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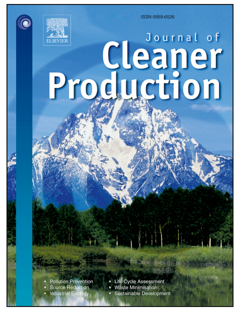

Understanding grain virtual water flux dynamics and drivers from a socio-ecohydrological perspective: A case study of landlocked developing countries of Africa

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Author Contribution Statement

Hubert Hirwa: Conceptualization, Methodology, Software, Investigation, Acquisition of data, Formal analysis, Writing, original draft, review & editing.

Li Fadong: supervising, reviewing, commenting, editing, funding acquisition.

Simon Measho: Writing – reviewing, editing and commenting.

Gang Chen: Writing – reviewing, editing and commenting.

Fabien Muhirwa: Writing – reviewing & editing, Formal analysis.

Qiuying Zhang: Writing – reviewing & editing, Resources.

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Theogene Niyonzima: Writing – reviewing & editing.

Understanding grain virtual water flux dynamics and drivers from a socio-ecohydrological perspective: A case study of landlocked developing countries of Africa

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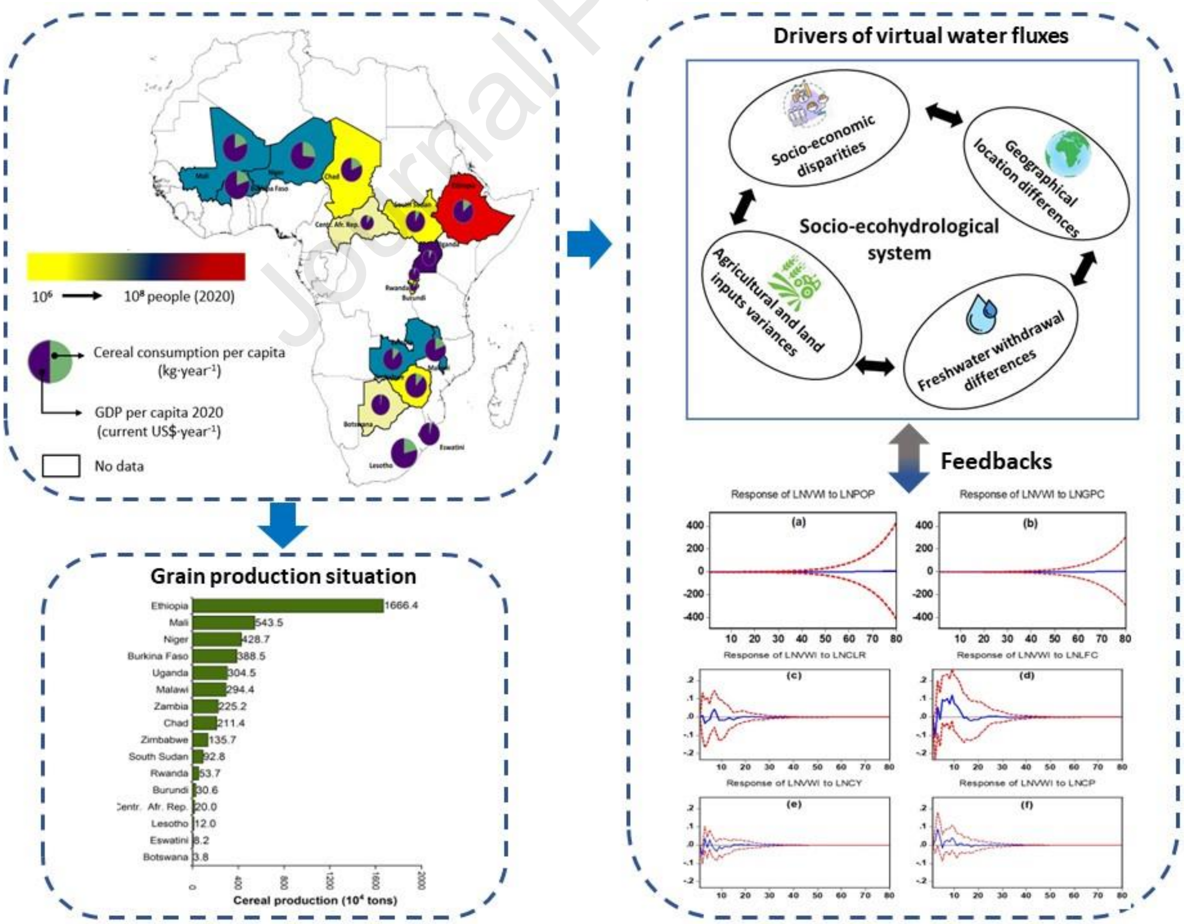
Highlights

- Broadly assessed the bilateral virtual water (VW) fluxes drivers.
- Developed a trade gravity model.
- Significantly enhanced the grain VW imports by population and per capita GDP.
- Proposed future research frontiers based on socio-ecohydrological approach.

Graphical abstract



Abstract

The virtual water (VW) approach offers a crucial heuristic tool to analyze water and food security by considering the water embedded in grain during the whole production process. African landlocked developing countries (LLDCs) continually suffer from an escalating food crisis and water resources and socioeconomic policy and water conservation strategy derived from the water-food nexus of virtual water trade (VWT) systems and resources may be the solution. Using a trade gravity model and multilateral data, this study evaluated grain VW flux patterns and 11 main drivers of VWT between 16 African LLDCs and their partners. Besides, the feedback path of VW flows corresponding to the socio-ecohydrological variability was studied using the impulse response function. The findings revealed that net virtual water import (VWI) varied across all 16 African LLDCs, ranging from 1.67 Bm^3 to 10.28 Bm^3 during 2000 and 2020, with an estimated yearly grain VWI of 105.61 Bm^3. Green, blue, and gray water accounted for about 79.3%, 14.7%, and 5.98% of the total grain VWI, respectively. Ethiopia had the highest grain VWI among the African LLDCs. Grain VWI fluxes were significantly and positively driven by population growth and per capita GDP, which were expected to continue in the future. It was concluded that the quantitative analysis of grain VWT patterns and driving forces using the VW theory for LLDCs can be instrumental for guiding the socioeconomic policy and water conservation strategy. To effectively achieve sustainable water security and grain production, earmarked future VW strategy is required. Decision-makers should incorporate rational VW strategies and socio-ecohydrological factors into the monitoring system from a multidisciplinary perspective.

Keywords: grain production; driving forces; socio-ecohydrology; gravity model; virtual water fluxes; Africa

1 Introduction

The co-evolution of societal and hydro-ecological phenomena has greatly increased the effects of expanding human-nature interactions on various scales on socio-economic growth (Botai et al., 2022). With progressive economic growth, changing dietary habits, and climate change, human water consumption has steadily increased (Sun et al., 2022), hence exacerbating water scarcity (Debaere, 2014). Among issues of rising population, social upheavals, environmental degradation, weak political institutions, ineffective resource management, willful leadership (Conca, 2015), food insecurity, and water scarcity are a great challenge owing to the uneven resource distribution that governments have to address (Acreman et al., 2021; Boretti and Rosa, 2019; Nkonya et al., 2016). To shoehorn water crisis and subsequent food insecurity, countries should make concerted efforts to establish ulterior domestic water supply strategies.

Africa accounts for ~ 9% of the planet's freshwater resources and ~ 16% of the world's population (Hirwa et al., 2022a; Ritchie and Roser, 2017). African countries currently experience notable socio-economic and population growth, particularly in agriculture and infrastructural development (Bjornlund et al., 2020). Ideally, the globalization of trade has led to the extensive exchange of cereal grains among counties. This free and open trading environment has encouraged countries to seek gains from trade other than growing domestically, affecting local economy development (Qiang et al., 2013). Furthermore, the average global food consumption from 2005 to 2007 is predicted to increase up to 60% by 2050, with the biggest surge in Sub-Saharan African (SSA) countries (Ittersum et al., 2016). Myeki et al. (2022) reported that the average growth rate of agrarian production in Africa was 0.73%$\cdot$yr^{-1}. During the period of 2016-2018, Africa imported ~85% of its agricultural products, equivalent to ~ $35bn, from overseas, which is expected to reach ~ $110bn by 2025 and double in size by 2050. For instance, SSA has recorded the highest rate of agricultural production growth (~4.3%$\cdot$yr^{-1}) of any region of the world (~2.75%$\cdot$yr^{-1}) since 2000 (UNCTAD, 2020). Therefore, it is crucial to pinpoint the governing factors of the VW flows for apprehending the imperfect water consumption patterns while structuring the well-acquainted regulations for durable water use efficiency.

Over the last decades, researchers have been using the concept of VW to study how the water resource interchanges around the globe embodied in goods and services during their production (Allan, John A, 1998; D'Odorico et al., 2019; Miglietta and Morrone, 2018; Tian et al., 2018). Agrarian products are traded internationally via which VW is transferred from production areas to consumption areas, thus compensating for low food production due to water restrictions (Hekmatnia et al., 2022). However, few investigations have been conducted to evaluate the VWT in Africa (Dabrowski et al., 2009). The international crop trade is estimated to be responsible for ~25 km$^3\cdot$yr^{-1} (equivalent to ~10%) of global groundwater degradation (Dalin et al., 2017), enhancing economic development and resilient local food security, but also a significant factor in the widespread depletion of aquifers beneath fertile land. The cereal grains specifically, wheat, maize, and rice are the major crops contributing to groundwater degradation, which are also widely traded, leading to hugely viable water footprints (Mekonnen and Gerbens-Leenes, 2020). Therefore, VWT as a policy measure of water resources management becomes an effective tool to identify key indicators for water policy decisions (Mohammadi-Kanigolzar et al., 2014; Nishad and Kumar, 2021). There is some evidence that VW flows can be used to alleviate Africa's spatial imbalance between water resources and water demand. In light of the logic mentioned above, VWT can be used to determine whether countries in Africa confront water scarcity, which aids the governments in deciding the needs of the international grain trade for long-term sustainability and equity of the trade.

This study aimed at assessing the dynamic patterns and driving forces of the grain VW fluxes in African LLDCs in the lens of socio-hydrological perspective. The central scientific question to be answered was: To what extent the socio-ecohydrological factors affect the grain VW fluxes in LLDCs and their main commercial partners? Therefore, the specific objectives were to: (1) assess the grain VW flows between 16 African LLDCs and their partners during 2000-2020, (2) quantify grain VWI components in LLDCs during 2000-2020, (3) explore the grain VW flow drivers of LLDCs by applying the trade gravity model, and (4) identify the future research frontiers and policy options through the lens of socio-ecohydrological approach. This study also demonstrated that the evaluation of the flows of water (in form of hidden water in agrarian products) between nations might serve as a useful tool to monitor water in case of scarcity stage.

2 Theoretical foundations and evidence

In 1993, the notion of embodied water was proposed by Allan (1993) to define to the amount of water resources involved in the production of products and services, i.e., the amount of VW condensed in products and services, including the water crossing borders through trade (Allan, J.A., 1998). VW includes direct and indirect consumption (Jiang et al., 2022). Moreover, VWT encompasses numerous elements and processes environmentally, socially, economically, culturally, politically, and institutionally on local, regional, and global scales (Antonelli and Sartori, 2015; Turton, 1999). In addition, Tony Allan awakened people's attention to the phenomenon that ‘‘economic trade has relieved the water shortage in dry areas”. Since then, the VW notion has been used widely as a quantitative evaluation index in the production chain of ''water resources input, commodity trade, and economic output'' (Akoto-Danso et al., 2019; Antonelli et al., 2017). Undoubtedly, the water consumption is mostly calculated using VW in the production and sale of food and consumer goods, usually agricultural products (Sun et al., 2021).

With the progress and expansion of production and consumption and the acceleration of globalization, VW plays a growing role in estimating the intake and production of water resources on various spatiotemporal scales (Hirwa et al., 2022a). VW breaks the traditional cognition of ''seeking ways to solve problems within the problem area'' by providing new ideas for solving internal problems in Africa (Konar and Caylor, 2013). Henceforth, some African countries have introduced and formulated coherent VW-based planning policies as coping strategies to reduce water scarcity (Horlemann and Neubert, 2006; Turton, 2000). VW is different from the current mainstream of water resources management in terms of both ends of supply (i.e., opening new water sources and water transfer) and demand (i.e., engineering construction and improved terminal utilization efficiency). By urging mankind to enhance water policies to boost efficient and perfect water resource, VW comprehensively addresses socio-economy from a system perspective (Cui et al., 2018; Lamastra et al., 2017; Wu et al., 2019). Therefore, eco-hydrosolidarity approach was used to investigate the traded-off and synergistic interrelationships of humans with water systems, and guide the utilization of water resources (Falkenmark and Folke, 2002). Falkenmark (2009) defined eco-hydrosolidarity as a problem-oriented subject that contemplated the two-way feedback loops of socio-hydrological and environmental sustainability. Currently, the research priorities of eco-hydrosolidarity mainly consist of four main components: (1) land cover change (Shrestha et al., 2018), (2) direct water uses, (3) massive waste production, and (4) ecosystem governance enhancement (Falkenmark and Wang-Erlandsson, 2021; Harrington, 2015).

The VW study has achieved significantly by opening a hotspot in water resources research, but concurrently, there are still some research gaps. Although VW is regarded as a genuine transdisciplinary subject, some scholars consider the VW concept fallacious and notably flawed (Jia et al., 2017; Wichelns, 2011), which is not able to provide insightful advice on global trading, water scarcity, and the determination of efficient management strategies as well as the optimal water allocations (Wichelns, 2015). For instance, Sun et al. (2021) indicated that water shortages were caused by local exploitation and political and economic strategies other than water shortage had a great impact on international trade (de Fraiture et al., 2004). Wichelns (2010) and Chapagain and Hoekstra (2004) estimated VW imports and exports of 77 countries and concluded that land resource endowment was an more appropriate indicator than water endowment when describing agricultural product trade. On the contrary, several studies showed that the driving factors of VW fluxes varied based on the different socio-economic, political, and ecological situations (Supplementary Table S1). As a whole, the assessment of VW flows and their driving forces has pros and cons. Therefore, VW flow patterns need to be dialectically evaluated before used as socio-ecohydrological indicators (**Fig. 1**).

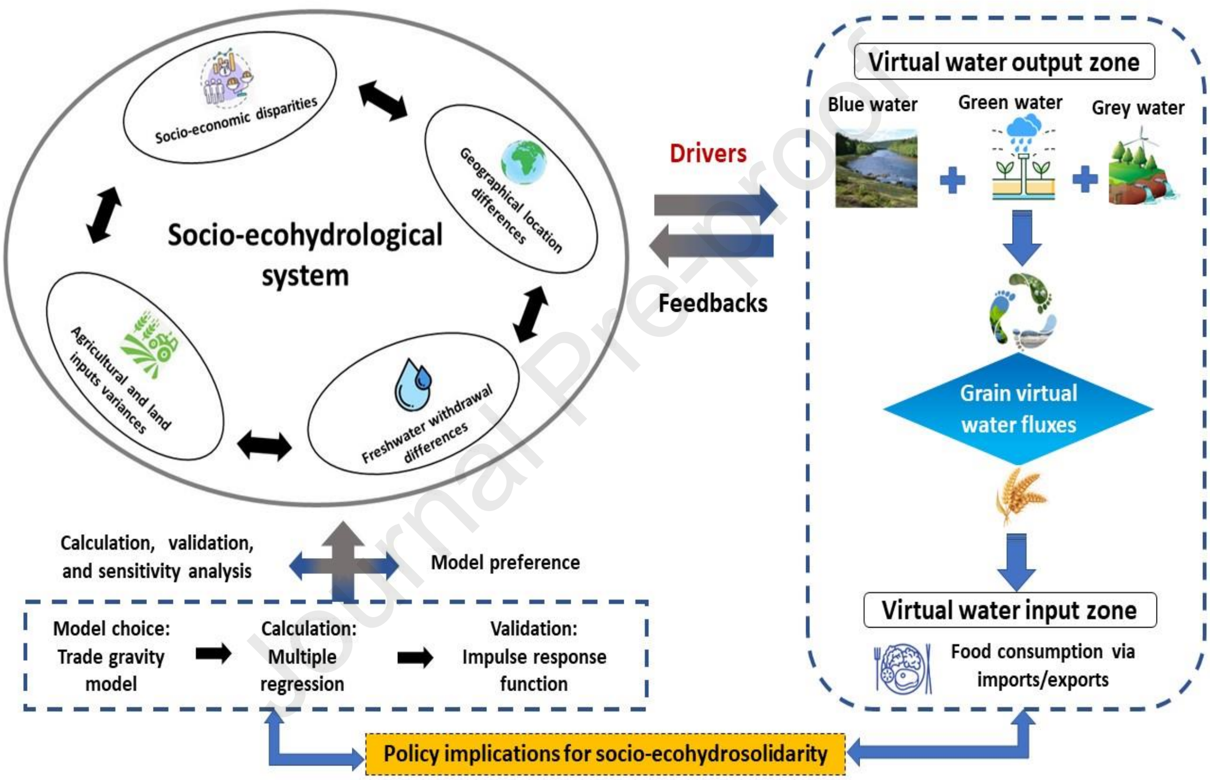


Fig. 1. A research framework for bridging the gap in eco-hydrosolidarity approach: assessing patterns of grain VW fluxes and drivers in LLDCs.

