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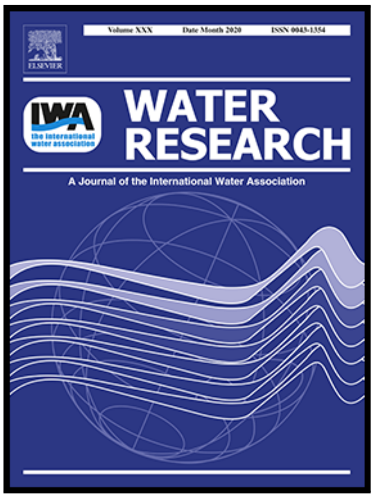

Water, energy, and carbon dioxide footprints of the construction sector: a case study on developed and developing economies

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Highlights

- Novel method for water, energy, and carbon footprints of construction
- Application to construction sectors in India, Italy, South Africa and the UK
- No significant correlation between water, energy, and carbon footprints
- Water footprints of construction activities range from 11.84 L/USD to 78.12 L/USD
- More developed economies exhibit a higher share of international WF than developing economies

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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 energy use and CO_2 emissions of buildings and construction have been quantified, 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 carbon (dioxide) footprints associated with the construction sector of India, Italy, South Africa, and the UK, disaggregating the supply chains driving these environmental effects by using structural path analysis. 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 (i.e. direct + indirect) 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 and carbon dioxide footprints in terms of sectoral contributions, even if the latter two are correlated. More developed economies

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exhibit a higher share of international WF than developing economies. The current focus on energy and carbon dioxide footprints might therefore miss out on significant water impacts caused by construction activities, 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

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1. Introduction

Buildings and construction are responsible for around 40% of greenhouse gas (GHG) emissions (Ibn-Mohammed et al., 2013), 50% of primary energy demand and resource consumption (Dixit, 2017), 30% of the waste flows generated (Pomponi and Moncaster, 2016) and 15% of freshwater use (Baynes et al., 2018), globally. Therefore, their role to transition to any form of future environmental sustainability is paramount (Pomponi and Moncaster, 2017, 2018). Yet, the contribution of buildings and construction to

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freshwater use is relatively uncertain. The 15% figure on freshwater reported above can be traced back to a review paper (Ding, 2014) from 2014, which in turn refers to two other studies (Mokhlesian and Holmén, 2012; Ramesh et al., 2010) where the origin of the number becomes blurry and hard to trace. Additionally, recent research (Miller et al., 2018) reports that concrete production alone was approximately responsible for 9% of global industrial water withdrawals[1] 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 (Rothausen and Conway, 2011), it is worth understanding what are the cumulative effects of construction activities.

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. WF refers to the total virtual water content of products, sectors, or countries in line with previous work that followed the same approach (Chapagain, 2006; Feng et al., 2011; Hoekstra et al., 2009; Hoekstra and Chapagain, 2006), thus excluding for instance the freshwater use in buildings (e.g. for drinking or hot water demand). 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) (Hoekstra and Mekonnen, 2012), we focus on blue water only.

Our aim translates into three distinct objectives:

[1] Water withdrawal (or water use) describes the total amount of water withdrawn from a surface water or groundwater source while water use is the portion of the withdrawn water permanently lost from its source (e.g. evaporation, people and animal consumption, etc.). (WRI, 2013)

1. to develop a transparent and replicable approach to estimate WF of construction activities at a national and international level.
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 evaluate the correlation between water, energy, and carbon dioxide footprints and establish whether energy or carbon dioxide assessments are a valid proxy for WF.

The need for information on water, energy, and carbon dioxide balances has been recognised as an important element to analyse environmental performance (Chini and Stillwell, 2020). No single indicator can accurately represent all environmental effects (Pomponi et al., 2016; Stephan et al., 2020), 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 (Ströbele and Lützkendorf, 2019). The article is structured as follows. Section 2 reviews previous works, to inform the development of our own approach. Section 3 presents both methods and data used. Results are shown and discussed in Section 4, along with policy recommendations and the main limitations of this research. Section 5 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 and that utilises an input-output based approach. Other research on embodied water has been conducted at the building level, (Crawford and Pullen, 2011; e.g. Crawford and Treloar, 2005; McCormack et al., 2007; Stephan and Athanassiadis, 2017; Stephan and Crawford, 2014), and at the construction

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material level (e.g. Gerbens-Leenes et al., 2018; Pfister et al., 2009; Shirkhani et al., 2018; Nezamoleslami and Hosseinian, 2020) but these fall outside the scope of this work.

