Water, energy, and carbon dioxide footprints of the construction sector: a case study on developed and developing economies

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Abstract

Buildings and construction are major driver of anthropogenic environmental effects. While a large number of studies has focused on quantifying energy use and CO_2 emissions of buildings and construction, their water footprint remains understudied from an economy-wide perspective.

We use environmentally-extended multi-regional input-output analysis to quantify the water, energy and CO_2 emissions associated with the construction sector of India, Italy, South Africa, and the United Kingdom. We adopt the Eora database and advanced structural path analysis to disaggregate the supply chains driving the environmental effects of the construction sectors in these economies. Comparisons are made in terms of contributions by country, by sector, by stage of the supply chain and in terms of actual supply chain pathways.

Results show that Italy and the UK have more disaggregated and international supply chains compared to India and South Africa. Total water footprints of construction sectors vary from 11.8 to 14.8 L/USD for all countries, except India at 78.1 L/USD. There was no notable correlation between water and energy-CO_2 emissions in terms of sectoral contributions, even if the latter two are correlated. These findings provide a basis to inform policymaking and for further research on the water footprint of the construction sector, globally.

Keywords: construction; water; carbon; footprint; embodied energy; environmentally extended; multi-regional; input-output analysis; structural path analysis.

Table of abbreviations:

EEMRIO: Environmentally Extended Multi Regional Input Output

GHG: Greenhouse gas

IEA: International Energy Agency

LCA: Life Cycle Assessment

OECD: Organisation for Economic Cooperation and Development

MRIO: Multi-Regional Input-Output

WF: Water Footprint

1. Introduction

Buildings and construction are responsible for around 40% of greenhouse gas (GHG) emissions [1], 50% of primary energy demand and resource consumption [2], 30% of the waste flows generated [3] and 15% of freshwater use [4], globally. Therefore, their role to transition to any form of future environmental sustainability is paramount [5–7]. However, the contribution of buildings and construction to freshwater use is relatively uncertain. The 15% figure on freshwater reported above can be traced back to a review paper by Ding [8] from 2014, which in turn refers to two other studies [9,10] where the origin of the number becomes blurry and hard to trace. Additionally, the referred studies are nearly a decade old, suggesting the need for more up-to-date information. This is further supported by recent research [11] reporting that concrete production alone was approximately responsible for 9% of global industrial water withdrawals and 1.7% of total global water withdrawals in a single year. If one material can have such significant effect on global water flows, and with increasing global demand for water and the need to adapt to climate change while mitigating GHG emissions [12], it is worth understanding what are the cumulative effects of construction activities. Further, lack of information and data scarcity on water footprints (WF) is one of the barriers to effective urban water governance [13]. There is therefore a need for a dedicated study on the WF of global construction activities.

1.1 Aim and scope

The aim of this paper is to quantify and disaggregate the water footprint of the construction sector, and its supply chain across various economies. The research focuses on a comparison between two so-called 'developed' and two 'developing' economies through the adoption of environmentally extended multi regional input output (EEMRIO) analysis. Within the scope of this paper, WF refers to the total virtual water content of products, sectors, or countries in line with previous work [14–17], thus excluding for instance the freshwater use in buildings during the operational phase (e.g. freshwater for drinking or hot water demand). While our focus is on the water needed directly by, or upstream in the supply chain of, the construction sector, it is worth stressing that water is required throughout many other phases of the life cycle of a building or city [18] and these should all be carefully considered given the scarcity of the resource.

Our aim can be translated into three distinct objectives:

1. to develop a transparent and replicable approach to estimate water footprint of construction activities at a national and international level. Specifically, within the distinction between the consumptive use of rainwater (green WF) and ground and surface water (blue WF), and volumes of polluted water (grey WF) [19], we focus on blue water only.
2. to demonstrate its applicability through case studies of developed and developing economies to evaluate the intensity of water use in different contexts.
3. to enrich our analysis with two additional impact categories for construction, energy demand and carbon-dioxide (CO_2) emissions, in order to establish impacts at the water-energy-carbon dioxide nexus and evaluate whether energy or carbon dioxide assessments can represent a valid proxy to also estimate the water footprint.

The need for information on water, energy, and carbon dioxide balances has been recognised as an important element to analyse and monitor cities and to help them improve their environmental performance [13]. No single indicator can accurately represent all environmental effects [20], and different indicators are needed to both expert and non-expert audiences to ensure support to a wider uptake of environmental consciousness in policy and practice [21].

The article is structured as follows. Section 2 reviews previous works in this field, to inform the development of our own approach. Section 3 presents both methods and data used in our analysis. Results are shown in Section 4 and discussed in Section 5 – which also concludes the article.

2. Previous works

In this section we review existing research which broadly falls in the domain of the water footprint of buildings and construction. This body of work is mostly concerned with either the micro-scale of materials or the macro-scale of cities and regions. Some other research on embodied water has been done at the building level, [e.g. 22–25], but these fall outside the scope of this work.

2.1 Water footprint studies at the material level

At the material level, Gerbens-Leenes et al. [26] analysed the blue and grey WF of steel, cement, and glass through data taken from the Ecoinvent 3.2 database using global datasets for inputs to, and outputs of, industrial processes and data from the OECD and the IEA [27]. They found that for all materials, the WF is dominated by grey water, which is 20-220 times larger than the contribution of blue water. Grey WFs vary from 210 L/kg for Portland cement to 2,270 L/kg for unalloyed steel. Similarly, Sameer et al. [28] carried out a process-based life cycle assessment (LCA) based on the GaBi construction materials database on Ultra-High-Performance Concrete (UHPC) focusing on greenhouse gas emissions, material and water footprints. While their results show that UHPC has higher environmental impacts per m^3, the authors state that UHPC could offer a reduction of 14%, 27% and 43% on GHG emissions, material and water footprints, when functionality is considered. While these are encouraging results to reduce the environmental effects of concrete, such studies do not provide an estimate of the WF of construction activities.

The work of Shirkhani et al. [29] belongs to the same category of studies. It uses a cement plant in Ilam, Iran as a case study to quantify the water footprint of cement-related processes. Underpinned by a process-based LCA complemented by the Water Stress Index (WSI) developed by Pfister et al. [30], they report values of 1.9 m^3_w and 2.3 m^3_w per tonne of clinker preparation and cement manufacture, respectively. Very similar values are obtained by Hosseinian and Nezamoleslami [31], who also focused on a cement manufacturing plant in (western) Iran and found water intensities of 2.126 m^3 per tonne of cement production. The work of Çankaya [32] is of similar nature. They used LCA to explore the effects of different fuel usages for cement production including water scarcity. Arosio et al. [33] focused on innovative concrete mixtures based on marine aggregates to estimate the potential reduction to the WF of concrete through LCA. Their results show that WF reductions can be obtained by mixing concrete with seawater (-12%) and by using marine aggregates (-84%) [33].