3 Materials and Methods

3.1 Study area

Out of Africa's 53 countries, 16 are landlocked, including BWA, BFA, BDI, CAF, TCD, ETH, LSO, MWI, MLI, NER, RWA, SSD, SWZ, UGA, ZMB, and ZWE (Appendix. Table A1).

All African LLDCs belong to SSA countries (**Fig. 2**), occupying ~ 8.6 × 10^6 km^2 of surface area, which were chosen as a case study. The LLDCs have a wide variety of climate zones or biomes, principally a dry winter season and a wet summer season (Amadou, 2019). The commonalities of Africa's northeastern countries include the frequent occurrence of severe droughts (e.g., northern UGA, ETH, and SSD), with most of Africa's southeastern countries (e.g., MWI, BDI, and Rwanda) experiencing two rainy seasons during the year (Nicholson, 2017). The 16 African LLDCs are home to ≥ 345 million people (Bjornlund et al., 2020) and ≥ 60% of the population of SSA are smallholder farmers. It was estimated that the average growth of cereal production was 2.42% and 1.66% during 2010 to 2019 and 2020 to 2029, respectively. In contrary, the agricultural trade growth was 1.8% during 2010 to 2019 and the expected trade deficit was –0.6 % during 2020 to 2029 (OGB, 2021).

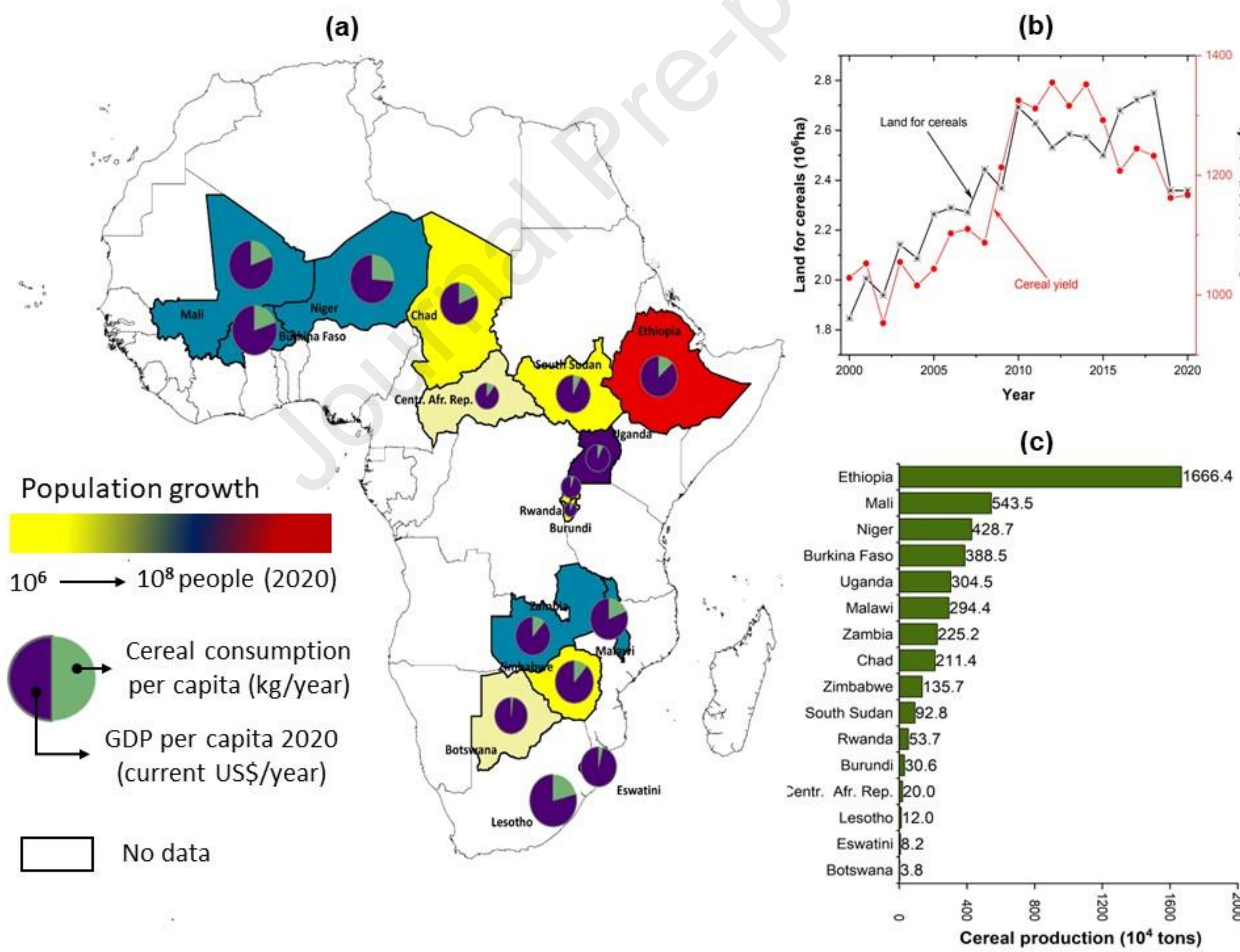


Fig. 2. (a) Localization of 16 African LLDCs (Case studies), population (10^8people), gross domestic product (US$·$yr^{-1}$), cereal consumption per capita (kg·yr^{-1}), **(b)** evolution of land for cereals (10^6ha) and cereal yield (kg·ha^{-1}) over time (2000–2020), and **(c)** yearly average of cereal production (10^4 tons) for the period 2000–2020.

3.2 Data and data source

Crop data, socioeconomic data, natural resource data, and hydrometeorological data were analyzed in this study. The crop production of this study referred to cereal grains, also called grains, which included any starchy seeds production of Poaceae such as barley, maize, wheat, rice, sorghum, and millet, etc. (Arendt and Zannini, 2013). Grains were marketed in their raw grain form or as ingredients in various food products. During 2000 to 2020, 16 African LLDCs covered ~ 8.6×10^6 km^2 of surface area. The crop data of cereal yields (kg·ha^{-1}) and production (metric tons) were collected from the Food and Agriculture Organization (FAO) database (FAO, 2022). The socioeconomic data of population (10^8 people), GDP per capita (current US$·$yr^{-1}$), and per capita cultivated land resources (ha·$person^{-1}$), and natural resource data of land use for cereal (10^8 ha) and agricultural water withdrawal (Bm^3·yr^{-1}) were obtained from World Bank (2021). The hydrometeorological data of temperature (^{0}C) and precipitation (mm·yr^{-1}) were collected from the National Aeronautics and Space Administration (NASA, 2022). The average physical distance (D) (km) between regions was collected from the geographical distance (GeoDist) database (Mayer and Zignago, 2011) as applied by Tamea et al. (2014).

3.3 Quantification of LLDCs' virtual water trade for grains

Crop-specific virtual water content (VWC) refers to the basis for estimating the extent of net virtual water trade (NVWT) in agrarian products between LLDCs and their trading partners. As a result of the availability of accurate data at the country and sub-country levels, this work adopted a bottom-up calculation technique (Van Oel et al., 2009), in which the grain VWC estimates relied on Mekonnen, Mesfin M and Hoekstra, Arjen Y (2011). The missing values in time series were forecasted using a regression equation proposed by Bertsimas et al. (2021). In addition, to assess the extent of virtual water export (VWE) and virtual water import (VWI) of grains, the computational technique proposed by Yang et al. (2006) was used, which were calculated by multiplication of country-specific VWC for cereal grains (VWC_p) by the quantity of exchanged grain (Mekonnen, M. M. and Hoekstra, A. Y., 2011):

$$VWE_p = \sum \left(Q_{e,t} \times VWC_p \right) \quad (1)$$

$$VWI_p = \sum \left(Q_{i,t} \times VWC_p \right) \quad (2)$$

where VWE_p and VWI_p are VWs (Bm^3) of grain for exporting area *e* and importing area *i*, respectively, $Q_{e,t}$ is the amount of grain exported (tons) at time *t*, and $Q_{i,t}$ is the amount of grain imported (tons) at the time *t*. The VWC_p stands for VWC of grains ($Bm^3 \cdot tons^{-1}$). For this study, the LLDCs were considered as importing regions whereas the African commercial partners were considered as exporting areas.

The gross volume of virtual water export (GVWE) to African LLDCs and gross volume of VWI (GVWI) from African LLDCs' trade partners were estimated as the dependent variables, which were equivalent to the total volume of water embodied in the grain products exchanged between LLDCs and partner regions (vice-versa) (Hoekstra, 2002):

$$GVWE_p = \sum \left(TQ_{e,t} \times VWC_p \right) \quad (3)$$

$$GVWI_p = \sum \left(TQ_{i,t} \times VWC_p \right) \quad (4)$$

where $GVWE_p$ is GVWE to Africa trade partners, $GVWI_p$ is GVWI to LLDCs, $TQ_{e,t}$, is the total VWE of partners of any LLDCs (Bm^3) during the study period, and $TQ_{i,t}$ is the total VWI of any LLDCs (Bm^3) during the study period. $GVWE_p$ and $GVWI_p$ stand for gross volume of VWE of the exporting country, which are equivalent to the VWs (Bm^3) of grain for exporting area *e*, and importing area *i*, respectively. The net virtual water imports (NVWI) flows of the selected country are thus given by:

$$NVWI_{i,e,p} = GVWI_p - GVWE_p \quad (5)$$

where $NVWI_{i,e,p}$ is the quantity of grain $VW_{(p)}$ ($Bm^3 \cdot yr^{-1}$) traded between exporting area *e* and importing area *i*.

3.4 Accounting and estimation of grain VW fluxes

Africa's landlocked countries belong to Sub-Saharan Africa (SSA) sub-regions. The SSA's present cereal self-sufficiency ratio is as little as ~ 0.8, making it among the (sub)continents with the lowest cereal self-sufficiency proportions, which have the highest anticipated rise in population and per capita GDP (Sulser et al., 2015; UN-DESA, 2019). Three sorts of VW accounts, explicitly, green water, blue water, and gray water were considered in this assessment. The green VW represents the water retained in the soil from rain that is available to growing crops, the blue VW represents the surface and ground water, and the gray VW represents the freshwater used to remove pollutants to meet water quality standards (Hoekstra et al., 2011; Sun et al., 2021). The grain VW fluxes for each country are calculated annually as described in Equation (6):

$$GFV_i = GO_i - P_i \frac{GO_N}{P_N} \tag{6}$$

where GFV_i refer to the net flow amount of grain for region i (tons), GO_i refers to the grain output of region i (tons), P_i refers to the population of the region i (capita), GO_N refers to the grain output of the country (tons), and P_N refers to the national population (capita). A positive value indicates grain export whereas a negative value indicates grain import.

The grain VW can have different implications based on Equations (7) and (8),

$$WV_i = \frac{GFV_i \times WF_i^p}{10} \quad \text{if} \quad GFV > 0 \tag{7}$$

$$WV_i = \frac{GFV_i \times WF_e^p}{10} \quad \text{if} \quad GFV < 0 \tag{8}$$

where WV_i refers to the virtual water flux (m^3) related to the grain in area *i*; WF_i^p refers to the water footprint of cereal production ($m^3 \cdot kg^{-1}$) in importing area *i*, WF_e^p refers to the water footprint of cereal production ($m^3 \cdot kg^{-1}$) in exporting areas. Moreover, a positive rate represents grain export, and a negative rate represents import.

3.5 Construction and specification of the trade gravity model (TGM) based on socio-ecohydrological factors

Socio-ecohydrological factors were also considered in this study to assess their effects on the grain VW fluxes between LLDCs and their partners. In African LLDCs, crop production, human resource, state governance, domestic investment, and trade openness absolutely and pointedly affect Africa's economic growth (Anyanwu, 2014). The grain production in LLDCs assists in graining self-reliance, but it cannot satisfy the food demands of all countries, which results in international grain trade and subsequent grain VW transfers (Bonilla-Cedrez et al., 2021). The grain exporting countries consume a lot of water resources for grain production whereas the grain importing countries utilize most local water resources for other developmental activities. Based on the comparison of the calculation findings, the so called ‘‘linear trade gravity model (TGM)’’ was designated to assess the drivers of VW. The pertinent influencing features of grain VW flux were selected to launch a TGM using multiple regression analysis, which was then used to analyze how socio-ecohydrological factors affected grain VW flux among African LLDCs and their partners.

Ultimately, the gravity model was a model derived from Newton’s physical theory of gravitation (Reinchenbach, 1978) (Equation 9). It was applied to the international trade theory to explain that bilateral trade flows that are determined by two regions’ socio-economic factors (e.g., GDP), hydrological factors (e.g., precipitation), and geographical factors (e.g., distance). The TGM was primarily employed to evaluate the international trade by Tinbergen (1962) and Pöyhönen (1963), and then extended by several scholars (Benedictis and Taglioni, 2011; Head and Mayer, 2014; Shepherd, 2016). The TGM explains the trade flows between trading partners, and resembles the universal law of gravitation (Bergstrand, 1985).

$$F_{ei} = \beta_0 \frac{v_e v_i}{d_{ei}^2} \quad (9)$$

where F_{ei} is the trade between countries *e* and *I*, v_e and v_i are values of the relevant variable for the country *e* and *i*, and *d* is the distance between the countries.

A general specification of the TGM includes a broader variety of determinants of bilateral trade Head and Mayer (2014):

$$Z_{ei} = G S_e^{\alpha} S_i^{\beta} S_{ei}^{\gamma} \quad (10)$$

where S_e denotes all the traits that have an impact on the exporter *e* as all partners, S_i captures all traits of *i* as a terminus of grain market from all sources, and Z_{ei} denotes as measure of the market accessibility *e* for the producers of region *i*, and it subsumes any other pair-specific factors influencing multilateral trade. Furthermore, the TGM as a model of bilateral trade interactions considers the multiplicative effects of size and distance (Fracasso, 2014).

In view of the countries selected for this study and quantitative examination of the factors affecting VW flux was taken into account generally based on the selection of the research objects and the existence of bilateral commerce between two locations. The basic form of the gravity model follows:

$$Q_{ei} = k \frac{Q_e Q_i}{D_{ei}} \quad (11)$$

where k indicates a constant, Q_{ei} indicates the trade volume between two areas, i.e., exporting region *e* and importing region *i*, M_e and M_i stand for the economic scales of the two areas, which are usually measured by per capita GDP, and D_{ei} is the distance between the two areas. Alternatively, equation (11) is frequently transformed to the linear form for empirical tests:

$$Q = X\beta + \varepsilon \quad (12)$$

where Q denotes the trade volume, X is a representation of many elements that influence the volume of trade, which is divided into three parts: supply of traded goods, demand for traded goods, and trade pushback, β denotes the coefficient vector, and ε denotes the error term, with $\varepsilon \sim N\ (0, \sigma^2)$.

