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The political ecology of our water footprints: Rethinking the colours of virtual water

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ABSTRACT

Virtual water trade and external water footprints could be regarded as a proxy for environmental damage and negative effects for local water users in water scarce areas of export production. A political ecological approach to virtual water trade looks at winners and losers of social metabolism in the Anthropocene and representation and recognition of local assessments of effects of the use of water for export production. Water scarcity weights have been added to virtual water analyses to better assess negative environmental and positive social effects of water use for export production. However, the commensuration of values and aggregation of data at country level result in indicators that miss out on a lot of local environmental and social effects of export agriculture and industry. This article proposes a contextualized bottom-up approach in which “red” virtual water indicates hotspots of water competition, water grabbing, and severe over-exploitation and contamination of water resources, negatively affecting ecosystems and the water security of local water users. “Silver” virtual water, or social water productivity, indicates local benefits of water use for export production in the form of income creation for smallholder farmers and workers. The concepts of red and silver virtual water can inform development studies as they bring to the fore the negative and positive effects of water use for export production. Red and silver virtual water analyses by local and national stakeholders can inform policy choices in directions of more sustainable and equitable supply chains. The bottom-up approach, with region and national organizations making the assessments of red and silver virtual water use, would empower groups affected and benefiting from water use for export production.

1. Introduction

The late Tony Allan coined the idea of virtual water (VW) in 1996 in relation to the highly contentious issue of importing wheat to improve food security of Egypt instead of waging war against Nile’s upstream riparians to secure water for food production (Allan, 1996, 1998, 2003). The water used to produce food is seen as embedded in the traded product as “virtual water”. A drawback of importing food is the dependency on the import from other countries that could lead to food insecurity in times of economic and political crises (Roth & Warner, 2008).

In the 2000s the virtual water concept was developed further to calculate water footprints (WF) of products, consumers, and countries (Hoekstra & Chapagain, 2008). The water footprint, similar to the land-based footprint of food, consumer goods and services, is an indicator of resource use and potential environmental and social damage inflicted by these goods’ production. In the era of the Anthropocene, with its enormous growth of international trade, the water footprint of export agriculture can be seen as a proxy for potential negative environmental and socio-economic effects of export of agricultural products. Effects vary enormously according to the conditions at the sites of production (Shah et al., 2007; Wada et al., 2010). Therefore, evermore complicated accounting methods have been developed to approximate the effects of virtual water trade (e.g. Chen & Chen, 2013; Lenzen et al., 2013; Yang et al., 2013; Vallino et al., 2021). However, local diversity of environmental and social circumstances over time and space are very difficult to take into account because of the unavoidable commensuration of values and the aggregation of data at the level of countries or river basins. Meanwhile, Allan himself remained focused on government policies and interventions regarding food trade related to food security, relative water availability and water grabbing (e.g. Allan et al., 2012).

Some authors, adopting a political ecology approach, criticize the water accounting conceptualization of virtual water arguing that it is based on the notions of comparative advantage, free international trade, and maximizing resource use efficiency, which in turn are associated to neoliberal economic approaches (Beltrán & Velázquez, 2015; Trottier &

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Perrier, 2017). The mainstream conceptualization of virtual water does not pay attention to winners and losers, power relations, agribusiness monopolies, water grabbing, specifics of local economies, specific cultural values of water, or specific ecological effects of water consumption and pollution (Roth & Warner, 2008; Vos & Boelens, 2016; 2018; Vos & Hinojosa, 2016). It implicitly or explicitly starts from the idea that international trade can save scarce water, and would increase overall resource use efficiency and overall welfare. Thus, virtual water should flow from relatively "water-rich" countries to relatively "water-poor" countries. In their book Hoekstra and Chapagain (2008: 138) phrased the neoliberal assumption about virtual water trade in this way: "Liberalization of trade seems to offer new opportunities to contribute to a further *increase of efficiency* in the use of the world's water resources" (emphasis added). They add that this will only function well if water is priced at its real cost. Not all VW studies take an explicit neoliberal stance, but most do not question the virtues of striving for resource use efficiency through international trade.

Notwithstanding the valid critique by political ecologists, the virtual water accounting of international trade does provide important insights in the metabolic rift of the social metabolism of the increasingly globalizing production and consumption market (Dalin et al., 2012). The strength of the virtual water concept is in its simplicity: the only metric is m^3 of virtual water (be it green, blue or grey, as will be explained in Section 4). This makes it easy to show trends over time, and compare among products, producers, countries and consumers. VW trade can be used to estimate environmental damage and negative social impacts, especially if production takes place in relative water scarce areas. Nonetheless, this water-centric approach might overlook the complex positive and negative effects of export production: jobs generated, income for small producers, biodiversity loss, dispossession, land use change, pollution, deforestation, displacement, exploitation of animals, soil erosion, poor labour conditions, or slavery. The larger the VW flow, the more risk of negative, but also positive, impacts. However, there is no need to use VW as a proxy indicator for these effects, be it for scientific research or policy recommendations: simpler trade data could be used as a proxy indicator for these effects, in combination with other indices that relate to potential negative of positive impacts of international trade. To be able to make meaningful use of the concept of virtual water for discussions on development, scientific research or for decision making, be it as consumer, retailer, or a policy maker, the VW analyses should be combined with other social and environmental indicators (Wichelns, 2010; 2015).

The main purpose of this article is to present a theoretical exercise to better understand and study the water-related effects VW trade. After the overview of the existing VW colours: green, blue, and grey in Section 4, the article introduces two new colours of VW: red and silver in Sections 5 and 6. These new concepts are heuristic tools that are added to the existing frameworks of green, blue and grey VW and water scarcity indexes. They are not meant to replace the currently used concepts of VW, but to offer a political ecology approach to VW trade analysis.

