Journal of Hydrology 589 (2020) 125171

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Dynamics of virtual water networks: Role of national socio-economic indicators across the world

Goutam Konapala[a,b], Ashok Mishra[b,*]

[a] Environmental Sciences Division, Oak Ridge National Laboratory, Clemson, SC 29634, United States
[b] Glenn Department of Civil Engineering, Clemson University, Clemson, SC, 29634, United States

ARTICLE INFO

This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Virtual water networks
Sustainability
Information theory
Hydro-economics

ABSTRACT

Intensified water usage due to rapid industrialization is often dictated by economic policies based on monetary growth rather than sustainable use of environmental resources. In addition, interdependence within economic sectors further interweaves water usage through product transactions, which further makes it difficult to quantify the dynamics of hydro-economic systems at regional, national and global scale. In this study, we investigated the dynamics of domestic virtual water networks (VWN) of 189 countries based on concept of information theory by quantifying network metrics that describes VWN flow capacity, robustness, efficiency and flexibility. These networks represent virtual water interconnected through economic sectors within a specified country built based on environmentally extended multi region input output (EE-MRIO) approach. We further estimated trends associated with network metrics, as well as coupling intensity between metrics with respect to socio-economic indicators, such as, population, Gross Domestic Product (GDP) and Gross National Income (GNI). It was observed that capacity and flexibility of VWNs are strongly and positively correlated indicating that a high capacity VWN can be more flexible. Our results also indicate that, in general a higher percentage of developing countries (i.e. both least developing and developing nations) have exhibited increasing trends in capacity, robustness, efficiency and flexibility of VWN compared to developed nations. It was revealed that the dynamics of VWNs are positively coupled with socio-economic growth for few countries, which indicates the sustainable behavior of VWN with socio-economic growth. Our results argue that the information theory-based metrics by embedding water footprints can holistically capture sustainability aspect of the VWN dynamics.

1. Introduction:

Improvement in living standards over past few decades have resulted in an increase in consumption of economic goods as well as natural resources leading to significant increase in carbon emissions. Many studies highlighted that economic growth and human well-being need to be decoupled from escalating resource use and to avoid negative environmental impacts in order to secure long-term socio-environmental sustainability (Charter and Tischner, 2017). For example, global water resources are under stress due to population explosion, rapid economic growth and better quality of life. Clean water resources are an essential part of world for sustainable livelihood as well as socio-ecosystem sustainability (Veettil and Mishra, 2020), and it is included as one of United Nations Sustainable Development Goals (UN, 2014). However, sustainable management of water resources is quite complex (Konapala and Mishra, 2020; Veettil and Mishra, 2020) as water is utilized in various activities, such as direct consumption by various sectors, such as, agriculture and domestic sectors (Veettil and Mishra, 2020), import of economic goods, and distribution of water through multiple linkage between the sectors (Dalin et al., 2012; Dalin et al., 2012; Pfister et al., 2011; Flach et al., 2016). As a result, water consumption among different economic sectors within a country can be represented as a network comprised of self-connections (direct consumption) and inter connections (indirect consumption) introducing the notion of virtual water flow (Allan, 1998; Chapagain and Hoekstra, 2004; Hoekstra et al., 2011; Konar et al., 2011). Therefore, the variability in water consumption in one sector may influence water utilization across other sectors. This would eventually result in a complex network of complicated supply chain spanning over different sectors. Given this inherent complexity, more holistic approaches to quantify virtual water networks and corresponding water use are needed (Chen et al., 2014; López-Ridaura et al., 2002; Konar et al., 2011).

In light of complexities involved, researchers have been exploring new directions for accounting consumption as well as distribution of

* Corresponding author.
E-mail address: ashokm@g.clemson.edu (A. Mishra).

https://doi.org/10.1016/j.jhydrol.2020.125171

Available online 12 June 2020
0022-1694/

water embedded in trade and their system level dynamics through interdisciplinary network approaches. For example, some of these studies investigated complex global water network primarily as agricultural water networks adopting a bottom-up approach (Suweis et al., 2013; Konar et al., 2011; Carr et al., 2012; D'Odorico et al., 2012; Tamea et al., 2014; D'Odorico et al., 2012). The bottom-up approach estimates virtual water content by accounting water used to produce specific commodity and further aggregates them into national water accounts. A key advantage of the bottom-up approach is that it provides total water content embedded in commodities directly used by general public, e.g., water embodied in rice, wheat, coffee Hoekstra and Chapagain (2006). However, it is often difficult to explore all economic outputs using this approach (Yu et al., 2013; Chen and Chen, 2013). In addition, this approach does not trace virtual water flows through supply chain resulting in underestimation of the embedded water content in a bottom-up approach (Feng et al., 2011; Kitzes, 2013). More detailed analyses have focused on importance of commodities to quantify virtual water and aspects of embodied water sources (Lenzen, 2009; Daniels et al., 2011; Mubako et al., 2013), as well as scarce water resources (Lenzen et al., 2013) through environmentally extended input-output analysis [EE-IOA], which is a top down approach. In this approach, total water content is calculated by locating entire supply chain at a global scale and hence avoids underestimation of water embedded in a trade network. This approach has been employed to analyze total water profiles at regional and global scale (Chen and Chen, 2013; Wiedmann and Lenzen, 2018; Holland et al., 2015; Duan and Chen, 2017; Guan and Hubacek, 2007; Zhao et al., 2010).

The above-mentioned studies investigated virtual water transfers among nations and provided several important insights, however they have not addressed whether the temporal dynamics of these virtual water networks are sustainable with respect to socio-economics sectors that are associated with evolution of VWN network. For instance, a VWN is shaped by virtual water flows within the socio-economic system, which needs to be consistent in the long term under varying conditions. Tracking of virtual water fluxes and pathways within this system will facilitate regulation of virtual water circulation and adjustment of the sector's responsibilities (Fang and Chen, 2015; Guo et al., 2016).

Multiple studies applied the information theory based approaches to investigate hydroclimatic processes (Mishra et al., 2009; Mishra et al., 2011; Konapala et al., 2017). Information theory-based network analysis can also quantify complexity through metrics such as capacity, efficiency, flexibility and robustness of a network (Ulanowicz, 2004). Some of these studies investigated whether water resources at watershed scale (Fang and Chen, 2015; Li et al., 2009) and city scale (Bodini et al., 2012) are sustainable using these metrics. However, these approaches have not been explored to investigate sustainability of domestic virtual water networks and their evolution over years at a global scale.

In addition to that, various water intensive economic activities such as agriculture (Tamea et al., 2014; D'Odorico et al., 2012), construction (Kucukvar and Tatari, 2013), petroleum (Scown et al., 2012; Wu et al., 2009) and textiles (Chapagain et al., 2006; Wang et al., 2013) are often dictated by economic policies based on monetary growth rather than sustainable use of environmental resources. Therefore, it is necessary to investigate association of socio-economic factors with sustainable evolution of these virtual water networks. However, to the best of our knowledge, we are not aware of such studies that investigated the relationship between information theory metrics of capacity, efficiency, flexibility and robustness with socio-economic factors such as Gross domestic Product (GDP), Gross national income (GNI) and population. One way to quantify this association is through computing the coupling intensity between evolution of these entropy-based metrics and socio-economic growth factors (Tapio, 2005). The concept of coupling intensity was found to be a reasonable approach to investigate the potential influence of socio-economic growth factors (Andreoni and Galmarini, 2012; Zhang, 2000; Mardani et al., 2019). Based on these perspectives, we aim to answer the following questions through this study:

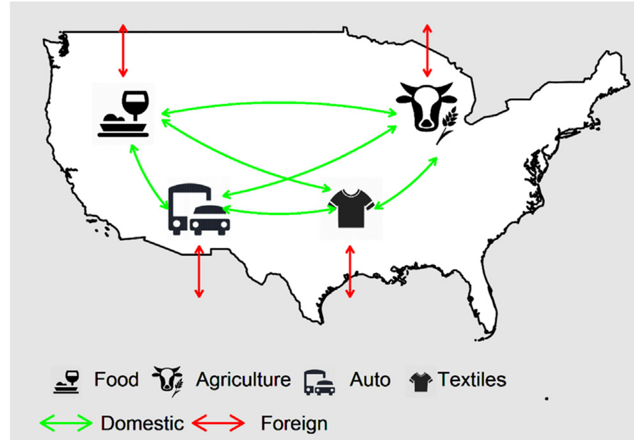

Fig 1. A hypothetical virtual water configuration for USA between economic sectors. The green colored arrows represent domestic virtual water transactions, whereas red colored arrows represent foreign virtual water trade. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Classification of coupling characteristics based on CI (Liang et al., 2014).

CI value	Coupling characteristic
CI < 0	Negative coupling
0 < CI < 1	Relative coupling
CI > 1	Absolute coupling

(1) How do temporal dynamics and spatial distribution of information theory based dynamic metrics (i.e., capacity, flexibility, efficiency, and robustness) vary for 189 countries across the world?
(2) How do the virtual water network dynamics and their relation to socio-economic growth differ among the developing, developed and least developed nations?

Beside this introduction, the manuscript is organized in to four sections: (i) Section 2 provides an overview of the data and methodology used to characterize the virtual water network within a country; (ii) The results and discussion associated with information theory metrics, non-parametric trend estimation and coupling intensity are provided in Section 3 and, (iii) and the conclusions and the future scope of the work are provided in Section 4.

2. Data and methodology

2.1. Data description:

The concept of environmentally extended input-output model (Kitzes, 2013) was used for constructing an interdependent VWN. The input-output (I-O) model structure represents financial transactions between economic sectors by maintaining an account of sale and purchase of products. It is well established that the production of economic goods consumes natural resources, therefore it is possible to evaluate natural resource utilization for goods and service produced using I-O scheme. This scheme generates interrelationships among sectors in a single geographical region.