According to the neoclassical growth theory (Solow, 1956), the input of production components, capital accumulation, and technological improvement are the key drivers of output growth. Based on relevant literatures about socio-hydrological perspective and VW approach (Sun et al., 2022; Wu et al., 2019), the explanatory variable was determined to be the amount of grain VWT. On contrary, the explanatory variables comprised the population (POP), per capita GDP (GPC), per capita cultivated land resources (CLR), land for cereal (LFC) and agricultural water withdrawal (AWW), cereal yield (CY), crop production (CP), cereal consumption per capita (CCC), precipitation (PRE), temperature (TEM), and geographical distance (DIS). With the basic gravity model, the explicit gravity model of driving forces of grain VW fluxes between LLDCs and their partners was built by incorporating the additional factors mentioned above:

$$VWT_{eit} = \propto + \beta_1 POP_{et} + \beta_2 POP_{it} + \beta_3 GPC_{et} + \beta_4 GPC_{it} + \beta_5 CLR_{et} + \beta_6 CLR_{it} + \beta_7 LFC_{et} + \beta_8 LFC_{it} + \beta_9 CY_{et} + \beta_{10} CY_{it} + \beta_{11} CP_{et} + \beta_{12} CP_{it} + \beta_{13} CCC_{et} + \beta_{14} CCC_{it} + \beta_{15} AWW_{it} + \beta_{16} AWW_{et} + \beta_{17} PRE_{et} + \beta_{18} PRE_{it} + \beta_{19} TEM_{et} + \beta_{20} TEM_{it} + \beta_{21} DIS_{it} + \varepsilon_{ei} \quad (13)$$

where e denotes the grain VW output area, i denotes the grain VW inflow area, t = 2000, 2001, …, 2020, $\propto$ is a constant term, β_1, β_2,⋯, β_n stand for the regression coefficients, and ε_{ei} denotes a random error term, which is often called impulses, or innovations or shocks.

To identify the exporting region by e and the importing region by i, two separate estimates are given for the VWT from region e to region i as follows:

$$VWE_{ei} = \beta_0 (POP_e)^{\beta_{1e}} (GPC_e)^{\beta_{2e}} (CLR_e)^{\beta_{3e}} \ldots (D_{ei})^{\beta_{4e}} (VW_e)^{\beta_{5e}} \ldots e \in \Omega_d (i) \tag{14}$$

$$VWI_{ei} = \beta_0 (POP_i)^{\beta_{1i}} (GPC_i)^{\beta_{2i}} (CLR_i)^{\beta_{3i}} \ldots (D_{ei})^{\beta_{4i}} (VW_i)^{\beta_{5i}} \ldots i \in \Omega_d (e) \tag{15}$$

where VWE_{ei} is the virtual water export, VWI_{ei} is the virtual water import, POP is the population, GPC is the per capita GDP, CLR is the per capita cultivated land resources, D is the distance between LLDCs and the commercial partner, and VW is the embodied water used in the grain production. Note that all socio-ecohydrological factors considered in this study can be included in Equation (14) and Equation (15). Equation (14) expresses the demand's pull for export, describing the VWE as a function of terminus features, appertained to as the export law. Similarly, Equation (15) expresses the supply's push for import, describing the VWI as a function of source characteristics, resorted to as the import law (Chouchane et al., 2018; Tamea et al., 2014).

Both explanatory and response variables are transmogrified into a logarithm of base 10. So, identifying the exporting region by e, importing region by i for grain p and time t, the following model was adapted for the gravity model. The gravity model of export is:

$$\ln(VWE_{eipt}) = \beta_0 + \beta_{1i} \ln(POP_{it}) + \beta_{2i} \ln(GPC_{it}) + \beta_{3i} \ln(CLR_{it}) + \cdots + \beta_{4i} \ln(D_{ei}) + \beta_{5i} \ln(VW_{pit}) + e_{eipt} \tag{16}$$

whereas the gravity model of import is:

$$\ln(VWI_{eipt}) = \beta_0 + \beta_{1e} \ln(POP_{et}) + \beta_{2e} \ln(GPC_{et}) + \beta_{3e} \ln(CLR_{et}) + \cdots + \beta_{3e} \ln(D_{ei}) + \beta_{5e} \ln(VW_{pet}) + e_{eipt} \tag{17}$$

3.6 Multiple regression and impulse response function

The multiple linear regression (MLR), an extension of linear regression models, was used to explain and analyze the relationship between multiple independent variables and one dependent or criterion variable, which was expressed as $Y_j = f(X_j, \beta) + \varepsilon_j$, where Y_j is the response variable, f is a function, X_j represents the explanatory variable, β is the unknown parameter, and ε_j is the error terms (Chou et al., 2008). The Poisson pseudo maximum likelihood (PPML) estimator was then utilized (Santos Silva and Tenreyro, 2011). Comparing this estimator to the conventional ordinary least squares (OLS) method, there are significant benefits. After collecting logs of the equation, it is simple to estimate the multiplicative form of the gravity equation using OLS estimators.

However, the vector autoregressive model's (VAR) impulse response function (IRF) is typically used to examine the effects of a unit random error shock on each endogenous variable's present and future, and it may visually depict the dynamic interaction between variables (Durlauf and Blume, 2016; Sims, 1980). Before the IRF analysis, a vector autoregression model is built. This study used LLDCs and their trading partners as the analysis materials and simulated the response trajectory of grain VW flow to the change shock of POP, GPC, CLR, LFC AWW, CY, CP, CCC, PRE, TEM, and DIS using the basic theory of impulse response. Finally, the *Eviews* software was used to carry out a data stationarity test (Augmented Dickey-Fuller, ADF) (Caspi, 2017) on lnVWT, lnGPC, lnPOP, lnCLR, lnLFC, lnAWW, lnCY, lnCP, lnCCC, lnPRE, lnTEM, and lnDIS. The test outcomes indicated that the logarithmic data was a non-stationary series for some parameters and were adjusted from 1st difference to 2nd difference accordingly, after which an impulse response assessment after the first difference processing on the data was performed.

The VAR model with different influences as follows:

$$y_t = \Phi_1 y_{t-1} + \Phi_2 y_{t-2} + \cdots + \Phi_p y_{t-p} + \varepsilon_t = \left(I_k - \Phi_1 L - \Phi_2 L^2 - \ldots - \Phi_p L^p\right)^{-1\varepsilon_t} = \left(I_k + \theta_1 L + \theta_2 L^2 + \ldots + \theta_p L^p\right) \varepsilon_t, t = 1,2,3\ldots, T \quad (18)$$

where *k* denotes multiple variables, *p* denotes the lag order, *T* denotes the number of samples, Φi, and Θi are the parameter's matrices, and $\varepsilon_t = (\varepsilon_{it})'$ denotes the random disturbance term, considering the following circumstances:

$$E(\varepsilon_{it}) = 0, \ for \ \forall_t, i = 1,2,3 \ldots i \quad (19)$$

$$var\ (\varepsilon_t) = E(\varepsilon_e \varepsilon_i) = \sum(\sigma_{ei}), \ for \ \forall_t \quad (20)$$

$$E(\varepsilon_{it}\,\varepsilon_{is}) = 0, for\ \forall_t \neq s, i = 1,2,3 \ldots i \quad (21)$$

the $i - th$ factor y_{it} of y_t can be expressed as:

$$y = \sum_{j=1}^{k}\left(\Theta_{ei}^{(0)}\varepsilon_{jt} + \Theta_{ei}^{(1)}\varepsilon_{jt-1} + \Theta_{ei}^{(2)}\varepsilon_{jt-2} + \ldots + \Theta_{ei}^{(n)}\varepsilon_{jt-n}\right),\ t = 1,2,3,\ldots n \quad (22)$$

The reaction mechanism brought on by the pulse of y_i is: $\Theta_{ei}^{(0)}, \Theta_{ei}^{(1)}, \Theta_{ei}^{(2)}, \ldots \Theta_{ei}^{(n)}$. Simultaneously, the cumulative response function represents: $\sum_{q=0}^{\infty}\Theta_{ei}^{(q)}$, where $\Theta_{ei}^{(q)}$ indicates a function of q and represents the response of $y_{e,i+q}$ to a unit shock of ε_{jt} in the case that the disturbance remains unchanged, and The disruptions are always present at other times.

An imaginary diagram of drivers associated with VWI or VWE between exporting country (e.g., EU-27) and importing country (e.g., Ethiopia) is represented in **Fig 3.** As shown in Fig. 3, population and GDP per capita of grain importing country significantly increased from 2000 to 2020. However, the cereal grain yield as well as the land for cereals was low compared to the exporting country, which implied that the LLDCs tended to import the high VW from developed countries to meet the particular grain demands.

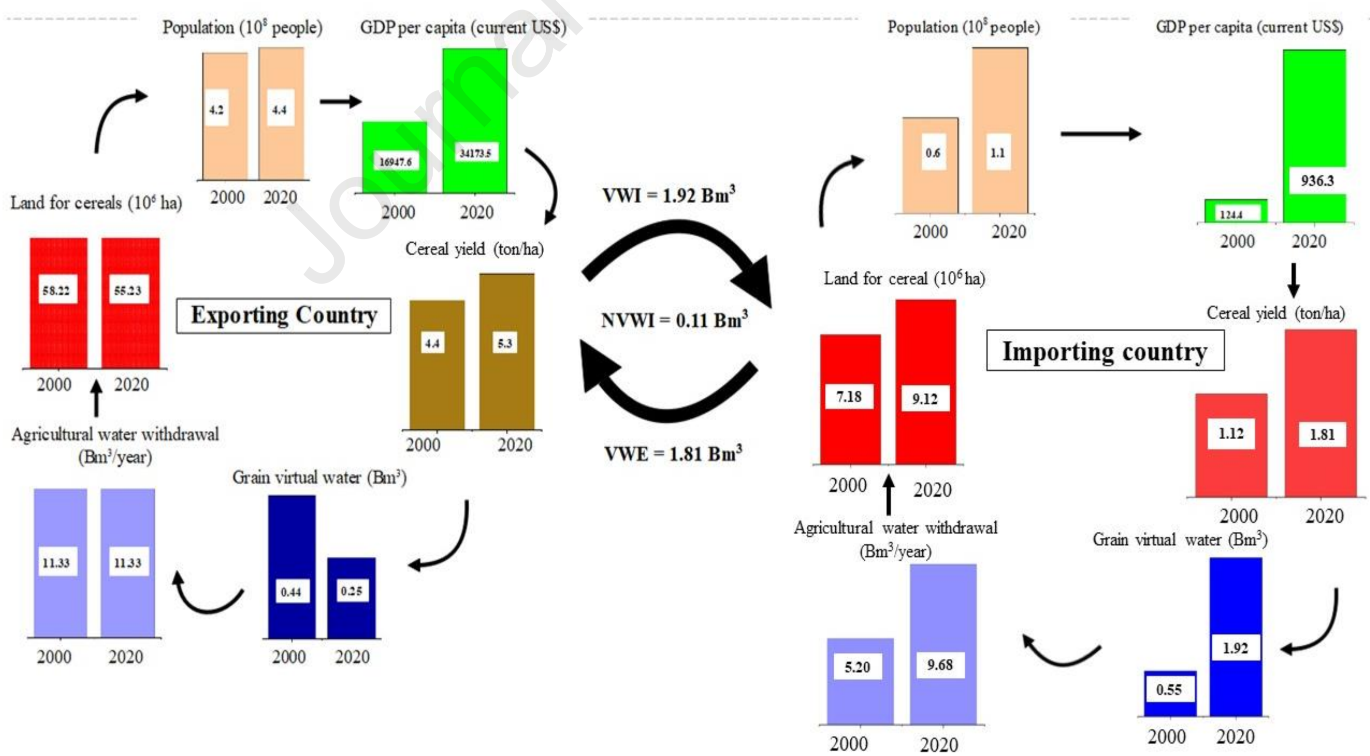


Fig 3. Hypothetical diagram illustrating the drivers associated with VW fluxes from exporting country to importing country.

3.6 Sensitivity analysis

We conducted a sensitivity analysis to determine how different drivers affect virtual water flows (VWF) in LLDCs under assumptions of this study. The sensitivity analysis helped us understand how data uncertainty propagated through the VWF and detect the model input variables that significantly affected the model outputs. Specifically, a first-order sensitivity analysis was performed with the functional dependence of VWF on each input parameter explained as Maclaurin series and abridged at the first order. In this way, a linear relationship between the VWF estimate and generic input parameter, *x*, was presumed in a small neighborhood of *x*. Parameters were perturbed one-at-a-time (OAT) of very small quantity, that was randomly selected. To assess and contrast the VWF's sensitivity to varying factors, we established a normalized sensitivity index (SI_x), for each variable, x, as described by Tuninetti et al. (2015):

$$SI_x = \left(\frac{\Delta VWF}{VWF_0}\right) / \left(\frac{\Delta x}{xref}\right) \quad (23)$$

where ΔVWF is the virtual water flow variation resulting from changing the parameter x of quantity ΔX. A positive and negative changeability not only shows the relationship between output and input but also the direction and magnitude of the change.

4 Results

4.1 Dynamics of grain VW flow between LLDCs and their trade partners, during 2000-2020

This study quantified the grain VW flow between LLDCs and their trade partners from 2000 to 2020 (**Fig. 4**). The grain VW flow was expressed in terms of VWI and VWE variability. The years of 2016, 2017, and 2018 showed the highest values of VWIs of 10.3 Bm^3, 8.39 Bm^3, and 8.28 Bm^3, respectively. Spatially, the main grains were distributed in Ethiopia, Burkina Faso, Uganda, and Mali. The principal exporters of grain VW in LLDCs were European countries (EU-27), India, USA, Russia, Ukraine, Argentina, and China. The VWI showed a significant increase and a fast growth rate. For instance, from 2013 to 2020, the rate of change drastically increased from 2312.9% to 9467.4%. Among the LLDCs, Ethiopia was the country with the largest volume of VWI with the inflow increased from 0.55 Bm^3 to 4.74 Bm^3, followed by Uganda, Burkina Faso, Zimbabwe, and Mali. On the contrary, European Union had the largest VWE with the outflow rising from 0.94 Bm^3 to 5 Bm^3 during 2000-2020, followed by India, Russia, and USA. Besides, the NVWI varied from 1.28 Bm^3 to –5.38 Bm^3 from 2000 to 2020. The average NVWI was –0.85 Bm^3, which indicated that African LLDCs were net VW importers (i.e., cereal grain dependency). The role played by LLDCs in VWI and VWE was not changed over the last two decades.