In this article I will first provide a brief introduction into the political ecology approach, including the concept of tele-coupling. Then I will outline the methodology used for this article. Next the article discusses the literature on the common virtual water colours: blue, green and grey (Section 4). After that I will introduce, in Section 5, the idea of "red" virtual water, based on the discussion on water scarcity-weighted virtual water analyses. Red virtual water indicates severe ecological damage and competing water uses. Some cases will be used to illustrate this new VW concept. Subsequently, I will introduce the idea of "silver" virtual water (Section 6), based on the concept of social water productivity. Silver virtual water indicates a relative high level of income generated for poor labourers or smallholder farmers. This concept will be illustrated with examples from Spain and Peru. The article concludes with a discussion (Section 7) on the introduced concepts and conclusions (Section 8).

2. Conceptual approach: Political ecology and tele-coupling

Political Ecology studies analyse the relations between ecology and society, and focus on power relations, distribution of access to resources and returns to capital and labour. Also, the narratives that legitimize those power relations and distributions are part of political ecological analysis. Critical socio-ecological analysis is explicitly political: addressing justice, equity, biodiversity loss, winners and losers. Karl Marx regarded the production, flow and use of materials – including building materials, food, fuel and waste – as the Social Metabolism of our planet. Marx was worried about the Metabolic Rift that was the result of a steady flow of nutrients from the rural area to the city. In the rural area this caused impoverished soils, and in the city this caused pollution. Virtual water flows can be regarded as part of the Social Metabolism and causing a global Metabolic Rift (Foster, 1999; Hargrove, 2021).

Thinking in Political Ecology has developed over time (Robbins, 2019). Environmental concerns were expressed since the start of the industrial revolution, and the effects of modern agriculture became first articulated in 1962 by Rachel Carson in her book "Silent Spring", on the environmental effects of the use of pesticides. The effects of economic growth without care for nature became a widely discussed problem by the publication of the influential 1972 report of the Club of Rome. From the 1970s the analyses of Political Economy concentrated on unequal distribution of access to productive resources, the power relations behind the exploitation of nature and humans, and the new social movements that addressed environmental injustices (Forsyth, 2004). Structural divisions in society, such as based on class, gender, ethnicity, and caste, were addressed. Studies of Political Ecology revealed the political realities behind so-called environmental myths (Blaikie, 1985; Hecht & Cockburn, 1990; Peluso & Watts, 2001) and described the struggle for empowerment and environmental justice of women and other deprived groups (Shiva, 1988).

In this approach to political ecology, virtual water trade can be conceptualized as form of tele-coupling. Tele-coupling is the mechanism were an activity in one place causes an effect in another (distant) place (Newig et al., 2020). The metabolic rift is a form of tele-coupling. According to Marxism, the metabolic rift implies an unequal ecological exchange resulting in an ecological debt at the consumer side, and an environmental footprint (in terms of land or water) at the production side (Foster, 1999; Hornborg & Martinez-Alier, 2016). World Systems Theory (Wallerstein, 2020) and Dependency Theory (Ghosh, 2019) analyse the exploitation of the periphery by the centre through unequal social, economic and political relations. A political ecological analyses of VW trade makes visible connections between regions, connections between producers and consumers: who wins, who loses, who moves those products (Sojamo et al., 2012) and who regulates this? Those questions can be applied to any commodity or export product, for example, tomatoes produced with fossil groundwater in Egypt exported to the Netherlands (Costa & Heuvelink, 2018).

In more recent political ecology approaches questions of knowledge and recognition gained importance. Attention shifted to ontological and epistemological questions on the knowledge about environmental realities and thinking about post-development. Indigenous people and environmental movements were considered marginalized groups that know much more than scientists about the environmental degradation and injustices because they are the ones suffering from it and struggling against it: the "environmentalism of the poor" (Guha & Martinez-Alier, 1997; Martinez-Alier, 2002). Issues of identity, diversity and positionality became more prominent (e.g. Escobar, 2011). Also, notions of multi-species resistance, climate change justice, governmentalities, and environmentality (Agrawal, 2005) were added to the environmental justice debate.

These notions go against approaches that look for essentialism and commensuration of values as is common in VW analyses. Therefore, the assessment of the impact of water use for export production should be done by local and national organizations of peasants, workers and environmental groups. In such a bottom-up approach to VW assessment the local knowledge and valuing will be taken into account. This bottom-up approach would empower the affected groups at the sites of water use for export production.

The question is who is the decision maker, and what political implications does the decision have? Is this the individual consumer that needs to make better choices when shopping? Or is it national governments when they negotiate international trade agreements or decide on subsidies for large-scale irrigation infrastructure? Is it retailer companies that should supply their supermarkets with products produced with smaller water footprints? Or is it multinational companies that should produce for export only in water-rich countries? For discussions on development and policy making it is very important to make these assumptions explicit and provide a clear perspective on who can, or is supposed to, take action based on the VW and WV analyses. And what would be the local consequences of the decisions?

For consumers it is very difficult to assess the environmental and social impact of a purchase. Most tele-coupled effects of consumption on water use and ecology are complex and diffuse. Many products are composed of many parts that come from different regions of the world. An enormous amount of information and individual judgements on sustainability and social equity issues in all these places with different circumstances are needed to make decisions on purchases of products. This escapes the capacity of individual consumers. General guidelines can be taken into account like reducing consumption of meat and dairy products and fresh fruits produced in dry areas like asparagus from the desert coast of Peru (Hepworth et al., 2010) or avocados from Chile (Madariaga et al., 2021) and Mexico (Zlolniski, 2011). However, overall responsibility for reducing negative effects lays especially with companies, retailers, supermarkets, and national governments.

The complex consequences of virtual water export show the need to contexualize stories of impact of VW export. To help tell these stories the concept of virtual water could be specified to better signal the products exported from places where severe negative effects of water depletion and pollution occur (these places are called “hotspots” in some literature, e.g., Van Oel et al., 2009; Mekonnen et al., 2015). Virtual water coming from these places could be called “red” virtual water, indicating its severe negative effects. One of the main positive effects of production for export could be the generation of income or jobs for the farmers and workers (Wichelns, 2010). “Silver” virtual water could indicate virtual water that contributes relatively well to generation of income for poor labourers of smallholder farmers, calculated as the social productivity of water. The notions of “red” and “silver” VW will be explained in Section 5.