Focused on steel production, Nezamoleslami and Hosseinian [34] combined process-based LCA and water footprinting and applied these to the largest plant of construction steel in Esfahan, Iran, with a production capacity of 2.9 million tonnes/year, finding a water consumption intensity of 19.61 m^3/tonne of steel. They highlighted the limitations of existing research, including the lack of assessment of the WF of personnel's food working in the plant. Interestingly, they showed that the WF of staff food represents 36.14% of the total WF [34]. With a similar focus, albeit food was excluded from the analysis, Tong et al. [35] assessed the life cycle water withdrawal of a case study of steel production in China through a combination of material flow analysis (MFA) and input-output (IO) analysis, finding values of 14.93 m^3_w/tonne of steel. Additionally, they focused on both direct and indirect water and material-energy-water flows, and found that the indirect water usage in energy and material flows is more important than the direct one, highlighting the need for an approach that covers upstream layers in a supply chain.

Importantly, most existing studies on the water footprint of construction materials rely on process analysis, which is known to truncate the system and underestimate environmental effects [36–38]. Analysing the recently created EPiC database of construction materials [39], which relies on the Path-Exchange Method for hybrid analysis [40], we find that across 131 unique construction materials, process data covered on average only 42% of the total water footprint, with a high variability (median = 37%, standard deviation = 24.6%, min=1%, max 98%).

While these individual values for key materials could be used to scale up a WF based on global figures on the use of steel, cement, concrete and glass, they would omit a large share of other materials used in construction and would also underestimate the total water footprint because of their reliance on process data.

2.2 Water footprint assessments at a city and regional level

Using a bottom-up approach, Stephan and Athanassiadis [41] quantified the embodied water in 13076 buildings in the City of Melbourne, Australia. Using a process-based hybrid approach for the life cycle inventory, they found that rebuilding the City of Melbourne today, would require a staggering 17.7 million m^3 of water per km^2. While their results enable a spatialization of the water footprint by material, assembly and building, across the city, they do not study economy-wide ramifications and supply chain drivers of water use.

Conversely, Hong et al. [42] used the 2010 multi-regional input-output (MRIO) table compiled by the Chinese Academy of Science to estimate the WF of the construction industry in China. The MRIO table includes monetary transaction data for 30 sectors from 30 regions of China, and the study found that the WF of construction is approximately equivalent to ∼9% of the total water use in China. In exploring the gap between direct and indirect effects, their research confirmed the significant importance of indirect effects incurred by iterations of trading processes and resource consumption upstream in the supply chain [42]. Hong et al. [42] further explored the (embodied) energy-water nexus, finding inconclusive correlation between the two: while some regions which were characterised by high embodied energy also showed a high WF, on average the construction sector in different Chinese provinces demonstrates a stronger water use than energy use. This suggests that energy might not necessarily be an accurate proxy for water at a sectorial level.

Cazcarro et al. [43] mapped the evolution of water use in the Spanish economy over the years 1980 – 2007 through a structural decomposition analysis (a method based on input-output tables). Construction is one of the key economic sectors considered by the authors, particularly for the substantial growth it experienced in Spain in the decades analysed. While its direct water use is negligible – which is also confirmed for the

Andalusia region by Velázquez [44] - its embodied WF averages at 3.79% of the total (2661 hm^3/year) [43], without significant shifts from 1980 (3.78%) to 2007 (3.64%).

Similarly, Wang et al. [45] adopted a regional IO model applied to the city of Zhangye in China to analyse direct and indirect sectoral WFs. Construction is one of the ten sectors covered by their analysis and it accounts for 5.2% of the total WF of the city (note the similarity with the 3.79% reported for Spain). The study identifies a significant gap between direct and indirect WF for the construction sector. Specifically, each m^3 of water directly used by the construction sector requires an additional 47.7 m^3 of indirect water use. It is interesting to note the significant input that farming has into construction, as 35.2 m^3 of those 47.7 m^3 (73%) are due to farming. In essence, this means that construction requires significant amounts of water, through goods produced by the farming sector as intermediate outputs, in order to satisfy its final demand.At a national level, the results for the Chinese construction sector from Zhang and Anadon [46] seem to be very different. Their results are based on the 2007 inter-regional IO table developed by Liu et al. [47] and point to construction being responsible for only 0.4% of embodied water withdrawals and 0.3% of embodied water consumption in domestic trade, and 0.3% (withdrawals) and 0.3% (consumption) in international trade. Strongly aligned values were obtained by Hubacek et al. [48], who analysed the Chinese ecological and water footprints based on historic data and projected trends into the future. Their analysis puts the share of construction in the WF of China at 0.6% in 1997 and projects it to being 0.4% in 2020.

These values seem to contrast other research that points to construction accounting for 3-5% of national WFs [43,45]. A possible reason for the study from Zhang and Anadon [46] is to be found in both water and construction data used. They report the sectoral economic value of construction in the domestic trade as 1.9% and 0.4% in international exports, which contradicts other figures positioning the construction sector's share of the GDP between averages of 5.5% (1997-2006) [49] to well over 6% (last five years) [50]. Due to the IO formulation used to estimate WFs, inaccurate monetary data can directly translate into inaccurate impact assessment. Zhang and Anadon [46] also assume an annual water efficiency improvement rate in the construction sector of 6%, aligned with the national average. While this seems a high value regardless of the sector, it is quite unrealistic for construction—a sector traditionally reluctant to embrace change and slow in improving its efficiency [51]. With respect to the results obtained by Hubacek et al. [48, p.1247]—who state to have addressed both direct and indirect water use linked to construction—it is hard to tell why the WF for construction is so low. This is particularly true when the authors conclude that the "key area is the development of choices made in the construction of new cities and towns" and report best practices from the UK on sustainable building design to alleviate environmental pressure as a way forward to China's development. Additionally, a recent article focused on the water-energy-food nexus in East Asia by White et al. [52] concluded that the construction sector in China is the second largest user of water with a total of 42.6 million m^3 (18% of the total). This result points further away from the very low values obtained by Zhang and Anadon [46] and Hubacek et al. [48].

Feng et al. [14] applied an EEMRIO model combined with geo-demographic consumer segmentation data to calculate both direct and indirect WFs for the UK, based on the UK 2004 national IO table, UK direct water use data from the Office for National Statistics (ONS), and foreign input-output data from GTAP [53]. Their analysis for the UK construction sector reveals a direct water intensity of 0.1 m^3/1,000 GBP, and a total WF of 333 million m^3, which corresponds to 1.45% of the national share [14]. However, when water imports are considered, construction is the ninth most water-intensive sector for the UK with a total WF of around 2,500 million m^3 (about 3% of the total), most of which originates in non-OECD countries [14]. Their findings are in line with those of Owen et al. [54] who found that the UK construction sector ranks eighth overall for water use with a share of 2.5%.