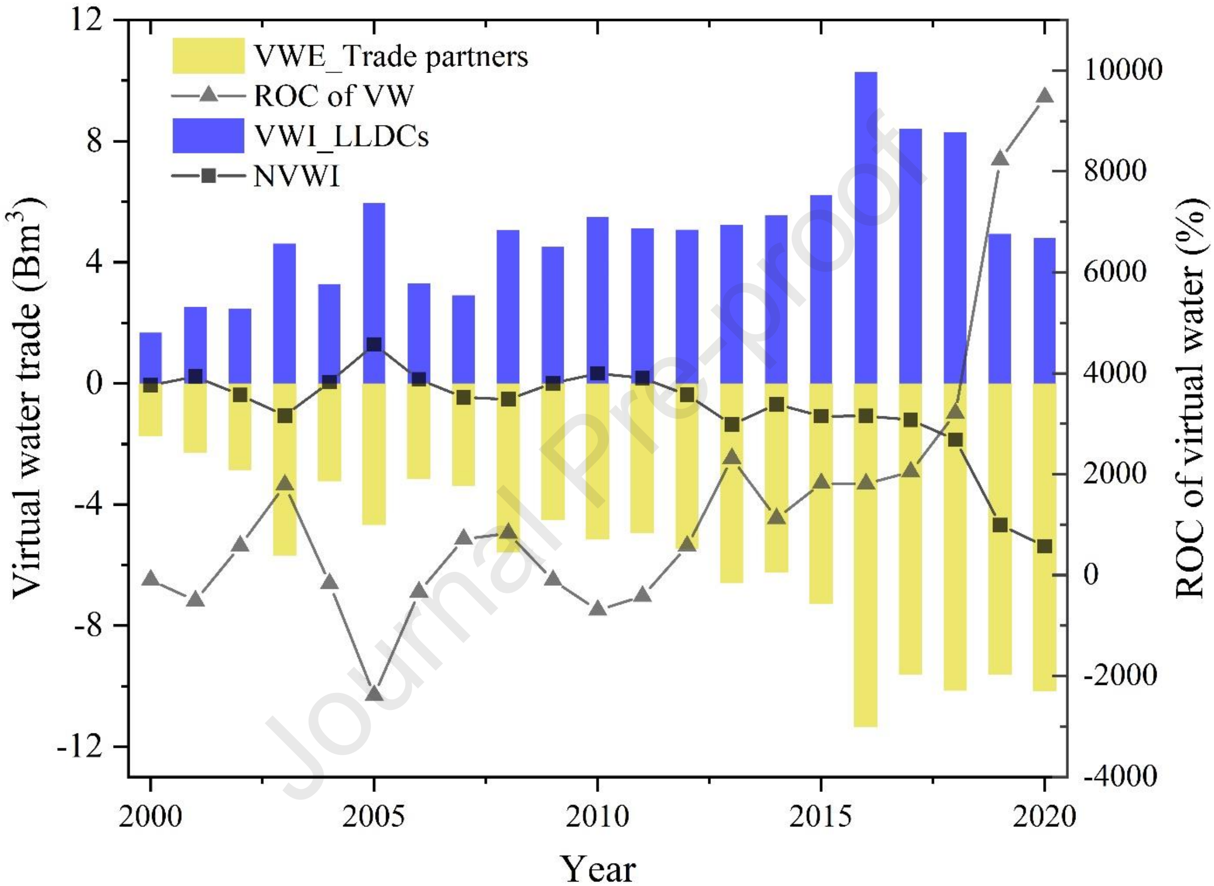
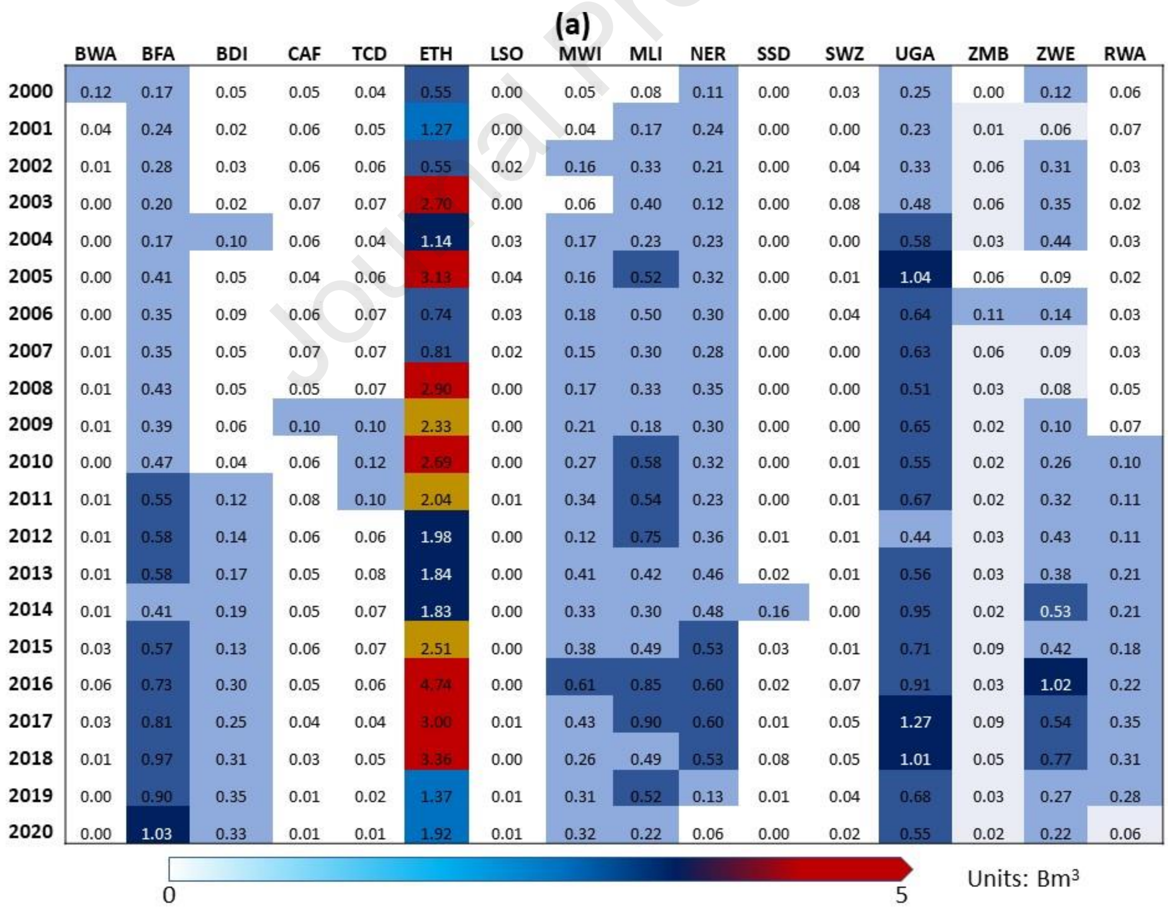


Fig 4. Proportion of VWE, VWI, NWVI, and rate of change (ROC) between LLDCs and their commercial partners during 2000-2020.

4.2 Quantification of grain production and consumption in LLDCs and their partners

The quantity and direction of grain VW fluxes between LLDCs and their partners are shown in **Fig. 5. a**. The grain VW trade flow between two regions through international trade was quantified as the trade volume of grains times their VWC. The VWC of grain varied temporally and spatially. The total quantity of grain VWI of LLDCs increased from 1.73 Bm^3 in 2000 to 10.2

Bm^3 in 2020, whereas the total quantity of VWE of African landlocked countries' partners increased from 1.67 Bm^3 in 2000 to 4.79 Bm^3 in 2020. The highest volume of grain was mainly distributed in eastern African countries (i.e., Ethiopia and Uganda), followed by western African countries (i.e., Burkina Faso and Mali). Ethiopia had the largest amount of VW input compared to other landlocked countries in Africa. Other countries that received a relatively small amount of grain VW included Zambia (0.86 Bm^3), Eswatini (Bm^3), Botswana (0.37 Bm^3), South Sudan (0.34 Bm^3), and Lesotho (0.21 Bm^3) (**Fig 5.a**). From 2000 to 2020, the total amount of grain VWI was ~ 105.6 Bm^3. The total amount of grain VWE from African LLDCs' trade partners is shown in **Fig. 5.b.** Between 2000 and 2020, the total amount of grain VWE was ~ 123.6 Bm^3. The highest value of VWE from 11 commercial partners of LLDCs was 11.3 Bm^3 in 2016 and the lowest was 1.79 Bm^3 in 2000. The countries with the highest VWE were EU-27, which varied from 0.55 Bm^3 to 5 Bm^3, whereas the countries with the lowest amount of VWE were China (5.19 Bm^3), Canada (2.37 Bm^3), Brazil (1.75 Bm^3), Turkey (0.9 Bm^3), and Iran (0.02 Bm^3).



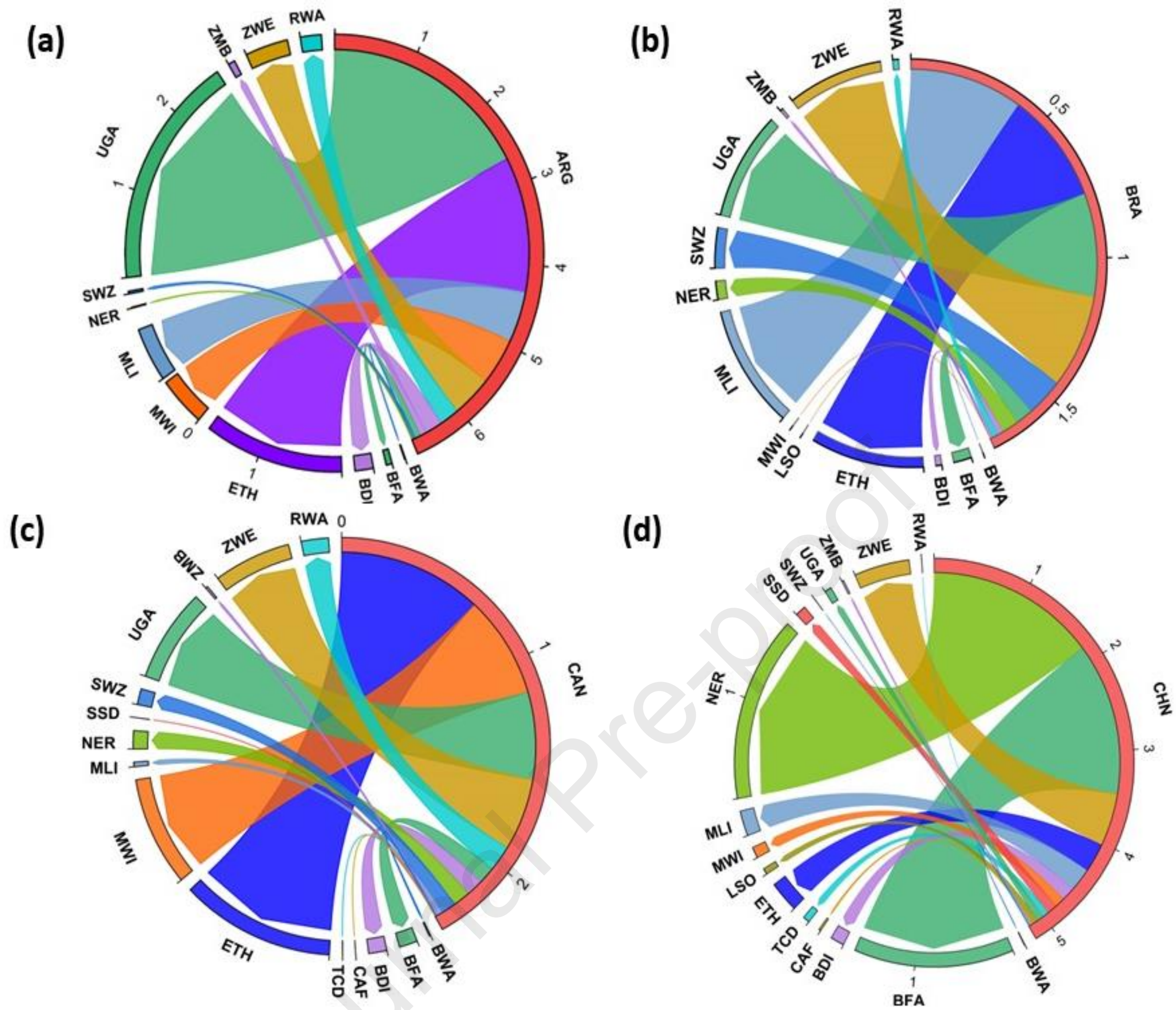
(b)

	ARG	BRA	CAN	CHN	EU-27	IND	IRN	RUS	TUR	UKR	USA
2000	0.07	0.00	0.02	0.32	0.94	0.01	0.00	0.00	0.10	0.00	0.27
2001	0.08	0.00	0.05	0.35	1.10	0.04	0.00	0.00	0.00	0.00	0.67
2002	0.04	0.13	0.02	0.65	0.99	0.60	0.00	0.00	0.00	0.00	0.43
2003	0.00	0.26	0.10	0.55	2.15	1.00	0.00	0.02	0.01	0.00	1.60
2004	0.35	0.01	0.08	0.34	0.55	0.55	0.00	0.00	0.01	0.00	1.34
2005	0.24	0.00	0.30	0.10	0.77	0.50	0.00	0.07	0.07	0.04	2.58
2006	0.12	0.02	0.08	0.12	1.36	0.37	0.00	0.14	0.06	0.12	0.78
2007	0.22	0.00	0.08	0.13	1.10	0.57	0.01	0.33	0.02	0.06	0.86
2008	0.28	0.00	0.17	0.16	3.05	0.47	0.01	0.27	0.02	0.28	0.85
2009	0.16	0.18	0.07	0.04	2.46	0.04	0.00	0.35	0.01	0.43	0.78
2010	0.06	0.12	0.04	0.04	2.45	0.05	0.01	0.42	0.03	0.64	1.30
2011	0.25	0.34	0.02	0.15	1.29	0.12	0.00	1.89	0.04	0.04	0.80
2012	0.87	0.34	0.04	0.11	1.26	1.56	0.00	0.49	0.02	0.19	0.57
2013	0.18	0.04	0.09	0.04	1.34	3.12	0.00	0.54	0.03	0.68	0.55
2014	0.01	0.00	0.14	0.04	1.90	1.22	0.00	1.39	0.02	0.78	0.73
2015	0.07	0.04	0.16	0.04	2.60	1.16	0.00	1.56	0.03	0.89	0.73
2016	0.19	0.05	0.24	0.19	5.00	1.79	0.00	1.81	0.09	0.85	1.28
2017	0.80	0.13	0.19	0.33	3.17	1.59	0.00	1.80	0.08	0.44	1.06
2018	0.47	0.05	0.22	0.30	2.29	1.92	0.00	3.41	0.10	0.53	0.86
2019	0.74	0.02	0.15	0.57	2.08	1.60	0.00	2.03	0.07	1.46	0.89
2020	1.52	0.01	0.12	0.60	1.81	2.66	0.00	1.65	0.08	0.59	1.11

0 – 5 Units: Bm^3

Fig 5. (a) Quantity of total VWI of LLDCs from 2000 to 2020. **(b)** Quantity of total VWE of partners from 2000 to 2020. The color gradient varies from white (low values) to red (highest value). Note: Here, the European Union (EU-27) is considered a region with 27 member states as Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. The countries' names and ISO code are presented in Appendix A, Table A1.