3. Methods

The methodology consists of literature scoping review and providing several illustrations of the proposed concepts with data from published research on cases in Spain and Peru. The scoping review was a combined systematic and narrative literature review method (Petticrew & Roberts, 2008), which allows for additional articles to be included in the reviewing process. The query was defined as: (TITLE-ABS-KEY({virtual water}) OR TITLE-ABS-KEY({water footprint}) AND TITLE-ABS-KEY (ecology OR impact)) AND PUBYEAR > 1989 AND PUBYEAR < 2024 AND (LIMIT-TO (LANGUAGE,“English”)). Results were retrieved from SCOPUS, based on English language literature. It included titles published between 1990 and December 2023. This query harvests the mainstream literature on virtual water. The query resulted in 1755 publications. Adding TITLE-ABS-KEY({political ecology}) to the query resulted in the following five articles that refer to political ecology approaches to virtual water analysis: Beltrán and Velázquez (2015), Beltrán and Kallis (2018), Perreault et al. (2018), Workman (2019), and Cazcarro and Bielsa (2020); This literature was used to inform the below analysis.

4. Blue, green and grey virtual water

4.1. Blue and green virtual water, and their limitations

In virtual water analyses often a distinction is made between green and blue virtual water (e.g. Hoekstra et al., 2011). Green virtual water is the water from rainfall that is taken directly from the soil by the roots of a crop. Blue virtual water is surface or groundwater applied to the root zone of a crop by means of irrigation, and then used by the crop. Sometimes also grey virtual water use of a product is calculated as an indication of the water pollution caused by the production process. Grey virtual water is determined by the volume of water needed to apply to a water body that is polluted by the manufacturing of a product to attain the environmental standards for that body of water.

In some VW and WF impact analyses both blue and green VW is taken into account (see e.g. Lenzen et al., 2013; Yang et al., 2013; Breu et al., 2016; Vallino et al., 2021). In other VW impact analyses only blue VW is analysed, as depletion of rivers and groundwater for irrigation is a direct negative effect of blue VW in water scarce regions (see e.g. Khan & Hanjra, 2009; Hoekstra, Mekonnen, Chapagain, Mathews, & Richter, 2012; Dell’Angelo et al., 2018; Mekonnen & Hoekstra, 2020). Ridoutt and Pfister (2010) and Hoekstra et al. (2011) stress that green water use can have negative effects, related to changes in land use. Furthermore, Te Wierik et al. (2020) argue for more attention for green and atmospheric water governance, as water policies almost exclusively pay attention to blue virtual water. In reality, blue, green and atmospheric water belong to the same system. There is a constant interaction between these waters, and changes in land and water management will influence all water colours, and their interactions.

Virtual water flow calculations for countries can be assessed by bottom-up and top-down virtual water calculations (Yang et al., 2013). In principle, both methods should give the same results. With bottom-up calculations the virtual water content of each product imported into each country from all other countries is determined taking into account the whole production chain. In the top-down calculations the international trade volumes data of all products (Multi-Regional Input-Output, or MRIO data) are multiplied with the virtual water content as calculated for the product produced in the country of origin.

Notwithstanding the complex calculations and ever bigger databases used for virtual water trade analyses, the calculations have clear limitations. One of the biggest limitations (but paradoxically also its strength) is the use of the unique metric of cubic meters of virtual water. This commensuration of valuing (the effects of using one cubic meter of virtual water is the same everywhere) makes that specific local impacts of the use of a cubic meter of water do not become explicit. Local effects are complex and might include negative effects like water resource overexploitation and water pollution, but also positive effects like generation of income for poor labourers or smallholder farmers. To assess the local impacts of virtual water trade it is necessary to assess these complex local effects. It is not only necessary to take into account time–space variability of conditions within counties and watersheds, but also the different socio-economic effects for different groups in society and their valuation of the effects (Vos et al., 2019).

VW analyses can inform discussions on global development and resource use. Depending on the type of analysis this can be the idea of saving water by producing in areas where production takes less water per unit of product; thus, increasing the overall water productivity and therewith saving water by trade. Another idea is to reduce the negative effects of production in water scarce areas by increasing the import of virtual water from relatively water rich areas to water scarce areas (e.g. Yang & Zehnder, 2002; Delbourg & Dinar, 2020). What is often implicit is who could and should take action to attain these goals. An exception is Hoekstra et al. (2011), who spell out the alternative choices for different decision makers.

4.2. Water-scarcity weighted virtual water calculations

To approximate the negative effects of virtual water export, various studies have used the relative water scarcity in the country or watershed of production to give a "weight" to the severity of the impact of virtual water export. The more water scarcity in the country or watershed, the more negative impact of the use of blue water can be expected (Ridoutt & Pfister, 2010; Kounina et al., 2013; Lenzen et al., 2013; Yang et al., 2013). Water scarcity can be calculated in different ways: an often-used method is to calculate the population of an area divided by total runoff (or in FAO terms: "internal renewable water resources") in that area (Falkenmark, 1989), or the inverse: m^3 per capita ($<1000\ m^3$/cap/yr is water scarce). Another way to is to calculate the ratio of water withdrawal in a certain area to total runoff in that area (Van Oel et al., 2009). Water scarcity can be assessed at the level of countries (e.g. Lenzen et al., 2013; Vallino et al., 2021), or at the level of river basins (e.g. Mekonnen & Hoekstra, 2020).

There is a marked (and heavily debated, see e.g., (Pfister et al., 2022) difference between scarcity-weighted virtual water that is expressed volumetrically (e.g. Boulay et al., 2018; Vanham & Mekonnen, 2021), and studies that use a scarcity index like Hoekstra et al. (2011), Lenzen et al. (2013); (Mekonnen and Hoekstra, 2020) and Vallino et al. (2021). The advantage of a volumetric analysis is that the metric still has a physical meaning, like the VW and WF indicators. The disadvantage is that this water scarcity-weighted volumetric indicator is hard to interpret as it does not indicate directly the physical water use of a crop or product. Boulay et al. (2018) present a water-scarcity index that uses absolute available water in a watershed and normalize that to an indicator that represents the equivalent volume of water use that would have the same impact across the globe. In this scarcity-weighted volumetric index the local impacts are expressed in a volume of water use, where each cubic meter of VW would have the same impact. This commensuration does not take into account the hydrological complexity and variability, nor cultural, ecological, historical, political, equity and climate change issues at play in each location of production.