Hong et al. (2019) 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, confirming the significant importance of indirect effects incurred by iterations of trading processes and resource consumption upstream in the supply chain (Hong et al., 2019). Hong et al. (2019) further explored the (embodied) energy-water nexus, finding inconclusive correlation between the two.

Cazcarro et al. (2013) 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 (2006) - its embodied WF averages at 3.79% of the total WF of the economy (2661 hm^3/year) (Cazcarro et al., 2013), without significant shifts from 1980 (3.78%) to 2007 (3.64%).

Similarly, Wang et al. (2009) 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. 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

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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. The same importance of indirect impact has been evidenced for carbon dioxide emissions of global construction activities by Huang et al. (2018). At a national level, the results for the Chinese construction sector from Zhang and Anadon (2014) seem to be very different. Their results are based on the 2007 inter-regional IO table developed by Liu et al. (2012) and point to construction being responsible for only 0.4% of embodied water withdrawals, 0.3% of embodied water use in domestic trade, and 0.3% in international trade. Strongly aligned values were obtained by Hubacek et al. (2009), who analysed the Chinese ecological and water footprints based on historic data and projected trends into the future. Their analysis evaluates 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% However, a recent article focused on the water-energy-food nexus in East Asia by White et al. (2018) 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 (2014) and Hubacek et al. (2009).

Feng et al. (2011) 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 (Lee et al., 2005). 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 (Feng et al., 2011). 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 (Feng et al., 2011). Their findings are in line with those of Owen et al. (2018) who found that the UK construction sector ranks eighth overall for water use with a share of 2.5%.

Overall, existing studies – mainly from China and the UK – do not point towards a consistent WF of the construction sector, relative to national WFs. Further, most existing studies rely on old input-output tables and adopt standard EEMRIO approaches, focusing on one country at a time. Additionally, the regional impacts resulting from water use are of the utmost importance as 1 L of water used in Scotland does not compare to 1 L of water used in South Africa. In a conventional IO-based analysis, the water use along the supply chain is allocated to the last supplier and spatial allocation is lost. 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 that retain spatial information. This study addresses this need.

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3. Data and methods

3.1 The EORA database and its fundamental calculus

Eora is a global MRIO (Lenzen et al., 2013, 2012a), which has been successfully used in a number of fields from city-level sustainability (Wakiyama et al., 2020) to greenhouse gas emissions , biodiversity loss (Chaves et al., 2020), international trade (Oita et al., 2016), and public health (Lenzen et al., 2012b; Malik et al., 2018). MRIO analysis, originally conceived by Nobel prize Laureate Wassily Leontief (Leontief, 1936), is an important tool to analyse environmental impacts, and has been included in United Nations standards (UN, 2017). As an environmentally extended MRIO, Eora also includes satellite accounts for environmental repercussions already reconciled with economic data. 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 in the world 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 calculus: $\mathbf{x} = \mathbf{T1} + \mathbf{y}$, 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 (Miller and Blair, 2009) 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 (Wiedmann, 2017). 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 (Wiedmann, 2017), which is a simple technique of decomposing total impact multipliers derived from input–output analysis, through a generalised supply and use table framework and explicitly distinguishing between industries and products. 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 (Crama et al., 1984; Defourny and Thorbecke, 1984). We use the *pyspa* Python® package developed by Stephan and Bontinck (2019) to conduct the analysis. The algorithm is described in detail in Stephan et al. (2018) 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 34 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

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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 driving 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 34 regions. The approach provides an unprecedented resolution of the results, which helps address the existing research gaps. In summary, for the scope of this research, the structural path analysis shows the water use at each supply chain stage, and along different pathways, rather than the aggregated water use in the first tier only.