Existing research reviewed in this section has shown that two distinct approaches exist to estimate WFs of construction. The first, which we can define as bottom-up, adopts process-based data for the most common materials to establish water intensities at a material level. These can inform process and product refinement and improvement but are insufficient to estimates impacts for the whole construction sector. The second approach, which can be defined as top-down, utilises national or international data to identify the share of impacts to be attributed to the construction sector. A number of studies exist – mainly for China and the UK – but the available results do not point towards a consistent WF of the construction sector, relative to national WFs. A third approach which has been briefly touched on in Section 2.2, consists of quantifying the (embodied) water footprint of built stocks. However, this is not further covered in this work due to the lack of consideration of economy-wide effects and the very few studies in the field. Most existing studies rely on old input-output tables and adopt standard EEMRIO approaches, focusing on one country at a time. There is therefore a need to quantify the water footprint of the construction sector for multiple countries, using recent and multi-regional data, as well as advanced EEMRIO modelling techniques. This study addresses this need.

3. Data and methods

3.1 The EORA database and fundamental calculus

Eora is a global MRIO [55,56], which has been successfully used in a number of fields from city-level sustainability [57] to greenhouse gas emissions, biodiversity loss, international trade, and public health [58–61]. MRIO analysis, originally conceived by Nobel prize Laureate Wassily Leontief [62], is an important impact assessment method that has been included in United Nations standards [63]. We build our global MRIO from the Eora database, focusing on 33 individual countries: Australia, the EU27, India, Russia, South Africa, the UK and the United States. All other countries are grouped into a Rest of the World (RoW) category to ensure no loss in the global economic and environmental data behind our work.

Global MRIO uses an $N \times N$ intermediate demand matrix $\mathbf{T}$, which links economic sectors as suppliers and users of commodities. This intermediate demand is added to the final demand $\mathbf{y}$, in order to determine the total output $\mathbf{x}$, which yields the fundamental identity of input-output accounting $\mathbf{x} = \mathbf{T1} + \mathbf{y}$, where the vector $\mathbf{1} = \{1,1,\dots,1\}$ is a summation operator. Global production can be described by the technical coefficient matrix $\mathbf{A} \coloneqq \mathbf{T}\hat{\mathbf{x}}^{-1}$, where the hat symbol denotes vector diagonalization. The $\mathbf{A}$ matrix captures direct supplier relationships but entire supply chains can be evaluated by using Leontief's ubiquitous inverse $(\mathbf{I} - \mathbf{A})^{-1}$. Therefore, the total output can be expressed as $\mathbf{x} = \mathbf{T}\hat{\mathbf{x}}^{-1} + \mathbf{y} \Leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, where $\mathbf{I}$ is an identity matrix [64] and $(\mathbf{I} - \mathbf{A})^{-1}$ is the standard Leontief's inverse, often also labelled as $\mathbf{L}$.

From input-output analysis stem direct and total impact multipliers (DIM and TIM), which show – respectively – the direct and total, economy-wide attribution of impacts from production to one unit of final demand [65]. TIMs (denoted as $\mathbf{m}$ in the following equation) are more relevant than DIMs for our work because they capture impacts occurring upstream in the supply chain and are defined as $\mathbf{m} = \mathbf{f} \cdot (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{f} \cdot \mathbf{L}$, where $\mathbf{f}$ is a matrix of DIMs. To decompose TIMs in this paper, we used the code and method developed by Wiedmann [65]. We utilise TIMs for three environmental flows: energy, carbon dioxide emissions, and blue water. In a number of sectors and cases we modified the original Eora data to include more accurate and realistic data. This has been an iterative approach during the research design, which is fully described and detailed in the supporting information (SI) attached to this article. The opportunity of identifying issues with data and impacts in the global supply chains was enhanced by the structural path analysis, which is described in the next section.

3.2 Structural path analysis

In order to be able to disaggregate the water, energy and carbon dioxide footprint of each construction sector, we rely on the structural path analysis technique [66,67]. We use the *pyspa* Python® package developed by Stephan and Bontinck [68] to conduct the analysis. The algorithm is described in detail in Stephan et al. [69] and thus we provide a summary of the approach here.

The code reads a square technological matrix representing the inputs and outputs of the 884 sectors across 35 regions. The code also reads a spreadsheet providing the metadata for each sector of each region, namely its *ID, Name, Region,* and its direct and total multipliers for water, energy and carbon dioxide emissions.

Once the data are read, the code conducts the structural path analysis of each target construction sector (for the case study countries specified below). The code iterates over the technological vector (column) in the square matrix, representing the target sector. It compares the total intensity of each input with the specified cut-off threshold of each environmental flow (specified as 0.1% of the total water/energy/carbon dioxide intensity). If the input is above or equal to the threshold, this input is considered and all upstream inputs are also screened using the same threshold, until no single input matches the threshold criteria or we have reached the maximum number of stages (in this case we specified 10 stages upstream). This is known as a *depth first* method. The code stores information on any number of environmental flows in one pass and is thus more efficient than similar algorithms that focus on one flow at a time.

The result of the structural path analysis is a list of pathways, ranked from the most contributing to the least, and containing a chain of inputs for each environmental flow. Each input, or *node* along the pathway is an input-output sector with a name and a region. This enables us to characterise the supply chains behind the WF, the energy footprint and the carbon dioxide footprint of the construction sector of each country, across the 884 sectors in the technological matrix and the 35 regions. The approach provides an unprecedented resolution of the results, which helps address the existing research gaps.

3.3 Case study countries

This study aims to firstly offer a novel approach to estimating the water footprinting and exploring the water- energy-carbon-dioxide nexus of construction sectors. Its potential is then tested on four countries as an exemplary application. We chose four countries: India (IND), Italy (ITA), South Africa (ZAF), and the UK (GBR) for both diversity and similarities they offer in terms of case study characteristics in line with representativeness and good practice of case study research [70]. On the similarities, for instance, both Italy and the UK have so-called 'developed' economies in the Global North with comparable gross domestic product (GDP) and population. Both India and South Africa are countries from the Global South with very different GDP and population values, thus allowing to single out the 'global South' characteristic. Further, India's GDP is comparable to those of Italy and the UK while its population is much larger. These reasons, among others, explain our choice of case study countries, but the approach used can be applied to any country, as long as data are available.

3.4 Data availability

All the data used in this study are made available in open-access on Figshare at https://www.doi.org/10.6084/m9.figshare.12661580 (*for reviewers*: the DOI is currently embargoed since the article is under review). This includes the square technological matrix and the metadata sheet describing each sector across each of the three flows considered.

