to its material use in which >50% of WF is of the energy used for manufacturing and processing.

If the energy sources of building material manufacturing and processing can be inclined toward alternatives with lower WFs (solar/wind/geothermal energy) it can be improved the water use performances of most of the common building materials. At the same time, the industry should seek new technologies to relieve higher WFs spotting critical points of freshwater efficiencies along its supply chains: reusing and recycling of materials, effluent treatment before discharge, encouraged rain and stormwater use in material manufacturing and processing, replacement of freshwater with seawater where workable (cooling activities), improved concrete curing technologies with lower WFs, promotion of local purchases of building materials to minimize the WF of transportation, etc.

4 Appraisal of WFs at Use Phase/Case Study Level

Moving forward from the WF analysis at the construction materials level, a review of water footprinting at the case study level is presented here based upon available literature. The study of the complete life cycle of buildings includes not only extraction and processing of raw materials, production, transport and on-site construction activities. It extends to the analysis of use, reuse and maintenance, recycling, and final disposal phases as well [15, 16]. Thus, environmental performances of a building construction should be comprehensively appraised through a systematic methodology (LCA based on ISO 14040 and ISO 14044) to produce inputs for well-judged sustainability assessments of natural resources [1, 23].

The importance of the inclusive analysis of building construction is exhibited in a WF assessment of Ultra-High-Performance Concrete (UHPC) in comparison to Conventional Concrete (CC) done by [23]. At the level of the materials, UHPC shows nearly three times higher WFs compared to CC for both ready-mix and precast concretes (from raw material production to construction site) (Fig. 4). Nevertheless, the UHPC design (a bridge design) compared to its corresponding CC design had a WF around 30% lower (Fig. 5). Further, as UHPC is superior to CC in compressive

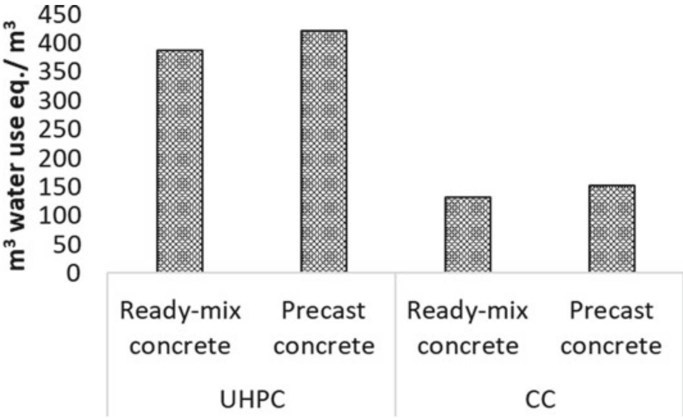

Fig. 4 Water footprints of ultra-high-performance concrete (UHPC) in comparison to conventional concrete (CC) [23]

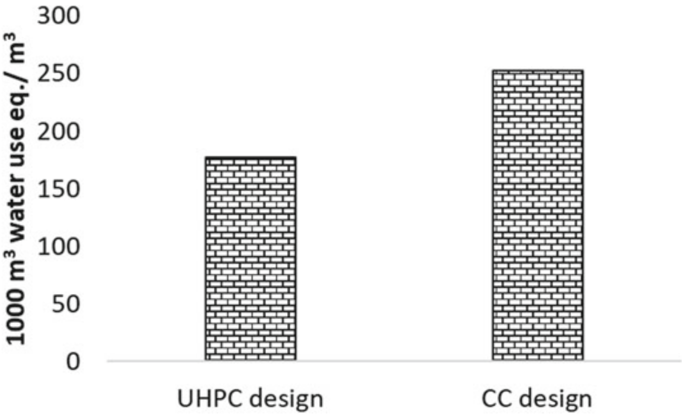

Fig. 5 Water footprints of two bridge designs of ultra-high-performance concrete (UHPC) and conventional concrete (CC) [23]

and tensile strengths, it is anticipated that the UHPC's end-of-life (EoL) phase would leave a relatively higher WF (especially of demolition) compared to the CC. Besides, the WF analyses should reach out to emerging sustainability-oriented applications in the sphere of building construction. For instance, in urban mining as a key approach of circular economy, the materials flow reverse bringing in new dimensions of process boundaries (e.g., concrete manufacturing from recycled aggregates in EoL-to-gate boundaries) [19].

