**Virtual water supply chains diversity buffers cities of the Global South against climate change**

**Abstract**

Water had a great influence on the rise and collapse of ancient civilizations. Nowadays, mankind faces water-related problems exacerbated by intensive farming, rapid urbanization, and climate change strikes. The world’s population is becoming increasingly dependent on water resource. However, most of the water humanity is currently consuming is invisible in nature, and we know less how this virtual water is circulating within the global economic supply chains. While the water footprint of cities of the Global North are profoundly analyzed, Global Southern cities remain poorly documented. To bridge this gap, we compute and decompose cities’ virtual water (Bleu and Grey) of the Global South, we used Extended Environmental Input-Output Analysis (EE-IOA). While the scientific literature asserts that North Africa is triggered as a climate change hotspot that is exposed to strong temperature increase and high drought risk, North African cities are importing more goods and services that contains larger amount of freshwater to reduce the burden of climate change and preserve local freshwater for drinking. Results showed that the average, across all the selected cities, virtual bleu water is estimated to 253 liters per capita/yr and for grey water is estimated to 285 liters per capita/yr which means that cities of the Global South are causing transboundary water pollution more than they import fresh water embedded within products and services. When decomposing the virtual water of the Global South we found that the major responsible sectors transport accounts for X% of the total footprint, followed by X with x% and x with X%. To place the climate-induced uncertainties in perspective, it is better to act in a pro-active approach and spread environmental consciousness regarding the purchase of products and services that are associated with less virtual water intensities (both Blue and Grey).

**Keywords**

Virtual water; input-output analysis; cities; water security; urban sustainability; Global South.

**Graphical abstract**



1. **Introduction**

Water is a finite resource and plays a major role in urban development and ecosystems sustainability. Thorough history, the first mankind’s revolutions testify on the relevance and the safety of water as resource (e.g., ancient human civilizations: Mesopotamia, Egyptian, Greek and Roman). Currently, 97% of the water on Earth is saltwater, leaving only 3% as freshwater, only 1% of which is readily available for human consumption. Unfortunately, the world’s population is becoming increasingly dependent on this valuable resource, and major water-related crises are expected.

The World Water Council’ Vision Report stated that there is a water management crisis which led both billions of people and the environment to suffer.

According to the World Water Council, XXX live without a cleaned water, ….etc (set countries too). From a planetary scale, agriculture is ranked the first for consummating water with …… However, these values are biased in industrialized countries, where the industry accounts for ½ of the total water consumption.

Unfortunately, we’re living in a changing climate, climate change is currently effecting water planning include changes in precipitation events, runoff patterns, and droughts. Despite recent advancements in climate research, there is still a lot of uncertainty about how and when the climate will change, and how these changes will affect water availability within an increasing demand for water, worldwide. Climatologists have blown the whistle regarding the perturbation of rainfall amount from year-to-year and there will be heat waves accompanied with drought episodes (Cook et al., 2016; Lelieveld et al., 2016).

Therefore, new optimistic scenarios of climate change coupled with irrigation technologies are required (Harmanny and Malek, 2019)

Yet, the direct water is clearly stated and monitored at planetary scale but the virtual water is largely lacking.

Many areas around the world are facing water-related issues such as Cape Twon in 2018 where the city experienced the Day-Zero. Therefore, they could enhance …

**Virtual water, what does it means?**

Contrary to the direct water that is used to produce commodities, goods and services, for instance, a car manufacture uses direct water throughout the production processes including surface treatment, paint spray booths, coating, washing, hosing, and rinsing that happened inside the manufacturing facilities. Summing up together, the value display the required amount of water to produce a product (a car in this example), that total is “virtual”, given the fact that the final consumers (owner of a car) it not aware of such water consumption; moreover, the final user also uses direct water (which stays qualified as “directed”) while using the car including washing, cooling, air-conditioning system. The virtual water, also known in the scientific literature as indirect, embedded, embodied water, is the quantity of water that has been consumed across the value chain of goods and services purchased from the global economic market, and it is often hidden from final consumers.