Lenzen et al. (2013) calculated the "international trade of scarce water" by multiplying the virtual water content of exported and important products with the Water Extraction Index (WEI) of each of the exporting countries. The virtual water exported included blue and green virtual water embedded in food and industrial products. The WEI is based on the yearly groundwater extraction compared to the total local renewable freshwater resources in a country. These data are taken from the FAO AQUASTAT. These calculations indicate which countries use most "scarce water" in absolute terms (India 346 Mm^3, China 190 Mm^3, Pakistan 112 Mm^3), and which countries import most "scarce virtual water" in absolute terms (India 265 Mm^3, China 165 Mm^3, USA 151 Mm^3). Lenzen et al. conclude that policy makers from importing and exporting countries, sector industries and consumers can take decisions based on the presented calculations.

This "scarce water trade" approach provides a general indication of negative effects of virtual water trade in exporting countries that have water deficits. It also shows what countries are importing most virtual water from countries that have water deficits. However, the approach has three major shortcomings. First, the WEI is based on total groundwater extraction compared to the total available groundwater: this disregards the impact of water extracted for irrigation from rivers and wetlands. Those extractions can also have large impact on downstream water users and ecosystems. Moreover, it does not take into account countries which use large volumes of green water for export agriculture. For example, Brazil exports large volumes of soy from rainfed agriculture for animal feed and uses relatively little groundwater for irrigation, and therefore ranks low in the WEI. Whereas the land use change because of the soy production for export does have a large impact on the water balance of downstream rivers in the Amazon basin like the Xingu River (Rizzo et al., 2020). The approach taken by Lenzen et al. leaves the whole environmental effect of export of animal feed and dairy and meat production out of sight. Second, in each "water scarce" country the effects of over-exploitation are different and also differ over time and space within the country. Also, different social groups might benefit or suffer in specific ways, and ecosystems are affected in different ways. In that respect, one particular, relatively small, export sector might have large negative social and ecological effects in a particular region, without appearing in the "scarce water trade" analysis at country level. Third, by calculating "net virtual water trade" of scarce water by country, the negative effects disappear as countries exporting large amounts of "scarce virtual water" often also import large amounts of "scarce virtual water". Thus, offsetting something negative with something equally negative.

Vallino et al. (2021) use a composite scarcity index to compare the water scarcity of the exporting and importing country. The composite water scarcity index (CWSI) combines physical and economic water scarcity. When the importing country has a lower water scarcity index as compared to the exporting country, Vallino et al. (2021: 4) consider this virtual water flow to be unfair as: "*This means that this amount of virtual water is exported from countries with a higher composite water scarcity than the one of the destination countries, suggesting an 'unfair exchange', where the importing country benefits from the water of another area of the world where this resource is scarcer either in physical, or in economic terms, or both*". This CWSI does incorporate fairness in the assessment of the VW flow, however, the locally specific effects for specific groups of people or ecosystems is not taken into account.

4.3. Grey virtual water

Apart from water quantity problems, also water quality is a major problem. Major contributors to water pollution are industry, household wastewater and runoff from agriculture (Giri, 2021). For pesticide use Devine and Furlong (2007) provide a general overview of the ecological effects of their application. Stehle and Schulz (2015) carried out a *meta*-analysis compiling information from 838 studies that reported on + 2,500 sites in 73 countries on pesticide concentrations in water and sediments. They found that in 68.5 % of the sites the concentration in either surface water or sediments exceeded the regulatory threshold level for pesticides.

As explained above, grey virtual water is defined as the volume of water needed to dilute polluted water to attain the national environmental standard of a water body (Hoekstra et al., 2011). To approximate the grey water footprint of traded industrial products Van Oel et al. (2009) used the yearly water withdrawals by industry as reported at country level by FAO's AQUASTAT divided by the value of exported industrial goods. It can then be calculated which country imports which part of this grey virtual water. For agricultural production often nitrate (N) and phosphate (P) pollution of water bodies is used to approximate the grey water footprint of crop and animal products.

De Girolamo et al. (2019) follow a bottom-up approach to calculate grey virtual water use of rainfed wheat in a small basin in Italy. It shows that modelling of runoff of nutrients and agrochemicals even in a small basin is cumbersome and has quite some uncertainties. Especially the environmental standard use for the calculation influences the volumes calculated for the grey virtual water content. Liu et al. (2017) applied a similar method to calculate the grey water footprint for maize production worldwide. They take one environmental standard and calculate the grey water footprint for nitrogen and phosphate contamination at the level of grid cells, countries and watersheds. At the level of the European Union, under the context of the EU Water Framework Directive, the EU countries report on the water quality of the surface waters. However, no link is made with specific production processes. In the same manner Dabrowski et al. (2009) calculated the grey virtual water of common cash crops in South Africa. They conclude that the water contamination by pesticides (Chlorpyrifos) for the cultivation of cotton results in the highest grey virtual water content per ton of produce.

All in all, it seems that it is hard to link specific production processes to specific ecological damage, with exception of a few cases (some of which outlined above). Most of the "ecocide" goes slow and involves many actors. Therefore, a more case-based conception of virtual water could be useful to link consumption and policy decisions to damage to ecosystems.

Thus, in the existing studies on VW trade discussed above, different indices have been developed to incorporate water scarcity in VW assessments. However, none have been able to capture the locally specific environmental, cultural, ecological and political issues that are relevant for impact analysis at local levels. Therefore, a bottom-up approach inviting local and national organizations of affected groups to make their assessment could be a way forward.

In the next two sections two new VW indices are introduced: red and silver VW. These start from a political ecology perspective focusing on winners and losers of water use for export production. Their usefulness and limitations will be discussed in Section 7.