Virtual water network based I-O model is derived based on the economic I-O modeling framework by incorporating statistical data of

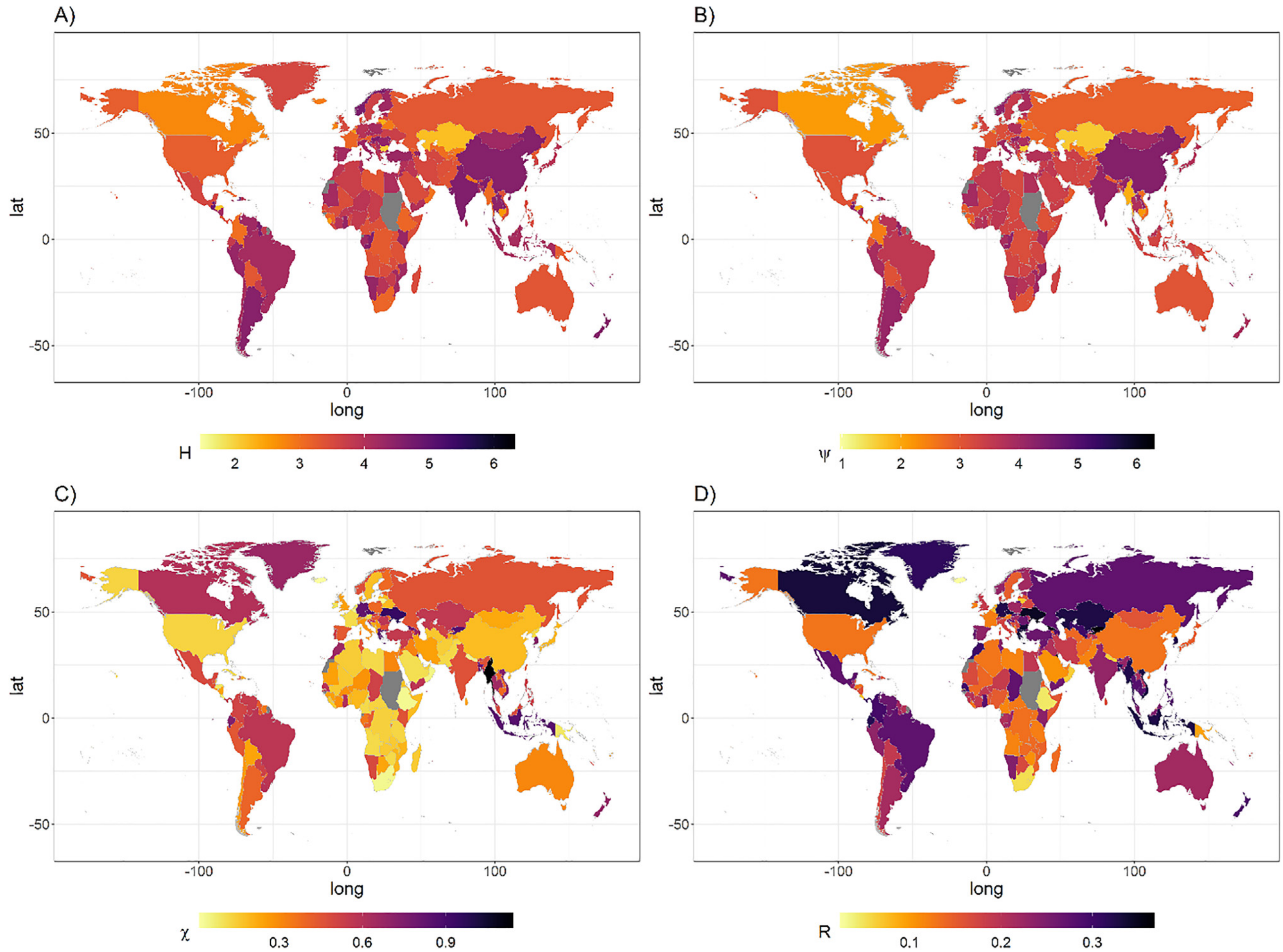

Fig 2. Spatial distribution of temporal means of a) capacity (H), b) flexibility (ψ) , c) efficiency (χ), d) robustness (R) for the 189 countries between 1990 and 2015.

water consumption for individual sectors. Several global multi-regional input-output databases are available, for example, WIOD database (http://www.wiod.org/new_site/data.htm), Global Trade Analysis Project (GTAP, https://www.gtap.agecon.purdue.edu/), EORA database (http://www.worldmrio.com/), and EXIOPOL (http://www.feem-project.net/exiopol/). These data sets provide water consumption information along with Multi-region Input Output (MRIO) tables. However, only EORA database (Lenzen et al., 2012; Lenzen et al., 2013) provides information for 189 countries with water data including the (i.e. stream flow) and green water (evapotranspiration and soil water content) components, and each country includes 26 economic sectors. The EORA database contains time series of MRIO tables from 1990 to 2015. Water data from EORA database are derived based on the calculations of water footprints conducted by Mekonnen and Hoekstra (2011). Throughout our study, we explicitly consider the sum of blue and green water (evapotranspiration and soil water content) as total water content in our analysis (Veettil and Mishra, 2020). Now that general structure of EE-MRIO and data source is established, we describe the methodology adopted to convert economic transactions to equivalent water transfers.

To quantify the potential role of socio-economic growth on VWNs, we extracted country level data on gross domestic product (GDP), gross national income (GNI) (based on 2011 price in US $), and population (POP) data from World Bank data repositories. The GDP measures a country's growth with respect to production, whereas GNI measures a country's growth with respect to its income.

2.2. Methodology

2.2.1. Virtual water network (VWN)

The VWN was constructed by integrating two components, where individual economic sector is expressed as a node, and links between nodes represent volume of virtual water flow between sectors within a country. The virtual water flows between sectors for a given country was calculated by multiplying economic transactions between sectors and virtual water intensity of corresponding sector. The network connections are thus determined by trade relationships and weight of each connection is quantified by volume of virtual water embodied in the sector. For a detailed explanation of MRIO, the reader is referred to Lenzen et al., (2010).

The VWN is derived by estimating the total economic output of any given sector i as shown in equation (1).

$$X_i = Z_{ij} + y_i \tag{1}$$

Eq. (1) represents a basic input-output model, where X_i is the total output of sector i, Z_{ij} is the flow from sector i to sector j, and y_i is final demand of sector i based on constant price of 2011 US dollar. In this MRIO database, the supply chain for a country is divided into 26 sectors. Therefore, sectors i and j vary from 1 to n = 26.

In the next step, water intensity for each sector is calculated as

$$WI_i = X_i / W_i \tag{2}$$

where, WI_i is water use intensity in sector i and W_i is total water consumed within a sector. Now the intermediate matrix of virtual water Input-Output model (F_{ij}) can be estimated as

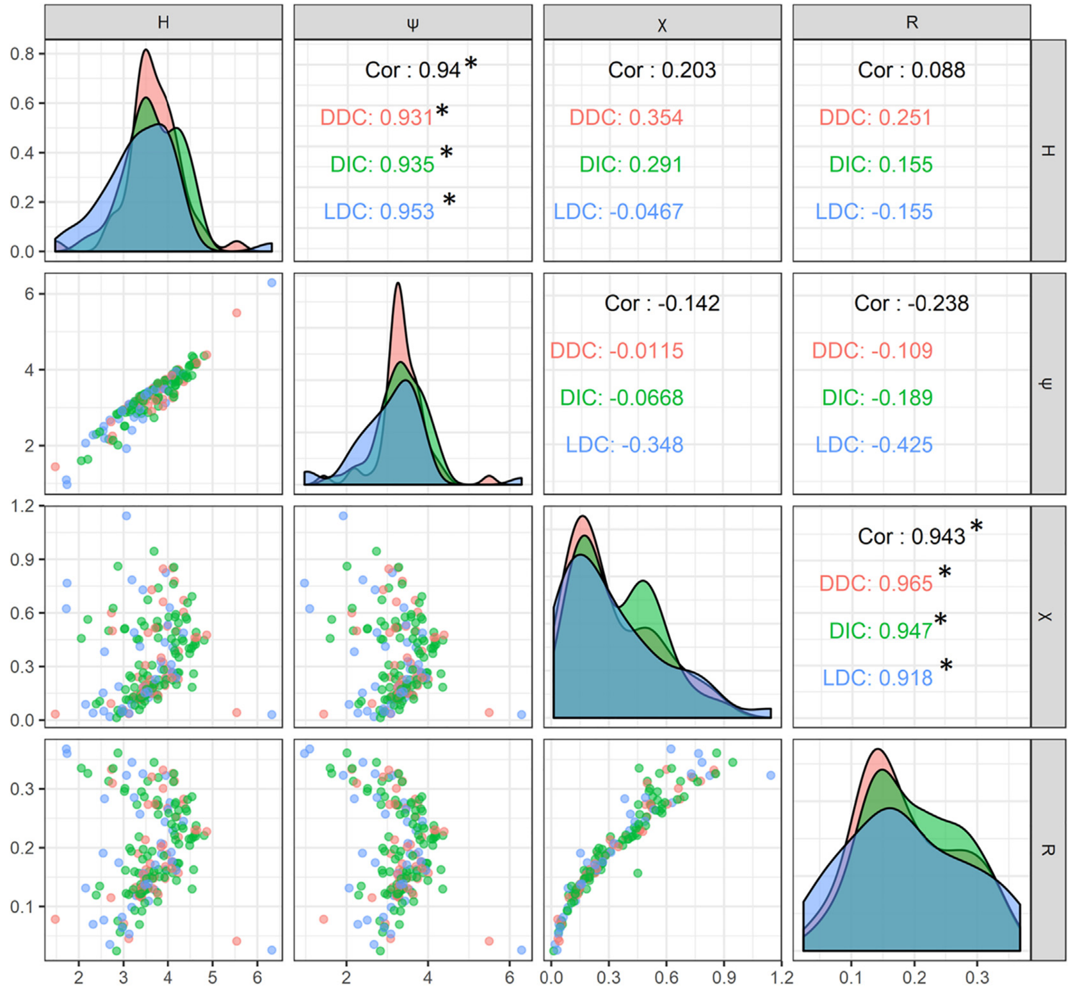

Fig 3. Correlogram among sustainability metrics and their distributions based on development classification i.e. Least developed countries (LDC), Developing countries (DIC) and developed countries (DDC). The * denotes that the correlation between considered two variables is statistically significant ($p < 0.05$) using *t*-test. [Note: This figure is arranged in the form of a matrix with scatterplots in the lower diagonal, densities on the diagonal and correlations written in the upper diagonal].

$$F_{ij} = WI_i * Z_{ij} \tag{3}$$

where, F_{ij} reflects virtual water trade hidden in production transactions within a socio-economic system. A steady-state system is reached for individual sector of a system, when total inputs are equivalent to total outputs including both inter-sectoral flows and boundary flows as

$$\sum_{i=1}^{n} F_{ij} + IM_j = \sum_{i=1}^{n} F_{ji} + EX_j \tag{4}$$

where boundary flows IM_j and EX_j are virtual water flows going in (i.e. imports) and going out (i.e. exports) through a boundary. To illustrate this concept, we provide a hypothetical virtual water transfers between the sectors in case of USA (Fig. 1). In the figure, the F_{ij} represents domestic virtual water transfers (within USA) represented by green arrows, whereas, export and import of virtual is represented as red arrows. In this study, we focused only on domestic sectoral flows within a given country. Overall, 189 countries are included in this study.

2.2.2. Information theory-based network analysis:

The information theory-based metrics can be used to quantify network flows of material, energy, or information. The concept has been previously applied to ecological discipline (Ulanowicz and Wolff, 1991; Mukherjee et al., 2015). Due to significant topological and dynamic similarities across flow systems (Goerner et al., 2009; Huang and Ulanowicz, 2014), the same concept has been applied in quantifying different properties of virtual water networks (Ulanowicz et al., 2009; Kharrazi et al., 2017). This approach is rooted in Shannon's definition of entropy (Shannon, 1948). The concept of entropy has been previously applied to investigate variability (dynamics) associated with hydro-climate variables (Mishra et al., 2009; Li et al., 2012; Mishra and Coulibaly, 2010; Mishra et al., 2011).