From the perspective of overall environmental impact, the WFs of building constructions should be appraised in tandem with other environmental footprints entailed (carbon footprint, energy footprint, material footprint, ecological footprint).

These environmental footprints do not always follow congruous patterns mutually. As per [21], no collinearity of WF with energy and carbon footprints was observed in environmental footprints associated with the construction sector of India, Italy, South Africa, and the UK. Further, in an environmental assessment of recycled concrete, the material footprint had a clear improvement though the water use remained without a significant saving [19]. This claim was confirmed in a cradle-to-gate assessment of environmental footprints for different design alternatives of building elements using recycled aggregates for concrete production [22]. Still, a contrasting finding was documented in the environmental assessment of UHPC compared to CC where all the footprints of carbon, material and water for UHPC recorded comparatively higher figures at the construction materials level [23]. At the same time, all the three footprints of UHPC had comparatively lower values than CC at the case study level (for a bridge design case study) of the same study. To cut short, it can be observed case-wise discrepancies of the way WF is left with other environmental footprints. Therefore, drawing recommendations for the practical applications of building construction becomes a multi-faceted phenomenon extending beyond materials level and case study level assessments of mere WF analyses.

Viewing the case study level from a different perspective, [5] carried out quantification of WFs of buildings in China considering the variable of building type. Its results divulge how the scale of heavy structural designs that directly depend on water-intensive steel and cement consumptions be predictors of their embodied WFs. Thereby, the public buildings preceded residential buildings in WFs while the urban residential buildings having 55–130% greater WFs in comparison to the rural residential buildings. Figure 6 shows the factual evidence of water withdrawals (surface and groundwater withdrawals) and water consumptions (permanent water withdrawals as no longer available for any other use) for the thirteen building subsectors studied under that analysis. Moreover, [11] assessed the effects of structural parameters of residential buildings on the WFs. The work declared WF mitigation recommendations by way of: concrete structures over steel structures, short structures over tall structures, composite slabs over steel deck and compute precast slabs, and building sites with dense soils over building sites with soft soils.

5 Challenges and Futuristic View

Even amidst the global pandemic, the developing economies, especially in Asian and African regions are in a healthy economic revival in terms of their Gross Domestic Product (GDP) growth rates [24]. Around one-third of the top twenty-five developing economies suffers with either lack of basic access to water for the majority of their populations (Eritrea, Ethiopia, Uganda) or higher baseline water stress (Turkmenistan, Syria, Egypt, San Marino, China) [10]. These countries undergo intensive infrastructure development projects that probably exert substantial impacts on the national freshwater resources. This crisis gets compounded with the outward-bound virtual waters related to the building industry in these developing economies. For

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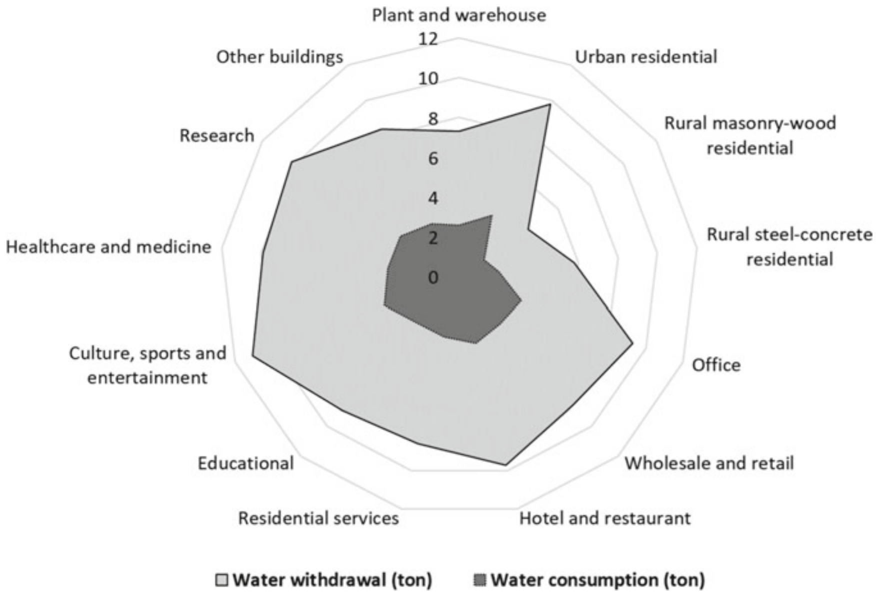