Despite the existence the existence of the Virtual Water Trade (VWT),

However, virtual water (also including virtual carbon, energy, nitrogen, phosphorus, human appropriation …) is not yet regulated by any national or international protocol.

**The role of water in urban development and sustainability future (urban metabolism approach)**

Supply and demand for water encompasses other non-climatic factors that might have a considerable effect on water including demographic growth, economic growth, affluence, and geopolitics. Cities are hyper-complex system that require inputs from the national and international markets to satisfy their development needs.

In addition, water pollution is increasing across the world which further shrink the available water for anthropogenic activities.

Water supply is bound with time, geography and climate hazards; therefore, societies of the global south should innovate new lifestyle patterns and

Developing economies are trying to grow so fast, without paying attention to the environmental degradation generated during this process.

**The novelty of this article**

The novelty of this study is that it computes the different types of virtual water namely blue and grey water for 181 cities belonging to the Global South (focusing on Upper Middle-Income -UMICs- and Lower Middle-Income -LMICs- classes) and decomposes each water footprint by major final consumptions categories (construction, electronics, food, goods, services, Transport, and Others) in order to allocate responsibilities to final demand sectors and trigger potential policy leverages. The final sample used for our analysis is based on 181 cities belonging to the Global South covering 23 countries and representing X% of the world’s population.

1. **Methods and Materials**

**Data collection:** Given the fact that the concept of virtual water trading is fundamentally economic (Reimer, 2012) and closely related to the international trade theory which goes back to (Vanek, 1968) extension of the Huckster-Ohlin model, two types of data were harvested. The first is urban expenditures surveys (UES) or consumers expenditures surveys (CES) (also denoted as city final demand vector - -) following COICOP-categorization of the 181 selected cities belonging to 23 countries of the Global South, see electronic supplementary information (ESI) file for further details. Data were retrieved from the office of statistics of each host-country. Notice that data collection methods and quality may vary from a country to country; hence, from a city to city (took as-is). Because of data scarcity in the Global South, cities final demand vectors - - were not taken at the same year because of the internal protocol of each host-country to establish and deploy the consumer expenditures surveys, some countries establish the surveys annually, while others quinquennial as such several limitations are to encounter while comparing results among selected cities (also highlighted in (Hachaichi and Baouni, 2021, 2020)). The second data constitutes of global Multi-Regional Input-Output (MRIO) tables which were retrieved from Eora global supply chain database (Lenzen et al., 2013, 2012). Eora provides multi-region input-output table (MRIO) model that provides a time series (from 1990 to 2021) of high-resolution Input-Output (IO) tables (capturing the inter-sectoral transfers amongst 15,909 sectors) with corresponding environmental and social satellite accounts () for 190 nations. We used Input-Output tables (version 199.82) harmonized to 26 sectors to enable a transparent and an accurate comparison across selected cities. Notice that the current virtual water estimations of the Global South exclude footprints attributable to (i) government final consumption and (ii) gross fixed capital formation for which city-specific data was not available.

**Method:** For this study we used an Environmental Extended Input-Output Analysis (EE-IOA) (Haberl et al., 2019; Kitzes, 2013; Miller and Blair, 2009; Raa, 2006, 2007). Our analysis process is divided into two parallel pre-processing steps (Fig.1). The first in which we collected raw CES data in local currencies and transformed into cities’ final demand vectors () that matches to the respective sectoral used by Eora (26 sectors), we aggregated the values (via a distributive process) to match Eora 26 sectors classification by constructing “correspondence table” that maps each value from the raw CES data to match Eora’s sectors. To use the virtual water coefficients provided by the Eora satellite accounts (), we converted cities’ final demand arrays () from local currencies into $US using the World Bank exchange rates (World Bank, 2021) and were mapped accordingly to the national import structure for each country to be used in the input-output calculations. In the second step, we computed the direct intensity vectors () as shown in Equation (1) (for each year corresponding the selected city’s final demand vector) for each virtual water category (Grey, and Blue water), after we computed the final demand vector () using the Leontief inverse (Leontief, 1986) as shown in Equation (2).