Entropy (H) is a measure of system uncertainty (Shannon, 1948). This uncertainty can further be divided into two components as $H = \chi + \psi$. Where χ represents the uncertainty that is represented by the network structure (average mutual information) and ψ is the residual (conditional entropy) uncertainty. In the context of a networked system, these variables can be described as below (Ulanowlcz and Norden, 1990):

$$H = -\sum_{i,j} \frac{F_{ij}}{F_{..}} log \frac{F_{ij}}{F_{..}} \tag{5}$$

$$\chi = \sum_{i,j} \frac{F_{ij}}{F_{..}} log \frac{F_{ij} F_{..}}{F_{i.} F_{.j}} \tag{6}$$

$$\psi = -\sum_{i,j} \frac{F_{ij}}{F_{..}} log \frac{F_{ij}^2}{F_{i.} F_{.j}} \tag{7}$$

where F_{ij} is the virtual water flow between any two sectors i to j, $F_{..} = \sum_{ij} F_{ij}$ is the sum of virtual water flow between all the nodes (i.e.,

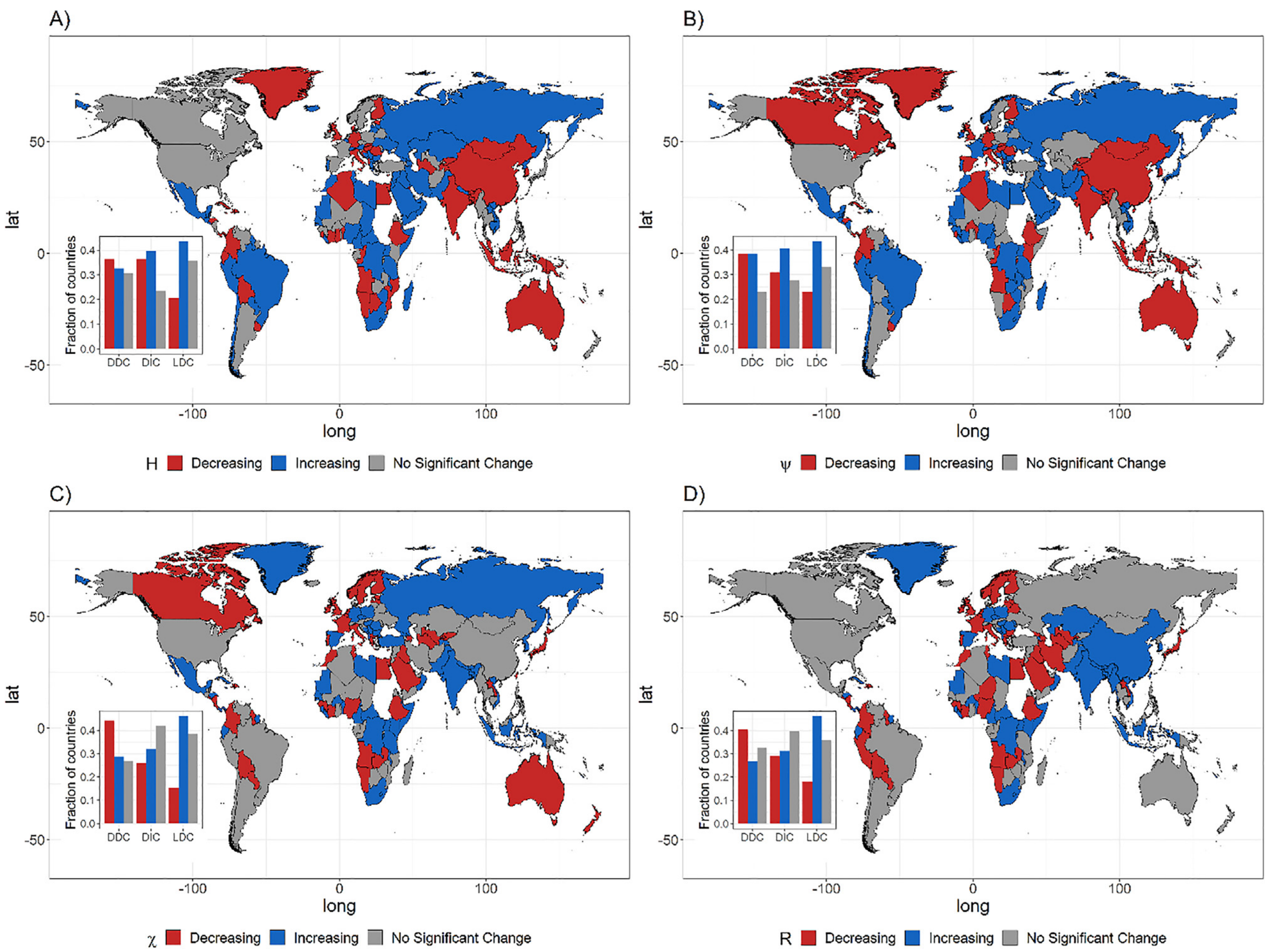

Fig 4. Spatial global maps of statistically significant trends exhibited by a) capacity (*H*), b) flexibility (ψ), c) efficiency (χ), d) robustness (*R*) in 189 countries between 1990 and 2015. In the inset of each map, fractions of countries exhibiting trends by development classification are provided.

across all the 26 sectors). Total virtual water flowing from any sector *(i)* is represented by $F_{i.} = \sum_j F_{ij}$ and $F_{.j} = \sum_i F_{ij}$ is the total virtual water flowing in to any given sector *(j)*.

The above analysis can be applied to *VWN*. Countries with $H = 0$ represents virtual flow of water from only one to another sector, and all other flows equal to zero. Whereas, a maximum value of *H* represents a uniform exchange of virtual water between all the sectors. Hence, low values of *H* indicate that VWN have low flow capacity, whereas higher values of *H* indicate a high virtual water flow capacity. Therefore, *H* is a non-negative number representing capacity of a VWN. The average mutual information (χ) of a system (i.e., VWN) quantifies the efficiency of the network's capacity over a longer period of time. A VWN with higher efficiency value indicates that the flows within the network are more concentrated to a limited number of links (pathways). In other words, in highly efficient networks fewer numbers of nodes controls VWN the flow capacity. However, if the key nodes within a highly efficient VWN fail, then there is higher chance that the flow within the VWN will be limited leading to less flexibility. The conditional entropy (*ψ*) represents flexibility of the VWN by capturing the residual uncertainty that may arise due to any uncertainty in virtual flow between the nodes. Higher diversity and connectivity of a VWN guarantees that the system will reserve diverse actions in case of disruption of nodes or linkages. Hence, the higher value of flexibility for a given VWN indicates that the networks are flexible to absorb external (internal) shocks.

Intuitively, networks having more diverse connections are more flexible to reroute flows in case of disruptions. A more efficient network relies on fewer key nodes (sectors) that can be used for growth and development. To determine the relationship between the efficiency and capacity, the relative order for a given system is defined as (Ulanowicz et al., 2009):

$$\alpha = \frac{\chi}{H} \tag{8}$$

where $0 \leq \alpha \leq 1$.

The robustness definition proposed by Ulanowicz et al. (2009) used in this study is a balance between system flexibility and organization. The robustness (Ulanowicz, 2011) of a system can be calculated by multiplying the relative order and Boltzmann measure, which is given by negative log of α:

$$R = -\alpha\log(\alpha) \tag{9}$$

Unlike other metrics, the maximum value of *R* is 1/e (e is the Euler's number) and R values closer to 1/e value indicate more robustness in a virtual water network for a given country. As highlighted before, the optimum state of R is a tradeoff between efficiency and flexibility metrics.

2.2.3. Assessment of trends

Trends associated with capacity, efficiency, flexibility and robustness based on individual countries were investigated using Theil-Sen slope method (Thiel, 1950; Sen, 1968), and their statistical significance were assessed using the Mann-Kendall statistical test (Hamed and Rao, 1998). A pre-whitening method (Yue and Wang, 2002) was applied to remove possible serial correlation in the time series. This statistical

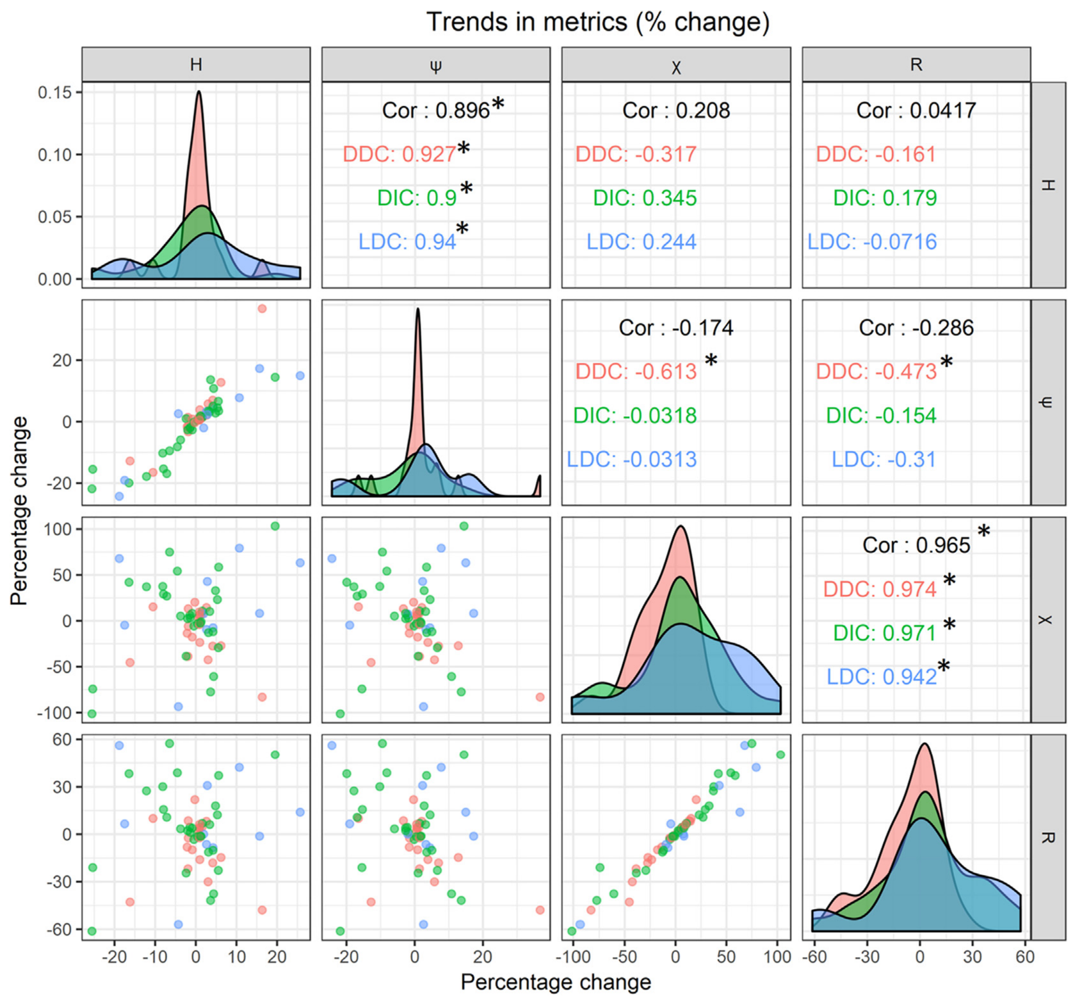

Fig 5. Same as in Fig. 3, but for percentage trends estimated by Theil-Sen slope method.

significance test is nonparametric and makes no assumptions regarding the marginal probability distribution of data. A 5% significance level was applied in all significance tests, so that p-values > 0.05 were deemed to be insignificant.