Furthermore, the detailed VWI transfers in the grain trade were obtained by multiplying the quantity of LLDC imported grain by the VWC (**Fig. 6**). 11 countries, including Argentina, Brazil, Canada, China, European Union-27, India, Iran, Russia, Turkey, Ukraine, and United States of America, were considered as the leading exporters (referential) of cereal grains to LLDCs because of their relatively large grain production. Grain demand in LLDCs was mainly dependent on the grain imports from these 11 trading partners. Ethiopia was the country with the largest volume of grain deficit with a grain VWI of 43.4 Bm^3. From the viewpoint of socio-ecohydrology and food security, the grain trade was unsustainable in LLDCs because of the improper water management practices and cultivated land management practices.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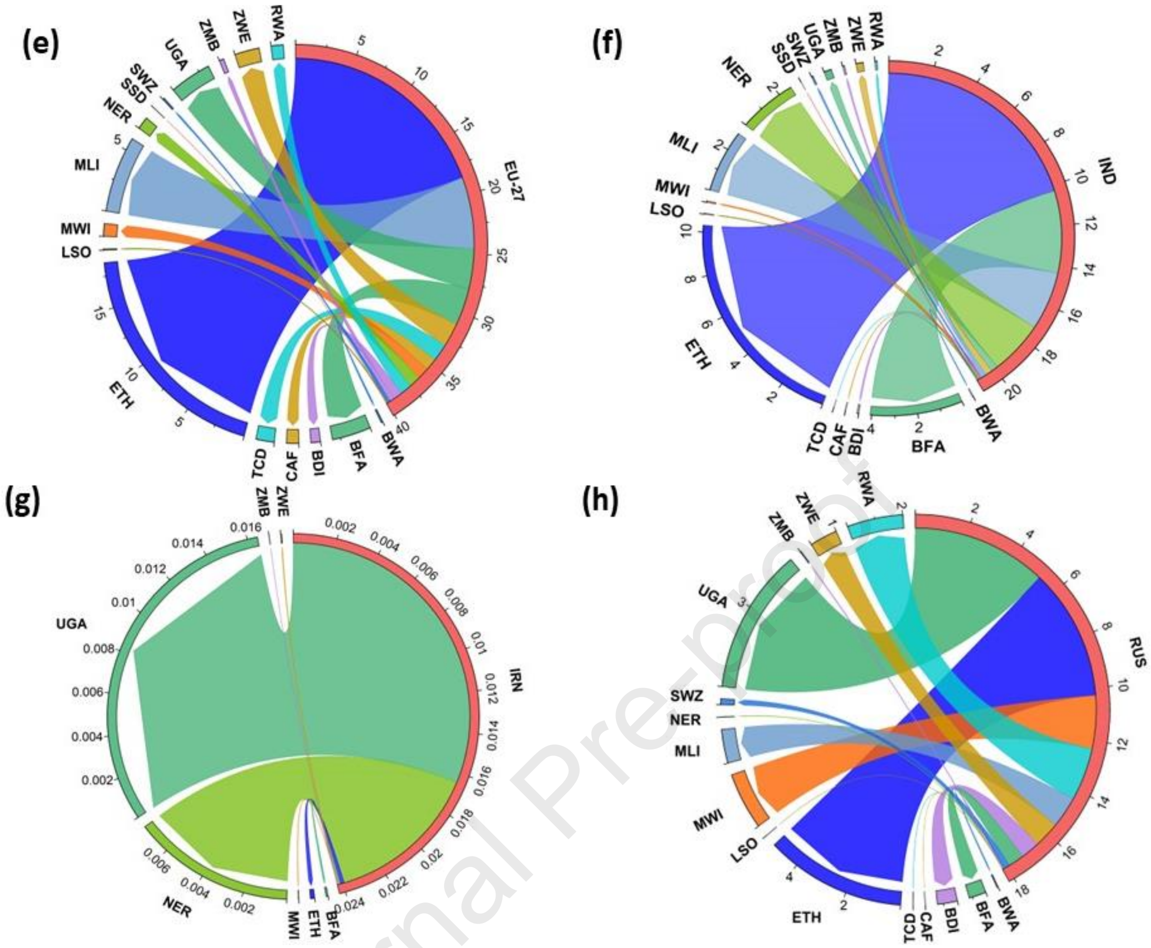
478 
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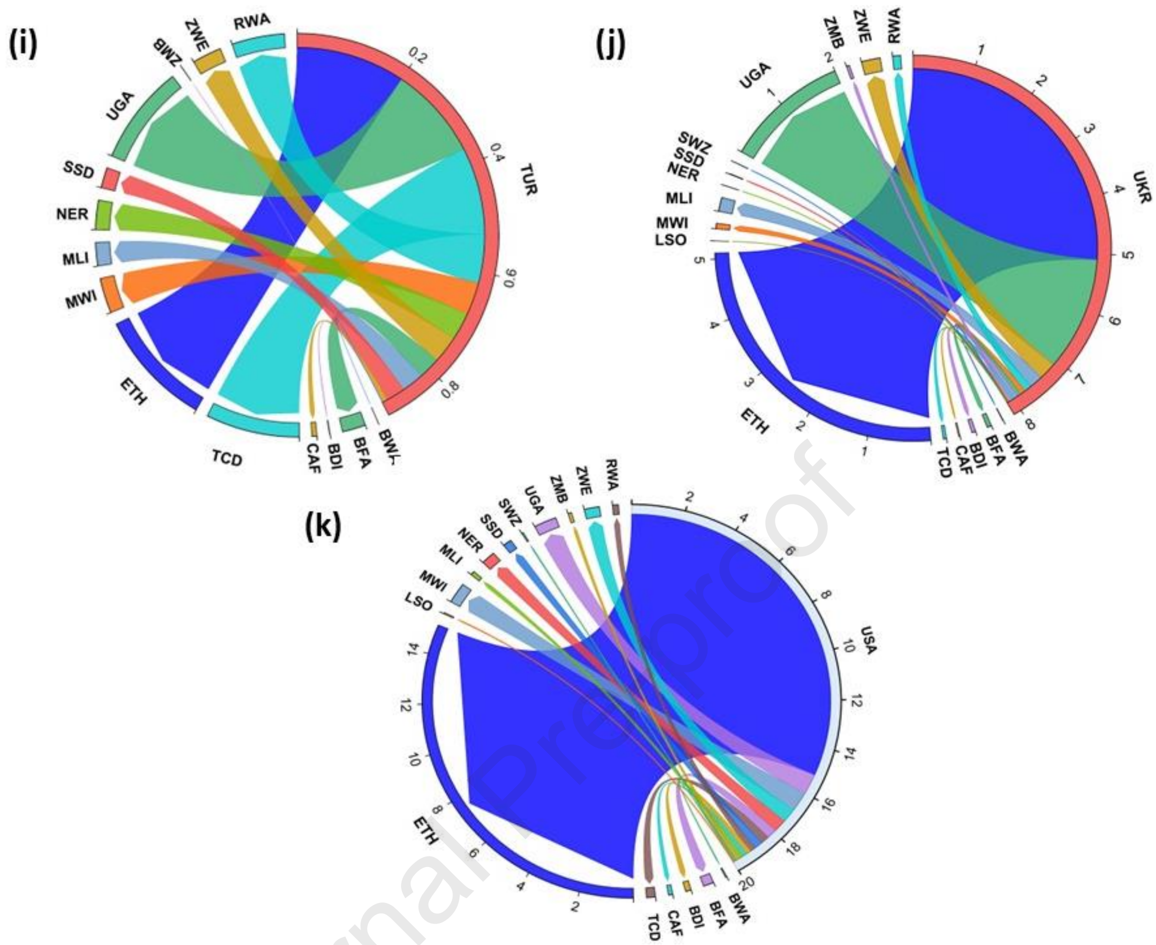


Fig 6. Direction of grain virtual water import from 11 trading partners of LLDCs from 2000-2020. An arrowhead indicates the direction in which flux flows. The bigger the arrow, the quantity (in Bm^3) is high. The countries' names and ISO code are presented in Appendix A, Table A1.

4.3 Assessment and comparison of blue, green, and grey VWI in LLDCs

Green water refers to the soil moisture from rainwater and freshwater, blue water refers to water from rivers, irrigation reservoirs, and aquifers used in the production activities, and grey water refers to the polluted water from the production. Actual information on grain VW fluxes in terms of blue water, green water, and gray water in African LLDCs is presented in **Fig. 7**. The quantity of green water VW embodied in grain was the most consumed in the last two decades, almost in the whole study area. It was apparent from **Fig 7**, that Ethiopia had the highest green water VWI, which was 2.08 Bm^3 higher than South Sudan, which had the lowest green VWI of

1.87 Bm^3. Subsequently, the green water, blue water, and grey water contributed 79.3%, 14.7%, and 5.98% of the total grain VWI. An evident increase in the three types of water was observed from 2000 to 2020, resulted from high grain VWI from other countries. Apart from the amount of green water VWI, the blue water VWI and grey water VWI showed a remarkable discrepancy in grains. The magnitude of green, blue, and grey water generally varied and decreased from country to country in the following order: Ethiopia > Uganda > Burkina Faso > Mali > Zimbabwe > Niger > Malawi > Burundi > Rwanda > Chad > Central Africa Republic > Eswatini > Zambia > South Sudan > Botswana > Lesotho. Obviously, there were substantial differences between various African landlocked countries and their trading partners. The period of 2010-2018 had a high blue water VW consumption, owing to the occurrence of extreme events (e.g., droughts) in the whole continent.

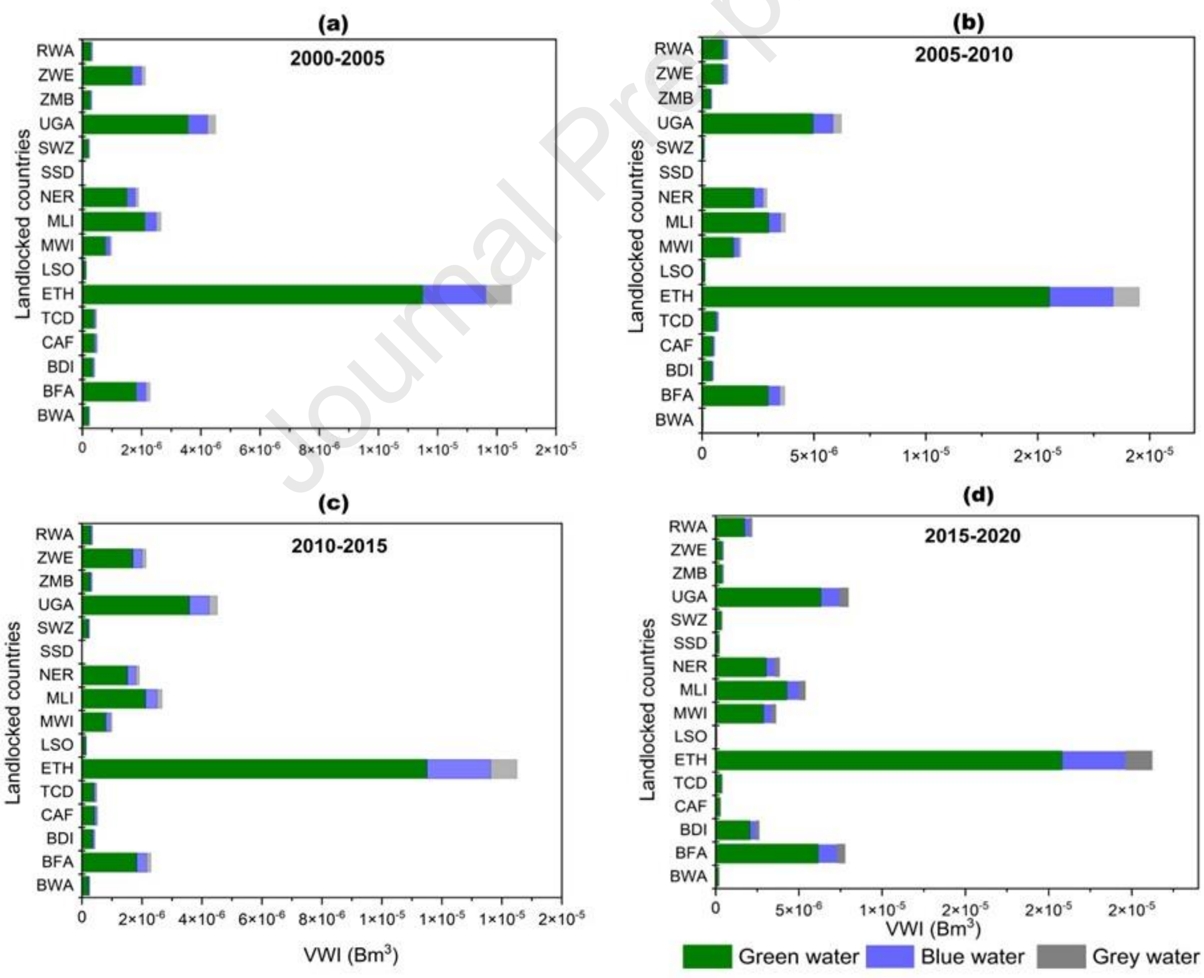


Fig 7. Green water, blue water, and grey water endowments on grain VWI fluxes in African LLDCs during the period of (a) 2000-2005, (b) 2005-2010, (c) 2010-2015, and (d) 2015-2020. The countries' names and ISO code are presented in Appendix A, Table A1.

4.4 TGM estimation results of grain VWI between the LLDCs and their trading partners

The estimation results of the TGM of LLDCs' VW fluxes and their trading partners are summarized in **Table 1**. Five models with alternation and combination of selected socio-ecohydrological factors were constructed and the panel data were balanced, where all LLDCs (cross-sectional units) had the same period (time series units). The estimation findings revealed that in the five mixed gravity models used in this work, the common variables utilized to assess the driving parameters of grain VW flow also had a strong explanatory power. Moreover, with the increase in the number of explanatory variables, the degree of explanation of the model also increased, with the value of R^2 rising from 0.46 to 0.99. In the 5th model, a combination of socio-economic and ecological factors revealed that the population, per capita GDP, followed by land use for cereal, crop yield, cereal consumption per capita, and agricultural water withdrawal had a significant positive driving effect on grain VWI in LLDCs, which were all in the confidence interval of 99.9% ($p < 0.01$), the same as at confidence interval of 95% ($p < 0.5$). The climatic variables did not have more significant effect on VWI in both LLDCs (i.e., grain importers) and partners (i.e., grain exporters). This meant that with the further drastic population growth and increase in GDP in LLDCs, the amount of grain VWI would further increase. In this study, the distance between the LLDCs was kept constant from each LLDC to one partner, thus implying that the distance between countries was not a factor that restricted bilateral grain VW transfers.

Table 1. The gravity model estimations of grain VWI between the LLDCs and their trading partners.

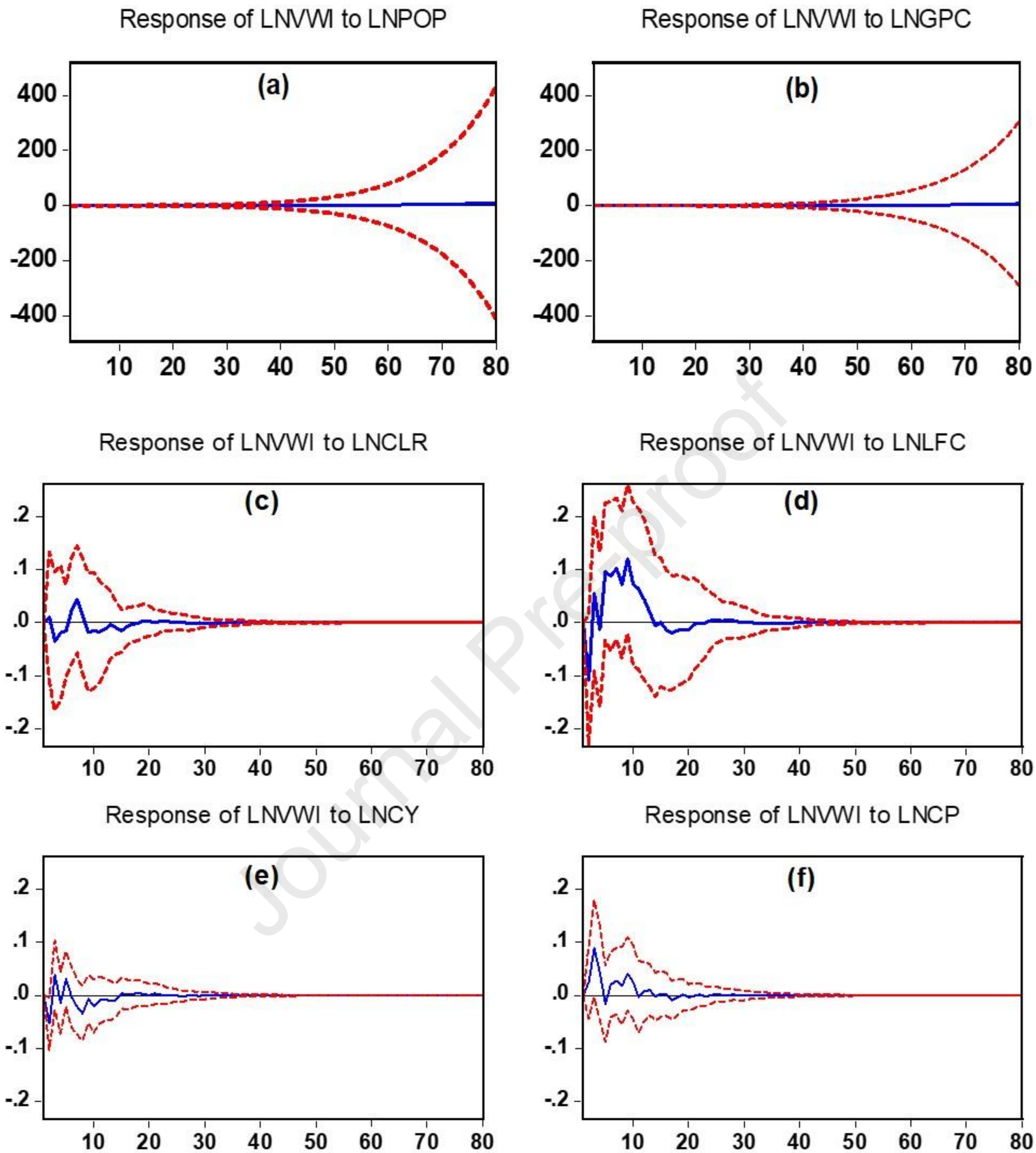
Factors	TGM 1	TGM 2	TGM 3	TGM 4	TGM 5
POP_e	1.69* (0.15)	–0.41*** (0.36)	0.0001*** (0.000)	–0.098*** (0.08)	–0.57*** (0.3)
POP_i	–0.67*** (0.15)	–0.56*** (1.18)	–4.69*** (1.31)	–0.43*** (0.33)	0.0007*** (0.000)
GPC_e	–0.73*** (1.18)	0.27** (1.49)	0.0007** (0.000)	–0.43*** (0.264)	1.15* (1.13)
GPC_i	0.0008*** (0.000)	0.14*** (0.33)	0.0003*** (0.002)	–0.03*** (0.074)	–0.45*** (0.28)
$DIS_{e,i}$	0.00028** (0.000)	0.02** (0.34)	0.04** (0.09)	–0.07** (0.05)	0.06** (0.11)
CLR_e		–0.006*** (0.004)	1.0372* (5.347)	–0.64*** (2.24)	1.37* (1.26)
CLR_i		–0.01*** (0.006)	–5.68** (7.4)	–4.91*** (3.09)	0.06 (0.26)