3.3 Case study countries

This study aims to firstly offer a novel approach to estimating the water footprint and exploring the correlation between water, energy and carbon dioxide footprints of construction sectors. Its potential is then tested on four countries as an exemplary application. We chose two developed and two developing economies: India (IND), Italy (ITA), South Africa (ZAF), and the UK (GBR). This is because previous research (Huang

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et al., 2018) has shown that the intensities of the construction sector's direct and indirect CO_2 emissions in developing economies were larger than in developed economies. Both India and South Africa are countries from the Global South with very different GDP and population values, thus allowing to single out potential 'Global South' characteristics. Further, India's GDP is comparable to those of Italy and the UK while its population is much larger. Such case study characteristics are in line with representativeness and good practice of case study research (Yin, 2020). However more than the specific countries we selected, we believe the novelty of our work is in the approach we developed to estimate WF of construction sectors, which 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. This includes the square technological matrix and the metadata sheet describing each sector across each of the three flows considered. These data enable readers to readily produce Sankey or tree diagrams of the water, energy and carbon dioxide emissions across the supply chains of construction sectors.

4. Results and discussion

This section presents the results, focusing on the water footprint and its intensity (Section 4.1), the sectoral makeup of the water footprint through a product layer decomposition (Section 4.2) and the water, energy, carbon dioxide footprints at sectoral level aggregated along the supply chain (Section 4.3). These results are based on a total of 41 009 346 data points extracted through structural path analysis broken down into

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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 share is 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

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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).

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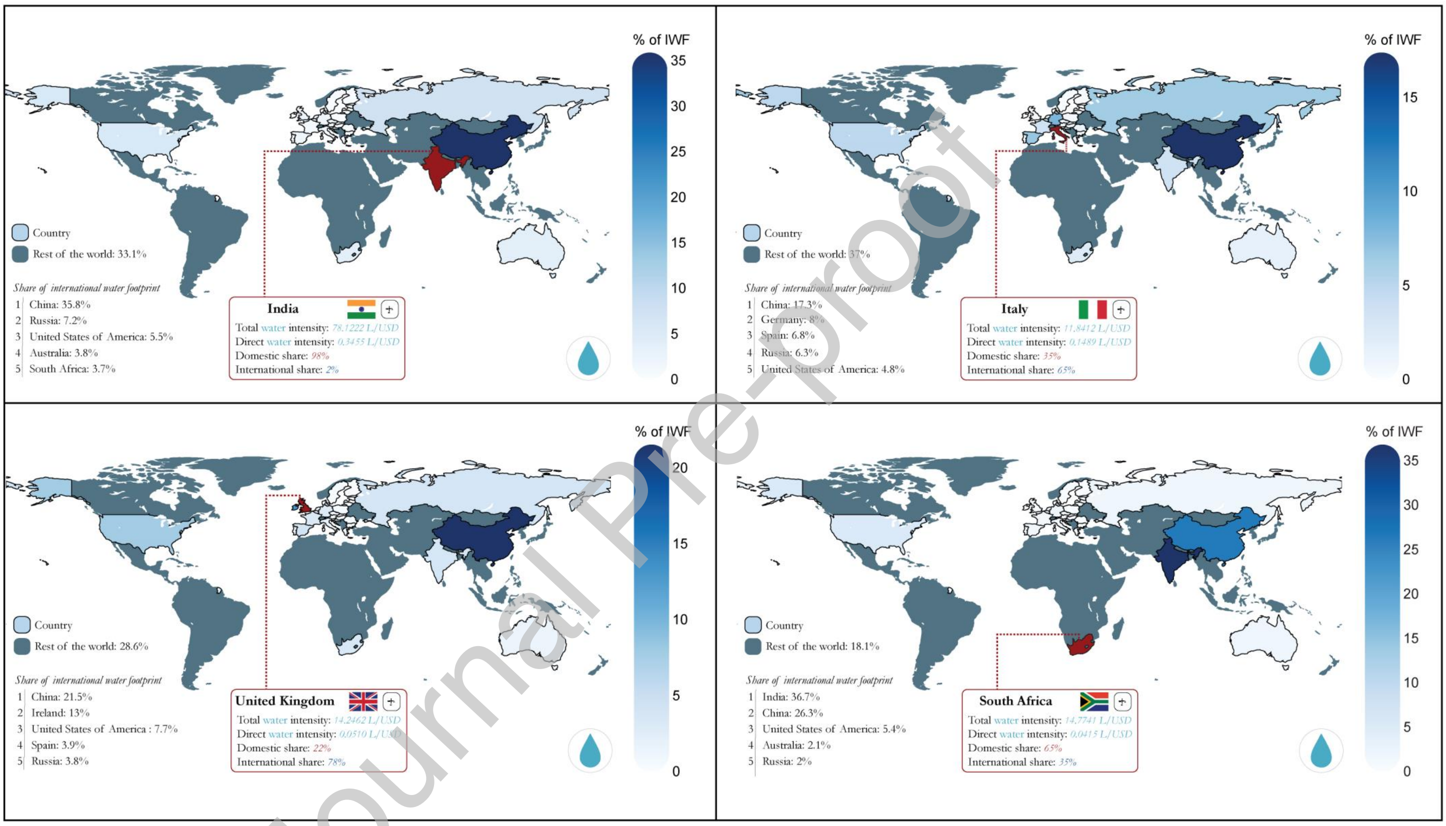