2.2.4. Quantification of the association of socio-economic factors with VWN

Various water intensive economic activities such as agriculture (Tamea et al., 2014, (D'Odorico et al., 2012), construction (Kucukvar and Tatari, 2013), petroleum (Scown et al., 2012; (Wu et al., 2009) and textiles (Chapagain et al., 2006; Wang et al., 2013), are often dictated by the economic policies. Therefore, it is necessary to investigate the association between socio-economic factors and sustainable evolution of these VWNs. We investigate this association by quantifying the coupling behavior of network metrics with socio-economic factors, such as, Gross domestic product, (GDP), Gross National Income (GNI), and population using Coupling Index (CI) (Tapio, 2005). The CI reflects responsiveness of metrics to unitary change in socio- economic factors over a period of time. CI is calculated (Table 1) by dividing relative percentage change of network metrics (Δm) with relative percentage change of socio-economic indicators (ΔSEI) as

$$CI = \frac{\Delta \mathrm{m}}{\Delta \mathrm{SEI}} \tag{10}$$

Negative coupling indicates that these metrics decreases with increase in socio-economic indicators. Whereas, absolute coupling indicates that these metrics have grown more rapidly than socio-economic indicators. Finally, relative coupling indicates that the metrics are increasing with an increase in socio-economic indicators but not growing as rapid as the socio-economic indicators in study (Liang et al., 2014). The percentage changes are estimated from Theil-Sen's slope method and only statistically significant changes are discussed throughout this article.

3. Results

3.1. Spatial distribution of average network metrics:

The spatial distribution of temporal means of four metrics: (a) capacity (*H*), (b) flexibility (ψ), (c) efficiency (χ), and (d) robustness (*R*) derived based on a time period 1990–2015 for 189 countries are shown in Fig. 2. In case of capacity metric (Fig. 2a), higher magnitude was observed for most of the countries located in South America, eastern Asia, western part of Europe, as well as few countries located in Africa. Most of the countries show higher flexibility similar to capacity metric as observed in Fig. 2b. Even in this case, South American countries have shown relatively higher flexibility values, along with countries in eastern Asia, Western part of Europe and countries scattered across Africa, which suggests a similar spatial pattern as shown in the case of capacity metric (Fig. 2a). Even though, many countries have witnessed higher capacity, it does not always translate to higher efficiency (Fig. 2b). Countries located in South America have shown relatively higher efficiency values, along with Thailand and Malaysia in South East Asia, Germany and Ukraine in Europe and few countries in the Africa. Finally, the robustness metric (Fig. 2d) indicates that regions

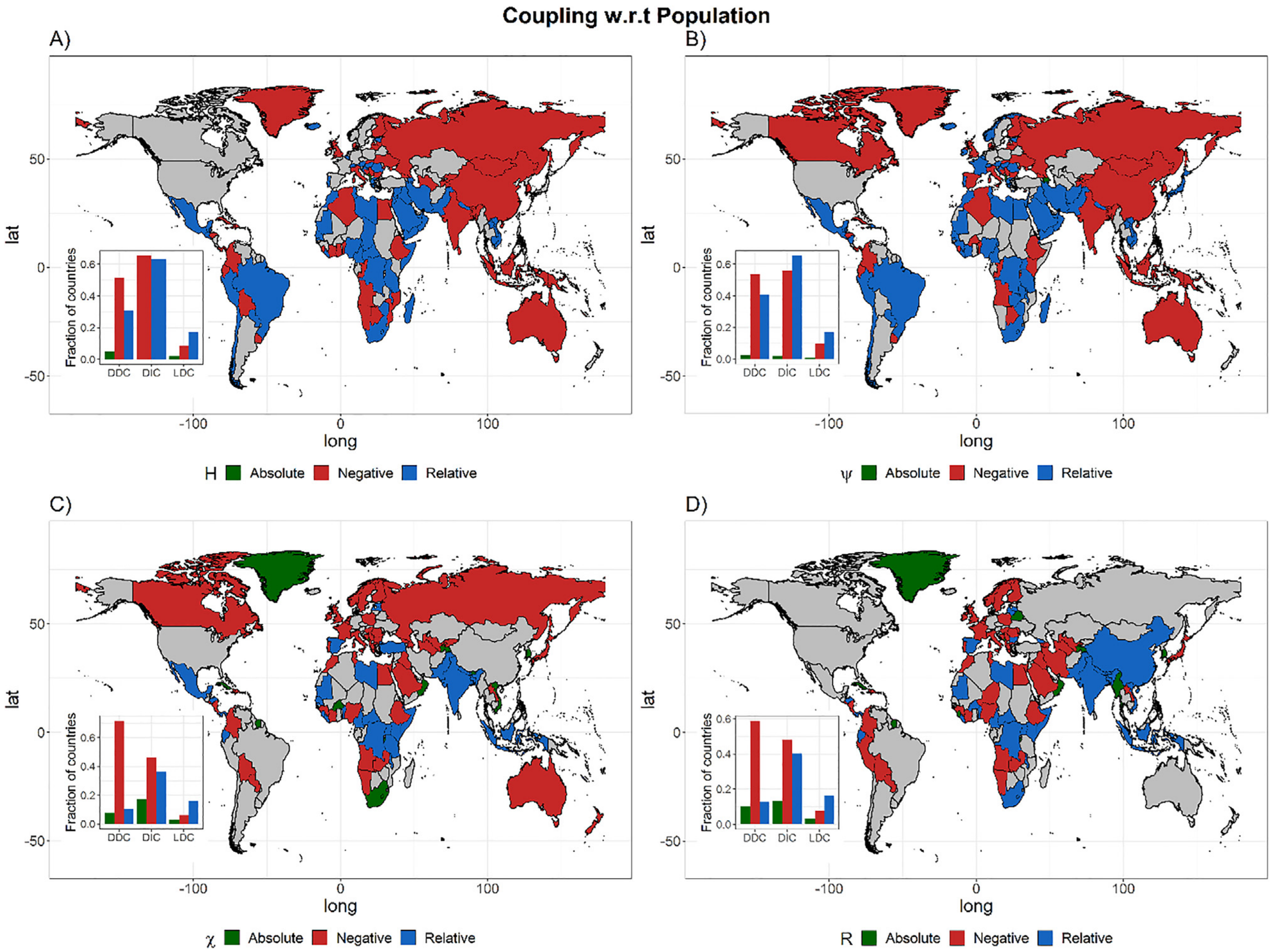

Fig 6. Global maps of statistically significant coupling behavior exhibited by a) capacity (*H*), b) flexibility (ψ), c) efficiency (χ), d) robustness (*R*) in 189 countries between 1990 and 2015 with respect to population. In the inset of each map, the fraction of countries exhibiting coupling behavior by development classification is displayed.

with higher efficiency and flexibility values, likely to have higher robustness (R) values. Most of South American countries have relatively higher values of efficiency and flexibility, therefore robustness values likely to be higher for these countries. Similarly, South East Asian countries, Germany, Ukraine and Italy in Europe, Mexico and Canada in North America have exhibited more robustness in domestic VWNs.

The association between network metrics and their distributions was carried out for Least developed countries (LDC), Developing countries (DIC) and Developed countries (DDC) based on correlogram analysis (Fig. 3). It was observed that high correlation exists between capacity and flexibility metrics, which suggests that in most of the countries, higher capacity is associated with higher flexibility irrespective of their development status. However, a clear pattern was not observed in the case of capacity's association with efficiency as well as robustness. Overall, it was observed that capacity is positively associated with flexibility, whereas, robustness is positively associated with the efficiency in case of domestics VWNs.

3.2. Trend analysis of network metrics of VWN

The spatial global maps of statistically significant trends exhibited by (a) capacity (*H*), (b) flexibility (ψ), (c) efficiency (χ), and (d) robustness (*R*) for 189 countries is shown in Fig. 4. A high value of H represents the higher capacity of a VWN of a system, whereas as χ shows the network's capacity to perform in an efficient and well-organized way over the long-term, higher values of ψ indicates more flexible under shocks. In the inset of each map, the fraction of countries exhibiting trends by development classification is provided. In the case of capacity (Fig. 4a), the Eastern Asia, Australia, South western part of Africa, Southern Europe and Northern parts of South America witness a significant decreasing trend. Whereas, an increasing trend was observed for the domestic capacity for countries located in Northern Asia, Middle East, Central Africa, Central America and Eastern South America. The higher fraction of LDC witness significant increase in capacity, which is followed by DIC. Also, a smaller number of LDC witness decreasing capacity. In case of flexibility (Fig. 4b), the Eastern Asia, Australia, South western part of Africa, Southern Europe and Northern parts of South America witnessed a significant decreasing trend. Whereas, an increasing trend was observed in Northern Asia, Middle east, Central Africa, Central America and Eastern South America. It was observed that the LDC followed by DIC has a higher fraction of countries with significant increase in flexibility. Also, a smaller number of countries have decreasing flexibility pattern in case of LDC. Capacity and flexibility have similar spatial patterns. However, the changes in efficiency (Fig. 4c) have a different pattern. South eastern Countries, central Africa and Eastern Europe have exhibited increased efficiency. Whereas, Western Europe, southern Africa and few countries located in the South America witness a decrease in efficiency.

It was observed that (inset figures) the LDC followed by DIC have a higher fraction of countries with significant increase in efficiency. Also, a smaller number of countries have decreasing efficiency in case of LDC. Changes in robustness have exhibited similar spatial pattern as changes

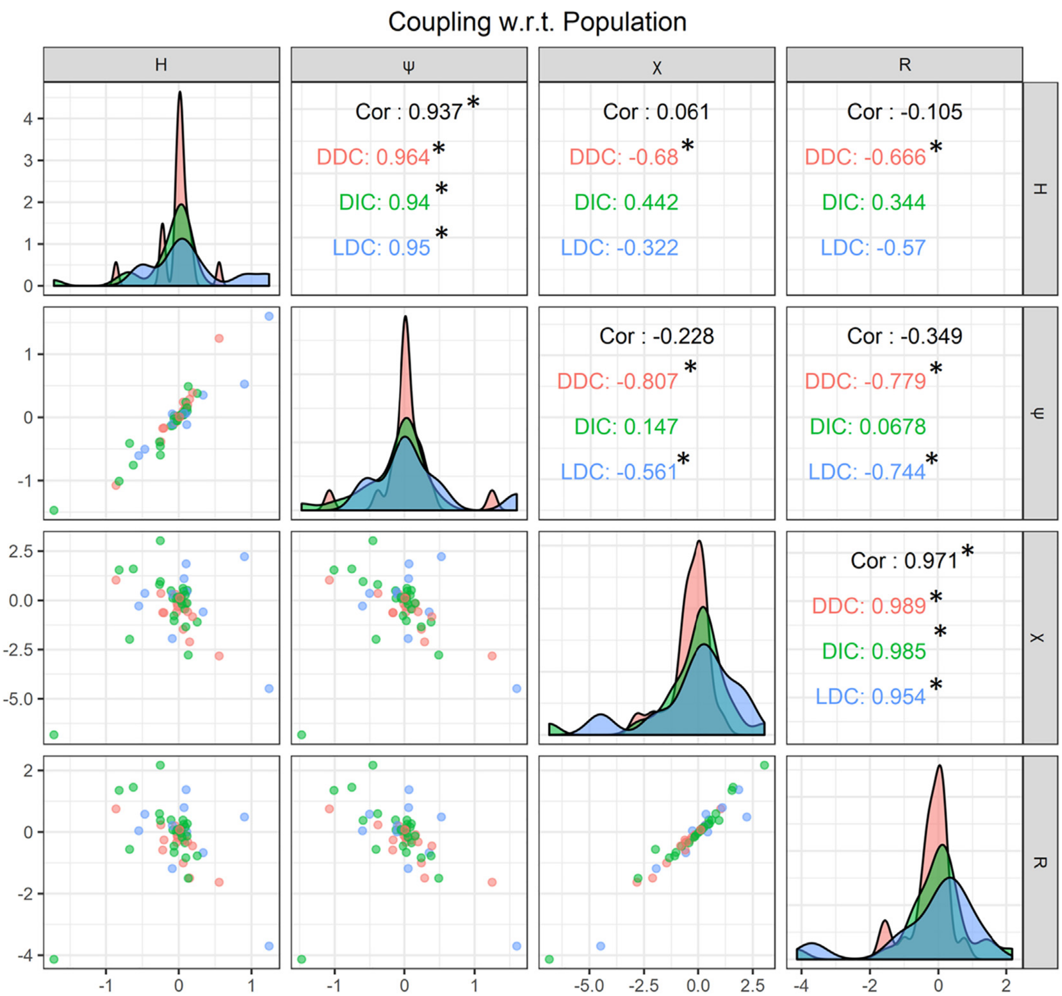

Fig 7. Same as in Fig. 3, but for coupling intensity of capacity (*H*), flexibility (ψ), efficiency (χ), robustness (*R*) with respect to population.