…(Eq.1)

… (Eq.2)

Next, cities final demand vectors - - were converted from purchases price (PP) to base price (BP) on a sector by sector basis using national BP/PP ratios computed from Eora’s Multi-Regional Input-Output (MRIO) tables as preformed in (Pichler et al., 2017). To compute cities’ virtual water footprints (for each sector), we multiplied element wise the total demand vector () with the city final demand vector () as shown in Equation (3).

... (Eq.3)

Where is the virtual water per capita for a given city (m3/year), is the total intensity vector, and is the city final demand vector ($US/year).

**Diagram, schematic

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**Figure 1:** Method utilized to compute cities’ virtual water of the Global South and data dissemination by final major consumption categories.

1. **Results and discussions**

We will discuss the results of 181 cities’ virtual water of the Global South in section (3.1) while decomposing each footprint (Blue and Grey) by major final consumption categories, income class, geography, and major industrial classes. Next, in section (3.2) we will shed the light on the leverage points to design effective policies to reduce the virtual water alongside what are the handicaps policymakers encounter while designing strategic multiscalar policies.

* 1. **Urban virtual water of the Global South: Learning from contexts**

Results (Fig.2) shows that, on average, Global Southern cities’ virtual blue water footprint is estimated to 93 ± 78.5 liters per cap/year, and for the Grey water footprint is estimated to 133 ± 144 liters per capita/year. This finding shows that, on average across all selected cities, cities of the Global South are causing water pollution, elsewhere on the globe, more than importing fresh water embedded within goods and services. However, it is important to highlight that several Asian cities are associated with highest grey water footprints such as Atolls (Maldives) with 668 liters per capita/year, followed by Chinese cities Beijing, Guangdong, Tianjin, Jiangsu with 623, 517, 487 liters per capita/year, respectively.

Diagram

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**Figure 2:** Distribution of virtual water across selected cities of the Global South by type (blue and grey).

Decomposing the virtual water footprints by income classes by Lower Middle-Income -LMICs- and Upper Middle-Income -UMICs- (Fig.3) showed that for blue water footprint, Upper Middle-Income countries of the Global South, across all the selected cities, is estimated to 104 ± 72.2 liters per capita/year, and to 166 liters per capita/year. Whereas for Lower Middle-Income countries of the Global South we found that the blue water footprint is estimated to 72.4 ± 86.4 liters per capita/year, and the grey water footprints is estimated to 70.4 ± 45.9 liters per capita/year. Our results corroborate other research (Fu et al., 2022; Hachaichi and Baouni, 2020; Hoekstra and Mekonnen, 2012; Lenzen and Foran, 2001; Pichler et al., 2019; Souissi et al., 2022; Weinzettel et al., 2013) whereby affluence is a driving force for environmental footprints.

A picture containing text, map, sky, light

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**Figure 3:** Distribution of virtual water across selected cities of the Global South by income class (Lower Middle-Income and Upper Middle-Income).

From a regional perspective (Fig.4), we decern that Asian cities accounts for both highest water footprints of grey and blue water with an average footprint across all Asian cities estimated to 139 ± 64.6 liter per capita/yr for Bleu water, and to 248.5 ± 166.8 liters per capita/yr for Grey water. While Africa accounted for 72.78 ± 82.4 liters per capita/yr for Bleu water and to 60 ± 35 liters per capita/yr for Grey water, and Latin America 23 ± 4.6 liters per capita for Blue water and 26.7 ± 4.5 liters per capita/yr for Grey water. Surprisingly, although that Latin America (8,520 US$) have the highest income per capita then Asia (5,635 US$) and Africa (1,809 US$) (World Bank, 2022), their water footprints seems to be less flattened; nevertheless, water footprint is correlated to expenditures (Wiedmann et al., 2020), the more you spend you the higher your water footprint gets (Hachaichi and Baouni, 2020); hence, we highly believe that this issue is related the sample size took from Latin America (33 cities), compared to Asia and Africa which hare represented by 71 cities each (see electronic supplementary information file for further details).