4. Results

This section presents the results, focusing on the water footprint and its intensity, the sectoral makeup of the water footprint through a product layer decomposition and the water-energy-carbon dioxide emissions nexus. These results are based on a total 41 009 346 data points extracted through structural path analysis broken down into 5 854 331 data points for India, 16 477 494 for Italy, 4 160 633 for South Africa, and 14 516 888 for the UK.

4.1 Water footprint of construction

The WF for the four countries we analysed is shown in terms of absolute values, domestic, and international contributions in Figure 1. Direct intensities are relatively low across all countries, but with significant differences ranging from 0.04 L/USD (South Africa) to 0.34 L/USD (India). Such differences are non-existent in terms of total water intensities for three countries (Italy, South Africa, and the UK) with values of 11.84, 14.77, and 14.24 L/USD respectively. India however, remains the country with the highest intensity and a sensibly higher value than the other countries (78.12 L/USD).

In terms of international dispersion of the WF, developed economies which are often characterised by a service-dominated economy, exhibit lower shares of domestic WF. Specifically, this is sits at 35% for Italy and 22% for the UK reflecting the lower manufacturing base that the UK has compared to Italy. Values are much higher for the two developing economies in our analysis, with South Africa's domestic WF accounting for 65% of the total and India's domestic WF basically representing the near totality (98%). Table 1 reveals that the water footprint of the construction sector in the UK and Italy includes other countries in the top ten inputs (Ireland's *Mining and Quarrying* as the top input for the UK and Bulgaria's *Metal Products* into Italy's *Metal Products* as the 5th input for Italy). In comparison, the top ten inputs for India and South Africa are all domestic.

In terms of contributing countries, China is – as expected – the top contributor to the international WF for India (35.8% of the international WF), Italy (17.3%), and the UK (21.5%). China is the second highest (26.3%) contributor to the WF of the construction sector in South Africa, which has its top international contribution from India (36.7%). Other large economies also feature as expected in the top five countries contributing to the international WF of the countries we analysed. Russia for instance ranges from 2% for South Africa to 7.2% for India, while the contribution of the United States of America goes from 4.8% (of the international WF of Italy) to 7.7% (of the international WF of the UK).

Other countries featuring in the top five seem justified by geographical proximity and/or long-established commercial routes. Australia for instance ranks fourth for both India (3.8% of international WF) and South Africa (2.1%), while Spain appears in the top five for both Italy (3rd, 6.8%) and the UK (4th, 3.9%). Neighbouring countries with established manufacturing and commercial routes in developed economies are also captured by our analysis since Germany ranks second for Italy with a contribution of 8% to Italy's international WF and Ireland ranks second for the UK with a contribution of 13% to the UK's international WF.

The 33 individual countries we covered in our MRIO data capture the large majority of the international WF of the four case study countries (63-87.9%). This coverage is highest for South Africa, with RoW accounting for 18.1% of the international WF. Values for the other three countries are more aligned around a ~ 30% contribution from the RoW (exact values are 33.1%, 37%, and 28.6% for India, Italy and the UK respectively).

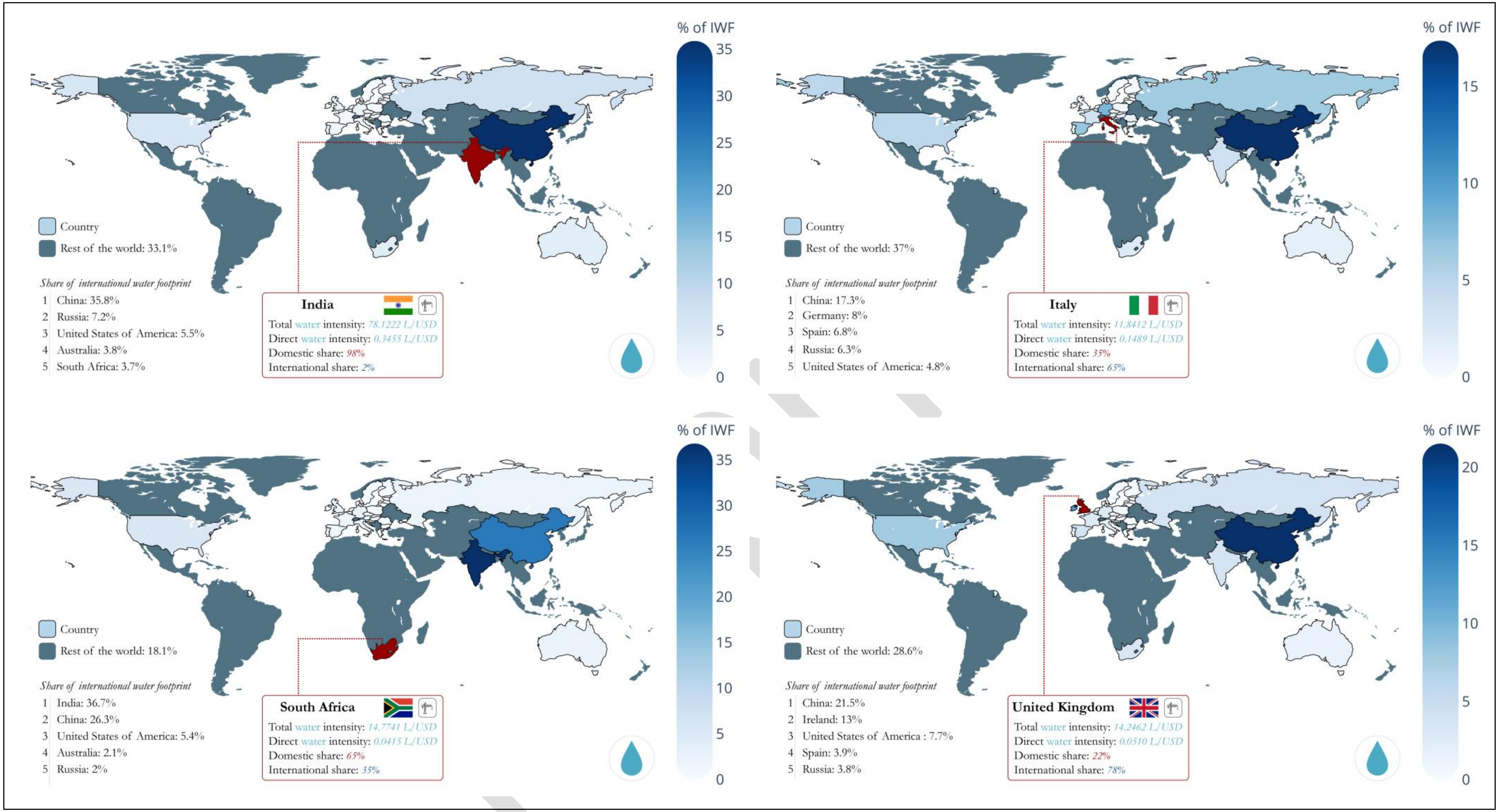


Figure 1 - Overview of domestic and global dispersion of water footprints for India (upper left), Italy (upper right), South Africa (lower left), and the UK (lower right). International Water Footprint (IWF) is reported for the 33 individual countries covered in our analysis, plus a Rest of the World region