5. Red virtual water, indicating severe aquatic ecological damage and social harm

5.1. Red virtual water: Indicating ecological damage and high competition, over-exploitation and water grabbing

"Red" virtual water could indicate severe damage to aquatic ecologies or severe competition between users because of over-exploitation and pollution of water. Red virtual water could be determined in different ways. One way would be to determine the green, blue, and grey VW impact of a product. In case local stakeholders identify harm to local communities or ecosystems related to soil moisture use the green VW would be converted in red VW; if groundwater or surface water use causes harm the blue VW would be converted into red VW; and grey VW would always be considered red VW. The total of red VW would be an indication of the water-related impact of the production.

Worldwide, many examples exist where ecosystems and riverine communities are affected severely by water extraction and contamination (Best, 2019). Agricultural, mining, oil, and manufacturing sectors overexploit and contaminate surface and groundwater leading to severe damage of aquatic ecosystems and competition over water between local users. Also, the disposal of waste and untreated waste water contributes significantly to the deterioration of water quality. Water extraction and contamination will have relatively more negative consequences for the aquatic ecosystem in water scarce situations.

Among the well-known examples are the shrinking of the Aral Sea on the border of Uzbekistan and Kazakhstan because of cotton cultivation. Before the large-scale diversion of water for cotton production, more than 20 species of fish lived in the Aral Sea, now none (Micklin, 2007). Oil spills on land and large open pit mining also form examples of activities that can have severe impacts on water resources. Large scale shrimp production for export in coastal areas affects mangroves, and causes salinization of coastal groundwater.

Exploitation and contamination that have severe effects but are a slow and continuous process are less visible than other disasters. Dams that are built for hydropower and irrigation prevent fish migration and disturb natural flow regimes of rivers, affecting aquatic ecosystems. Irrigation water extracted from rivers and groundwater has depleted rivers to the extent that many now no longer reach the sea. These so-called "closed basins" can be found around the world: from the US (the Colorado River and Rio Grande) to the Jordan River in the Middle East (Molle et al., 2010). In Spain groundwater overextraction has severely damaged fragile ecosystems like the Tablas de Daimiel wetland (Martínez-Santos et al., 2018) and dried the Jucar River (Sanz et al., 2019), and pumping of water for strawberries has affected the Doñana wetlands in the south of Spain (Navedo et al., 2022).

5.2. Red virtual water: Ways of assessment

Red virtual water could be determined in different ways. As indicated above, the green, blue and grey VW could be converted into red VW in case of negative impacts on society and/or damage ecosystems. For top-down assessment of red VW several methods described in the virtual water literature could be adopted. For example: identification of "hotspots" (Hoekstra et al., 2011; Mekonnen et al., 2015) by using assessments like the "water debt indicator" (Tuninetti et al., 2019), "scarcity weighted VW" (see Section 4.1), "blue water scarcity" (Chiarelli et al., 2022) or "water grabbing related VW" (Dell'Angelo et al., 2018) indexes.

Tuninetti et al. (2019) present a "water debt indicator" showing areas around the world that use more water than available. These places are concentrated in the north and west of India, central and western China, central US and the Middle East.

Water grabbing is linked to virtual water trade. Direct foreign investments (DFI) in land deals imply export of virtual water (Mehta et al., 2012; Breu et al., 2016). Dell'Angelo et al. (2018) calculated the risk of blue virtual water being used in production areas that are regarded as sites of "water grabbing". They first identified water scarcity at country level and determined the prevalence of undernourishment in the exporting country. Then they calculated the risk of blue virtual water export of signed and operationalized DFI land deals as reported by The Land Matrix database (2016). Based on these calculations they estimate that 28 % of blue virtual water exported and planned to be exported from DFI land deals is from countries with high levels of water scarcity and prevalence of undernourishment. This methodology allows for considering the potential effects on ecosystems and vulnerable groups in society. However, the analysis at country level does not show the large diversity of water scarcity and undernourishment that can exist in a country. For example, Peru is not presented as a water scarce country, but the exported asparagus and grapes are cultivated in the extremely dry desert coast.

Many examples of "hotspots" of negative effects on water by export production are documented worldwide: In Tanzania and Ecuador flower production for export takes away surface water for downstream smallholders (De Bont et al., 2016; Mena-Vásconez et al., 2016). In the northwest of Argentina tobacco production for export leads to land and water grabbing (Iribarnegaray et al., 2017). In Mexico groundwater is overexploited for producing vegetables and fruits for the US market (Zlolniski, 2011; Hoogesteger, 2018).

Three more examples provide illustrations of "hotspots" of severe over-exploitation, high competition and water grabbing. First, in Colombia the turnover of a smallholder irrigation system called Marialabaja-Bolivar of some 25,000 of irrigated land in 1994 led to land and water grabbing by palm oil industry and paramilitary violence (Quiroga Manrique & Vallejo Bernal, 2019). Colombia is the 6th largest exporter of palm oil (OEC, 2022). A second example is Egypt, where a plan is being developed to increase the produce cereals and vegetables (unions, tomatoes) of a total of 1.5 million acres in the Western Desert, partly for export. Irrigation water is drawn mainly from fossil groundwater (Gabr, 2023). Shalby et al. (2023) found already a significant depletion of fossil groundwater in the Nile Delta aquifer since 2007. Small farmers, with shallow wells have increasingly difficulty in accessing groundwater. A third example is in India where groundwater levels are dropping because of production of cotton for export. Also here, small farmers will shallow wells suffer from loss of access to irrigation water (Dangar et al., 2021). India is regarded as the country with the highest total use and also highest export of 'scarce water' (Lenzen et al., 2013; Wada et al., 2012).

Thus, "red" virtual water could be calculated in a "top down" way by identifying "hotspots", or by bottom-up approaches that would start from detailed case studies in which the specific effects on ecosystems would be studied and local society would be involved. As indicated by Iribarnegaray et al. (2017) the case analyses should start from the understanding and evaluation of the problems and opportunities by the affected communities. Involving affected communities in the assessment of the impacts will empower those communities and their organisations and will increase their influence in policy making regarding export production and trade.