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**Figure 4:** Distribution of virtual water across selected cities of the Global South by continent (Africa, Asia, and Latin America).

Results (Fig.3 and 4) for the Blue water category shows that Asian and North African cities are the among the highest Global Southern cities that imports fresh water from the global economic market. For Asia, three Chinese cities have the highest quantities of imported water embedded within goods and services namely Beijing with 328.45 liters per capita/yr, followed by Guangdong with 267.42 liters per capita/yr, and Jiangsu with 248 liters per capita/yr. From North African region, we find Tunis (Tunisia) is associated with 314.65 liters per capita/yr, while Casablanca, Tangier and Laayoun (Morocco) are associated with the respected total embedded fresh water of 301.1, 285.6, and 251.65 liters per capita/yr. North Africa is considered a climate change hot spots (Diffenbaugh and Giorgi, 2012; Schmitz et al., 2013) with a strong temperature increase (Nashwan et al., 2019; Zeroual et al., 2019) and high drought risks (Hertig and Jacobeit, 2008), particularly there are greater climate vulnerabilities in term of water resources (Lionello and Scarascia, 2018; Tramblay et al., 2018) in Algeria, Egypt, Libya, Morocco, and Tunisia as highlighted by (Schilling et al., 2020) with major social implication (given the fact that all North African countries -except Algeria- are dependent on agriculture as the primary input for GDP and particularly employment, and any fluctuations may lead to social instability and most likely encourage climate immigration towards Europe). The combination of climate change and rapid population expansion in North Africa is extremely likely to exacerbate the already precarious water situation (Haddadin, 2001) paling countries belonging to this region among the highest countries with the highest Hydrological Water Stress Index (HWSI) and Social Water Scarcity Index (SWSI); therefore, this may explain why Norther African cities are purchasing goods and services from the global economic market with high embedded water quantities.

We know that the rainfall is projected to decrease (according to CMIP5 from the GCM) by -10% to -20% for large parts in North Africa (IPCC, 2013) while (Droogers et al., 2012) by simulating future water resources (until 2050) found that the region will decrease in water supply by -12% and an increase in water demand by +50%. This projections are confirmed via different approached namely by Global Climate Models (GCMs) as in (Collins et al., 2013), Regional Climate Models (RCMs) as in (Bucchignani et al., 2018) and statistical projections as in (Hertig and Jacobeit, 2008). However, it is important to highlight that human activities have had a far greater impact on North African aquifers than climate variability (Leduc et al., 2017; Lezzaik and Milewski, 2018), overexploitation has resulted in a reduction in groundwater levels in various Maghreb subregions during the last 50 years (Treidel et al., 2011; Zkhiri et al., 2019) this has also resulted in a decrease in the quality of water in certain aquifers of the region and put a heavy burden on water availability.

On the other hand, results for the Grey water category showed that Atolls (Maldives) have the highest virtual water consumption across all the selected cities with value estimated to 667.99 liters per capita/yr, the Maldives considering it’s geographical attributes it’s facing several environmental risks among them all water availability and food insecurity (Zubair and Nijamdeen, 2022) alongside to being the 1st South Asian tourism destination the city heavily relay on the global economic market to satisfy local development, local citizens and tourists requirement. Atolls is followed by the three Chinese’ major cities such as Beijing with 622.8 liters per capita/yr. Chinese cities represent a share of the top Global Southern cities’ freshwater footprint Guangdong with 516.64 liters per capita/yr, and Tianjin with 486.80 liters per capita/yr.