LFC_e		–0.005*** (0.004)	–2.77*** (4.59)	–3.17*** (1.92)	1.3* (1.082)
LFC_i		–0.000*** (0.002)	0.89* (1.85)	0.003** (0.77)	–0.24*** (0.9)
CY_e			0.87* (0.39)	0.28* (0.41)	–0.10*** (0.2)
CY_i			–0.37*** (0.4)	0.03*** (0.41)	0.13** (0.19)
CP_e			–0.001*** (0.002)	–0.54*** (2.12)	–0.22*** (0.89)
CP_i			–0.000*** (0.002)	–0.6*** (2.05)	–0.33*** (0.86)
CCC_e				0.01*** (0.02)	8.30 (22.00)
CCC_i				0.003** (0.01)	–0.4*** (12.35)
AWW_e				0.003** (0.002)	0.21 (2.20)
AWW_i				0.000** (0.00212)	–0.08*** (1.003)
PRE_i					–2.00*** (1.93)
PRE_e					0.09* (1.18)
TEM_e					–0.49* (0.59)
TEM_i					–0.44* (0.20)
Constant	84.62 (39.17)	349.08 (227.67)	64.34 (45.9)	12.64 (39.3)	10.66 (6.14)
R^2	0.46	0.85	0.96	0.99	0.99
AIC	0.51	0.04	–3.16	–3.47	–5.33
SC	0.96	0.88	–2.32	–2.63	–4.78

Note: The TGM with different numbers represent the five mixed gravity models tested. The subscripts *e* represents exporting region whereas *i* importing region, for grain cereals p. The numbers outside the parenthesis are the regression coefficients (r), whereas values in the parenthesis are standard deviations (std); *, **, and *** means reject the null hypothesis at $p<0.1$, $p<0.05$, and $p<0.01$, significance levels, respectively. AIC refers to Akaike Information Criteria (AIC) whereas Schwarz criteria (SC) to help quantify and choose the least complex probability model among multiple options (Pauler, 1998).

4.5 Analyzing socio-ecological variables using the impulse response function

The trade gravity model was used to assess the socioeconomic and environmental parameters impacting the grain VW flux in LLDCs and their trading partners. Though, the impulse response function was utilized to further trace the interactive impact of VW flux on the change of each dependent variable in the LLDCs. The shifting range variation depended on the influencing factors during the study period. Following a shock caused by different influencing factors, the response of ln VWI to ln POP and ln GPC ranged from + 400 to – 400 (**Fig. 8.a and Fig. 8.b**); for ln CLR, ln LFC, ln CY, and Ln CP, it varied from +2 to –2 (**Fig. 8.c, Fig. 8.d, Fig. 8.e and Fig. 8.f**); and for lnCCC, lnAWW, lnPRE, and lnTEM, it varied from + 4 to –4 (**Fig. 8.g, Fig. 8.h, Fig. 8.i and Fig. 8.j**). Per capita GDP and population shocks were the most significant influences with a great impact on grain VWI flows in LLDCs, followed by land use for cereal, crop yield, cereal consumption per capita, and agricultural water withdrawal. The impact of climatic factors (i.e., precipitation and temperature) was small. The influence of each variable on the VWI tended to be zero around the 40^{th} period, which only increased for population and per capita GDP. This indicated that the grain VWI in LLDCs was less restricted by ecological and hydrological factors but more influenced by socio-economic factors, and this situation would continue to exist in the future (around the 80^{th} period) (**Fig. 8.a and Fig. 8.b**). Thus, it is evident that as the population and per capita GDP increase while the cultivated land for cereal decreases, the grain VWI in LLDCs will continue to increase in the future.


Response of LNVWI to LNPOP
(a)
Response of LNVWI to LNGPC
(b)
Response of LNVWI to LNCLR
(c)
Response of LNVWI to LNLFC
(d)
Response of LNVWI to LNCY
(e)
Response of LNVWI to LNCP
(f)

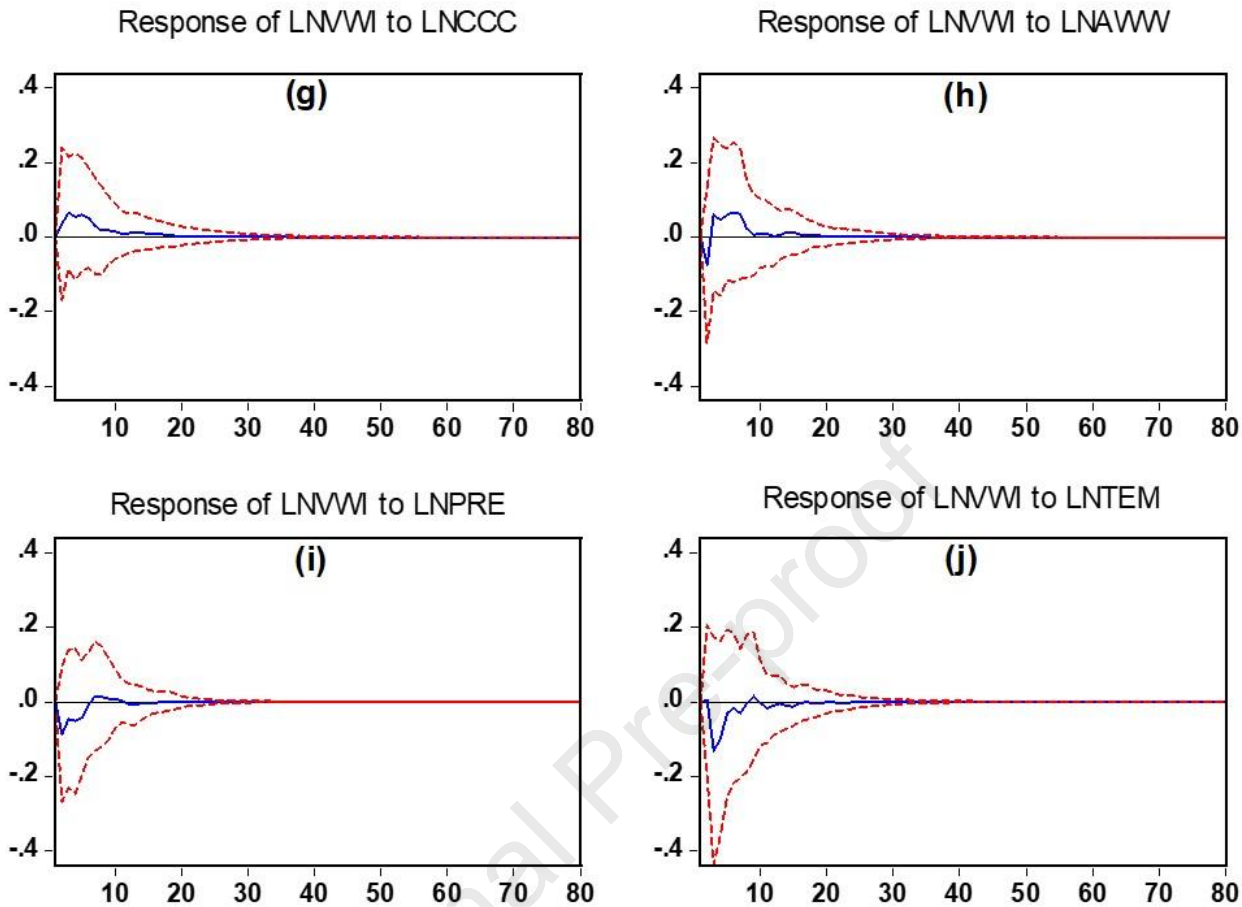


Fig. 8. Flow response caused by shocks of fluctuation in grain VWI **(a)** population, **(b)** per capita GDP, **(c)** cultivated land resources per capita, **(d)** land for cereals, **(e)** crop yield, **(f)** crop production, **(g)** cereal consumption per capita, **(h)** agricultural water withdrawal, **(i)** precipitation, and **(i)** temperature in LLDCs. Note: The solid blue line depicts the impulse response function, while the dashed red line depicts the deviation band of double plus-minus standard deviation. The horizontal axis depicts the number of lag periods (years) of the shock effect, and the vertical axis depicts the response of the VW flux.

5 Discussions

5.1 Characteristics of overall grain VW flows in LLDCs

This study examined the grain VW exchanges in LLDCs and their trading partners from 2000 to 2020. The results in **Fig. 4** showed that exchanges of grain VW experienced a great increase during the study period. This process was linked to increased trading, modifications in the main traded cereal grains and the source of embodied water, as well as changes in the most significant water exporters and importers and increases in yield (Duarte et al., 2019). In the earlier studies conducted by Johansson et al. (2016); Yin et al. (2021), the cereal grains were found to be water-intensive compared to other crops. Over the past two decades, the VW concept has been introduced and several studies have been conducted to provide accurate information on water resources management. VW trade has proved adequate in the water use efficiency in developing countries. Based on regional and international trade activities associated with major grains, African LLDCs were identified as grain NVW importers with substantial connection and instabilities in terms of economic wealth, which were in accordance with the results of prior research (Hirwa et al., 2022a; Konar and Caylor, 2013) and consistent with this study. The clear disparities between developed countries (i.e., net exporters) and developing countries (i.e., net importers) indicated that LLDCs consumed more grain VW via trade. However, the results imply that there was no single overarching reason for Africa's rising food imports.

The findings (**Fig. 5.a**) indicated a monotonously high increase in VWI. This implies that if no mitigation and adaptation measures are taken, the amount of NVWI will keep increasing in the future. Besides, landlocked countries such as Ethiopia and Uganda had several advantageous agroclimatic features for cereal grain production. However, the crop production was impaired by coupled adverse effects of the socio-economic profile of smallholder farmers, who confronted low disposable income, low soil nutrient depletion and land fertility, inappropriate soil and water management practices, limited access to work or investment capital and market, and sociopolitical instability (Ward, 2016). This situation was aggravated by climate change (Raza et al., 2019). At present, African LLDCs must cope with low grain production by enhancing crop intensification programs, accelerating the pace of climate-resilient cereal grain and varietal adoption, increasing the availability of hybrids, and enhancing improved soil fertility management practices that are adapted to local conditions. Alternatively, to lessen the high grain VWI in LLDCs, diversification of cereal grain imports, reduction of per capita consumption of grain-related products, application of cost savings to other food security interventions, and adaptation of the agriculture sector to imminent water shortages and climate-related threats are suggested.

5.2 Analysis of the current state of the green, blue, and grey water components

The quantity of green water, blue water, and grey water imported through the trade of grain in LLDCs is shown in **Fig. 7**. During 2000-2005, 2005-2010, 2010-2015, and 2015-2020, the volume of grain VWI of green water in most LLDCs simultaneously increased, so did the blue water and grey water. Surely, grains imported from outside Africa caused this problem. Afterward, the amount of imported green water VW tended to be more outrageous for Ethiopia than any other African landlocked country, thus confirming the fact that green water was the main source of water for food production (Schyns et al., 2019). Generally, the detected high increase of green and blue water in most fast-developing economies was associated with socio-economic development (e.g., improved lifestyle) and climatic factors (e.g., drought occurrence). The study of Johansson et al. (2016) indicated that in Africa, grain production required an average of 3304 $m^3 \cdot ha^{-1}$ of green water and 45 $m^3 \cdot ha^{-1}$ of net blue water, respectively, which varied with irrigation pattern, crop type, and climate. More productive use of green water resources (i.e., rainfall) is a critical step in strengthening food security and climate resilience in African LLDCs. Irrigation expansion over rainfed croplands that are water-stressed is a successful agricultural adaptation strategy in response to climate change (Rosa et al., 2020). Another study showed that utilizing both green and blue water with improved irrigation techniques increased farming productivity while fostering dependable and robust crop production (Zaveri and Lobell, 2019). To sustainably reduce and stabilize all the three types of VWIs, there is a need to promote sustainable irrigation expansion, which has been identified as a suitable and important tool to enhance water consumption in agriculture while protecting environmental flows and freshwater stocks. In addition, technologies with improved water use efficiency (WUE) and expansion of agricultural land for cereal must be implemented on the whole continent.

5.3 Decoupling socio-ecohydrological drivers of virtual water flows and their complexity

Virtual water flow illustrates the transfer of virtual water in geographic space, which has a significant impact on regional water resources and the environment (Caro et al., 2021). Over the years, landlocked countries have been importing VW from their business partners, and some of them have remained the major importers. In an attempt to assess driving forces for VWIs, this study considered 16 African LLDCs as the representatives of net grain VW importers and 11 countries as net grain VW exporters. Based on the improved trade gravity model (as displayed in **Table 1**), we observed that the rise in population and per capita GDP have significantly boosted the grain VW fluxes, which was in harmony with the findings derived from the multiple regression analysis (Yang et al., 2006). In an earlier research study conducted by Xia et al. (2022) on the drivers of VWT, GDP was found to be an important driver of VWI for regions without water deficit, and a large number of local water resources would not plainly hinder the driving force of economic strength. This was in agreement with the findings of this study (**Table 1**). Many scholars (Supplementary **Table S1**) combined different models for the assessment, such as Decomposition Analysis (DA), Gravity Model, Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT), Logarithmic Mean Divisia Index (LDMI), and among others, thus concluded that VW trade between countries was highly influenced by socio-economic, ecological geographical, and institutional factors (D'Odorico et al., 2019; Qian et al., 2019; Tamea et al., 2014). Conversely, some other studies showed that the driving forces were frequent, and several available literatures provided outcomes that are contentious, making it difficult to determine their relevant significance (Odey et al., 2021). Previous studies reported that socio-economic factors (e.g., populations and economic development level) and environmental factors were usually considered as the main influencing factors of VW flows on the global (Duarte et al., 2019), regional scale (Fu et al., 2021), and national scale (Cai et al., 2019; Sun et al., 2022), which were in agreement with the findings of this study.