The added value of red virtual water compared to the existing water scarcity weighted virtual water indexes is that red virtual water would directly draw attention to the negative effects of the water use in the production site, and that it could be used to take decisions on consumption, purchases, and investment projects. Bottom-up assessment of red virtual water would allow for a direct communication from local communities to decision makers about the negative impacts of water use.

6. Positive effects of VW trade: From social water productivity to "silver" virtual water

6.1. Social productivity of water

Water use for export production can create livelihood opportunities for smallholder producers and workers. "Social productivity of water", or "pro-poor water productivity", reflects the economic benefit for poor people by the use of 1 m^3 of water for the production of a product or service (see e.g. Vives-Solbes, 2003; Varillas, 2010; Dumont, 2015; Novo et al., 2015). The idea is that "More jobs per drop"[1] is a relevant criterion for decision making on water allocation in water scarce areas. By striving for a high social productivity of water, this scarce resource is allocated to generate income for relatively poor labourers and smallholder farmers, thus contributing to poverty alleviation. Falkenmark and Lundqvist (1998) expressed this as "Relative economic return per unit of water for the farmer" comparing relative benefits for different crops in Tamil Nadu.

The metric of "jobs per drop" is especially relevant when comparing the impact of water allocation decisions regarding one and the same source: a river, reservoir, or an aquifer. In the choice between two alternative allocations of water in a closed river basin, the alternative with the highest social water productivity (expressed in US$/$m^3$) would be the best option regarding poverty alleviation. Thus, national and local governments, companies and international development banks could take the social productivity of water into account when making decision on investments in water infrastructure, and water saving programs. Governments could also consider the social productivity of water when designing the reallocation of water use rights and other water use regulations.

For investment programs in water saving or for increasing water productivity it is useful to look at the social water productivity. An example is the production of bananas for export in the water-scarce Chira Valley in northern Peru. In the Chira Valley bananas are produced by smallholder associations that obtain a relatively large share of the sales price compared to labourers on banana plantation owned by multinational companies. Programs to increase the water productivity of banana production by the smallholders in the Chira Valley therefore benefit those small producers relatively more than a similar program for banana companies (Clercx et al., 2014).

In a comparison between alternative investments across different river basins, or the purchase of goods, the social productivity of water parameter would only make sense if water scarcity and poverty in both places would be similar. Thus, companies, governments and international development banks could take into account "social productivity of water" when making decisions on investments in water infrastructure that will change the use of water in a water scare river basin. Construction of new water infrastructure often implies water reallocation. Within one watershed the reallocation from one use to another usually has big impacts on the ecology and different effects on different social groups. Water infrastructure can create jobs for marginal groups and thus contribute to social equity. However, this should be weighed against the investment costs for the government, the negative effects for other users and the environment.

Social water productivity can be conceptualized as "silver" virtual water. Silver virtual water would then be an index indicating the relative social water productivity. This index could be calculated based on the jobs or income for poor labourers and smallholder farmers from the use of 1 m^3 or 1 Mm^3 of water. This absolute number could be made into an index value when comparing social water productivity between sites, production systems within a watershed (or using water from the same aquifer). In the case of comparing between sites or production systems from different river basins or aquifer the index on the social productivity of water only makes sense if poverty and water scarcity levels are similar.

6.2. Silver virtual water, indicating relative positive effects for income generation for the poor: Two "bottom up" examples from Spain

Two examples from Spain can illustrate the idea of "social productivity of water". The first case is presented in a report from the regional government of Andalucía, in the dry south of Spain. The report (Vives-Solbes, 2003) presents data on "social efficiency" of irrigation water use. According to the report 300,000 m^3 of water is used in rice irrigation in Andalusia to generate one job, while 5,000 m^3 of irrigation water applied in greenhouses also generates one job. The message is that water should be reallocated from rice to greenhouses, when it comes to generating income for farmers from the scarce water resources available.

The other case concerns the use of groundwater in the dry central plateau of Spain. Dumont (2015) and Novo et al. (2015) show that illegal use of groundwater in the Western Mancha Aquifer is used by smallholder farmers for irrigating vineyard and vegetables that have higher socio-economic productivity (jobs/Mm^3) as compared to irrigated cereals by large farmers. Maize generates 2.9 jobs/Mm^3, while vineyards generate 12.5 jobs/Mm^3 and garlic 60.0 jobs/Mm^3. Vineyards were irrigated illegally, as vineyards were only allowed to be irrigated from the 1990s, and since 1994 no new water use rights were granted. Owners started to irrigate from illegal wells, while the aquifer was declared over-exploited in 1989, and over-exploitation affected negatively the Tablas de Daimiel Wetland. The government did not want to stop the illegal irrigation as this sector provided many jobs and much income, and closing wells would lead to protests and social unrest. The government tried to install a water right market, but this failed as the farmers with illegal wells did not want to buy water rights from original water right holders as they considered the original water right allocation unfair. The Special Upper Guadiana Plan (SUGP), implemented from 2008 to 2012, made it possible for the regional government to purchase water rights used for cereals and reallocate it to small vineyards and vegetable growers, thus increasing the socio-economic productivity of water (Dumont, 2015).

In both case the comparisons of the social water productivity is in places and production systems using the same water resource. Therefore, the absolute numbers can be used to compare the crops or productions systems.