in efficiency. Overall, it was observed that least developing countries have shown more significant increasing trends than decreasing trends based on all the selected metrics followed by developing countries. Like Fig. 3, it was observed that a strong positive association exists between changes in capacity (robustness) and flexibility (efficiency) irrespective of the country's development classification (Fig. 5). The probability distributions for the four metrics (shown in the diagonal panel) highlight that LDC has a fatter tail at the ends. This indicates that VWN for the least developing countries are becoming sustainable (unsustainable) at a faster rate in comparison to developing and developed countries. Whereas, DDC has a higher density around zero indicating less change in highly developed countries. DDC countries has a more established supply chain networks compared to the DIC and LDC (Vachon and Mao, 2008; Kagawa et al., 2015). Therefore, VWN which are associated with the supply chain networks are less likely to change as they are already well established. However, in LDC countries, supply chain networks relatively newer and less mature compared to the DDC and DIC and hence they are more likely to change.

3.3. Association of socio-economic factors with the VWNs

We investigated the coupling behavior of the network metrics with respect to the socio-economic factors, such as, Gross domestic product, (GDP), Gross National Income (GNI), and population using Coupling Index (CI) (Tapio, 2005). The CI reflects the responsiveness of metrics to unitary change in socio economic factors over a time period. As highlighted before, negative coupling indicates that these metrics decreases with the increase in socio-economic indicators. Absolute coupling suggests that the metrics have grown more rapidly compared to the socio-economic indicators. Whereas, relative coupling indicates metrics are increasing with an increase in socio-economic indicators, but at a slower rate compared to the socio-economic indicators (Liang et al., 2014).

3.3.1. Population

Spatial global maps of statistically significant coupling behavior exhibited by (a) capacity (H), (b) flexibility (ψ), (c) efficiency (χ), and (d) robustness (R) for 189 countries with respect to the population are shown in Fig. 6. In case of capacity (Fig. 6a), the Eastern Asia, Australia, South western part of Africa, Southern Europe and Northern parts of South America have exhibited negative coupling with respect to population indicating that the capacity decreases along with the increase in population. Whereas, relative coupling is observed in Northern Asia, Middle east, Central Africa, Central America and Eastern South America. This indicates that in these countries, capacity is increasing with an increase in population but not growing as rapid as the population in study. Lesser number of regions have shown absolute coupling. In case of flexibility (Fig. 6b), the Eastern Asia, Australia, South western part of Africa, Southern Europe, Canada and Northern parts of South America have exhibited negative coupling with respect to the population, which suggests that the flexibility decreases along with the increase in population. Whereas, relative coupling is observed in Northern Asia, Middle east, Central Africa, Central America and Eastern South America. Lesser number of regions have shown absolute

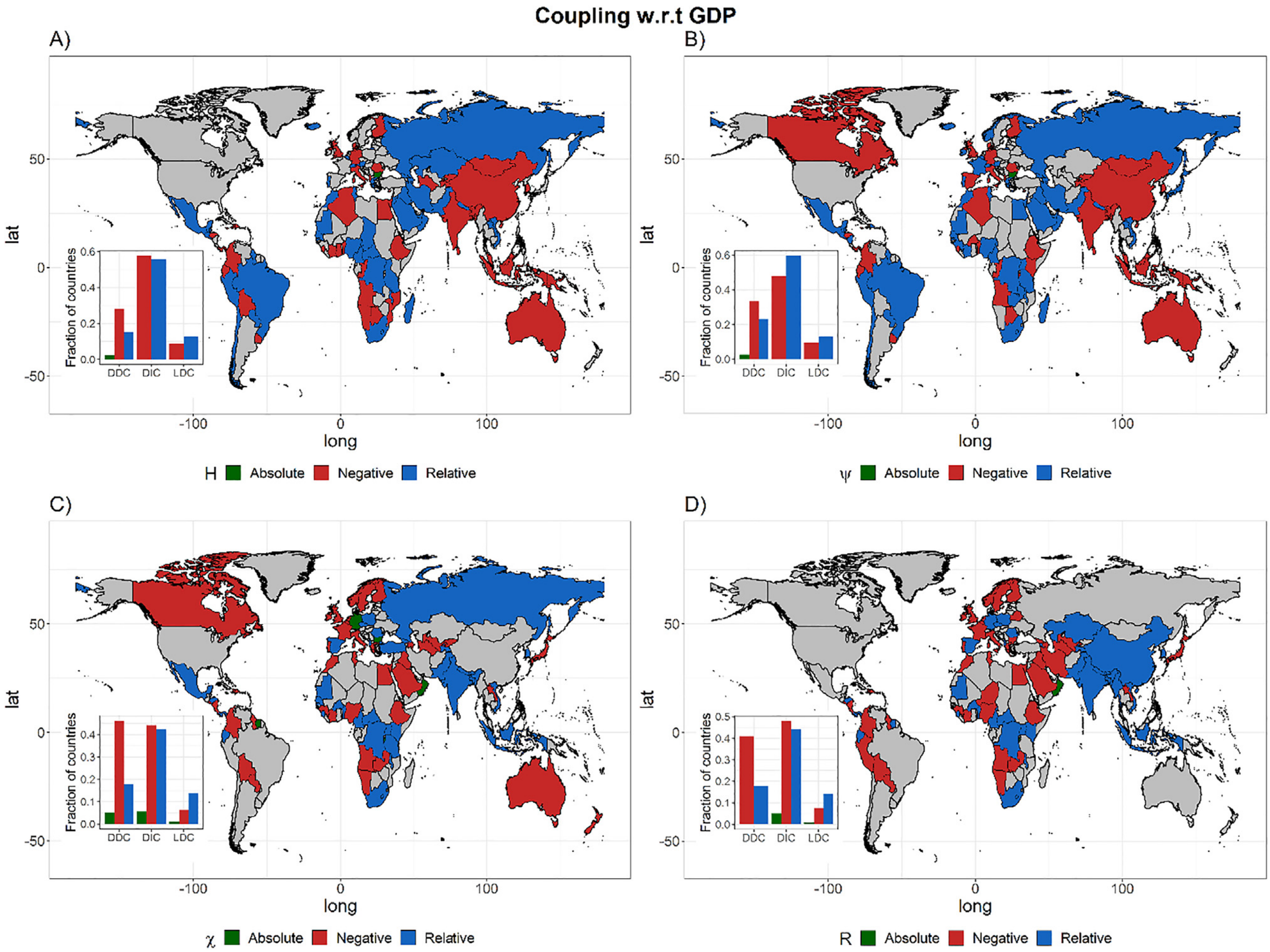

Fig 8. Global maps of statistically significant coupling behavior exhibited by a) capacity (*H*), b) flexibility (ψ), c) efficiency (χ), d) robustness (*R*) in 189 countries between 1990 and 2015 with respect to GDP. In the inset of each map, the fraction of countries exhibiting coupling behavior by development classification is displayed.

coupling. In case of efficiency (Fig. 6c), the countries witness negative coupling includes Russia, Australia, majority of the European nations, South western part of Africa, Canada and Northern parts of South America. Whereas, relative couplings are observed for the Southeastern Asia, Central Africa and Central America. Lesser number of countries like Greenland, South Africa, Afghanistan have shown absolute coupling. Based on the robustness analysis, the countries, exhibited negative coupling are Middle east, majority of European nations, South western part of Africa, North western parts of South America, which indicates that the robustness decreases along with the increase in population. Whereas, relative couplings are observed in the Eastern Asia and Central Africa. Lesser number of countries like Greenland, Thailand, Afghanistan have shown absolute coupling. Our analysis indicated that not all the metrics have shown a negative relationship with population indicating that in spite of increasing population, countries can become more sustainable. In addition, we found out that in all cases, The LDC have relatively a higher percentage of countries exhibiting relative coupling followed by DIC. Similarly, negative coupling is found to be higher in DDC and least in LDC.

As observed previously, there is a strong positive association between capacity's (robustness's) and flexibility's (efficiency's) coupling with population irrespective of the country's development classification (Fig. 7). However, unlike the case of Figs. 3 and 5, capacity's coupling has exhibited significant negative associations with robustness's and efficiency's coupling in case of DDC. Whereas, flexibility's coupling has exhibited significant negative associations with robustness's and efficiency's coupling in case of DDC as well as LDC. Hence, in case of DIC there is no such correlation. In addition to that based on the probability distribution of the metrics with respect to LDC have fatter tails towards the positive end. This indicates the more number of LDC countries' network are becoming sustainable rapidly with respect to growth in population and are more sensitive to changes in population in comparison to developing and developed countries.