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**Figure 5:** Top 20 Global Southern cities with highest values of virtual water.

Decomposing the virtual water footprint of top 20 cities of the Global South with highest virtual water footprints (Fig.5) show uneven sectoral distribution of the virtual water footprint. For instance, Tunis (Tunisia) the “Food” sector account for 93% of the total freshwater footprint, followed by “Transport” with 3%, as stated earlier North African countries are extremely vulnerable to climate variabilities and fluctuated precipitation regimes (Prudhomme et al., 2014), and mostly their agriculture is qualified as “rain-fed” agriculture (Schilling et al., 2020); hence, North African cities tends to rely heavily on the global economic market for agriculture-related products to mitigate the impact of climate change and the local mismanagement of water resources. On the other hand, the sector of “Services” represents the bulk of the virtual water footprint for the city of Atolls (Maldives) by a share estimated to 70%, followed by “Food” sector with a footprint estimated to 10%. Not surprisingly, Maldives is a pure touristic country, and therefore it imports most of its touristic services, worldwide.

Considering the Grey water footprint, results showed that, unlike other cities virtual water distribution, Chinese cities are causing water pollution elsewhere, and the vast majority of this pollution is allocated to the “Transport” sector whereby, for instance, in Beijing represents 41.7% of the total grey water footprint of the city knowing that China detains the highest share (33.5%) of owning German (BMW) cars worldwide, followed by the USA with 13.2% (Statista, 2022), followed by “Food” with 28% knowing that China has experienced a crop failure which led to a significant rise in wheat imports, contributing to a doubling of global wheat prices (Sternberg, 2012), and “Energy” sector with 22% given the fact that China is currently under a major economic development and requires energy to support its growth (Lin and Wang, 2012; Yin and Lam, 2021).

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**Figure 6:** Top 20 Global Southern cities with highest values of virtual water decomposition by final major consumption categories.

Decomposing the water footprint by major final consumption categories and by income category show that almost the same sectoral decomposition by income class but not by type of virtual water. For instance, Lower Middle-Income Countries Grey virtual water is dominated by Transport sector with a share estimated to 48% of the total grey virtual water, followed closely by the Food sector with 23%. A switch in the flip is triggered, while LMICs cities grey virtual water is dominated by Transport sector, LMICs blue virtual water is dominated by the Food sector accounting for 43% followed by the Transport sector with 27%. Following the same structural decomposition of LMICs’ virtual water, Upper Middle-Income Countries (MICs) blue virtual water is by the Food sector (32%), followed by Energy (26%), and Transport (23%). On the other hand, UMICs Grey virtual water is dominated by Transport sector (with 34%), followed by Energy sector (with 23%), and Food with 22%. However, it is important to highlight that UMICs virtual water decomposition accounts higher values in the Services sector while in the LMICs was estimated to 1%, virtual water footprint in the UMIC is estimated to 4% of the total water footprint. This finding suggest that LMICs and UMICs are in different stages of economic development; hence, they requires different inputs from different sectors to satisfy their local growth requirements.



**Figure 7:** Global South’s virtual water decomposition by major consumption categories.

From a regional perspective (Fig.8), while decomposing the virtual water by continents results showed almost the same sectoral composition across continent whereby for the grey virtual water is mostly dominated by the transport sector, followed by the food sector. However, results also display that Asian cities are somehow having higher water footprints issued attributed to the services sector compared to African and Latin American cities. On the other hand, the blue water footprint across continent showed a major dominance of the food sector, followed by transport and energy. Notice that fundamental and systemic shifts are reshaping value chains, commerce, and financial flows as a result if the global energy revolution, and each country and thus each city will face unique energy-related challenges. With the value of fossil fuels is expected to decline in the near future, resource-rich countries of the Global South (such as Algeria, Libya, Nigeria, Venezuela, etc.) should anticipate the problem of “standard assets”. For instance, Algeria fossil fuels export constitute 96% of the total exports of the country with a share of 60% of the country’s GDP.