Fig. 6 Water withdrawal and water consumption values estimated per 1 m^2 of building area in China [5]

instance, having a swelling building industry China is one of the countries with the most deficient per capita water resources of which the spatial distribution is highly uneven [13]. Further, China extensively exports virtual waters via building materials and other inputs of the construction sector putting extra pressure on local freshwater resources [21]. Thus, alleviation of this crisis through mindful freshwater appropriations is a crying need that ought to be placed top in sustainable management practices. Along with the collective effort toward Sustainable Development Goals (SDGs) intended to be achieved by 2030 and mid-century climate goals, the building industry's role is decisive due to its significant contribution to the global environmental burden. Therefore, to overcome the challenges posed by irreconcilable demands of environmental, economic and social interests all the stakeholders of water handling (industry, academia, regulators and general public) have to seek water-efficient alternatives.

With special regard to the local context of Sri Lanka, a set of potential challenges can be anticipated in gearing water-efficient alternatives in the building industry. In the Sri Lankan construction sector, there are few inherent drawbacks that may pose challenges to the aspiring transition of sustainable water management. Low level of new technological development and transfer, poor documentation and communication, reluctance in using innovative building materials and disadvantaged industry-oriented research and developments reported by [6] may probably loom by way of potential challenges.

These challenges are to be tackled in a participatory approach with all the key stakeholders of the industry through information, communication and education. At the same time, sustainable water management should be integrated into the water governance by the national government to regulate freshwater appropriations of the industry [26]. However, the industry demand for freshwater is to be compromised with other priorities of freshwater uses (e.g., freshwater demand for agriculture to assure national food security) [12]. Ultimately, the industry well-being should be secured under the developing economy of Sri Lanka through economic analysis of water-efficient alternatives (life cycle costing of water-efficient materials/technologies). AQ1