Table 1 - Top ten pathways for the four case study countries for the water footprint

United Kingdom		**Italy**		**India**		**South Africa**	
Top 10 pathways	Contribution	Top 10 pathways	Contribution	Top 10 pathways	Contribution	Top 10 pathways	Contribution
IRL_Mining and Quarrying	2.35%	ITA_Mining and Quarrying	3.83%	IND_Agriculture	27.79%	ZAF_Wood and Paper ← ZAF_Agriculture	10.32%
CYP_Agriculture(CYP) ←	2.24%	ITA_Metal Products ← ITA_Recycling	1.71%	IND_Recycling	5.88%	ZAF_Wood and Paper ← ZAF_Fishing	10.32%
IRL_Recycling	1.48%	ITA_Recycling	1.48%	IND_Petroleum, Chemical and Non-Metallic Mineral Products ← IND_Agriculture	5.06%	ZAF_Petroleum, Chemical and Non-Metallic Mineral Products ← ZAF_Agriculture	4.84%
GBR_Recycling(GBR)	1.14%	ITA_Petroleum, Chemical and Non-Metallic Mineral Products ← ITA_Mining and Quarrying	1.36%	IND_Agriculture ← IND_Agriculture	2.57%	ZAF_Petroleum, Chemical and Non-Metallic Mineral Products ← ZAF_Fishing	4.84%
FRA_Mining and Quarrying(FRA)	1.00%	DIRECT Stage 0	1.26%	IND_Metal Products ← IND_Recycling	2.06%	ZAF_Recycling ← ZAF_Fishing	3.66%
PRT_Wood and Paper ← PRT_Agriculture	0.99%	ITA_Metal Products ← BGR_Metal Products	1.01%	IND_Wood and Paper ← IND_Agriculture	1.95%	ZAF_Recycling ← ZAF_Agriculture	3.66%
HUN_Mining and Quarrying	0.98%	ITA_Hotels and Restraurants ← ITA_Food & Beverages	0.78%	IND_Mining and Quarrying	1.89%	ZAF_Wood and Paper ← ZAF_Wood and Paper ← ZAF_Agriculture	2.37%
ZAF_Wood and Paper ← ZAF_Agriculture	0.91%	ITA_Wholesale Trade ← ITA_Agriculture	0.74%	IND_Wood and Paper	1.68%	ZAF_Wood and Paper ← ZAF_Wood and Paper ← ZAF_Fishing	2.37%
ZAF_Wood and Paper ← ZAF_Fishing	0.91%	ITA_Petroleum, Chemical and Non-Metallic Mineral Products ←	0.58%	IND_Transport ← IND_Hotels and Restraurants ← IND_Agriculture	1.24%	ZAF_Construction ← ZAF_Wood and Paper ← ZAF_Agriculture	1.75%
BEL_Mining and Quarrying	0.84%	ITA_Hotels and Restraurants ← ITA_Agriculture	0.56%	IND_Metal Products	1.24%	ZAF_Construction ← ZAF_Wood and Paper ← ZAF_Fishing	1.75%
TOTAL	**12.84 %**	**TOTAL**	**13.31 %**	**TOTAL**	**51.36 %**	**TOTAL**	**45.88 %**

4.2 Product layer decomposition analysis

Product layer decomposition (PLD) can be employed to identify the most important contributions to the production layers in the upstream stages of the supply chain [71]. We show this for the WF of the four case study countries in Figure 2.