3.3.2. Gross domestic product (GDP)

The spatial global map of statistically significant coupling behavior exhibited by (a) capacity, (b) flexibility, (c) efficiency, and (d) robustness for 189 countries respect to GDP is shown in Fig. 8. The countries located in Eastern Asia, Australia, South western part of Africa, Southern Europe and Northern parts of South America exhibited negative coupling indicating that the capacity decreases along with the increase in GDP (Fig. 8a). Whereas, the relative coupling is observed in Northern Asia, Middle east, Central Africa, Central America and Eastern South America. This suggests that capacity is increasing with an increase in GDP but not growing as rapid as the GDP for these selected countries. Lesser number of regions have shown absolute coupling. The least developing countries have relatively a greater number of countries exhibiting relative coupling followed by developing countries. Similarly, negative coupling is found more in developing countries and least in developing countries. In the case of flexibility in network (Fig. 8b), the Eastern Asia, Australia, South western part of Africa, Southern Europe, Canada and Northern parts of South America have exhibited

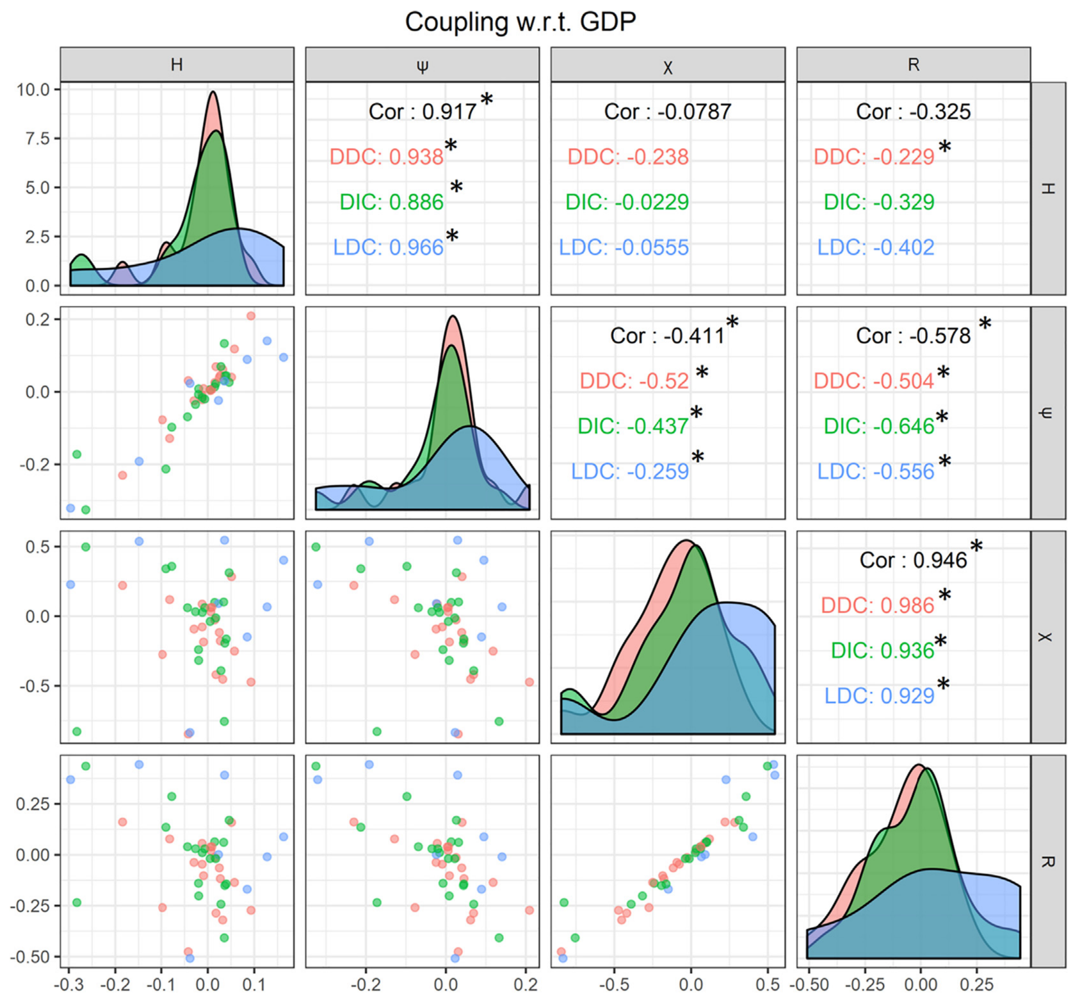

Fig 9. Same as in Fig. 3, but for coupling intensity of capacity (*H*), flexibility (ψ), efficiency (χ), robustness (*R*) with respect to GDP.

negative coupling indicating that the flexibility decreases along with the increase in GDP. Whereas, relative coupling is observed in Northern Asia, Middle east, Central Africa, Central America and Eastern South America. Lesser number of regions have shown absolute coupling. In the case of efficiency (Fig. 8c), the countries located in Australia, Western European nations, South western part of Africa, middle eastern countries Canada and Northern parts of South America have exhibited negative coupling indicating that the effectivity decreases along with the increase in GDP. Whereas, the relative couplings are observed in Southeastern Asia, Russia, Central Africa and Central America. The higher percentage of least developing countries exhibits relative coupling followed by developing countries. Based on the robustness analysis (Fig. 8d), the Middle east, western European and Nordic nations, South western part of Africa, Northern western parts of South America have exhibited negative coupling indicating that the robustness decreases along with the increase in GDP. Whereas, relative couplings are observed in the Eastern Asia, Central Africa. Lesser number of countries have shown absolute coupling. The inset histograms in Fig. 8 indicated that similar to network metrics response to population, it was observed that the LDC have relatively a higher percentage of countries exhibiting relative coupling followed by DIC. Similarly, negative coupling is found to be higher in DDC and least in LDC.

A stronger positive association was observed between capacity and flexibility, as well as between robustness and flexibility (efficiency's) coupling with respect to GDP irrespective of the country's development classification (Fig. 9). In addition, significant negative associations between flexibility's and robustness's as well as efficiency's coupling can be observed. Unlike coupling intensity (which is CI $>$ 1) with respect to the population, the coupling intensity with respect to the GDP in majority of LDC is less than 1. This indicates that the sustainability of VWN in LDC countries is more sensitive to changes in population than GDP. In addition to that based on the probability distribution of the metrics with respect to LDC have fatter tails towards the positive end. Hence, the VWN metrics in LDC countries do increase relatively with increase in GDP.

3.3.3. Gross national income (GNI)

The spatial global map of four selected metrics with respect to GNI for 189 countries is shown in Fig. 10. It was observed that in the case of capacity (Fig. 10a), the Indian sub-continent, Australia, South western part of Africa, Southern Europe and Northern parts of South America have exhibited negative coupling indicating that the capacity decreases along with the increase in GNI. Whereas, the relative coupling is observed in Russia, Middle east, Central Africa, Central America and Eastern South America. This indicates that the capacity of the network is increasing with an increase in GNI, but not growing as rapid as the GNI. Lesser number of regions have shown absolute coupling. In case of flexibility (Fig. 10b), the Indian sub-continent, Australia, Southern Europe, Canada and Northern parts of South America have exhibited negative coupling indicating that the flexibility of the network decreases along with the increase in GNI. Whereas, the relative coupling is observed in Russia, Middle east, Central America and Eastern South America. In case of efficiency (Fig. 10c), Australia, Western European nations and Canada have exhibited negative coupling indicating that

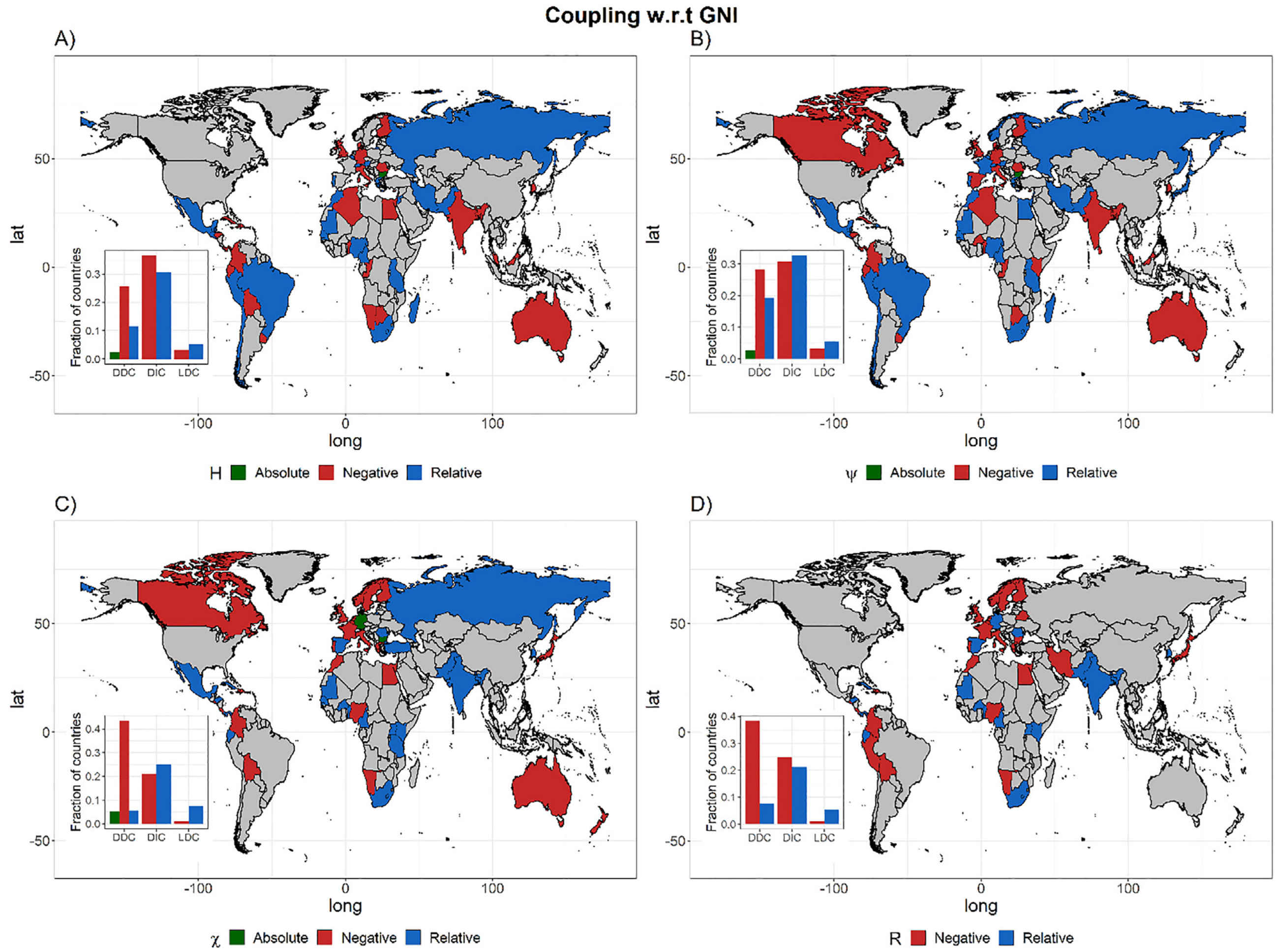

Fig 10. Global maps of statistically significant coupling behavior exhibited by a) capacity (*H*), b) flexibility (ψ), c) efficiency (χ), d) robustness (*R*) in 189 countries between 1990 and 2015 with respect to GNI. In the inset of each map, the fraction of countries exhibiting coupling behavior by development classification is displayed.

the efficiency decreases along with the increase in GNI. Whereas, relative coupling is observed in Russia, scattered across Africa and Central America. Lesser number of countries have shown absolute coupling. Based on the robustness (Fig. 10d), Western European and Nordic nations, Northern western parts of South America have exhibited negative coupling with respect to the GNI indicating that the robustness decreases along with the increase in GNI. Whereas, relative coupling is observed in Indian subcontinent, and information theoretic metrics few countries scattered Africa and Europe. None of the countries have shown absolute coupling. Similar to population and GDP, higher fraction of LDC witness relative coupling followed by DIC. Whereas, negative coupling in found more in DDC and lowest in LDC (Fig. 11).

Even in this case, there is a strong positive association between capacity's (robustness's) and flexibility's (efficiency's) coupling irrespective of the country's development classification. Unlike other associations, the developing countries have a positive association among the metrics, whereas other countries have negative associations. As in the case of GDP, the coupling intensity with respect to the GNI of LDC countries has a fatter tails on the positive ends indicating more number of LDC countries increase relatively with increase in GNI.