Figure 1 - Overview of domestic and global dispersion of water footprints for the construction sectors of India (upper left), Italy (upper right), South Africa (lower left), and the UK (lower right). International Water Footprint (IWF) is reported for the 33 individual countries covered in our analysis,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

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Table 1 - Top ten pathways contributing to the water footprint of the construction sector for each of India, Italy, the United Kingdom and South Africa.

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 ←	0.78%	IND_Mining and Quarrying	1.89%	ZAF_Wood and Paper ← ZAF_Wood and	2.37%

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		ITA_Food & Beverages				Paper ← ZAF_Agriculture	
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 %**

Note: A Pathway is defined as the chain of inputs from one sector to the other, into the construction sector. The contribution of the pathway is the direct environmental flow input into its most upstream sector (excluding other inputs further upstream). Therefore a pathway containing one sector (e.g. IRL_Mining and Quarrying) represents the water input from that Irish sector into the construction sector of the relevant country (e.g. the UK).

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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 (Lenzen et al., 2003). We show this for the WF of the four case study countries in Figure 2.

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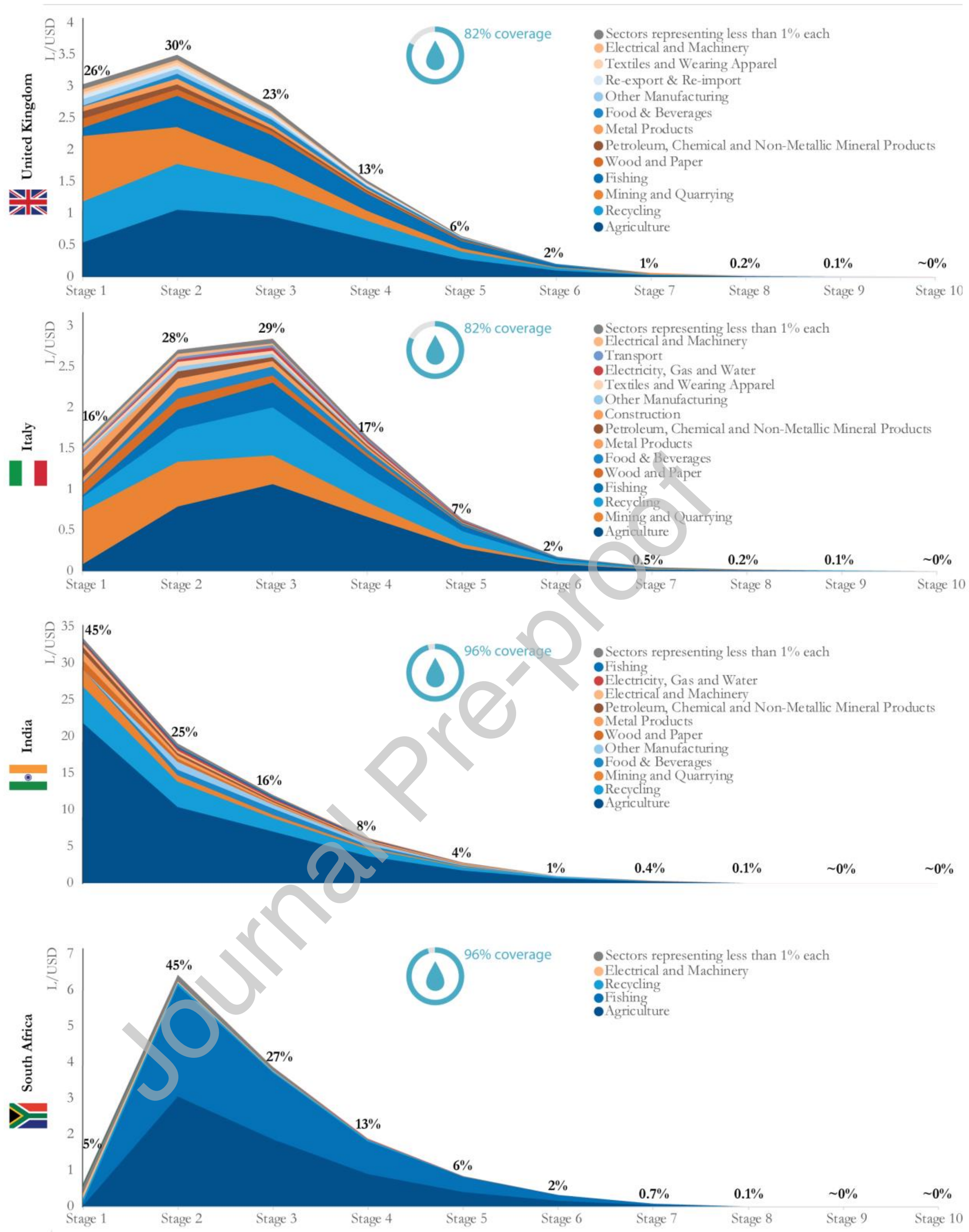