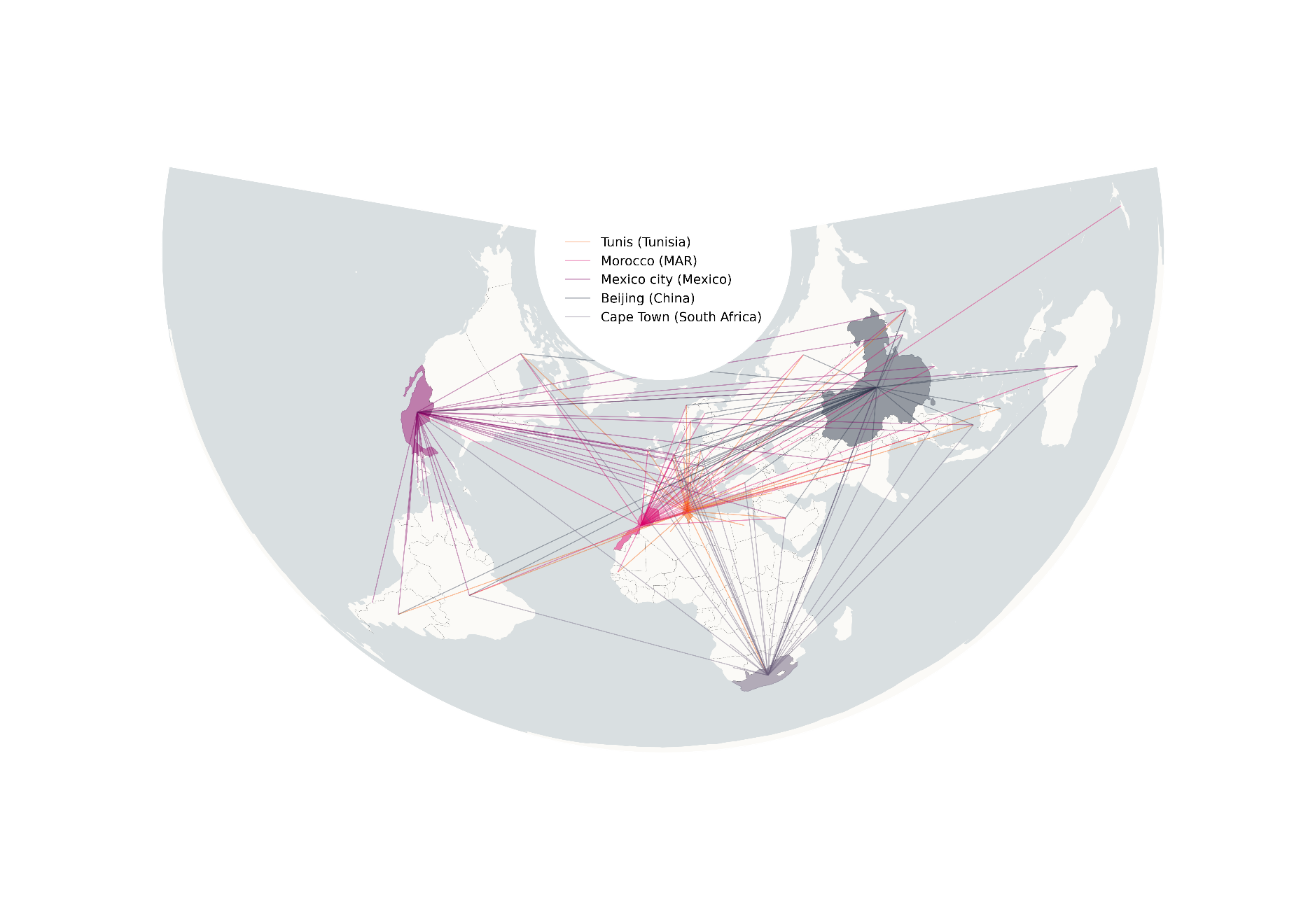
**Figure 8:** Global South’s virtual water decomposition by major consumption categories and by continent.