6.3. Social water productivity example from Peru

The following example from Peru provides another illustration of the use of the social productivity of water concept: the Ica Valley case. In the lower part of the Ica valley in South Coast of Peru two different production systems take water from the Ica River and groundwater: the

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[1] Van Koppen put as title of her PhD thesis in 1998 "More jobs per drop: Targeting irrigation to poor women and men", indicating the importance of irrigation to generate income for poor women and men, however, she did not do a quantification of jobs per volume of water.

smallholder communities and the export agribusiness (Pronti et al., 2024). The smallholder systems comprise of the La Achirana and the Ica River irrigation system (Oré et al., 2014). In total some 10,000 smallholders irrigate some 16,000 ha of desert land along the riverbanks. Without irrigation nothing can be cultivated on these lands. These irrigation systems have a history that dates back at least five centuries (Oré et al., 2014). The main crops have varied throughout the years, but include cash crops like cotton and maize, and crops for the local market and family consumption like grapes, beans and corn. Many smallholders have a licence to use groundwater, but use mainly water from the Ica River. The agribusiness companies are situated further away from the river. There are about sixty agribusiness companies, among which ten major companies (<200 ha). The biggest has some 2,150 ha, others vary from 200 to 1,200 ha, with a total of about 10,000 ha. The agribusiness companies use only groundwater. The main crops are table grapes, asparagus, and avocados, all are produced for the export market. In the upper part of the Ica valley the climate is wet, and here water is stored in the large Choclococha reservoir. This water is released to the desert coast in the dry season, exclusively for the smallholders. Currently a canal of about 10 km captures water that would otherwise flow to the Amazon river, and transfers it to the Choclococha reservoir.

In 2003 the regional government of Ica proposed to expand the water transfer from the Amazon basin to the Pacific coast. This project, called Proyecto Especial Tambo – Ccaracocha (PETACC), with the transfer canal called Ingahuasi, would transfer 300 Mm^3 of water per year to the export companies on the Coast. This project led to fierce protest of the highland communities in Huancavelica that felt the transfer would deprive them of water they needed for irrigation of highland crops like potatoes, and irrigate pastures for grazing of animals (Hoogesteger & Verzijl, 2015).

According to the Ica regional government the PETACC project was justified because of the higher productivity of the land and water in the export companies, as compared to the highland communities. This would not only benefit the export companies but also the poor communities as the plantations would generate jobs. At a first glance this seems a valid argument according to the calculations presented by Varillas (2010): the net income for a landowner that produces export asparagus on the coast is some 8,900 US$/ha/yr. This is about 20 times more than the 470 US$/ha/yr obtained by the highland smallholders. However, land is not the limiting factor in this case; water is. The picture for water productivity is similar: net income for the landowner per cubic meter of water used in export asparagus is some 0.94 US$/$m^3$, whereas a smallholder would gain some 0.18 US$/$m^3$ when selling her or his subsistence crops on the local market. It is also true that many poor people work in the plantations, and alternative employment for them in their rural areas of origin is hard to find because of lack of irrigation water, and alternative employment in urban areas will pay less and will be more irregular. In the Ica valley some 10,000 people work as day labourers gaining some 7 US$ per day (in the year of the above study 2010, currently some 10 US$/day is paid).

However, social water productivity of water used in the export plantations is significantly lower as compared to the highland smallholder's subsistence agriculture. The net income for the plantation workers is only 0.08 US$/$m^3$, against the aforementioned 0.18 US$/$m^3$ for the highland smallholders. In this sense, if the regional government of Ica wants to alleviate poverty, they should not allocate the project water to the export companies but to the smallholders that would benefit much more of this water. The communities of Huancavelica brought the case against the PETACC water transfer project to the Latin American Water Tribunal in Mexico in 2007 and won their case (Hoogesteger & Verzijl, 2015). The regional government of Ica paused the project, but the agribusiness companies keep on lobbying in favour of the project.

6.4. How could "silver" virtual water inform development at international level?

"Silver" virtual water – social water productivity – analysis makes mainly sense when comparing production systems that take water from the same river basin or aquifer, like the two examples from Spain and the example from Peru presented above. This can be classified as the "bottom-up" approach for silver virtual water analysis.

In a top-down approach silver virtual water would indicate export of products with a relatively high social water productivity, or in other words: a high number of jobs per drop. This indicator is only relevant to compare products produced in the same watershed or with water from the same aquifer, or if they are produced in areas with similar levels of water scarcity and poverty. Falkenmark and Lundqvist (1998, Fig. 4) refer to a study from the Tamil Nadu Agricultural University, Coimharore, calculating the relative economic return of different crops per unit of water for a farmer in Tamil Nadu. It shows that paddy rice has a six times lower return per cubic meter of water used as compared to tomatoes. Thus, in this case shifting from paddy to tomatoes would considerably increase the income for small farmers per cubic meter of water.

An example of a comparison of silver virtual water export from different river basins is the production of coffee by smallholders in Peru compared to coffee produced at large plantations in Brazil. If an international organisation decides to increase the water productivity of coffee (more coffee with the same amount of water) this would increase relatively more the income of poor farmers as compared to the income of the poor plantation workers in Brazil. In this case the silver virtual water flow of coffee from Peru would be higher per amount of money invested compared to investment of the same amount in Brazil. An example of a top-down approach to silver virtual water is provided by (Rosa, Chiarelli, Rulli, Dell'Angelo, & D'Odorico, 2020). They made an analysis of the regions in the world where water is available for irrigation, but where irrigation infrastructure is not yet developed. According to this study the blue water surplus should be used for irrigation to produce food and generate income.

7. Discussion

Virtual water trade analyses can reveal the tele-coupled effects of consumption by showing the connection with over-exploitation of water resources at the site of production. However, the effects on ecosystems and generation of income for poor labourers and smallholder farmers in export agriculture are complex.

Red virtual water analysis with a top-down approach will identify places with high potential for ecological and socio-economic damage because of high levels of export production. This is what Hoekstra et al. (2011) and Mekonnen et al. (2015) call "hotspots". Red virtual water analysis with a bottom-up approach will use detailed case studies on damage to ecosystems and vulnerable groups because of export production. The comprehensive case studies can detail the complexities, time–space variabilities, and differentiated effects on different social groups. Many of these cases become known because of environmental movements or NGOs that actively campaign and protest against water pollution, over-extraction and water grabbing related to export agriculture (see e.g. the EJOLT Atlas of Environmental Conflicts (Temper et al., 2018)). These top-down and bottom-up approaches can mutually strengthen each other: the identification of "hotspots" can lead researchers to important cases of ecological damage and social impacts, and detailed case studies can help define and fine-tune conceptual models that identify potential "hotspot" areas. The added value of red VW is that is signals negative effects and thus facilitates communication and decision making concerning the water-related effects of consumption, purchases, and investments.