Eventually, the results of the trade gravity model were presented without distinguishing between each other. The socio-ecohydrological factors (independent variables) of VW fluxes (dependent variables) were decomposed as schematically presented in **Fig. 8**. It was observed that the population and per capita GDP was steadily increasing while the cultivated land for cereal was decreasing, confirming that the grain VWI in LLDCs would continue to increase in the future (Dalin et al., 2012). The GDP was considered as a standard measure of wealth, which was tied with the ability to invest and swell agrarian and/or industrial production and/or trade, thus determining the amount of VWIs (Odey et al., 2021). Some African LLDCs had not experienced the water scarcity problems but still imported grains. VW trade from areas with higher water productivity – defined as water use per unit of production – to those with lower water productivity was confirmed to have taken effect (Liu et al., 2019). Likewise, regions with high populations and moderately insufficient cereal production (i.e., grain deficit) can import grain from areas with more grain reserves. Insofar, the continuous population growth may increase water scarcity, this led to an expansion of the demand for food imports and thus VW swaps.

Cultivated land for cereals was also a crucial factor influencing VW fluxes, pigeonholed by producing crops for food supply on a seasonal basis. The availability of land for grain production as well as the irrigated land area negatively or positively increased or decreased the VW flows between countries. There had been a notable increase in crop yields on irrigated lands in most Sub-Saharan Africa (SSA) countries, such as Malawi, Ethiopia, Zambia, and Rwanda. Meantime, the farmer-led irrigation development can be a promising driving force in enhancing water use efficiency for agriculture by improved knowledge, advanced technology, investment opportunities, market affinity, and polity of the land-water-food system (Woodhouse et al., 2017). In addition, agricultural productivity (i.e., yield and efficiency) influenced the VW fluxes (Yang et al., 2006).

The travel distance in the form of VW from the producer (i.e., farmer) to the end-user (i.e., consumer) was also a momentous measure of the globalization of VW trade. The transport costs from inland to the coast in LLDCs were high, which had an impact on the prices of goods. This situation influenced VW between regions. The study of Tamea et al. (2014) concluded that the closer the states were, the larger the exchanged VW flows were, and vice-versa. Recently, Luo et al. (2018) confirmed that VWT among regions was driven by geographical proximity and traffic, considering the major impact of the cost of transportation. Accordingly, numerous factors including the level of food demand, employment status, trade structure, exchange rate, value chain system, product price level, climate change, Human Development Index (HDI), agricultural technology advancement, government policies and international trade agreements, and national income level have been documented to influence the VW fluxes (Allan et al., 2015; Dietzenbacher and Velázquez, 2006; Lenzen et al., 2013; Ma et al., 2006; Qian et al., 2019; Saha and Kapuria, 2021; Yang et al., 2006; Zhao et al., 2019). The assessment of international bilateral trade of VW and its drivers, including socio-economic and ecological factors, showed an alarming situation of water scarcity in African LLDCs when it entered the arena of international VW trade. Finally, the LLDCs can increase the cultivated land resources and apply water resources management strategy (i.e., VW strategy) to ensure long-term sustainable water-food nexus.

5.4. Sensitivity analysis of virtual water fluxes

The sensitivity analysis focused on two main important drivers, namely population growth and GDP per capita. Depending on the drivers' standard deviation, average, and range of variation, the enforced variations vary from one parameter to another. The results showed that VWF variation was most sensitive (10%) to population growth and GDP per capita in LLDCs. The sensitivity of VWF varies not with the population and GDP, but also within different spatial and temporal scales considered in this study.

5.5 Apprising water-food-ecological security and policy implications

The results of this research have important implications for LLDCs. Our results (**Fig. 8**) provided a clear explanation for the growing VW fluxes and their drivers during 2000-2020. Understanding the changes in LLDCs' VWT and the driving forces behind those variations plays a crucial role in defining the water-food-environment nexus. Besides, the population as well as grain VW imports increased in the study area and study period. This implied that there was remarkable socio-economic growth in line with different national development strategies, which led to more VWI. However, based on Africa Water Vision by 2025 (AWV 2025) (Mutschinski and Coles, 2021), close linkages are expected to be established in the formulation and enactment of policies and priorities in the water, environment, agriculture, and energy sectors, but may not in VW trade strategy. African nations also need to lessen their reliance on commodities, which has been one of the major factors raising their susceptibility to food insecurity. Hopefully, the full implementation of the African Continental Free Trade Area (AfCFTA) opportunities will profoundly affect the policy direction of Africa grain trade as it aspires to achieve a thorough and mutually advantageous trade agreement among African Union (AU) member states, therefore incorporating LDCs into local, regional, and international value chains.

Based on the trade gravity model results, economic growth had a stronger impact on the increase of imported VW fluxes than the consumption ones and the patterns between the LLDCs and their partners. GDP growth for Africa had augmented by more than 3.7% during the past two decades and most of LLDCs (for instance, Rwanda and Ethiopia) had retained rapid economic development pace. If this growth rate is sustained, VW flows' effects on future physical and economic water scarcity will be amplified. Furthermore, major importers had benefited economically at the expense of other nations' limited water resources. To overcome the sustainable development related challenges, further transit developing parties and development partners could promote stronger sub-regional integration and cooperation on policies, and greater support in areas such as connectivity in transport infrastructure development, export diversification, value addition, and trade as well as energy security, food security, biodiversity conservation, and healthcare programs. Our outcomes also provided critical policy implications for other regions with uneven distribution of water resources in the entire Africa (Konar and Caylor, 2013), European Union countries (Fu et al., 2021), and China (Xia et al., 2022). To achieve sustainable water security of LLDCs, the improvement of water use efficiency (Hirwa et al., 2022b) and constrains on water-intensive agricultural products should be promoted to diminish the effect of VW flows on national and continental water scarcity situation.

5.6 Study limitations and future research directions

Despite the useful findings from the VW trade and driving forces, there are significant limits to this study. The key ones include the methodology's set of assumptions as well as the availability, accuracy, and quality of the data. For instance, limitations were confronted for the dependent variable, i.e., the acquisition of the amount of VW fluxes. The study object was LLDCs' grain VW fluxes. However, due to data constraints, the calculations of the quantity of VW flow mainly depended on the bottom-up method, which referred to the input-output technique. Some averaged values were used for some parameters, which may therefore lead to a certain level of error. Simultaneously, in the trade gravity model, institutional factors had always been regarded as important certain forces (drivers) of commercial transactions, such as product prices and trade agreements (Vos and Boelens, 2016), which were not considered in this study due to lack of data. Uncertainty influences the results, and it affects input data. Sensitivity and uncertainty assessments should be applied to evaluate the effect of uncertainty, but they require substantial computational and time investments. This work attempted to reduce the effect of uncertainty with multiple runs and by extracting reliable results from the official database. Climate factors (e.g., precipitation and temperatures) and their impact on water resources, arable land, and crop yields in both irrigated and rainfed cultivation were not deeply investigated in this study.

Considering the difficulties described above, future research could address all of these challenges, including specific cereal grain products, and related goods and services. Each of the shortcomings could be addressed in a separate study. A few points are worth considering in terms of applying the current trade gravity approach in other regions with similar conditions to those prevailing in LLDCs. Scholars could synthesize information based on the study's flowchart (**Fig. 1**) and reduce the possible challenges. Additionally, based on this work, one can obtain results for other regions with updated data. Hence, in the evaluation of grain VW flux patterns, Further discussion and research are required to determine whether to choose influencing elements based on the chosen study area. The advantage of this work's approach is that it is independent of input information, and then can be easily duplicated by other scientists in other regions. As a truly global challenge, the future development of research direction is to further reinforce the combination of socio-ecohydrological factors and VW flux and explore the driving factors and eco-hydrosolidarity of VW flow based on socio-ecohydrology globally. Due to the increasingly prominent contradictory challenges between the water-food-economic growth-trade relationship, the research on embodied water in grains and trade in developing countries is urgent.

6 Conclusions

The interactive water-food-ecology relationship is a major restriction on food security in agrarian product trade systems. The main objective of assessing the dynamics and drivers of grain VW fluxes from a socio-ecohydrological perspective was to comprehend the goal of substantially increased of water use efficiency and optimized allocation of water resources in the African LLDCs to ensure sustainable water consumption and agricultural product supply, thereby promoting high-quality continental development. Based on bilateral data and standard methods, the grain VW flows were evaluated between 16 African LLDCs and their main commercial partners during 2000-2020. A novel TGM was used, where the impulse response function was employed to examine the impact of unit random error shock on the current and future of each dependent variable in the VAR model, and facilitate to uncover the changeable interaction between variables. In this regard, this study is the first attempt to evaluate the drivers and flow patterns of international grain VWT in African LLDCs by considering combined limiting and competing socio-economic factors and ecological factors. Year-over-year, substantial differences were observed between various African landlocked countries and their potential business partners. The VWI showed a large increment and a swift growth rate with an average NVWI of –0.85 Bm^3, which implied that African LLDCs were grain importing countries. The total amount of grain VWI of LLDCs rose from 1.73 Bm^3 in 2000 to 10.2 Bm^3 in 2020. The highest volume of grain was mainly distributed in eastern African countries (e.g., Ethiopia and Uganda) and western countries (e.g., Burkina Faso and Mali). Ethiopia had the largest volume of grain deficit with a grain VWI of 43.4 Bm^3. Green water contributed approximately 79.3% of the total grain VWI, followed 14.7% by blue water and 5.98% by grey water, respectively. In terms of drivers of grain VW fluxes, population growth and per capita GDP had a significant positive driving effect on grain VWI fluxes at a confidence interval of 99.9% ($p<0.01$) whereas climatic variables (i.e., precipitation and temperature) did not have significant effect on VWI in both LLDCs and trading partners. Inasmuch as the major drivers were evaluated, it was concluded that the grain VWT was unsustainable in LLDCs. This situation will endure in the future. In this context, to achieve sustainable water resources management, water policy targeting to lessen the impact of VW flows from national to continental water scarcity should focus on the perfection of water use efficiency and disincentive the consumption of water-intensive agrarian products. LLDCs should be integrated into international trade while reducing trade costs. More emphasis needs to be paid to the interdependence between socio-ecohydrological aspects as well as governance systems in the future.

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Data availability statement

All data used are publicly available and have been presented in this article. We are very grateful to Mekonnen, Mesfin M and Hoekstra, Arjen Y (2011) for their outstanding work in providing detailed information of international VW research.

Authorship Contribution Statement

All authors read, discussed the results at all stages, and refined the work. **Hubert Hirwa**: Conceptualization, Methodology, Software, Investigation, Acquisition of data, Formal analysis, Writing, original draft, review & editing. **Li Fadong**: supervising, reviewing, commenting, editing, funding acquisition. **Simon Measho**: Writing – reviewing, editing and commenting. **Gang Chen**: Writing – reviewing, editing and commenting. **Fabien Muhirwa**: Writing – reviewing & editing, Formal analysis. **Qiuying Zhang**: Writing – reviewing & editing, Resources. **Yunfeng Qiao**: Writing – reviewing, editing. **Peifang Leng**: Writing – reviewing & editing. **Chao Tian**: Writing – reviewing & editing. **Alphonse Kayiranga**: Writing – reviewing & editing. **Guang Yang**: Writing – reviewing & editing. **Jean Baptiste Baranyika**: Writing – reviewing & editing. **Shu Wang**: Writing – reviewing & editing. **Claudien Habimana Simbi**: Writing – reviewing & editing. **Eric Izerimana**: Writing – reviewing & editing. **Peng Yu**: Writing – reviewing & editing. **Hyacinthe Ngwijabagabo**: Writing – reviewing & editing. **Theogene Niyonzima**: Writing – reviewing & editing.

Declarations 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 study.

Appendix.

Table A1. Countries and ISO code.

Full name	Abbreviations	Full name	Abbreviations	Full name	Abbreviations
Botswana	BWA	Mali	MLI	Argentina	ARG
Burkina Faso	BFA	Niger	NER	Brazil	BRA
Burundi	BDI	South Sudan	SSD	Canada	CAN
Central Africa Republic	CAF	Eswatini	SWZ	China	CHN
Chad	TCD	Uganda	UGA	European Union	EU
Ethiopia	ETH	Zambia	ZMB	India	IND
Lesotho	LSO	Zimbabwe	ZWE	Iran	IRN
Malawi	MWI	Rwanda	RWA	Russia	RUS
Turkey	TUR	Ukraine	UKR	United States of America	USA

References

Acreman, M., Smith, A., Charters, L., Tickner, D., Opperman, J., Acreman, S., Edwards, F., Sayers, P., Chivava, F., 2021. Evidence for the effectiveness of nature-based solutions to water issues in Africa. Environmental Research Letters 16(6), 063007.

Akoto-Danso, E.K., Karg, H., Drechsel, P., Nyarko, G., Buerkert, A., 2019. Virtual water flow in food trade systems of two West African cities. Agricultural Water Management 213, 760-772.

Allan, J.A., 1993. Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. Priorities for water resources allocation and management 13(4), 26.

Allan, J.A., 1998. Virtual water: a strategic resource. Ground water 36(4), 545-547.

Allan, J.A., 1998. Virtual Water: A Strategic Resource Global Solutions to Regional Deficits. Groundwater 36(4), 545-546.

Allan, T., Keulertz, M., Woertz, E., 2015. The water–food–energy nexus: an introduction to nexus concepts and some conceptual and operational problems. International Journal of Water Resources Development 31(3), 301-311.

Amadou, I., 2019. Millet based fermented beverages processing, in: Alexandru Mihai Grumezescu, A.M.H. (Ed.) Fermented beverages. Elsevier, pp. 433-472.

Antonelli, M., Sartori, M., 2015. Unfolding the potential of the virtual water concept. What is still under debate? Environmental Science & Policy 50, 240-251.

Antonelli, M., Tamea, S., Yang, H., 2017. Intra-EU agricultural trade, virtual water flows and policy implications. Science of The Total Environment 587-588, 439-448.

Anyanwu, J.C., 2014. Factors Affecting Economic Growth in Africa: Are There any Lessons from China? African Development Review 26(3), 468-493.

Arendt, E.K., Zannini, E., 2013. Cereal grains for the food and beverage industries. Elsevier.

Benedictis, L.D., Taglioni, D., 2011. The gravity model in international trade, The trade impact of European Union preferential policies. Springer, pp. 55-89.

Bergstrand, J.H., 1985. The gravity equation in international trade: some microeconomic foundations and empirical evidence. The review of economics and statistics, 474-481.

Bertsimas, D., Delarue, A., Pauphilet, J., 2021. Prediction with Missing Data. arXiv preprint arXiv:2104.03158.

Bjornlund, V., Bjornlund, H., Van Rooyen, A.F., 2020. Why agricultural production in sub-Saharan Africa remains low compared to the rest of the world – a historical perspective. International Journal of Water Resources Development 36(sup1), S20-S53.

Bonilla-Cedrez, C., Chamberlin, J., Hijmans, R.J., 2021. Fertilizer and grain prices constrain food production in sub-Saharan Africa. Nature Food 2(10), 766-772.

Boretti, A., Rosa, L., 2019. Reassessing the projections of the World Water Development Report. npj Clean Water 2(1), 15.

Botai, C.M., Botai, J.O., Murambadoro, M., Zwane, N.N., Adeola, A.M., de Wit, J.P., Adisa, O.M., 2022. Scope, trends and opportunities for socio-hydrology research in Africa: A bibliometric analysis. South African Journal of Science 118, 1-8.

Cai, B., Zhang, W., Hubacek, K., Feng, K., Li, Z., Liu, Y., Liu, Y., 2019. Drivers of virtual water flows on regional water scarcity in China. Journal of Cleaner Production 207, 1112-1122.

Caro, D., Alessandrini, A., Sporchia, F., Borghesi, S., 2021. Global virtual water trade of avocado. Journal of Cleaner Production 285, 124917.

Caspi, I., 2017. Rtadf: Testing for bubbles with EViews. Journal of Statistical Software 81, 1-16.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations, Value of Water Research Report Series p. 80.

Chou, C.-C., Chu, C.-W., Liang, G.-S., 2008. A modified regression model for forecasting the volumes of Taiwan’s import containers. Mathematical and Computer Modelling 47(9), 797-807.