Figure 2 - Product layer decomposition (PLD) of the water intensity of the Construction sector for each of India, Italy, the United Kingdom and South Africa. Note that scale is different on the y-axis of each country.

Interestingly, sectoral contributions and curve trends are very different. For instance, Stage 1 contributions range from 5% for South Africa to 45% for India. All curves peak

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before or by Stage 3, with a plateau observed from Stage 7 onwards in line with previous research (Lenzen, 2000). 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). Numbers 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 'leapfrog' the potential pitfalls ahead in terms of economic development.

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4.3 Water, energy and carbon dioxide footprints

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 reveal 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 (McKinnon et al., 2010, 2009), which are more common in developed economies.

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Water, Energy and Carbon Dioxide inputs into the Construction sector

Key: Water / Energy / Carbon Dioxide — 0% 30% 60%

Retail trade ≤2% across all flows and countries

	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		
Inputs into the Construction sector	Water	Energy	CO_2	Water	Energy	CO_2	Water	Energy	CO_2	Water	Energy	CO_2
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)

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Figure 3 – Heatmap of the water, energy, and carbon (dioxide) footprints for the Construction sector, across all sectors, and for each of the United Kingdom, Italy, India and South Africa

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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 significant.

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 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 three footprints (water, energy and carbon dioxide) 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 with water but this is expected and in line with previous works on embodied energy and embodied greenhouse gas emissions (e.g. Pomponi et al., 2015; Stephan et al., 2020). 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 was an outlier in this case).

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4.4 Advancing research on the water, energy and carbon dioxide footprints of the construction sector

This work has both confirmed previous findings and produced novel contributions. These are discussed below.

Firstly, we demonstrate the domestic share and international dispersion of the WFs of the construction sector 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 (Cazcarro et al., 2013) and China (Hong et al., 2019; Wang et al., 2009). This reinforces the need to steadily transition to methods of analysis which promote both accuracy and completeness, such as hybrid LCA (Crawford et al., 2018; Pomponi and Lenzen, 2018), since the truncation error that process-based methods introduce can influence results and conclusions. Thirdly, we extract 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. However, coarse sectoral resolution which is common in IO data does limit the potential for interventions since it does not show which products within a sector represent the 'hotspots' for the impacts. Spatially, we find that India and South Africa tend to have less dispersed supply chains, enabling potential significant gains by targeting key domestic sectors. This is harder to achieve in the economies of the UK and Italy, which require multi-sectorial plans to potentially achieve the same