References

1. Abd El-Hameed AK, Mansour YM, Faggal AA (2017) Benchmarking water efficiency of architectural finishing materials based on a "cradle-to-gate" approach. J Build Eng 14:73–80
2. Arosio V, Arrigoni A, Dotelli G (2019) Reducing water footprint of building sector: concrete with seawater and marine aggregates. IOP Conf Ser Earth Environ Sci 323:012127
3. Bardhan S (2011) Assessment of water resource consumption in building construction in India. Ecosyst Sustain Devel VIII 144:93–102
4. Berger M, Finkbeiner M (2013) Methodological challenges in volumetric and impact-oriented water footprints. J Ind Ecol 17(1):79–89
5. Chang Y, Huang Z, Ries RJ, Masanet E (2016) The embodied air pollutant emissions and water footprints of buildings in China: a quantification using disaggregated input–output life cycle inventory model. J Clean Prod 113:274–284
6. De Silva N, Rajakaruna R, Bandara K (2008) Challenges faced by the construction industry in Sri Lanka: perspective of clients and contractors. Build Resilience 158
7. FAO (2021) AQUASTAT—FAO's global information system on water and agriculture. Available at: http://www.fao.org/aquastat/en/. Accessed on 7 Sept 2021
8. Gerbens-Leenes P, Hoekstra A, Bosman R (2018) The blue and grey water footprint of construction materials: steel, cement and glass. Water Res Ind 19:1–12
9. Hoekstra AY (2016) A critique on the water-scarcity weighted water footprint in LCA. Ecol Ind 66:564–573
10. Hofste RW, Reig P, Schleifer L (2019) 17 countries, home to one-quarter of the world's population, face extremely high water stress
11. Hosseinian SM, Ghahari SM (2021) The relationship between structural parameters and water footprint of residential buildings. J Clean Prod 279
12. IWMI (2021) IWMI in Sri Lanka :: IWMI. Available at: https://www.iwmi.cgiar.org/about/where-we-work/asia/south-asia-region/sri-lanka/. Accessed on 7 Sept 2021
13. Liu S, Zhang F, Li K, Wang K, Shang B, Li D (2020) Analysis on research status of water footprint of ceramic tile (board). IOP Conf Ser Earth Environ Sci 526:012220
14. Loucks DP (2000) Sustainable water resources management. Water Int 25(1):3–10
15. Mannan M, Al-Ghamdi SG (2020) Environmental impact of water-use in buildings: latest developments from a life-cycle assessment perspective. J Environ Manage 261:110198
16. Marrero M, Wojtasiewicz M, Martínez-Rocamora A, Solís-Guzmán J, Alba-Rodríguez MD (2020) BIM-LCA integration for the environmental impact assessment of the urbanization process. Sustainability 12(10):4196
17. Matarazzo A, Gambera V, Suriano E, Conti MC (2017) Water footprint applied to construction sector. Environ Eng Manage J (EEMJ) 16(8)

18. Meng J, Chen G, Shao L, Li J, Tang H, Hayat T, Alsaedi A, Alsaadi F (2014) Virtual water accounting for building: case study for E-town, Beijing. J Clean Prod 68:7–15
19. Mostert C, Sameer H, Glanz D, Bringezu S (2020) Urban mining for sustainable cities: environmental assessment of recycled concrete. In: IOP conference series: earth and environmental science
20. Pfister S, Boulay A-M, Berger M, Hadjikakou M, Motoshita M, Hess T, Ridoutt B, Weinzettel J, Scherer L, Döll P (2017) Understanding the LCA and ISO water footprint: a response to Hoekstra (2016) A critique on the water-scarcity weighted water footprint in LCA. Ecol Ind 72:352–359
21. Pomponi F, Stephan A (2021) Water, energy, and carbon dioxide footprints of the construction sector: a case study on developed and developing economies. Water Res 194:116935
22. Sameer H, Mostert C, Bringezu S (2020) Product Resource and climate footprint analysis during architectural design in BIM. In: IOP conference series: earth and environmental science
23. Sameer H, Weber V, Mostert C, Bringezu S, Fehling E, Wetzel A (2019) Environmental assessment of ultra-high-performance concrete using carbon, material, and water footprint. Materials 12(6):851
24. The World Bank (2021) GDP growth (annual %)|Data. Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG. Accessed on 7 Sept 2021
25. The World Bank (2017) Annual freshwater withdrawals industry (% of total freshwater withdrawel)-Sri Lanka. Available at https://data.worldbank.org/indicator/ER.H2O.FWIN.ZS?locations=LK. Accessed on 7 Sept 2021
26. UNDP (2021) What is water governance? Water governance facility—water governance facility. Available at: https://www.watergovernance.org/governance/what-is-water-governance/. Accessed on 7 Sept 2021
27. Vollmer D, Regan HM, Andelman SJ (2016) Assessing the sustainability of freshwater systems: a critical review of composite indicators. Ambio 45(7):765–780
28. World Economic Forum (2021) On the Agenda/Water|World Economic Forum. Available at: https://www.weforum.org/agenda/archive/water. Accessed on 7 Sept 2021
29. World Vision (2020) 10 worst countries for access to clean water|World Vision. Available at: https://www.worldvision.org/clean-water-news-stories/10-worst-countries-access-clean-water. Accessed on 7 Sept 2021