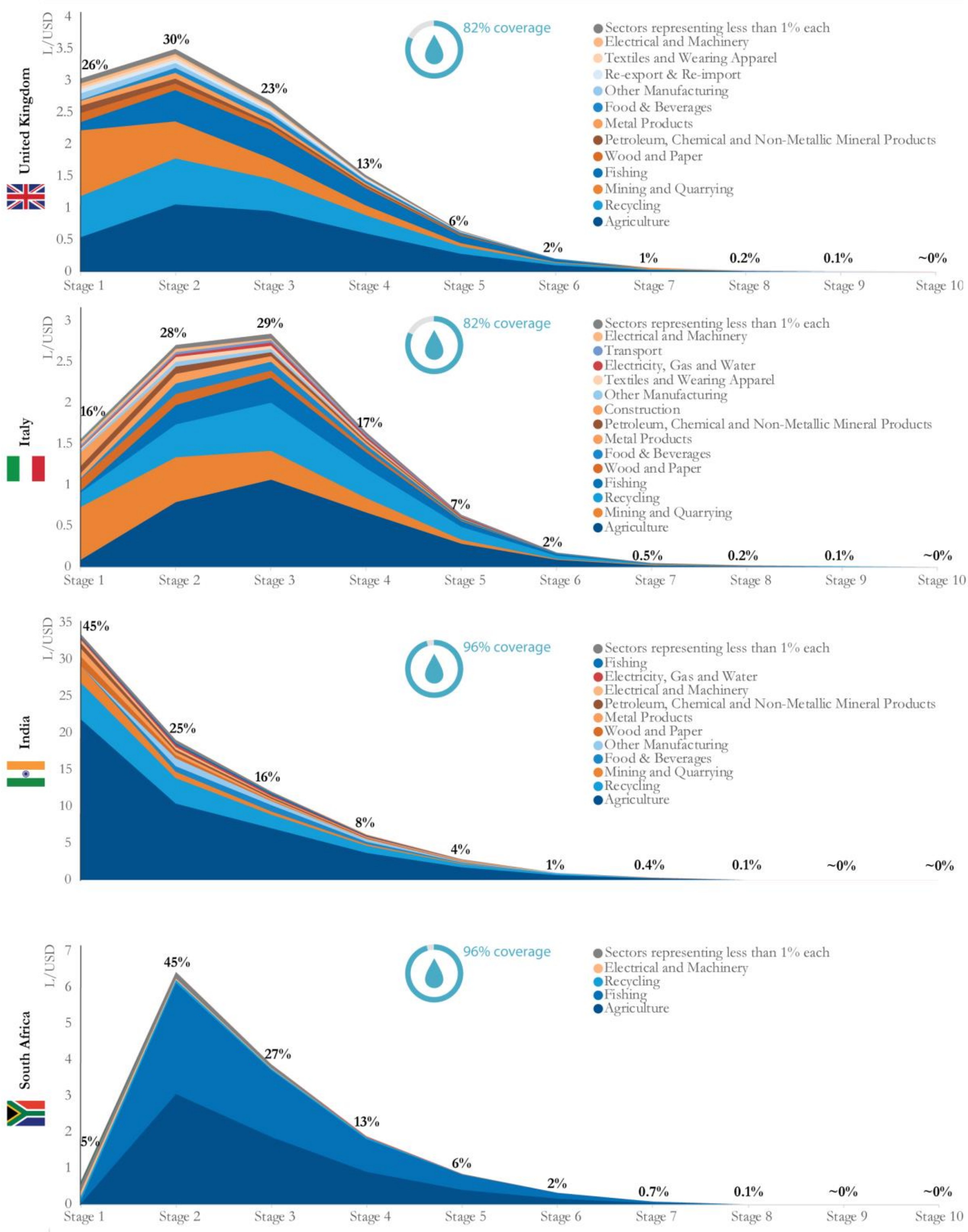


Figure 2 - Product layer decomposition (PLD) of the water intensity for the case study countries. Note that scale is different on the y-axis of each country.

Interestingly, sectoral contributions and curve trends are very different. For instance, Stage 1 contributions go from 5% for South Africa to 45% for India. All curves peak before or by Stage 3, with a plateau observed from Stage 7 onwards in line with previous research [36]. The developed economies of Italy and the UK exhibit a broader and more '*sectorally*' varied contribution whereas the number of contributing sectors diminishes for India and is minimal for South Africa. *Agriculture* is expectedly high but while it peaks at Stage 1 for India, its highest contribution is at Stage 2 for the UK and South Africa, and Stage 3 for Italy. This dispersion of the supply chains in developed economies and consolidation in developing economies is also witnessed when studying the top ten supply chain pathways of the water footprint, by country (see Table 1). Figures in Table 1 show that the top ten pathways represent 12.84% and 13.31% of the total WF in the case of the UK and Italy, compared to 45.88% for South Africa and 51.36% for India. The raw data from the structural path analysis also demonstrate this dispersion pattern. We extracted 748,082 and 805,338 individual pathways to cover 82.4% and 81.64% of the WF of the British and the Italian construction sectors, respectively. In comparison, 95.93% and 96.04% of the WF of South Africa and India are covered by 236,220 and 220,727 pathways, respectively.

This sort of information offered by PLD and the structural path analysis is useful to identify opportunities for improvement: for instance the direct contribution of *Agriculture* into *Construction* in India suggests an easier identification of actions, measures and policies to reduce the WF of *Construction* for India than it would be for other countries since agricultural contributions are much more diluted and dispersed in upstream layers of the supply chain. It is important to seize such opportunities while they last, in order to 'leap-frog' the potential pitfalls ahead in terms of economic development.

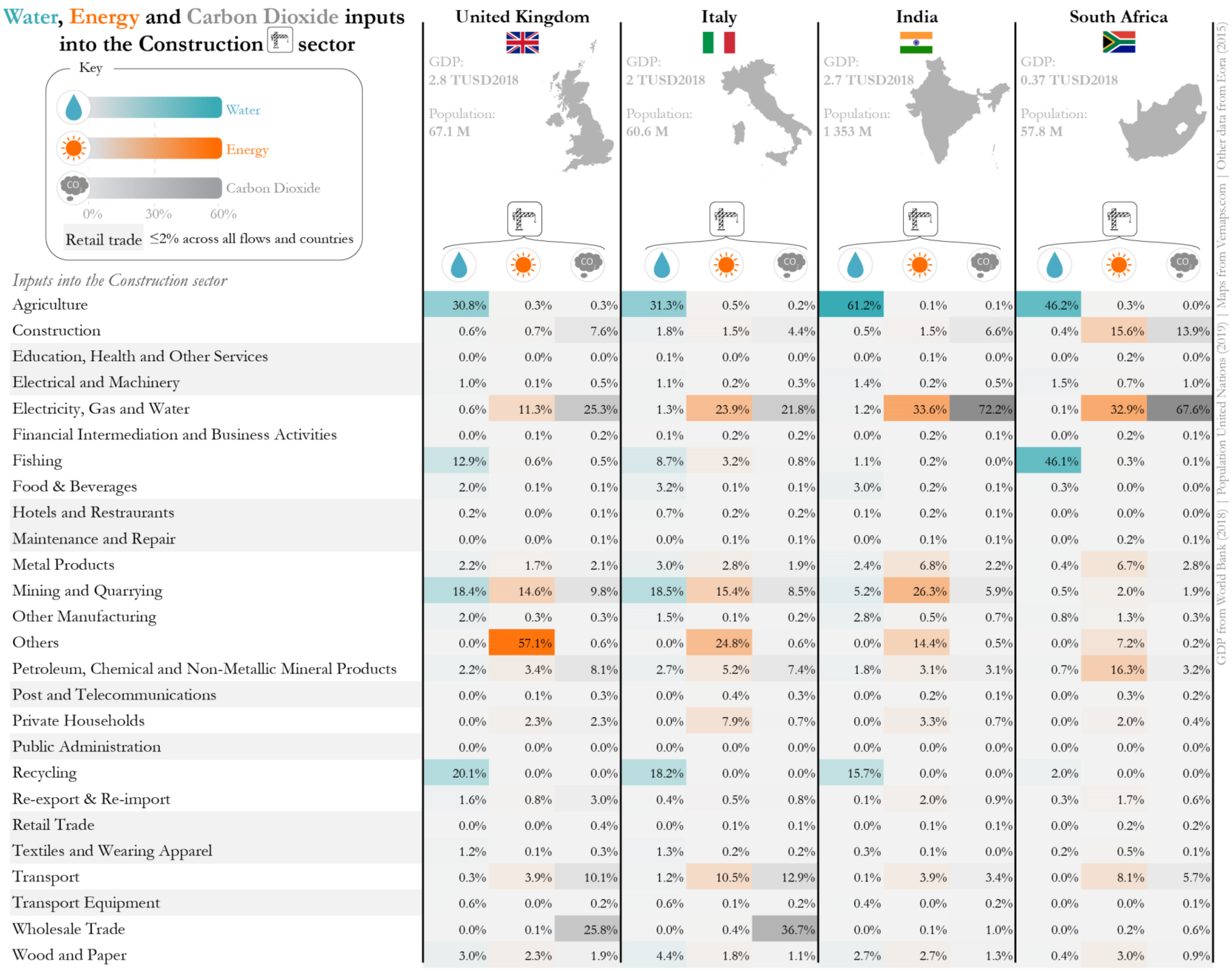
4.3 The water-energy-carbon dioxide nexus

A heatmap dashboard, capturing a synoptic overview of the key results from this study across the three flows is shown in Figure 3. It can be seen that across all countries, *Agriculture* plays a substantial role in the WF with values ranging from 30.8% (UK) to 61.2% (India). Conversely, *Agriculture*'s role on both energy and carbon dioxide is negligible with values << 1% for both flows across all four countries. This highlights the diversity between the three flows and the need for a dedicated focus on water. This is reinforced by the results for *Electricity, Gas and Water* which is constantly among the sectors with the highest contribution to both energy use and carbon dioxide emissions, ranging from 11.3% (energy, UK) to 72.2.% (carbon dioxide, India). Its sectoral relevance when it comes to water however is marginal at best, ranging from 0.1% (South Africa) to 1.3% (Italy).