Decomposing the water footprint by major final consumption categories, major industrial sectors and income class. Results showed that almost the same distribution across sectors except for the services sectors counts higher percentages both in blue and grey water footprints in cities belonging to Upper Middle-Income Countries (UMICs). Overall, the sectoral decomposition of both water footprints are following the same pattern by major industrial categories except for Hotels & Restaurants sectors with account higher shares in UMICs compared to those of LMICs for the tertiary category, same applied for the Service sector in the light manufacturing category. According to Fig.9 we notice that the heavy industry category is dominated by the “Transport” sector with a share of 98%, followed by “Construction” sector with almost 2%. The light manufacturing sector is dominated by the “Food” sector which accounts for an average share of 78% of the total water footprint. On the other hand, primary industry category is dominated by the “Energy” sector representing a total share of 93% followed by “Goods” and “Commodities” with 7%. While the tertiary category is dominated by the “Services” sector with a share of 96% for cities belonging to Lower Middle-Income Countries (LMICs), and around 75% for cities belonging to Upper Middle Income Countries (UMICs).



**Figure 9:** Global South’s virtual water decomposition by industrial sectors and income classes.

Because of the huge distances and accompanying expenses, real water trade between water-rich regions and water-poor regions is impracticable nevertheless trading water embedded in goods and services in feasible (Hoekstra, 2003). As such, cities of the North African region (Tunis, Algiers, Marrakesh, and Tangiers) are importing water-intensive commodities (goods and services) from geographically diverse water-abundant countries which can provide water security and buffering cities of the Global South against climate change impacts at the local scale and adapt to drought episodes though the purchase of products and services with water-demanding commodities instead of producing them locally. (Allan, 1998, 1997) results showed that Middle Eastern countries were importing commodities with higher embedded water which helped in flattening water shortages in the region, and reduce the likelihood of a long-predicted major conflicts over water.



**Figure 10:** Top 40 locations of Global South’s virtual water imports from the global economic market.

* 1. **Virtual water policy: Hotspots and architectures of handicaps**

Water is not only a unique problem, but instead it is a part of a holistic complex system denoted Water-Food-Energy nexus. Therefore, actions that are placed on water are also affecting the other two sub-systems (energy and food).

Virtual water in the “Food” category include those from electricity generation, solid waste treatment,

Virtual water from “transport” category include the production and maintenance of private cars

The Australian Industry Group (AIG) further discusses

Virtual water from “Energy” category include the

1. **Conclusion**

Water is not unequally distributed across countries and regions, and its availability is highly dependent on the future pathways of Earth’s climate system. Moreover, most of the water humanity is currently consuming is invisible by nature. It is embedded within goods and services purchased from the global economic market. Hence, it is also vital to be prepared to manage the virtual part of water while making fundamental decisions or evaluating future choices and strategies.

Health problems and environmental risks can be abstained.

Water is not a singular problem, but rather it manifest in a highly complex system merging food security, energy accessibility and social stability.

Cities of the Global South can import goods and services that require massive water input from the global economic market in order to amortize the current and future climate impacts on the local water sources.

Results showed that North African region while its people are being on the frontlines of climate change impacts, their imports regime is shifted towards products and services with highest embedded virtual water for soften the burden of water scarcity. One important research question would be to study the impacts of such disruption with the regional migration from the South towards the North.

For future research, we will couple the future climate scenarios driven from the Global Climate Models (GCMs) established by Coupling Models Inter-comparison Project (CMIP) and future imports of the Cities of the Global South using Partial Convolutional Neural Networks (PCCN) to examine the possibilities and probabilities if Global Southern’ cities will adjust their imports pattern towards a more sustainable and climate neutral consumptions.

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