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levels of improvements. Fourthly, we contribute to the growing literature on studies investigating the potential proxy-role of some impacts and flows (e.g. Hong et al., 2019; Owen et al., 2018; White et al., 2018) to facilitate and support environmental decision-making. We show that the water, energy, carbon dioxide footprints 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 average direct water intensity of the four construction sectors (~0.15 L / USD) are lower than what previous work (Feng et al., 2011) found ($1m^3$ / 1,000 GBP, which turns into 0.61-0.8 L/USD with an exchange rate of 1.63 and 1.25, respectively) or values for non-residential building construction in a recent database (Crawford et al., 2019) (0.25 L/USD). The 0.25 L/USD value comes from perhaps the most recent database for construction (Crawford et al., 2019) – whose water use data was developed from primary data – thus suggesting that the 2010 range of 0.6-0.8 L/USD from (Feng et al., 2011) might be a very high estimate. Yet, these 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. One potential explanation for our lower estimate is that in several cases, as detailed in the SI, we lowered original water use data in Eora as this seemed in contrast with other water-focused data sources. Perhaps, had we left the higher values of water use in Eora's satellite accounts, we would have obtained results closer to the other averages. The main point, however, remains that as water footprinting of entire sectors at national and international levels develops, great attention must be paid to the data that underpin such analyses.

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4.5 Policy recommendations

Targeting the water footprint of the construction sector while controlling energy and carbon dioxide inputs sits at the interplay of sustainable development goals 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production) (UN, 2015). In order to reduce the water footprint of the construction sector, we propose three main recommendations in light of the results.

Firstly, and as demonstrated by this paper, both developed and developing economies need to invest in sourcing the most accurate and systemically complete data on environmental flows, across sectors and processes. Uncertainty in the data will systematically result in uncertainty in the decision-making process and the enaction of policies. Mapping additional processes across the economy, a (much) higher sectorial resolution for input-output sectors, and a consistent method to collect and compile input-output data (UN, 2018) should be mandated. This will enable a much more refined understanding of the supply chains of the construction sector, the identification of water 'hotspots', and their management. Secondly, embodied water (and other embodied environmental flows) needs to be made more visible in the construction industry if we are to tackle them. Building regulations, higher education, and the public sector, need to further enforce the consideration of embodied water, energy and greenhouse gas emissions, as called for by a number of researchers, e.g. Szalay (2007), Stephan and Crawford (2014), Pomponi et al. (2018). Thirdly, it is important to note that with the majority of the forecasted population growth taking place in developing economies (UN, 2019), the majority of construction assets to be built in the coming 50 years will be in those economies. With droughts and water scarcity disproportionally affecting countries in the Global South now and into the future (with the notable

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exceptions of Australia, California and the Mediterranean Basin (Parish et al., 2012)), a careful selection of construction materials with low water (and energy and carbon dioxide) footprint(s) will be necessary. Critically, bio-based materials need to be by-products or waste products from existing agriculture activities and certainly not from dedicated plantations that might take the water away from vital crops or even replace them. In this sense, capturing the economy-wide linkages for bio-based construction materials will be critical, as possible through the methods put forward in this paper.

4.6 Limitations and future work

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 (Sev, 2009) and these should all be carefully considered given the scarcity of the resource. This is one of the limitations of our work, along with a number of others. 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 (2000). This can be resolved with further disaggregation of the global economy into even more country-sector pairs (Lenzen et al., 2017), and hybrid life cycle inventories which yield more accurate results (Pomponi and Lenzen, 2018) are starting to be developed nationally (Crawford et al., 2019). 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

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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 type (i.e. blue, green, grey). These factors will need to be considered in future research to improve the relevance and specificity of the results. Further, recent work (Tarne et al., 2018) has shown that for the automotive industry EEMRIO databases have poor accuracy in inter-regional coverage of the supply chain when compared with real-life observations. Construction is generally a "more local" sector than automotive but the accuracy of the spatial representation, potentially due to the time lag that exists in IO data, should be considered in future works. In addition, water scarcity, which is a critical factor (Iglesias et al., 2007; Ridoutt and Pfister, 2010), was not integrated into the analysis. This is an important element of future work, for instance following the methods by Boulay et al. (2018) or Berger et al. (2018).

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5. 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, and 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 offering 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 (water, energy, and carbon dioxide emissions) 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.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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. FP revised the paper with the help of AS.

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