In line with expectations, *Mining and Quarrying* is a sector that is relevant across the three flows. Yet, its strong contribution is mostly evident in the developed economies of Italy and the UK, where it represents ~15% and 18% of the energy and water intensities, respectively. These intensities are higher than the shares observed for carbon dioxide emissions (~ 9%). Nonetheless the *Mining and Quarrying* sector in these two countries represents the only instance where the three flows show some significant alignment and correlated impact intensities. For the developed economies, results differ greatly, with *Mining and Quarrying* only exhibiting a high value when it comes to energy for India (26.3%) with far more modest contribution to the WF (5.2%) and carbon dioxide emissions (5.9%) and very marginal contributions across the three flows (from 0.5% for water to 2% for energy)for South Africa.

Other significant sector-flow pairs that we observe are the carbon dioxide emissions linked to *Wholesale Trade* in the UK (25.8%) and Italy (36.7%) which testify to a CO_2-intensive trade sector in developed economies. The water footprint of *Fishing* is remarkably high for South Africa (46.1%), but noteworthy also for the UK (12.9%) and Italy (8.7%).

Transport is another expected contributor with noticeable inputs in terms of energy and carbon dioxide emissions across all four case study countries. More specifically, it seems that developed economies have more CO_2-intensive modes of transport than developing ones despite the usually stricter environmental regulations. This might be due to more lorries running only partly full to meet 'just-in-time' procurement routes for instance [72,73], which are more common in developed economies.



Water, Energy and Carbon Dioxide inputs into the Construction sector

Inputs into the Construction sector	United Kingdom			Italy			India			South Africa		
	GDP: 2.8 TUSD2018 Population: 67.1 M			GDP: 2 TUSD2018 Population: 60.6 M			GDP: 2.7 TUSD2018 Population: 1 353 M			GDP: 0.37 TUSD2018 Population: 57.8 M		
	💧	☀	CO	💧	☀	CO	💧	☀	CO	💧	☀	CO
Agriculture	30.8%	0.3%	0.3%	31.3%	0.5%	0.2%	61.2%	0.1%	0.1%	46.2%	0.3%	0.0%
Construction	0.6%	0.7%	7.6%	1.8%	1.5%	4.4%	0.5%	1.5%	6.6%	0.4%	15.6%	13.9%
Education, Health and Other Services	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.2%	0.0%
Electrical and Machinery	1.0%	0.1%	0.5%	1.1%	0.2%	0.3%	1.4%	0.2%	0.5%	1.5%	0.7%	1.0%
Electricity, Gas and Water	0.6%	11.3%	25.3%	1.3%	23.9%	21.8%	1.2%	33.6%	72.2%	0.1%	32.9%	67.6%
Financial Intermediation and Business Activities	0.0%	0.1%	0.2%	0.1%	0.2%	0.2%	0.0%	0.2%	0.1%	0.0%	0.2%	0.1%
Fishing	12.9%	0.6%	0.5%	8.7%	3.2%	0.8%	1.1%	0.2%	0.0%	46.1%	0.3%	0.1%
Food & Beverages	2.0%	0.1%	0.1%	3.2%	0.1%	0.1%	3.0%	0.2%	0.1%	0.3%	0.0%	0.0%
Hotels and Restraurants	0.2%	0.0%	0.1%	0.7%	0.2%	0.2%	0.1%	0.2%	0.1%	0.0%	0.0%	0.0%
Maintenance and Repair	0.0%	0.0%	0.1%	0.0%	0.1%	0.1%	0.0%	0.1%	0.1%	0.0%	0.2%	0.1%
Metal Products	2.2%	1.7%	2.1%	3.0%	2.8%	1.9%	2.4%	6.8%	2.2%	0.4%	6.7%	2.8%
Mining and Quarrying	18.4%	14.6%	9.8%	18.5%	15.4%	8.5%	5.2%	26.3%	5.9%	0.5%	2.0%	1.9%
Other Manufacturing	2.0%	0.3%	0.3%	1.5%	0.1%	0.2%	2.8%	0.5%	0.7%	0.8%	1.3%	0.3%
Others	0.0%	57.1%	0.6%	0.0%	24.8%	0.6%	0.0%	14.4%	0.5%	0.0%	7.2%	0.2%
Petroleum, Chemical and Non-Metallic Mineral Products	2.2%	3.4%	8.1%	2.7%	5.2%	7.4%	1.8%	3.1%	3.1%	0.7%	16.3%	3.2%
Post and Telecommunications	0.0%	0.1%	0.3%	0.0%	0.4%	0.3%	0.0%	0.2%	0.1%	0.0%	0.3%	0.2%
Private Households	0.0%	2.3%	2.3%	0.0%	7.9%	0.7%	0.0%	3.3%	0.7%	0.0%	2.0%	0.4%
Public Administration	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Recycling	20.1%	0.0%	0.0%	18.2%	0.0%	0.0%	15.7%	0.0%	0.0%	2.0%	0.0%	0.0%
Re-export & Re-import	1.6%	0.8%	3.0%	0.4%	0.5%	0.8%	0.1%	2.0%	0.9%	0.3%	1.7%	0.6%
Retail Trade	0.0%	0.0%	0.4%	0.0%	0.1%	0.1%	0.0%	0.1%	0.1%	0.0%	0.2%	0.2%
Textiles and Wearing Apparel	1.2%	0.1%	0.3%	1.3%	0.2%	0.2%	0.3%	0.1%	0.0%	0.2%	0.5%	0.1%
Transport	0.3%	3.9%	10.1%	1.2%	10.5%	12.9%	0.1%	3.9%	3.4%	0.0%	8.1%	5.7%
Transport Equipment	0.6%	0.0%	0.2%	0.6%	0.1%	0.2%	0.4%	0.0%	0.2%	0.0%	0.0%	0.1%
Wholesale Trade	0.0%	0.1%	25.8%	0.0%	0.4%	36.7%	0.0%	0.1%	1.0%	0.0%	0.2%	0.6%
Wood and Paper	3.0%	2.3%	1.9%	4.4%	1.8%	1.1%	2.7%	2.7%	1.3%	0.4%	3.0%	0.9%

GDP from World Bank (2018) | Population United Nations (2019) | Maps from Vemaps.com | Other data from Eora (2015)

Figure 3 – Heatmap of the water-energy-carbon dioxide emissions nexus for the Construction, across all sectors, and for each of the United Kingdom, Italy, India and South Africa

Construction (as a direct contributor to itself) only seems to play an important role in South Africa, and only as far as energy and carbon dioxide emissions are concerned. A generally higher value is observed in its share of carbon dioxide emissions but never to a point where its contribution appears remarkable.