4. Discussion and conclusion

In this study, we applied the information theory-based metrics (capacity, flexibility, efficiency and robustness) to investigate the dynamics of domestic virtual water networks of 189 countries, their trends and coupling intensity with population, GDP and GNI based on the 1990–2015 data.

Overall a greater fraction of least developing countries (LDC) have shown an increase in the information theoretic properties of domestic VWNs followed by developing nations (DIC). Also, a higher fraction of developed nations has exhibited a decrease in these metrics followed by developing nations. It was observed that with the growth in socio-economic conditions, the domestic VWN's networks metrics is increasing more in case of LDC in comparison to developing and developed nations. The developed countries already have a well-established infrastructure built during a period when the sustainable use of water might not be a priority for the economic activities (Vachon and Mao, 2008; Kagawa et al., 2015)]. However, in case of developing and least developed nations, there was relatively less infrastructure in previous decades.

The current infrastructure is relatively more modern and sustainable due to increased awareness and benefits of environmental sustainability. This kind of leapfrogging towards a more environmentally sustainable technology has already been observed in energy sector (Rajan and Sen, 2002; van Benthem, 2015; Murphy, 2001); Agriculture sector (Kimenyi and Moyo, 2011; Castro e Silva and Silva, 2015; Juma, 2015), transportation sector (Walz, 2010; Winston and Mannering, 2014) and manufacturing sector (Hobday, 1994; Yap and Rasiah, 2017; Lee et al., 2014). In addition to that, availability of ample monetary resources in developed countries might have a negative influence on dynamics of the domestic VWNs as in the case of virtual water

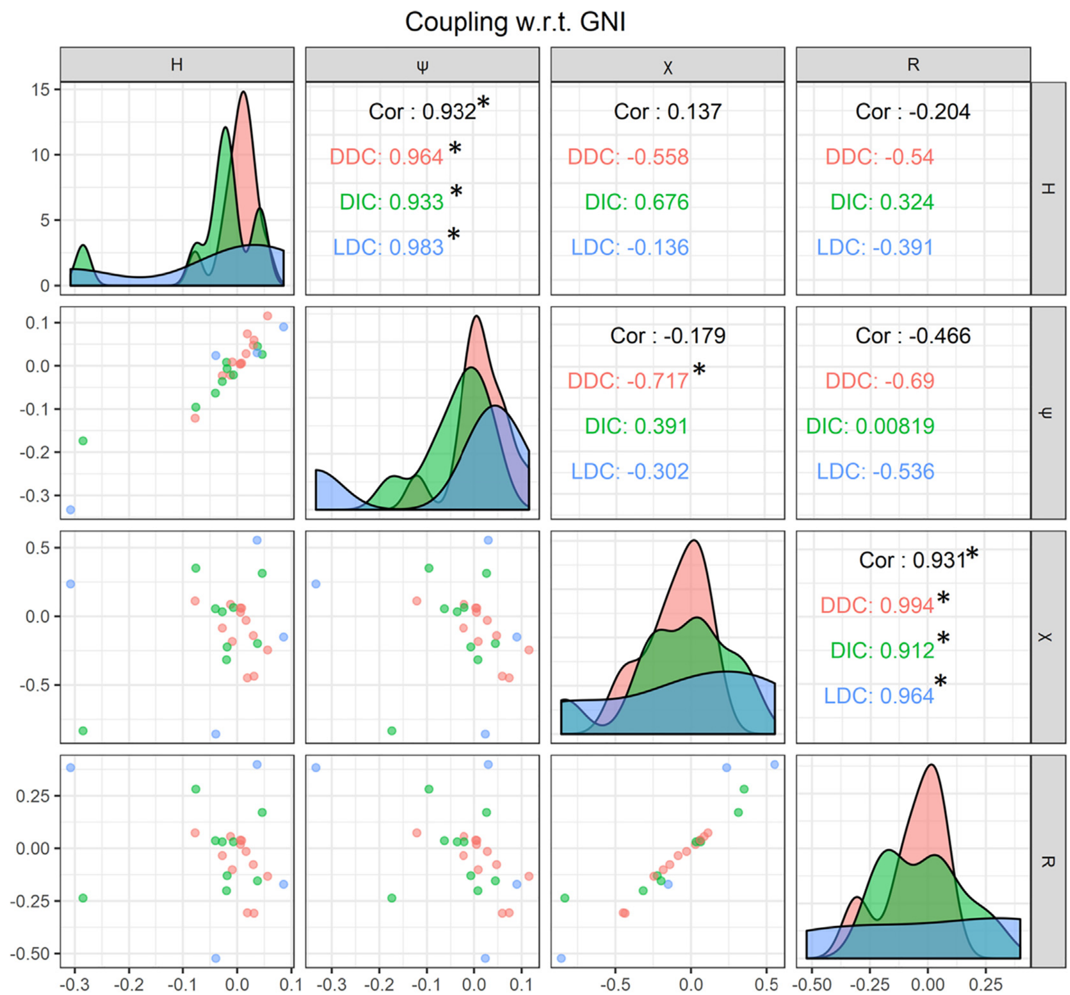

Fig 11. Same as in Fig. 3, but for coupling intensity of capacity (*H*), flexibility (ψ), efficiency (χ), robustness (*R*) with respect to GNI.

international trade (Wang et al., 2016); Soligno et al., 2018; Wada and Bierkens, 2014; Tamea et al., 2014).

There is a strong positive association between trends in capacity and flexibility. As a result, an increase in capacity of VWN might translate to increase in flexibility (robustness) of VWN. Therefore, to exhibit an all-round growth (i.e. increase in all the four metrics), the virtual water transfers between economic sectors in domestic VWN should evolve over time in such a way that both capacity and effectivity should increase. The same association can also be seen in the case of coupling intensities of these dynamics. However, unlike the case of trends, there appears to be a moderate negative association between other combinations (i.e. between robustness and flexibility). In this case, achieving a positive coupling behavior of network dynamics with socio-economic growth might be more complicated due to the presence of negative associations. Previous studies have indicated that, it is not always possible to decouple environmental pollution with socio-economic growth due to the absence of appropriate quantification of sustainability (Ward et al., 2016; Victor, 2018). We believe that our proposed method can provide an alternative to directly integrate the dynamic aspects of networks with socio-economic growth to measure coupling intensity.

Even though it is now widely accepted that, economic growth and human wellbeing should be decoupled from negative environmental impacts (UNEP, 2011), our coupling analysis has indicated not all the countries have exhibited this behavior. In those countries, policy implementations which include putting a price on water usage (Höglund, 1999; Qin et al., 2012), redirecting investments to more water efficient green infrastructure (Benedict and McMahon, 2002; Gaffin et al., 2012; Ellis, 2013), production systems and technologies that allow products and services to be delivered at a much lower environmental cost (lower water intensity) are technically achievable and economically viable options. In addition to that, since the VWN is interdependent, identifying the sectors that influence the dynamics of the whole network and restructuring the virtual water flows might also help in increasing the sustainability of domestic VWN (Kharrazi et al., 2017).

While the information-based approach can help to address network dynamics though capacity, efficiency, flexibility, and robustness, the approach is weak in addressing extensive dimensions of sustainability concerning the need to quantify the total utilization and availability of water resources. Even though, the metrics used in this study are computed using the information of the total resources used in the system, these metrics do not include the availability of resources in its computations. Also, it is common that the virtual water transfers between economic sectors are heterogeneous in nature (i.e. VWN may be dominated by agriculture compared to other sectors), and those flows are unified into a single unit for the purpose of system-level analysis in this analysis. Hence, a multi-dimensional extension which gives the insights in to sustainability aspects of the individual sectors is not provided here. Alternatively, by integrating the water footprint concepts (Veettil and Mishra, 2020) in conjunction with the information theory approach can be adapted for an overall assessment of the VWN dynamics.

CRediT authorship contribution statement

Goutam Konapala: Conceptualization, Data Curation, Formal Analysis, Methodology, Validation, Writing - original draft. **Ashok Mishra:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

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.

Acknowledgement

This study was supported by the National Science Foundation (NSF) award # 1653841. We wish to thank Editor and reviewers for their constructive suggestions that helped up to improve the quality of the manuscript.