Silver virtual water analysis with a bottom-up approach focusses on comparison of the social water productivity of different production systems used the same source of water. It is a comparative indicator that shows which of the production systems results in more income for poor labourers or smallholder farmers. Silver virtual water analysis with a top-down approach would compare social water productivity among different production systems in sites located in different river basins or aquifers. This only makes sense if the levels of water scarcity and poverty are similar. Table 1 provides an overview of examples of top-down and bottom-up approaches of red and silver virtual water approaches.

In this study a political ecology approach was applied to propose two new concepts to analyse water-related effects virtual water trade. This approach is different from the current quantitative approach making evermore detailed calculations of green, blue, and grey virtual water flows. The suggested new colours of red and silver VW draw a more direct relation with positive and negative effects for involved communities and ecosystems, different from the more technical blue, green and grey VW definitions. Silver VW relates with the neo-Marxist approach as it stresses the importance of the control over the income generated from resource use. In the capitalist system the profits from labour are skimmed of by powerful players in the production chains. Silver VW focuses on the income for smallholder farmers and labourers derived from the use of water for export production. The bottom-up approach of allowing the affected people to determine the effects of VW export empowers those people. In this way the winners and loses of the VW trade establish the trade-off between positive and negative effects, according to the political ecology approach suggested.

The red and silver VW indicators also have clear limitations. The proposed new VW colours are theoretical conceptualizations: they need to be worked out in concrete cases to show their usefulness. Furthermore, water is only one element of environmental justice, so trade of export products can have many more effects on communities and ecosystems besides water-related issues (see e.g. Perreault et al., 2018).

Table 1
Overview of red and silver virtual water indicators in water scarce areas.

Concepts	Top-down VW and WF assessment approaches	Bottom-up VW and WF assessment approaches
Red virtual water Severe damage to ecosystems and/or competition with others' water rights and future generations (incl. water grabbing)	• "Scarce water export" at country level (Lenzen et al., 2013) • "Water debt indicator" in grid cells and countries (Tuninetti et al., 2019) • Water grabbing in water scarce countries (Dell'Angelo et al., 2018): • "Hotspots" of water scarcity (Mekonnen et al., 2015)	Case studies as described by affected communities, NGOs and protest movements e.g.: • Water and agricultural related case in the EJOLT Atlas of environmental conflicts (Temper et al., 2018) • Water grabbing in Africa (Fonjong & Fokum, 2015) • Asparagus from Peru (Hepworth et al., 2010) • Avocados from Chile (Madariaga et al., 2021) • Vegetable export from Mexico (Zlolniski, 2011).
Silver virtual water Social productivity of water	Focus on labour intensive production Comparison among different watersheds and aquifers only relevant if water scarcity and poverty levels are similar, so very difficult to make worldwide indicators Water available for irrigation development (Rosa, Chiarelli, Rulli, Dell'Angelo, & D'Odorico, 2020)	Case studies of comparisons within watershed and aquifers: comparison of benefits the poor per m^3 E.g. Varillas, 2011 in Peru; and Vives-Solbes, 2003 Dumont, 2015; Novo et al., 2015 on Spain "Relative economic return per unit of water for the farmer" in Tamil Nadu (Falkenmark & Lundqvist, 1998)

Local circumstances are complex and the effects of water use are different for different groups and vary over time. Therefore, using different indicators like ecosystem quality, income, water overexploitation and water rights to assess virtual water export from a place will result in different appraisals for each indicator and often contradicting judgements. For example, production and export of asparagus from the desert coast of Peru might deplete the aquifer at a fast rate but generate relative many jobs for poor workers. In that case the conceptual model of the VW analysis will have to give different function and weight to different indicators. From a political ecology point of view, it is important to start from the valuing of the different effects by the affected communities.

Scientific studies on water productivity and water use efficiency combined with scarcity-weighted WF start from the implicit assumption that more crops have to be produced worldwide, but preferably in a more sustainable way (e.g. Drastig et al., 2021). This does not take into account the interests of local producers, nor the need for countries in the Global North to change to more plant-based diets (e.g. Springmann et al., 2018). Red and silver virtual water analysis can be used to critically look at discourses of water use efficiency, water saving, water pricing, ecosystem services and other modernization and water stewardship policies and programs.

8. Conclusions

A political ecological approach to virtual water and water footprint analyses starts with questions on who loses and who wins with virtual water trade. Use of water for export can cause severe damage to ecosystems and deplete water resources. General calculations of blue, green en grey VW and WF can reveal magnitudes of VW export flows and trends over time. Red virtual water can be defined as virtual water exported from sites where water use severely affects local ecosystems and communities. Silver virtual water can be defined as social water productivity: the water use contributing relatively much to income generation for poor workers and farmers.

It is important to tell the stories of who are the losers and winners. The often used blue, green, grey, and 'scarce' virtual water indicators do not point directly to damage to ecosystems nor negative effects for marginalised groups. For these indicators to be meaningful for decision makers – being consumers, water infrastructure planners, business managers or policy makers – the indicators should denote environmental and social risks or benefits. Red and silver VW concepts could be helpful tools in contextualized decision making, overcoming the decontextualization of the top-down use of the blue, green and grey virtual water concepts.

The added value of red and silver VW concepts is that they bring to the fore the local assessments of positive and negative consequences of water use for export production in highly diverse realities. This commensuration hides the diversity, but provides a clear message about the negative and positive effects as evaluated by inhabitants at the site of production.

Top-down studies (based on large databases) can be used to identify "hotspots". However, local circumstances and effects for different groups of people will vary within countries, watersheds and grid cells. Therefore, bottom-up studies that unravel the local effects for different stakeholders and different parts of the ecosystem are needed to tell the story of the effects of water use, based on local knowledge and values, and locally felt effects. Decision makers should base their decision on these bottom-up stories. Bottom-up analysis can start from comprehensive case studies based on the understandings and evaluations by the affected communities and their organizations.

CRediT authorship contribution statement

Jeroen Vos: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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