Lastly, but very importantly, the *Recycling* sector tends to be very water-intensive in all countries but South Africa. Values are significant: contributions range from 15.7% (India) to 20.1% (UK), with Italy in the middle at 18.2%. One of the limitations of IO analysis, i.e. sectoral aggregation, arises here too with the sector *Others* accounting for rather significant values of energy. These range from a staggering 57.1% for the UK (implying that more than half of the energy use is obscurely embedded in other sectors of the economy that are not made explicit in the original database that we use in our analysis) to a 7.2% for South Africa, with India (14.4%) and Italy (24.8%) in the middle. Overall, it seems that the water- energy-carbon dioxide nexus for the construction sector in the case study countries cannot be proxied by any one of the individual flows covered in our analysis. This is because sectors with high WF show low contributions in terms of energy and carbon dioxide emissions and vice versa. Energy and carbon dioxide are more strongly related than any of them two with water but this is expected and in line with previous works on embodied energy and embodied carbon [e.g. 74,75]. Where a direct relationship between the three flows was observed (e.g. *Mining and Quarrying*) it did not hold true for all four case study countries (South Africa in this case).

5. Discussion

5.1 Advancing research on the water footprint and the water-energy-carbon dioxide emissions nexus of the construction sector

This work has both confirmed previous findings and produced novel contributions.

Firstly, we for the first time demonstrate the domestic share and international dispersion of WFs for developed and developing economies. More developed, service-based economies have the majority of their WF coming from abroad and sometimes from water scarce regions (Figure 1). Secondly, for the case study countries we confirm the significant difference between direct and total WF of construction sectors (Figure 1), also observed in previous analyses in Spain [43] and China [42,45]. This reinforces the need to steadily transition to methods of analysis which promote both accuracy and completeness, such as hybrid LCA [38,76], since the truncation error that process-based methods introduce can influence results and conclusions. Thirdly, we unravel the pathways that lead to the individual WFs showing both contributing sectors and contributing upstream layers of the supply chain (Figure 2). This approach sheds light on the fundamental difference of each country's economic structure, helps identify where hotspots occur and can support the development of policies and mitigation actions. We find that India and South Africa tend to have less dispersed supply chains, enabling potential significant gains by targeting key sectors. This is harder to achieve in the economies of the UK and Italy, which require multi-sectorial plans to potentially achieve the same levels of improvements. Fourthly, we contribute to the growing literature on studies investigating the nexus of environmental impacts and flows [e.g. 42,52,54]. We show that the water-energy-carbon dioxide nexus for the construction sectors of the case study countries cannot be proxied by any one of the three flows and broad analysis are required to capture the breadth, variation, and local and global extent of impacts. Lastly, while a direct comparison is almost impossible when different data and methods are used, our results for direct water intensity of the UK construction sector (0.05 L / USD) do not align with what previous work [14] found (1m^3 / 1,000 GBP, which turns into 0.65-0.8 L/USD with an exchange rate of 1.55 and 1.25, respectively). The two studies are not based on the same data, and this suggests and confirms the relevant role that underlying data play in determining the outcome of a life cycle assessment.

5.2 Limitations and future research

As in any other research, this work suffers from a number of limitations. Firstly, the results are as accurate as the base multi-regional input-output data. As such, they suffer from the accumulated limitations of data gathering, aggregation, assumptions, computing errors and linearity. More information on the limitations of input-output analysis can be found in Lenzen [36]. This can be resolved with further disaggregation of the global economy into even more country-sector pairs [77], and hybrid life cycle inventories which yield more accurate results [76]and are starting to be developed nationally [39]. Secondly, the structural path analysis does not provide a 100% coverage of the supply chain, when disaggregating it into its individual inputs. While we have ensured coverages of ~80-95%, we are still missing a share of the water/energy/carbon dioxide emissions in our analysis. Thirdly, this study focuses on four selected case study countries, which might not be representative of other developed or developing economies. As such, another research is needed to investigate the construction sector across every single country for which data is available, in order to draw more conclusive insights and recommendations. Fourthly, the underlying data did not allow us to robustly produce water footprints by water use (i.e. blue, green, grey). In addition, water scarcity, which is a critical factor [78,79], was not integrated into the analysis. These factors will need to be considered in future research to improve the relevance and specificity of the results.

6. Conclusions

Buildings and the construction sector are some of the most significant contributors to global environmental burdens. They represent both a challenge and an opportunity to work towards mid-century climate goals and beyond. While the embodied energy and greenhouse gas emissions of buildings and construction have received global research attention, the embodied water or water footprint (WF) of construction activities remains understudied. The global water footprint of construction is currently unknown with only one estimate from over a decade ago.

In this research, we use global multi-regional input-output (MRIO) data and structural path analysis (SPA) and apply them to four case study countries (India, Italy, South Africa and the UK) to quantify and evaluate the water-energy-carbon dioxide emissions of their construction sectors. Our results do not align with previous works where a comparison was possible—suggesting lower direct and higher total water footprints, and also offer a richer picture of the distribution of impacts across geographies and sectors.

Total WFs of construction activities range from 11.84 L/USD (Italy) to 78.12 L/USD (India), with more developed economies exhibiting a higher share of international WF (average for Italy and the UK is 71.5%) than developing economies (average for India and South Africa is 18.5%). We also observe a lack of correlation between the three flows considered in our analysis (energy, carbon dioxide emissions and water) when the construction sector is considered.

Water is perhaps the most critical resource upon which life on our planet depends. Reducing the water footprint of the construction sector will therefore contribute to alleviate the pressure on this highly-sought-after and unevenly distributed resource..

Acknowledgements:

This work was financially supported by the UK’s Engineering and Physical Sciences Research Council (EPSRC) Grant No. EP/R01468X/1.

Authors contribution:

FP designed the original research idea. FP extracted and adjusted the base data. AS produced the structural path analyses of selected construction sectors. FP and AS wrote the paper and produced its figures.

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