References

Allan, John A., 1998. Virtual water: a strategic resource. Ground Water 36 (4), 545–547.
Andreoni, V., Galmarini, S., 2012. Decoupling economic growth from carbon dioxide emissions: a decomposition analysis of Italian energy consumption. Energy 44 (1), 682–691.
Benedict, M.A., McMahon, E.T., 2002. Green infrastructure: smart conservation for the 21st century. Renewable Resour. J. 20 (3), 12–17.
Bodini, A., Bondavalli, C., Allesina, S., 2012. Cities as ecosystems: growth, development and implications for sustainability. Ecol. Model. 245, 185–198.
Carr, J., D'Odorico, P., Laio, F., Ridolfi, L., Seekell, D., 2012. Inequalities in the networks of virtual water flow. Eos, Trans. Am. Geophys. Union 93 (32), 309–310.
Castro e Silva, M., Silva, M., 2015. Leapfrogging agriculture as usual: the potential contribution and sustainability benefits of organic farming to carbon sequestration in Portugal. Int. J. Agric. Innov. Res. 4 (1), 205–211.
Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. (Value of Water Research Report Series; No. 16). Delft: Unesco-IHE Institute for Water Education.
Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H., Gautam, R., 2006. The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol. Econ. 60 (1), 186–203.
Charter, M., Tischner, U. (Eds.), 2017. Sustainable Solutions: Developing Products and Services for the Future. Routledge.
Chen, S., Chen, B., Fath, B.D., 2014. Urban ecosystem modeling and global change: potential for rational urban management and emissions mitigation. Environ. Pollut. 190, 139–149.
Chen, Z.M., Chen, G.Q., 2013. Virtual water accounting for the globalized world economy: national water footprint and international virtual water trade. Ecol. Ind. 28, 142–149.
D'Odorico, P., Carr, J., Laio, F., Ridolfi, L., 2012. Spatial organization and drivers of the virtual water trade: a community-structure analysis. Environ. Res. Lett. 7 (3), 034007.
Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proc. Natl. Acad. Sci. 109 (16), 5989–5994.
Dalin, C., Suweis, S., Konar, M., Hanasaki, N., Rodriguez-Iturbe, I., 2012. Modeling past and future structure of the global virtual water trade network. Geophys. Res. Lett. 39 (24).
Daniels, P.L., Lenzen, M., Kenway, S.J., 2011. The ins and outs of water use–a review of multi-region input–output analysis and water footprints for regional sustainability analysis and policy. Econ. Syst. Res. 23 (4), 353–370.
Duan, C., Chen, B., 2017. Energy–water nexus of international energy trade of China. Appl. Energy 194, 725–734.
Ellis, J.B., 2013. Sustainable surface water management and green infrastructure in UK urban catchment planning. J. Environ. Plan. Manage. 56 (1), 24–41.
Fang, Delin, Chen, Bin, 2015. Ecological network analysis for a virtual water network. Environ. Sci. Technol. 49 (11), 6722–6730.
Feng, K., Chapagain, A., Suh, S., Pfister, S., Hubacek, K., 2011. Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. Econ. Syst. Res. 23 (4), 371–385.
Flach, R., Ran, Y., Godar, J., Karlberg, L., Suavet, C., 2016. Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities. Environ. Res. Lett. 11 (7), 075003.
Gaffin, S.R., Rosenzweig, C., Kong, A.Y., 2012. Adapting to climate change through urban green infrastructure. Nat. Clim. Change 2 (10), 704.
Goerner, S., Lietaer, B., Ulanowicz, R.E., 2009. Quantifying economic sustainability: implications for free-enterprise theory, policy and practice. Ecol. Econ. Elsevier B.V. 69, 76–81.
Guan, D., Hubacek, K., 2007. Assessment of regional trade and virtual water flows in China. Ecol. Econ. 61 (1), 159–170.
Guo, R., Zhu, X., Chen, B., Yue, Y., 2016. Ecological network analysis of the virtual water network within China's electric power system during 2007–2012. Appl. Energy 168, 110–121.
Hamed, K.H., Rao, A.R., 1998. A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol. 204 (1–4), 182–196.
Hobday, M., 1994. Technological learning in Singapore: a test case of leapfrogging. J. Develop. Stud. 30 (4), 831–858.
Hoekstra, A.Y., Chapagain, A.K., 2006. Water footprints of nations: water use by people as a function of their consumption pattern. In: Integrated Assessment of Water Resources and Global Change. Springer, Dordrecht, pp. 35–48.
Hoekstra, A.Y., Chapagain, A.K., Mekonnen, M.M., Aldaya, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Routledge.
Höglund, L., 1999. Household demand for water in Sweden with implications of a potential tax on water use. Water Resour. Res. 35 (12), 3853–3863.
Holland, R.A., Scott, K.A., Flörke, M., Brown, G., Ewers, R.M., Farmer, E., Barrett, J., 2015. Global impacts of energy demand on the freshwater resources of nations. Proc. Natl. Acad. Sci. 112 (48), E6707–E6716.
Huang, J., Ulanowicz, R.E., 2014. Ecological network analysis for economic systems: growth and development and implications for sustainable development. PLoS ONE 9, 1–8.
International Resource Panel, United Nations Environment Programme. Sustainable Consumption, & Production Branch, 2011. Decoupling natural resource use and environmental impacts from economic growth. UNEP/Earthprint.
Juma, C., 2015. The New Harvest: Agricultural Innovation in Africa. Oxford University Press.
Kagawa, S., Suh, S., Hubacek, K., Wiedmann, T., Nansai, K., Minx, J., 2015. CO2 emission clusters within global supply chain networks: implications for climate change mitigation. Global Environ. Change 35, 486–496.
Kharrazi, A., Rovenskaya, E., Fath, B.D., 2017. Network structure impacts global commodity trade growth and resilience. PLoS ONE 12 (2), e0171184.
Kimenyi, M.S., Moyo, N., 2011. Leapfrogging development through technology adoption. Foresight Africa, 13.
Kitzes, J., 2013. An introduction to environmentally-extended input-output analysis. Resources 2 (4), 489–503.
Konar, M., Dalin, C., Suweis, S., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2011. Water for food: the global virtual water trade network. Water Resour. Res. 47 (5).
Konapala, G., Mishra, A., 2020. Quantifying climate and catchment control on hydrological drought in the continental United States. Water Resour. Res. 56. https://doi.org/10.1029/2018WR024620.
Konapala, G., Mishra, A., Leung, L.R., 2017. Changes in temporal variability of precipitation over land due to anthropogenic forcings. Environ. Res. Lett. 12 (2), 024009.
Kucukvar, M., Tatari, O., 2013. Towards a triple bottom-line sustainability assessment of the US construction industry. Int. J. Life Cycle Assess. 18 (5), 958–972.
Lee, K., Park, T.Y., Krishnan, R.T., 2014. Catching-up or leapfrogging in the Indian IT service sector: Windows of opportunity, Path-creating, and moving up the value chain. Dev. Policy Rev. 32 (4), 495–518.
Lenzen, M., Kanemoto, K., Moran, D., Geschke, A., 2012. Mapping the structure of the world economy. Environ. Sci. Technol. 46 (15), 8374–8381. https://doi.org/10.1021/es300171x.
Lenzen, M., 2009. Understanding virtual water flows: a multiregion input-output case study of Victoria. Water Resour. Res. 45 (9).
Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013. International trade of scarce water. Ecol. Econ. 94, 78–85.
Li, C., Singh, V.P., Mishra, A.K., 2012. Entropy theory-based criterion for hydrometric network evaluation and design: maximum information minimum redundancy. Water Resour. Res. 48, W05521. https://doi.org/10.1029/2011WR011251.
Li, Y., Chen, B., Yang, Z.F., 2009. Ecological network analysis for water use systems a case study of the Yellow River Basin. Ecol. Model. 220, 3163–3173.
Liang, S., Liu, Z., Crawford-Brown, D., Wang, Y., Xu, M., 2014. Decoupling analysis and socioeconomic drivers of environmental pressure in China. Environ. Sci. Technol. 48 (2), 1103–1113.
López-Ridaura, S., Masera, O., Astier, M., 2002. Evaluating the sustainability of complex socio-environmental systems. The MESMIS framework. Ecol. Indic. 2 (1–2), 135–148.
Mardani, A., Streimikiene, D., Cavallaro, F., Loganathan, N., Khoshnoudi, M., 2019. Carbon dioxide (CO2) emissions and economic growth: a systematic review of two decades of research from 1995 to 2017. Sci. Total Environ. 649, 31–49.
Mishra, A.K., Coulibaly, P., 2010. Hydrometric networks evaluation for Canadian watersheds. J. Hydrol. 380, 420–437.
Mishra, A.K., Ozger, M., Singh, V.P., 2011. Association between uncertainties in meteorological variables and water-resources planning for the state of Texas. J. Hydrol. Eng. 16, 984–999.
Mishra, A.K., Ozger, M., Singh, V.P., 2009. An entropy-based investigation into the variability of precipitation. J. Hydrol. 370 (1–4), 139–154.
Mubako, S., Lahiri, S., Lant, C., 2013. Input–output analysis of virtual water transfers: case study of California and Illinois. Ecol. Econ. 93, 230–238.
Mukherjee, J., Scharler, U.M., Fath, B.D., Ray, S., 2015. Measuring sensitivity of robustness and network indices for an estuarine food web model under perturbations. Ecol. Model. 306, 160–173.
Murphy, J.T., 2001. Making the energy transition in rural East Africa: is leapfrogging an alternative? Technol. Forecast. Soc. Chang. 68 (2), 173–193.
Pfister, S., Bayer, P., Koehler, A., Hellweg, S., 2011. Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ. Sci. Technol. 45 (13), 5761–5768.
Qin, C., Jia, Y., Su, Z., Bressers, H.T., Wang, H., 2012. The economic impact of water tax charges in China: a static computable general equilibrium analysis. Water Int. 37 (3),

279–292.
Rajan, R.S., Sen, R., 2002. A decade of trade reforms in India. World Econ. 3 (4), 87–100.
Scown, C.D., Nazaroff, W.W., Mishra, U., Strogen, B., Lobscheid, A.B., Masanet, E., McKone, T.E., 2012. Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production. Environ. Res. Lett. 7 (1), 014011.
Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63 (324), 1379–1389.
Shannon, C.E., 1948. A mathematical theory of communication. Bell Syst. Tech. J. 27 (379–423), 623–656.
Soligno, I., Malik, A., Lenzen, M., 2018. Socio-economic drivers of global blue water use. Water Resour. Res.
Suweis, S., Rinaldo, A., Maritan, A., D'Odorico, P., 2013. Water-controlled wealth of nations. Proc. Natl. Acad. Sci. 110 (11), 4230–4233.
Tamea, S., Carr, J.A., Laio, F., Ridolfi, L., 2014. Drivers of the virtual water trade. Water Resour. Res. 50 (1), 17–28.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy 12 (2), 137–151.
Thiel, H., 1950. A rank-invariant method of linear and polynomial regression analysis, Part 3. Proceedings of Koninalijke Nederlandse Akademie van Weinenschatpen A 53, 1397–1412.
Ulanowicz, R.E., Goerner, S., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol Complex. 6, 27–36.
Ulanowicz, R.E., Wolff, W.F., 1991. Ecosystem flow networks: loaded dice? Math Biosci. 103, 45–68 Available: http://www.ncbi.nlm.nih.gov/pubmed/1804441. PMID: 1804441.
Ulanowicz, R.E., 2011. 9.04-Quantitative Methods for Ecological Network Analysis and Its Application to Coastal Ecosystems. Treatise on Estuarine and Coastal Science Academic Press, Waltham, pp. 35–57.
Ulanowicz, R.E., 2004. Quantitative methods for ecological network analysis. Comput. Biol. Chem. 28, 321–339.
Ulanowlcz, R.E., Norden, J.S., 1990. Symmetrical overhead in flow networks. Int. J. Syst. Sci. 21 (2), 429–437.
UN, 2014 : United, Nations. The Millennium Development Goals Report 2014. New York: United Nations (2014).
Vachon, S., Mao, Z., 2008. Linking supply chain strength to sustainable development: a country-level analysis. J. Cleaner Prod. 16 (15), 1552–1560.
van Benthem, A.A., 2015. Energy leapfrogging. J. Assoc. Environ. Resour. Econ. 2 (1), 93–132.
Veettil, A.V., Mishra, A., 2020. Water security assessment for the contiguous United States using water footprint concepts. Geophysical Research Letters, 47(7), e2020GL087061.
Victor, P.A., 2018. Managing Without Growth: Slower by Design, Not Disaster. Edward Elgar Publishing.
Wada, Y., Bierkens, M.F., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9 (10), 104003.
Walz, R., 2010. Competences for green development and leapfrogging in newly industrializing countries. IEEP 7 (2–3), 245–265.
Wang, L., Ding, X., Wu, X., 2013. Blue and grey water footprint of textile industry in China. Water Sci. Technol. 68 (11), 2485–2491.
Wang, R., Hertwich, E., Zimmerman, J.B., 2016. (Virtual) water flows uphill toward money. Environ. Sci. Technol. 50 (22), 12320–12330.
Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H., Simmons, C.T., 2016. Is decoupling GDP growth from environmental impact possible? PLoS ONE 11 (10), e0164733.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11 (5), 314–321.
Winston, C., Mannering, F., 2014. Implementing technology to improve public highway performance: a leapfrog technology from the private sector is going to be necessary. Econ. Transp. 3 (2), 158–165.
Wu, M., Mintz, M., Wang, M., Arora, S., 2009. Consumptive water use in the production of ethanonl and petroleum gasoline (No. ANL/ESD/09-1). Argonne National Lab. (ANL), Argonne, IL (United States).
Yap, X.S., Rasiah, R., 2017. Catching up and leapfrogging in a high-tech manufacturing industry: towards a firm-level taxonomy of knowledge accumulation. Knowledge Manage. Res. Practice 15 (1), 114–129.
Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land use. Global Environ. Change 23 (5), 1178–1186.
Yue, S., Wang, C.Y., 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. Water resources research, 38(6), 4-1.
Zhang, Z., 2000. Decoupling China's carbon emissions increase from economic growth: an economic analysis and policy implications. World Dev. 28 (4), 739–752.
Zhao, X.U., Yang, H., Yang, Z., Chen, B., Qin, Y., 2010. Applying the input-output method to account for water footprint and virtual water trade in the Haihe River basin in China. Environ. Sci. Technol. 44 (23), 9150–9156.