Chouchane, H., Krol, M.S., Hoekstra, A.Y., 2018. Virtual water trade patterns in relation to environmental and socioeconomic factors: A case study for Tunisia. Science of The Total Environment 613-614, 287-297.

Conca, K., 2015. An unfinished foundation: The United Nations and global environmental governance. Oxford University Press, USA, New York.

Cui, X., Wu, X., He, X., Li, Z., Shi, C., Wu, F., 2018. Regional suitability of virtual water strategy: Evaluating with an integrated water-ecosystem-economy index. Journal of Cleaner Production 199, 659-667.

D’Odorico, P., Carr, J., Dalin, C., Dell’Angelo, J., Konar, M., Laio, F., Ridolfi, L., Rosa, L., Suweis, S., Tamea, S., Tuninetti, M., 2019. Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. Environmental Research Letters 14(5), 053001.

Dabrowski, J.M., Masekoameng, E., Ashton, P.J., 2009. Analysis of virtual water flows associated with the trade of maize in the SADC region: importance of scale. Hydrol. Earth Syst. Sci. 13(10), 1967-1977.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proceedings of the National Academy of Sciences 109(16), 5989-5994.

Dalin, C., Wada, Y., Kastner, T., Puma, M.J., 2017. Groundwater depletion embedded in international food trade. Nature 543(7647), 700-704.

de Fraiture, C., Cai, X., Amarasinghe, U., Rosegrant, M., Molden, D., 2004. Does international cereal trade save water?: the impact of virtual water trade on global water use. IWMI.

Debaere, P., 2014. The global economics of water: Is water a source of comparative advantage? American Economic Journal: Applied Economics 6(2), 32-48.

Dietzenbacher, E., Velázquez, E., 2006. Virtual water and water trade in Andalusia. A study by means of an input-output model, Working papers series. Universidad Pablo de Olavide, p. 26.

Duarte, R., Pinilla, V., Serrano, A., 2019. Long Term Drivers of Global Virtual Water Trade: A Trade Gravity Approach for 1965–2010. Ecological Economics 156, 318-326.

Durlauf, S., Blume, L., 2016. Macroeconometrics and time series analysis. Springer.

Falkenmark, M., 2009. Ecohydrosolidarity–towards better balancing of humans and nature. Waterfront 2(09), 4-5.

Falkenmark, M., Folke, C., 2002. The ethics of socio-ecohydrological catchment management: towards hydrosolidarity. Hydrology and Earth System Sciences 6(1), 1-10.

Falkenmark, M., Wang-Erlandsson, L., 2021. A water-function-based framework for understanding and governing water resilience in the Anthropocene. One Earth 4(2), 213-225.

FAO, 2022. FAOSTAT Online Database. http://www.fao.org/faostat/en/#data/QC. (Accessed Accessed: 25/01/2022 2022).

Fracasso, A., 2014. A gravity model of virtual water trade. Ecological economics 108, 215-228.

Fu, T., Xu, C., Huang, X., 2021. Analysis of Virtual Water Trade Flow and Driving Factors in the European Union. Water 13(13), 1771.

Harrington, C., 2015. Toward a critical water security: hydrosolidarity and emancipation. Canadian Foreign Policy Journal 21(1), 28-44.

Head, K., Mayer, T., 2014. Gravity equations: Workhorse, toolkit, and cookbook, Handbook of international economics. Elsevier, pp. 131-195.

Hekmatnia, M., Safdari, M., Ahmadi, A., Monibi, H., 2022. National Savings in Freshwater Consumption in Iran by Virtual Water Imports (A Case Study on Cereals). Water and Environment Journal n/a(n/a).

Hirwa, H., Peng, Y., Zhang, Q., Qiao, Y., Leng, P., Tian, C., Yang, G., Muhirwa, F., Diop, S., Kayiranga, A., Li, F., Chen, G., 2022a. Virtual water transfers in Africa: Assessing topical condition of water scarcity, water savings, and policy implications. Science of The Total Environment 835, 155343.

Hirwa, H., Zhang, Q., Li, F., Qiao, Y., Measho, S., Muhirwa, F., Xu, N., Tian, C., Cheng, H., Chen, G., Ngwijabagabo, H., Turyasingura, B., Itangishaka, A.C., 2022b. Water Accounting and Productivity Analysis to Improve Water Savings of Nile River Basin, East Africa: From Accountability to Sustainability. Agronomy 12(4), 818.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The water footprint assessment manual: Setting the global standard. Routledge.

Hoekstra, A.Y., Hung, P.Q.,, 2002. Virtual water trade a quantification of virtual water flows between nations in relation to international crop trade, Value of Water Research Report Series. IHE DELFT, IHE DELFT, THE NETHERLANDS, p. 120.

Horlemann, L., Neubert, S., 2006. Virtual water trade-a realistic concept for resolving the water crisis? German Development Institute, Bonn, Germany.

Ittersum, M.K.v., Bussel, L.G.J.v., Wolf, J., Grassini, P., Wart, J.v., Guilpart, N., Claessens, L., Groot, H.d., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., Oort, P.A.J.v., Loon, M.P.v., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences 113(52), 14964-14969.

Jia, S., Long, Q., Liu, W., 2017. The fallacious strategy of virtual water trade. International Journal of Water Resources Development 33(2), 340-347.

Jiang, Y., Xu, L., Chen, Y., 2022. Research on virtual water-embodied energy consumption and efficiency accounting in Liaoning. Environmental Challenges, 100525.

Johansson, E.L., Fader, M., Seaquist, J.W., Nicholas, K.A., 2016. Green and blue water demand from large-scale land acquisitions in Africa. Proceedings of the National Academy of Sciences 113(41), 11471-11476.

Konar, M., Caylor, K.K., 2013. Virtual water trade and development in Africa. Hydrol. Earth Syst. Sci. 17(10), 3969-3982.

Lamastra, L., Miglietta, P.P., Toma, P., De Leo, F., Massari, S., 2017. Virtual water trade of agri-food products: Evidence from italian-chinese relations. Science of The Total Environment 599-600, 474-482.

Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013. International trade of scarce water. Ecological Economics 94, 78-85.

Liu, W., Antonelli, M., Kummu, M., Zhao, X., Wu, P., Liu, J., Zhuo, L., Yang, H., 2019. Savings and losses of global water resources in food-related virtual water trade. WIREs Water 6(1), e1320.

Luo, K., Tao, F., Moiwo, J.P., 2018. Transfer of virtual water of woody forest products from China. Sustainability 10(2), 410.

Ma, J., Hoekstra, A.Y., Wang, H., Chapagain, A.K., Wang, D., 2006. Virtual versus real water transfers within China. Philosophical Transactions of the Royal Society B: Biological Sciences 361(1469), 835-842.

Mayer, T., Zignago, S., 2011. Notes on CEPII's distances measures: The GeoDist database, CEPII Working Paper.

Mekonnen, M.M., Gerbens-Leenes, W., 2020. The Water Footprint of Global Food Production. Water 12(10), 2696.

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrology and Earth System Sciences 15(5), 1577-1600.

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15(5), 1577-1600.

Miglietta, P.P., Morrone, D., 2018. Managing water sustainability: Virtual water flows and economic water productivity assessment of the wine trade between Italy and the Balkans. Sustainability 10(2), 543.

Mohammadi-Kanigolzar, F., Ameri, J.D., Motee, N., 2014. Virtual water trade as a strategy to water resource management in Iran. Journal of Water Resource and Protection 2014(6), 141-148.

Mutschinski, K., Coles, N.A., 2021. The African Water Vision 2025: its influence on water governance in the development of Africa's water sector, with an emphasis on rural communities in Kenya: a review. Water Policy 23(4), 838-861.

Myeki, L.W., Bahta, Y.T., Matthews, N., 2022. Exploring the Growth of Agricultural Productivity in AFRICA: A Färe-Primont Index Approach. Agriculture 12(8), 1236.

NASA, 2022. NASA, Prediction of Worldwide Energy Resources (POWER). NASA Langley research Center (LaRC), https://power.larc.nasa.gov/data-access-viewer/.

Nicholson, S.E., 2017. Climate and climatic variability of rainfall over eastern Africa. Reviews of Geophysics 55(3), 590-635.

Nishad, S.N., Kumar, N., 2021. Virtual water trade and its implications on water sustainability. Water Supply 22(2), 1704-1715.

Nkonya, E., Johnson, T., Kwon, H.Y., Kato, E., 2016. Economics of Land Degradation in Sub-Saharan Africa, in: Nkonya, E., Mirzabaev, A., von Braun, J. (Eds.), Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer International Publishing, Cham, pp. 215-259.

Odey, G., Adelodun, B., Kim, S.H., Choi, K.S., 2021. Conflicting Drivers of Virtual Water Trade: A Review Based on the “Virtual Water Concept”. Water Economics and Policy 7(03), 2150011.

OGB, 2021. Agriculture in Africa 2021: Focus Report. Oxford Business Group, p. 35.

Pauler, D.K., 1998. The Schwarz Criterion and Related Methods for Normal Linear Models. Biometrika 85(1), 13-27.

Pöyhönen, P., 1963. A tentative model for the volume of trade between countries. Weltwirtschaftliches Archiv, 93-100.

Qian, Y., Tian, X., Geng, Y., Zhong, S., Cui, X., Zhang, X., Moss, D.A., Bleischwitz, R., 2019. Driving Factors of Agricultural Virtual Water Trade between China and the Belt and Road Countries. Environmental Science & Technology 53(10), 5877-5886.

Qiang, W., Liu, A., Cheng, S., Kastner, T., Xie, G., 2013. Agricultural trade and virtual land use: The case of China's crop trade. Land Use Policy 33, 141-150.

Raza, A., Razzaq, A., Mehmood, S.S., Zou, X., Zhang, X., Lv, Y., Xu, J., 2019. Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review. Plants 8(2), 34.

Reinchenbach, H., 1978. The theory of motion according to Newton, Leibniz, and Huyghens, Hans Reichenbach Selected Writings 1909–1953. Springer, pp. 48-68.

Ritchie, H., Roser, M., 2017. Water Use and Stress. Our World in Data.

Rosa, L., Chiarelli, D.D., Rulli, M.C., Dell'Angelo, J., D'Odorico, P., 2020. Global agricultural economic water scarcity. Science Advances 6(18), eaaz6031.

Saha, R., Kapuria, P., 2021. Finding solutions to water scarcity: The potential of virtual water trade in agricultural products. ORF Occasional Paper(298).

Santos Silva, J.M.C., Tenreyro, S., 2011. Further simulation evidence on the performance of the Poisson pseudo-maximum likelihood estimator. Economics Letters 112(2), 220-222.

Schyns, J.F., Hoekstra, A.Y., Booij, M.J., Hogeboom, R.J., Mekonnen, M.M., 2019. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. Proceedings of the National Academy of Sciences 116(11), 4893-4898.

Shepherd, B., 2016. The gravity model of international trade: A user guide (An updated version). United Nations publication, Thailand.

Shrestha, S., Bhatta, B., Shrestha, M., Shrestha, P.K., 2018. Integrated assessment of the climate and landuse change impact on hydrology and water quality in the Songkhram River Basin, Thailand. Science of the Total Environment 643, 1610-1622.

Sims, C.A., 1980. Macroeconomics and Reality. Econometrica 48(1), 1-48.

Solow, R.M., 1956. A contribution to the theory of economic growth. The quarterly journal of economics 70(1), 65-94.

Sulser, T.B., Mason-D'Croz, D., Islam, S., Robinson, S., Wiebe, K., Rosegrant, M.W., 2015. Africa in the global agricultural economy in 2030 and 2050. International Food Policy Research Institute (IFPRI), Washington, DC.

Sun, J., Sun, S., Yin, Y., Wang, Y., Zhao, X., Wu, P., 2022. Evaluating grain virtual water flow in China: Patterns and drivers from a socio-hydrology perspective. Journal of Hydrology 606, 127412.

Sun, J.X., Yin, Y.L., Sun, S.K., Wang, Y.B., Yu, X., Yan, K., 2021. Review on research status of virtual water: The perspective of accounting methods, impact assessment and limitations. Agricultural Water Management 243, 106407.

Tamea, S., Carr, J., Laio, F., Ridolfi, L., 2014. Drivers of the virtual water trade. Water Resources Research 50(1), 17-28.

Tian, X., Sarkis, J., Geng, Y., Qian, Y., Gao, C., Bleischwitz, R., Xu, Y., 2018. Evolution of China's water footprint and virtual water trade: A global trade assessment. Environment International 121, 178-188.

Tinbergen, J., 1962. Shaping the World Economy; Suggestions for an International Economic Policy. Twentieth Century Fund, New York, New York, USA.

Tuninetti, M., Tamea, S., D'Odorico, P., Laio, F., Ridolfi, L., 2015. Global sensitivity of high-resolution estimates of crop water footprint. Water Resources Research 51(10), 8257-8272.

Turton, A.R., 1999. Water scarcity and social stability: towards a deeper understanding of the key concepts needed to manage water scarcity in developing countries, Proceedings of the Ninth Stockholm Water Conference, 1999. p. 23.

Turton, A.R., 2000. A strategic decision-makers guide to virtual water, Workshop Virtual Water in Southern Africa, held at Maseru. Citeseer, pp. 3-4.

UN-DESA, 2019. World Population Prospects (2019). United Nations, New York, USA.

UNCTAD, 2020. COVID-19: A threat to food security in Africa, in: Akiwumi, P. (Ed.). UNCTAD, Geneva, Switzerland.

Van Oel, P., Mekonnen, M., Hoekstra, A.Y., 2009. The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment. Ecological Economics 69(1), 82-92.

Vos, J., Boelens, R., 2016. The Politics and Consequences of Virtual Water Export, in: Jackson, P., Spiess, W.E.L., Sultana, F. (Eds.), Eating, Drinking: Surviving: The International Year of Global Understanding - IYGU. Springer International Publishing, Cham, pp. 31-41.

Ward, C., 2016. Improved agricultural water management for Africa’s drylands. World Bank Publications.

Wichelns, D., 2010. Virtual Water: A Helpful Perspective, but not a Sufficient Policy Criterion. Water Resources Management 24(10), 2203-2219.

Wichelns, D., 2011. Virtual water and water footprints. Compelling notions, but notably flawed. GAIA-Ecological Perspectives for Science and Society 20(3), 171-175.

Wichelns, D., 2015. Virtual water and water footprints do not provide helpful insight regarding international trade or water scarcity. Ecological Indicators 52, 277-283.

Woodhouse, P., Veldwisch, G.J., Venot, J.-P., Brockington, D., Komakech, H., Manjichi, Â., 2017. African farmer-led irrigation development: re-framing agricultural policy and investment? The Journal of Peasant Studies 44(1), 213-233.

World Bank, 2018. Beyond Scarcity: Water Security in the Middle East and North Africa. World Bank Group, Washington, DC.

World Bank, 2021. Indicator: Data Development Indicator. World Bank Group, https://data.worldbank.org/indicator.

Wu, X.D., Guo, J.L., Li, C.H., Shao, L., Han, M.Y., Chen, G.Q., 2019. Global socio-hydrology: An overview of virtual water use by the world economy from source of exploitation to sink of final consumption. Journal of Hydrology 573, 794-810.

Xia, W., Chen, X., Song, C., Pérez-Carrera, A., 2022. Driving factors of virtual water in international grain trade: A study for belt and road countries. Agricultural Water Management 262, 107441.

Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrol. Earth Syst. Sci. 10(3), 443-454.

Yin, Y.L., Sun, S.K., Wang, Y.B., Li, C., Sun, J.X., Wu, P.T., 2021. Impact of grain virtual water flow on surface water and groundwater in China. Advances in Water Resources 150, 103848.

Zaveri, E., Lobell, D., 2019. The role of irrigation in changing wheat yields and heat sensitivity in India. Nature Communications 10(1), 4144.

Zhao, D., Hubacek, K., Feng, K., Sun, L., Liu, J., 2019. Explaining virtual water trade: A spatial-temporal analysis of the comparative advantage of land, labor and water in China. Water Research 153, 304-314.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: