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SDG indicator 6.4.1 "change in water use efficiency over time": Methodological flaws and suggestions for improvement

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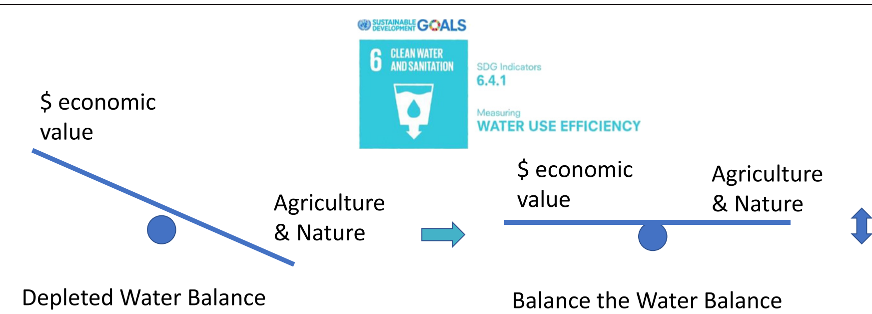
HIGHLIGHTS

- SDG indicator 6.4.1 monitors change in economic growth to volume of water withdrawn.
- This definition ignores social and environmental values of water.
- This definition is very sensitive to changes in the relative water use by agriculture.
- The definition ignores the effects of diminished return flows to the environment.
- An alternative, disaggregated definition linking water use to the water balance is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable Development Goal indicator 6.4.1 is defined as the change in water use efficiency over time and measured as the change in the ratio of gross economic value added by irrigated agriculture, industry and the services sector to the volume of water withdrawn over time. The rationale behind this indicator is to decouple a country's economic growth from its water use. Yet, this unwittingly results in an economic distortion of the water balance, favouring increased water withdrawal in service of higher water-use efficiency, at the expense of environmental sustainability. This paper discusses three methodological flaws. First, aggregation of only economic values across all sectors ignores social and environmental values and is very sensitive to changes in the relative water use by agriculture versus industry and services. Second, the economic value derived from agriculture and from imports cannot in fact be decoupled from agricultural water use. Third, the indicator completely ignores the effects of diminished return flows to the environment due to increased re-use of water. A novel alternative, disaggregated WUE approach is therefore proposed, which links water consumption to the water balance. It is defined as the economic value of irrigated and rainfed agriculture combined with water consumption (ET_a) by rainfed and irrigated agriculture per area based on earth observation data. It is measured as the change in the ratio of gross economic value added by irrigated and rainfed agriculture to the volume of water consumed by rainfed and irrigated agriculture over time. This approach is more consistent and objective, while being methodologically, hydrologically and environmentally sound. It acknowledges the coupling of economic growth and water depletion, and the need to strike a balance between opportunities for economic growth and environmental sustainability. This better serves the full breadth of the water and sanitation goal as defined in SDG 6.

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1. Introduction

In September 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development consisting of 17 Sustainable Development Goals (SDGs) with 169 targets under the various goals (UN, 2015; UN, 2017; UN-Water, 2018a). Achieving the SDGs requires monitoring of progress towards the goals (UN, 2017; UN-Water, 2017; Gain et al., 2016). The multiplicity of essentially non-comparable sustainable development targets within the SDG framework necessitated generation of “relevant” indicators, so that “clear, unambiguous messages can be conveyed to users” (Hák et al., 2016). The UN Inter-Agency and Expert Group on SDG Indicators (IAEG-SDG) was charged to draft these relevant indicators. Despite criticisms that many of the suggested indicators lack comprehensive, cross-country data and even lack agreed statistical definitions (Schmidt-Traub et al., 2017), the United Nations Statistical Commission (UNSC) adopted a set of 232 indicators proposed by IAEG-SDG in March 2016 as a starting point for progress monitoring (Allen et al., 2017).

The 2030 Agenda includes a goal on water and sanitation (SDG 6). Within it, target 6.4 addresses water-use efficiency and water stress. That target aims, by 2030, to “substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity” (FAO, 2018; GEMI, 2019). Two indicators were developed to track progress towards this target: 6.4.1 “change in water-use efficiency over time” and 6.4.2 “level of water stress: freshwater withdrawal as a proportion of available freshwater resources”. A third indicator was proposed for the number of people suffering from water scarcity, but there was no agreement on it. The first indicator has received less attention than the second indicator, which was evaluated by Vanham et al. (2018). They noted, however, that indicator 6.4.2 only monitors blue water stress, and gives no information on green or green-blue water scarcity or on water quality. They also pointed out that water stress should be measured based on net abstraction, in addition to gross abstraction. Indicator 6.4.2 currently also misses the link with the water balance and consequently water re-use is adding water beyond net abstraction.

Measurement and international reporting on the comprehensive set of SDG topics is coordinated by a range of international agencies. These agencies, including the OECD, WHO, FAO, IMF, World Bank and ILO, have developed statistical and measurement expertise in the particular areas falling within their mandates. Under the auspices of IAEG-SDG, various agencies were given “custodianship” for finalization of appropriate indicators related to the different SDG targets and coordination of data collection following endorsement of the indicators, including liaison with other international agencies. FAO is the custodian of indicators 6.4.1 and 6.4.2.

According to a progress update from UN-Water (2021) on indicator 6.4.1, water-use efficiency (WUE) increased in most reporting countries between 2015 and 2017. The global WUE value rose by 4% during this period, from 22.5 $/m^3 to 23.4 $/m^3. This sounds optimistic, but what does it mean? Did returns to water increase? Did the shares of sectors with higher economic value per unit of water used increase? Did economic growth become less dependent on the use of water resources? And, what does this mean for total water use and sustainability? To address these questions requires insight into the definition and rationale of this indicator.

The WUE concept was introduced 100 years ago by Briggs and Shan'rz (1913) to express a relationship between plant productivity and water use. They defined WUE as the amount of biomass produced per unit of water consumed by a plant – a definition still widely applied in the field of agronomy. However, other definitions of WUE have emerged and are in use. The agronomic WUE (plant product over water consumed) has been redefined as Water Productivity in the field of agricultural water management (de Wit, 1958; Giordano et al., 2017; Kijne et al., 2003; Keller and Seckler, 2006; Steduto et al., 2007; Bluemling et al., 2007; Zwart and Bastiaanssen, 2004) as a means to focus on the need to produce “more crop per drop” to sustain the global food security in era of increasing water scarcity (CA, 2007). The Water Footprint (WF), defined as water consumed per kg of product, the inverse of WP, has gained prominence in the field of global water sustainability assessments to compare global production practices and areas through generic modelling (Hoekstra and Mekonnen, 2012; Hoekstra et al., 2012; Vanham and Leip, 2020; Vanham and Mekonnen, 2021). Traditionally, efficiencies are defined as dimensionless ratios for irrigation performance, where efficiency is defined as the ratio water consumed over water applied (van Halsema and Vincent, 2012). As data on water consumed (actual evapotranspiration) has been notorious scarce and laborious to obtain in the past, cross “pollution” of data and indicators, where water applied is used instead of water consumed, has not been uncommon. Van Halsema and Vincent (2012) examined the use and abuse of various definitions and applications of the concept of WUE for different scales and domains of water use. Fernández et al. (2020) provides a recent good overview.

Indicator 6.4.1 was designed to address the economic component of SDG target 6.4 by assessing the relationship between economic growth and water use. It measures the change in the ratio of gross economic value added by irrigated agriculture, industry and the services sector in US dollars to the volume of water withdrawn in cubic metres over time (Rossi et al., 2019). Yet, this SDG definition of WUE is inconsistent with the WUE definition applied by the AQUASTAT database, which is the FAO global information system on water resources and agricultural water management. It collects, analyses and provides free access to statistics on more than 180 variables and indicators by country. AQUASTAT defines WUE as the ratio between effective water use, i.e. water consumed (in m^3), and actual water withdrawals (in m^3). This difference in definitions is rather remarkable, as AQUASTAT data play a key role in monitoring progress towards indicator 6.4.1.

The lack of terminological clarity is seen more widely too. Although the term “water-use efficiency” is promoted and used, no universal definition has been agreed and adopted. In the water sector, the term “water-use efficiency” is generally understood to be a dimensionless ratio between water used and water withdrawn, while in the agriculture sector it is often applied to measure the efficiency of crops (irrigated or rainfed) in producing biomass and/or harvestable yield. Analysis of the literature shows not only confusion in the use of terms such as water-use efficiency and water productivity, but also a lack of agreement on the equations (Fernández et al., 2020).

The SDG WUE efficiency indicator thus re-introduces a productivity parameter ($ of economic value) into the efficiency debates, based on water applied (defined as water withdrawn) instead of water consumed (used). This is problematic as it confounds the hydrological water balance and cycle from which water is withdrawn, but in which also water is recycled when wastewater (or non-consumed water) flows from agriculture (irrigated and rainfed), industries and services to recharge aquifers and rivers for further downstream use or sustenance of the environment. This risks confounding water withdrawn/applied with water consumed/used and neglect, through a blind spot, the existence of return flows in the hydrological water balances of the world's blue water resources. A practice that has led to confounding “dry” with “wet” (or true) water savings in the past (Seckler, 1996). More recently the field of water accounting has emerged to specifically assess and monitor the water balances of river basins and aquifers, making use of recent developments in Earth Observation to assess water consumed, and identify the return flows in the water balance (Molden and Sakthivadivel, 1999; Karimi et al., 2013; Steduto et al., 2009). This provides specific targets to particularly focus on reducing consumed fractions, rather than reallocate withdrawn fractions that may feed the water balance through return flows.

The aim of this paper is to examine the definition of indicator 6.4.1 and its rationale, to determine the definition's implications for water resources sustainability and make recommendations for improvement.

Section 2 examines the monitoring concept for the SDG indicator. Section 3 critically reflects on how progress on the indicator has been monitored. Concerningly, social and environmental values of water seem to be disregarded; values from imports seem to be decoupled from water use; and economic efficiency seems, unwittingly, to be propagated at the expense of return flows to the water resources base. The implications of this are explored. Section 4 presents an alternative approach to monitor progress towards indicator 6.4.1 and examines the role that earth observation data can play in bringing WUE monitoring back to consumed rather than withdrawn water fractions. Section 5 draws conclusions.

2. The rationale and definition of SDG indicator 6.4.1

As stated in SDG target 6.4, quoted above, the 2030 Agenda framework establishes a clear link between water-use efficiency and the sustainability of the water resources base. Further, though more implicit than explicit, it relates growing incidence of water scarcity worldwide to unbridled economic growth. This framing of sustainable development sets the task as to redress the sustainability of the water resources base and reduce the incidence of water scarcity by increasing the water-use efficiency (WUE); in other words, by more economical water use. The target does not stipulate whether such increase in WUE is to be achieved primarily by reducing water use while attaining the same economic value or by realizing a higher economic return on every additional unit of water used. This might initially seem a semantic quibble – as any realized increase in WUE is, after all, an indication of improved economic utilization of water. However, it matters, as will be argued in this paper, in its physical effect on the sustainability of the water resources base. By deconstructing (Bonisoli et al., 2018; Derrida, 1974, 1978) indicator 6.4.1, it will be shown that its current definition and method of decoupling economic growth from water use unwittingly result in an economic distortion of the water balance favouring increased water withdrawal in service of economic efficiency, at the expense of environmental sustainability and exacerbating water scarcity.

Indicator 6.4.1 tracks the change in WUE due to economic activity over time, measured as the change in the ratio of gross economic value added in US dollars to the volume of water withdrawn in cubic metres. This is computed as the sum from the three sectors, agriculture, services and industry (with industry composed of mining, manufacturing, power supply and construction; hereafter also referred to as MIMEC), weighted according to the proportion of water withdrawn by each over total water withdrawal (Box 1). The indicator allows a country to assess the extent that its economic growth is decoupled from its water use.

Thus, the monitoring concept for indicator 6.4.1 can be summed up as follows (GEMI, 2019):

- The aim is to assess the impact of economic growth on water resources utilization.
- Only runoff water and groundwater are considered (so-called blue water) in computing the indicator. For this reason, a specific parameter (C_r) was introduced to estimate the amount of agricultural production done under rainfed conditions.
- Rather than considering the water productivity of a crop, the indicator tracks the degree to which economic growth is decoupled from water use.

Indicator 6.4.1 was newly introduced by the SDG process. Thus, an entirely new methodology had to be developed to monitor the indicator. This also meant that no previous data existed for the indicator, resulting in new data computations and related interpretations of the results. Though the needed data on water withdrawals can be found in the AQUASTAT database (FAO, n.d.), it is important to note that AQUASTAT is only a repository of data. It does not produce new data. Without a specific effort by countries, no updates, and consequently no monitoring, can be done. Regarding data on value generation in different sectors of economies, this is commonly provided by national statistics agencies.

Although the indicator is defined as the change in WUE, it is interesting to note that the absolute WUE, as measured by indicator 6.4.1, tends to be higher in more advanced economies. It is strongly influenced by a country's economic structure and the relative size of water-intensive sectors (UN-Water, 2018b).

Rossi et al. (2019) show that the average WUE is significantly higher among European countries (which are mainly developed economies) – at 79.66 $/m^3 – than in Southeast Asia (at 4.11 $/m^3), Sub-Saharan Africa and Latin America and the Caribbean (at respectively 17.40 and 17.44 $/m^3). However, considerable differences can be found even within Europe. In Europe, the highest WUEs are found in countries with relatively large MIMEC shares and, especially, large services sectors (e.g., Luxembourg, Denmark and Switzerland). In Switzerland the WUE was for example 390 $/m^3 in 2017 due to sizeable services sectors, while in the Netherlands the WUE was 44 $/m^3 in 2017 (Annex A). On the other hand, a lower GDP per capita and higher contribution of agriculture to GDP and to total water use are generally associated with lower WUEs. In sub-Saharan Africa, extremely low WUE values are found in countries where agriculture accounts for 80-90% of total reported water withdrawals (e.g., Madagascar, Mali and Somalia), while very high WUEs are found in countries with sizeable oil, gas and mining sectors, where MIMEC accounts for an important share of GDP and water-use and presents high sectoral WUE (e.g. Equatorial Guinea, Angola, Congo) (Rossi et al., 2019). It is also interesting to note that for a number of countries, such as Thailand and Senegal, absolute values of all water abstraction data remain constant for the reported years 2007, 2012 and 2017, which does not seem to be very realistic.

According to Rossi et al. (2019) WUE has increased in most of the major developed economies and in most of the newly-industrialized countries over the past three to four decades due to growth of the industry and services sector. With regard to the latter, the increase in WUE was particularly pronounced in India (+240%) and especially China (+923%), while in other countries (e.g. Brazil, Malaysia and South Africa) fluctuations were recorded between the various periods within an overall growth trend.

WUE in agriculture ranges between 0.7 and 1.9% of WUE in MIMEC and services, except in Africa (Rossi et al., 2019). As WUE in agriculture tends to be significantly lower, by up to several orders of magnitude, than in MIMEC and services, the indicator is very sensitive to changes in the share of water withdrawn for agriculture versus the other two sectors. This means that the easiest gains in WUE can be achieved by allocative changes; that is, transforming economic growth away from agriculture, towards industry and services. Agriculture is, however, indispensable to sustain future food security. Also, within agriculture there are differences in WUE between crops. For example, flowers have a higher WUE than wheat. However, it is important to be cautious in supporting abandonment of crops with a relatively low WUE (such as wheat) in favour of crops with a relatively high WUE (such as flowers).

3. Flaws in the definition

In the previous section it became clear that the rationale behind indicator 6.4.1 is to provide insight into the reliance of economic growth on the exploitation of water resources. Monitoring change in WUE over time – defined as the change in the ratio of gross economic value added in US dollars to the volume of water withdrawn by all sectors in cubic metres – makes a number of simplifications, posing several methodological and conceptual flaws: (i) the aggregation of only economic values across all sectors promotes simplistic reallocation of water from low to high WUE activities while ignoring social and environmental values of water; (ii) decoupling economic growth from the associated water use disregards water used by imports and the physically delimited scope for reducing water use in agriculture; and (iii)

Box 1
WUE components according to GEMI (2019).

$$WUE = A_{we} \times P_A + M_{we} \times P_M + S_{we} \times P_S$$

where

WUE = Water-use efficiency (US \$/m^3)

A_{we} = Irrigated agriculture plus livestock plus aquaculture water-use efficiency (US \$/m^3)

M_{we} = MIMEC water-use efficiency (US \$/m^3)

S_{we} = Services water-use efficiency (US \$/m^3)

P_A = Proportion of water used by the agricultural sector over the total use

P_M = Proportion of water used by the MIMEC sector over the total use

P_S = Proportion of water used by the services sector over the total use

$$A_{we} = (GVA_{al} + GVA_{aa} + [GVA_{air} \times (1-C_r)])/V_a$$

where

GVA_{al} = Gross value added of the livestock subsector (US \$)

GVA_{aa} = Gross value added of the aquaculture subsector (US \$)

GVA_{air} = Gross value added by the irrigated and rainfed agriculture subsector (US \$)

C_r = Proportion of GVA_{air} produced by rainfed agriculture (%)

V_a = Volume of water used by irrigation, livestock and aquaculture (m^3)

$$M_{we} = GVA_m/V_m$$

where

GVA_m = Gross value added by MIMEC, including energy (US \$)

V_m = Volume of water used by MIMEC, including energy (m^3)

$$S_{we} = GVA_s/V_s$$

where

GVA_s = Gross value added by services (US \$)

V_s = Volume of water used by the services sector (m^3)

water use is not linked to the water balance, as will be explained in more detail below. The implications of these flaws are illustrated below.

3.1. Aggregation of only economic values

Aggregation of only economic values across sectors is a methodological flaw, as changes in WUE are very sensitive to changes in the proportion of water use accounted for by agriculture versus industry and services, since the latter two have a considerably higher economic value per unit of water used than agriculture. Besides, there is no direct relationship between the water withdrawn and the GDP generated for most industries and services. Agriculture is the largest water consumer, accounting for some 70% of all withdrawals globally and as much as 90% in some arid countries (CA, 2007).

In Switzerland the change in the gross value added of the service sector between 2012 and 2017 has led for example to an increase in the WUE of 26.7% (see Annex 1 Table A1). Also in China the increase in the WUE between 1997 and 2007 from respectively 3.73 \$/m^3 to 20.99 \$/m^3 is mainly due to the quadrupling of the WUE of MIMEC and services (see Annex A Table A3). So, the change in the WUE is dominated by the economic performance of the highest water withdrawing sector, whereas for countries with a high dependency on irrigated agriculture it is far more difficult to improve their WUE significantly. This means that high irrigation countries are systemically dwarfed in their WUE growth rate, as any significant economic growth in industries and services is diminished by the low fraction of water withdrawal rates these sectors have in relation to irrigated agriculture.

In the Netherlands the main water consumer rainfed agriculture is not considered (see Annex A Table A2). Besides the SDG indicator completely ignores the (virtual) water imports of industrialized economies of food and fibres from which the industries and services derive their economic value and impose water scarcity impacts on the environment outside their national borders (see Section 3.2).

Diverting water away from irrigated agriculture to the industry and services sectors increases the WUE, as water is reallocated from a lower to a higher WUE activity. However, whether this is desirable is another issue, as it can make a country more dependent on food imports and trade and hence more vulnerable to price spikes and fluctuations due, for instance, to subsidy programmes and political trade shocks. A country may therefore seek food security through self-sufficiency.

Furthermore, reallocation of water to higher WUE activities is not attainable and sustainable at the global level, as achieving high WUE implies that all food production in future would have to be derived from rainfed agriculture. In an era of increasing climate change impacts this would be, at best, a precarious undertaking.

Indicator 6.4.1 assigns increases in WUE solely to an increase in economic value derived from water withdrawn by all sectors. This ignores the social values of water for local purposes, such as environmental conservation, as well as values such as food security, food self-sufficiency, rural development, equity and environmental sustainability (Hellegers and Van Halsema, 2019). Nonetheless, economic value is not the only policy objective that matters. It is important to link these larger-scale social values of water (i.e. the multiple values of water) to local uses and impacts, and vice versa (Hellegers and Van Halsema, 2018). Though irrigated agriculture has a low WUE, it is indispensable for food security and affordable food provision. Worldwide, irrigated agriculture produces 40% of all food on 20% of the land, whereas rainfed agriculture produces the remaining 60% on 80% of the land (Comprehensive Assessment of Water Management in Agriculture, 2007). The UN (2021) acknowledges that different interests and diverging perspectives inherent in the social, cultural, environmental, ecological and economic values of water drive diverse resource-related decisions. By only considering the gross economic value generated by irrigated agriculture, indicator 6.4.1 significantly undervalues water.

Implicitly, increased WUE, defined as a positive indicator of sustainability, favours a shift away from low-value water use to high (or higher) value uses, not only across the different components of the economy (e.g., low WUE agriculture to high WUE services), but also within agriculture. Shifting from low-value irrigated staples to higher value crops (say, avocados or flowers) will yield increases in WUE. While economically logical, this disregards the burden and task of the agricultural sector to provide enough food at affordable prices (SDG 2). A solution is to consider disaggregated changes in WUE per sector. This is acknowledged by UN-Water (2018b), which stated “it would be futile to try to devise policies that aim to move water from one economic sector to another to increase the value of WUE”. Nonetheless, it remains ignored in the practice of aggregating the value added of all sectors.

3.2. Decoupling

Indicator 6.4.1 does not take into account water used for imported livestock feed and raw materials for industry or energy sources, or forestry, though these are a big component of the livestock and (food) industries and energy sector. Hence, it decouples economic growth from the associated water use for imports, which are ever-present in a globalized world. The indicator fails to distinguish the source of imports and production. This has implications for the WUE in agriculture, for instance, in the Netherlands, which depends on large imports of livestock feed and other primary products to derive economic value from its livestock and food processing industries. This means that the gross value added is attributed to the Netherlands, but not the water use associated with feed and primary product imports, as that is accounted to the country of origin. About 89% of the water footprint, which is a measure of humanity's appropriation of fresh water in volumes of water, of the Netherlands is external and 11% is internal (van Oel et al., 2009). Only 44% of virtual-water import, which is water embedded in products imported, relates to products consumed in the Netherlands, thus constituting the external water footprint. For agricultural products this is 40% and for industrial products this is 60%. The remaining 56% of the virtual-water import to the Netherlands is re-exported. The impact of the external water footprint of Dutch consumers is highest in countries that experience serious water scarcity (van Oel et al., 2009).

In the example given in the methodological manual (GEMI, 2019), the WUE for agriculture in the Netherlands is very low, as the value added by food processing is allocated to industry. This skews the overall WUE for the Netherlands in favour of high value-added industry and services, bypassing the water withdrawals associated with its needed primary products (mainly imports such as soya, palm oil, coffee, cocoa and flowers). Methodologically, these are considered goods that do not have to be accounted for in terms of their water use, which favours processing industries as value-adding enterprises.

Indeed, the Netherlands' very low water withdrawals for agriculture are largely attributable to the definition of the indicator, which only counts water withdrawals for irrigation purposes (sprinkler) and ignores sub-surface irrigation (it is misattributed as rainfed agriculture). In the Netherlands most agricultural area is managed by controlling groundwater levels to feed sub-surface irrigation. Such use of groundwater (actively manipulated by groundwater management) is attributed to green water use, not accounted for in the WUE calculations of indicator 6.4.1.

Decoupling crop production from water use (i.e. increasing yield without increasing water use) is only possible up to the point of maximum output per unit of water used (maximum agronomic WUE). After this point, increased water use is needed to increase production, due to the fact that there is limited scope for improvement in the linear physical relation between biomass and transpiration (De Wit, 1958; Steduto et al., 2009; Van Halsema and Vincent, 2012). In other words, decoupling of production from water use does not work in agriculture. There is scope for improvement, though it is physically delimited, through fertility management, crop variety development and choice, and precise management of deficit irrigation.

The WUE in Spain has increased for instance in the period between 1997 and 2002 from respectively 21.4 to 25.33 $/m^3, which is considered as an improvement. However, total water-use also increased during that period from 34.9 to 35.94 $/m^3 (Rossi et al., 2019). The increase in WUE over time has thus come at the expense of environmental sustainability. This is not revealed by indicator 6.4.1.

3.3. Water use is not linked to the water balance

Indicator 6.4.1 disregards the environmental sustainability of resources. Rather, it is geared towards further exploitation and consumption of water at the expense of the environment. This is worrying given the sustainability targets set in SDG 6. An increased WUE for irrigated agriculture, for instance, by investments in drip irrigation and agricultural intensification, could be regarded as positive in full disregard of the environmental impact this may have, as the consumption of water by agriculture may increase at the expense of return flows to aquifers and rivers (Perry, 2011; Van Halsema and Vincent, 2012).

Indeed, a 100% efficiency, which means that all water withdrawn is effectively used (i.e. consumed) or recycled is not desirable, as this would mean full abstraction of water from nature with no outlet to rivers and seas. Recycling of the consumed fraction (actual evapotranspiration) is physically not feasible and part of the natural hydrological cycle. It is therefore important to consider return flows and water re-use.

A focus on water consumed instead of water withdrawn is recommended. By focusing on water consumed, rainwater and soil moisture utilized by rainfed agriculture also enter the equation (as well as the gross value of rainfed agriculture). This makes sense, as expansion of rainfed agriculture can reduce the blue water available for water withdrawals and environmental sustainability. Indicator 6.4.1 disregards the environmental sustainability of water resources. It favours further exploitation and consumption of water at the expense of the environment, though environmental protection is an integral part of the SDG framework. It also contravenes a number of UN conventions on environmental sustainability.

Furthermore, indicator 6.4.1 does not take account of changes in population, with WUE in services being particularly sensitive to such changes (Rossi et al., 2019). Nor are regional differences in climate and water availability considered in the interpretation of this indicator, though these are especially important for agriculture. In addition, from

Box 2
Methodological description of water use in agriculture according to GEMI (2019).

3.1.1.1 Agriculture water-use (km^3/year)

Annual quantity of self-supplied water used for irrigation, livestock and aquaculture purposes. It includes water from renewable freshwater resources, as well as water from over-abstraction (i.e. abstraction beyond replenishment rates) of renewable groundwater or abstraction of fossil groundwater, direct use of agricultural drainage water and (treated) wastewater, and desalinated water. This definition refers to self-supplied agricultural establishments not connected to the public water supply networks. If connected to such networks, water used for agriculture may be included in the services water-use, unless disaggregated data are available.

the methodological description of water use in agriculture (Box 2), it becomes clear that water withdrawals by the sector could be counted double or triple, depending on the number of times it is re-used. This ignores the environmental impact of water withdrawals and inflates the WUE growth rate.

The problem is best illustrated on the basis of a water balance (Fig. 1). Using the SDG methodology, the WUE of the system depicted in Fig. 1 is calculated as follows: *WUE* = gross value added/water withdrawn, or \$(20 + 20 + 10) / (100 + 40 + 10) m^3 = 0.3 \$/m^3. However, from a water balance perspective, only 65/100 of the water withdrawn is consumed (ET_a), as 35 m^3 are returned to the environment. Thus, from a water balance perspective, the WUE would amount to \$50/65 m^3 = 0.77 \$/m^3.

Fig. 2 presents a revised water balance incorporating investments to increase the amount of water re-used. The WUE calculated using the SDG framework methodology then becomes \$(20 + 40 + 10) / (100 + 60 + 10) m^3 = \$70/170 m^3 = 0.41 \$/m^3. The water balance-based WUE becomes \$70/85 m^3 = 0.82 \$/m^3, while the return flows to the environment diminish from 35 to 15 m^3 and only 115 m^3 of water instead of 135 m^3 remains available at the resource, affecting the sustainability of water withdrawal.

This points to three problems with the currently used SDG definition of indicator 6.4.1. First, it completely ignores the environmental impact of water withdrawals and the effect of increased re-use of water in diminishing return flows to the environment. Second, it inflates the percentage increase in WUE through increased water re-use rates, as illustrated by the SDG-based WUE, ((0.41 − 0.3) / 0.3) ∗ 100 = 36.7%, compared to the water balance-based WUE, ((0.82 − 0.77) / 0.77) ∗ 100 = 6.5%. Third, increases in WUE come at the expense of the environment. In our example, using the water balance-based WUE, the economic efficiency of water use remained the same in terms of consumption (i.e. \$20/20 m^3 versus \$40/40 m^3), but the WUE increased by 37% at the expense of the environment. Expansion of water consumed is thus confused with higher efficiency.

The same principles also apply to industry and services. Indicator 6.4.1 does not properly assess increased re-use of water by industry and services. Figs. 3 and 4 below show that an increased re-use of water by industry reduces the return flows from 90 m^3 to 70 m^3 and only 170 m^3 of water instead of 190 m^3 remains available at the resource, affecting the sustainability of water withdrawal. So, the re-use of (waste) water goes at the expense of recharge, detaching WUE completely from the physical water balance. The WUE calculated using the SDG framework indicator[1] becomes \$(600 + 600 + 600) / (100 + 90 + 80) m^3 = \$1800/270 m^3 = 6.67 \$/m^3. The water balance-based WUE becomes \$1800 / (100 − 70) m^3 = 60 \$/m^3. Although the SDG indicator shows a 10% increase in the WUE, this comes at the expense of the aquifer. So, SDG indicator 6.4.1 does not give an appropriate signal for the realization of the admirable target set out in the 2030 Agenda in the case of water reuse.

4. From allocative efficiency towards technical efficiency linked to the water balance

This section proposes an alternative technical WUE approach focused on (i) the economic value of rainfed and irrigated agriculture, (ii) consumptive water use that is non-recyclable and (iii) linking water use to the water balance. This provides a better grip on water abstraction rates from nature, and the economic value derived from those abstractions. In our view, this better encompasses the full breadth of SDG 6 wherein economic efficiency is directly related to the targets set for environmental sustainability of the resources base and water scarcity.

The currently used AQUASTAT data are national and lack spatial detail, whereas spatial assessment of water consumption is needed for regional policy support (Giupponi et al., 2018). A way forward is to assess the consumptive use of water by rainfed and irrigated agriculture (i.e. actual evapotranspiration, ET_a) and associated trends in time and geography. Advances in earth observation (EO) data, such as WaPOR, can help establish this capacity. The WaPOR database was recently developed by FAO and other partners (FAO, 2018). It provides open access data on EO-derived biomass and ET_a data for Africa and the Near East at various resolutions: 250 m, 100 m and 30 m.

ET_a data allow for direct estimation of the amount of water consumed by each spatial unit (pixel), which is a suitable indicator for the volume of water consumed to produce vegetation (biomass) by the agricultural sector (ESA, 2020). This capability enables a meaningful, and fairly straightforward, refinement of the WUE assessment methodology, when employed for the estimation of agricultural water use. Applying land use masks that distinguish rainfed from irrigated agriculture (Tantawy, 2019), available in AQUASTAT, yearly estimates of the

[1] If wastewater is treated by a wastewater plant indicator 6.4.1 counts it as water withdrawal (see Fig. 4). However, if it is reused within the own factory indicator 6.4.1 does not count it as water withdrawal.

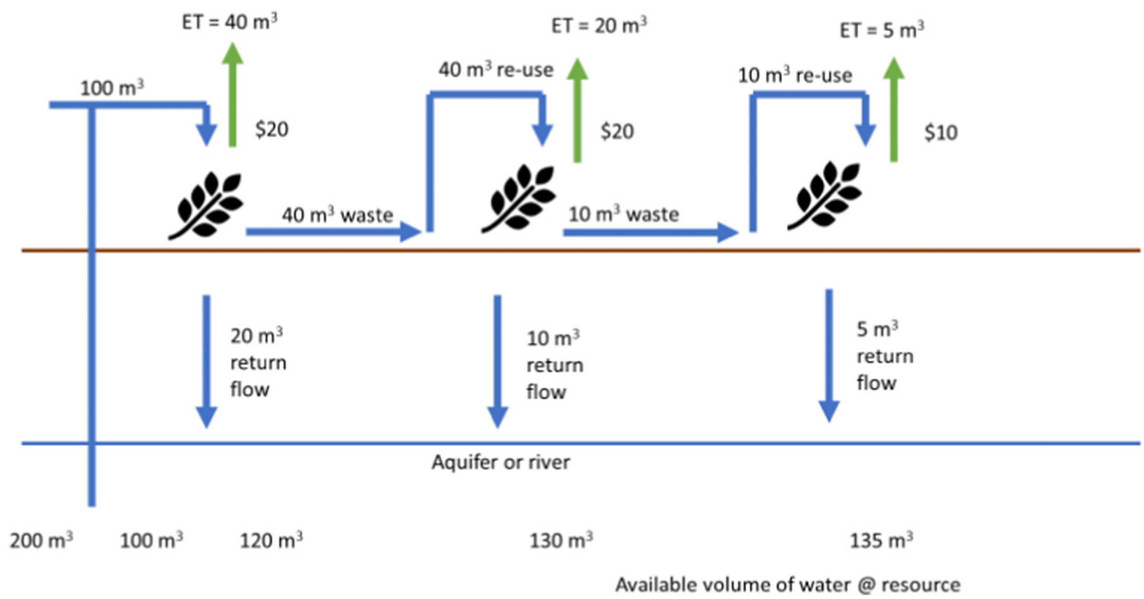

Fig. 1. Schematization of water flows from a water balance perspective.

amount of water consumed (sum of ET_a) can be derived per sector, to determine the economic efficiency of agricultural water use (gross value/ET_a). From a water balance perspective, this has the marked advantage that any increase in observed ET_a is attributable to an increase in water abstraction – making less water available for nature and industries and services, and vice-versa. A margin of fluctuation will have to be accommodated to allow for the effect of climatic variations on yearly ET_a figures in agriculture. This methodology will also enable monitoring of allocative and economic shifts between rainfed and irrigated sectors, as well as expansion of arable agricultural land at the expense of the environment. To safeguard the SDG targets on environmental sustainability and water scarcity, caps on the consumed (and abstracted) fraction will need to be introduced to indicate environmental stress thresholds. As these will vary per region and may be subject to temporal change due to the effects of climate change, the setting of these thresholds is currently the subject of further research.

To monitor (the scope for) improvements in efficiency of water use in agriculture, approaches are being developed to estimate the spatial crop water productivity, defined as kg yield/m^3 of ET_a (Bastiaanssen and Steduto, 2017). Whereas productivity is clearly constrained by agronomic and biophysical limitations governing crop growth (De Wit, 1958; Steduto et al., 2009; Van Halsema and Vincent, 2012), variations in abiotic and biotic stress-induced yield losses may result in variations in productivity. The complexity of capturing these variations across fine spatial and temporal scales has inhibited efforts to incorporate these into a global assessment framework like the SDGs. However, present-day EO data provide a powerful and cost-effective way to assess agricultural water consumption, though some limitations remain (Graveland et al., 2016; Tantawy, 2019. ESA, 2020).

EO data can be used to establish actual evapotranspiration and, to some degree, biomass data, but not yield and crop water productivity, as EO data do not provide insight into the harvest index. Indicator

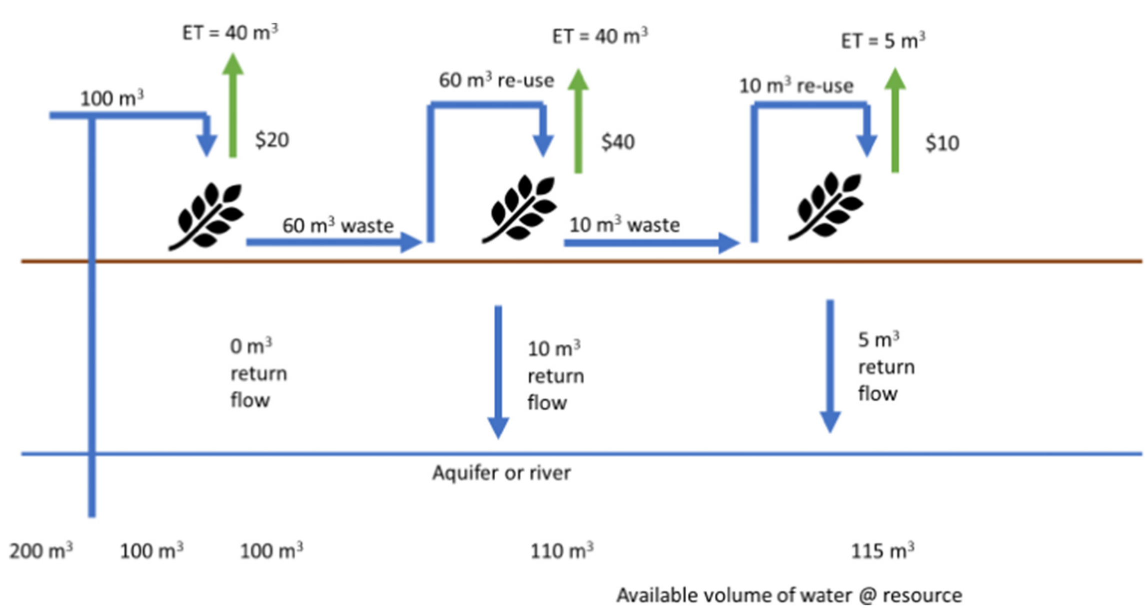

Fig. 2. Schematization of water flows after investment in water re-use.

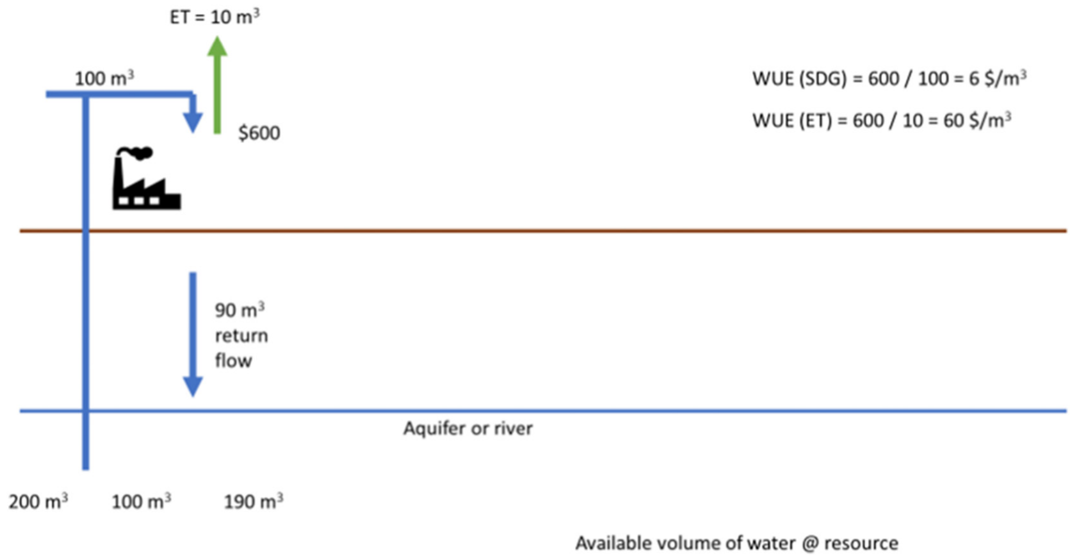

Fig. 3. Schematization of water flows from a water balance perspective.

6.4.1, however, already monitors the gross value added by irrigated and rainfed agriculture (GVA_{air}) separately. This data can then be combined with water consumption (ET_a) for rainfed and irrigated agricultural areas based on EO data. Such separation allows monitoring of shifts in rainfed and irrigated agriculture and their comparison over time. It could be computed as follows:

$$A_{wuei} = [GVA_{air} \times (1-C_r)]/ET_{ai}$$

$$A_{wuer} = [GVA_{air} \times C_r] + GVA_{al} + GVA_{aa}/ET_{ar}$$

where

A_{wuei} = Irrigated agriculture water-use efficiency (US \$/m^3)
A_{wuer} = Rainfed agriculture plus livestock plus aquaculture water-use efficiency (US \$/m^3)
GVA_{air} = Gross value added by irrigated and rainfed agriculture (US \$)
C_r = Proportion of GVA_{air} produced by rainfed agriculture (%)
ET_{ai} = Volume of water consumed by irrigated agriculture (m^3)
ET_{ar} = Volume of water consumed by rainfed agriculture (m^3)

To provide insight into changes in WUE per sector without distortions from changes in sector WUE allocations, an approach that monitors and presents disaggregated WUE per sector linking water use to environmental sustainability is recommended. The current, aggregated indicator does not provide such insights. The WUE of industry and services can be computed as shown in Box 1, but should be presented separately as it is based on water withdrawal instead of water consumed. Both sectors use water, but their consumption is limited. They can

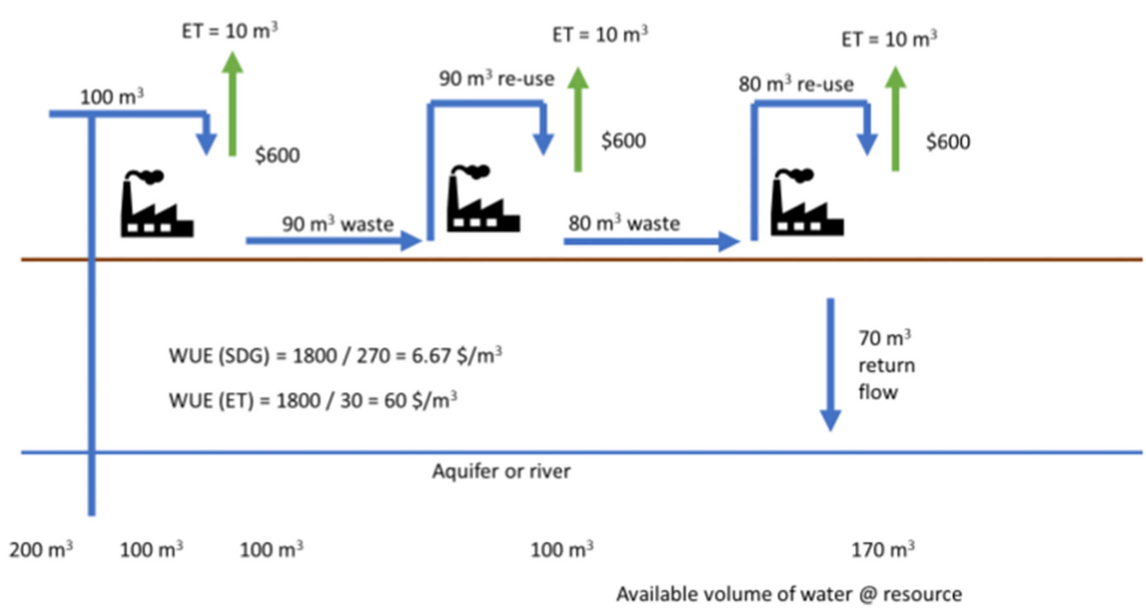

Fig. 4. Schematization of water flows after investment in water re-use.

recycle water indefinitely, though this should not lead to double counting as done in the current approach. Elaboration and sophistication of our proposed approach is a promising avenue for further research.

Our proposed novel approach does not resolve the issue of decoupling imports of livestock feed and primary agricultural products from water use— these remain to be accounted in the water use in the country of origin, while the added economic value is attributed to the country of processing. This remains difficult to resolve within one indicator. To address this issue, additional indicators will have to be introduced. Also this, remains an area for further research.

5. Conclusions

This paper demonstrated that the current definition and methodology of indicator 6.4.1 is very sensitive to changes in the proportion of water withdrawal accounted for by agriculture versus industry and services. Moreover, the indicator aggregates only economic values across all sectors, ignoring social and environmental values. Furthermore, it has been shown that the value of agricultural production cannot in fact be decoupled from agricultural water use. Finally, the definition completely ignores the effects of diminished return flows to the environment due to increased re-use of water. By decoupling economic gains from the water balance, economic efficiency is, unwittingly, propagated at the expense of the return flows to the water resources base. This directly undermines the sustainability of the resources base and exacerbates water scarcity. So, indicator 6.4.1 is often not an appropriate signal for the realization of the admirable target set out in the 2030 Agenda. Using the two indicators water efficiency and water stress separately in a complementary way is needed to measure progress to and to deliver on SDG target 6.4 (Vanham and Mekonnen, 2021).

A novel alternative, disaggregated WUE approach is proposed linking water use to the water balance and using the economic value of irrigated and rainfed agriculture as monitored by the current indicator, combined with water consumption (ET_a) by rainfed and irrigated agriculture per area based on EO data. This approach is more consistent and objective, while being methodologically, hydrologically and environmentally sound. It acknowledges the coupling of economic growth and water depletion, and the need to strike a balance between opportunities for economic growth and environmental sustainability.

So SDG indicator 6.4.1 does not provide an adequate (water balance-based) coupling of economic growth and sustainability. Indeed, it suggests that economic growth is unchallenged and unlimited by the sustainability of the water resources base. It is important to redress this and establish a clear link between the water consumed, the economic value derived and the sustainability of the water resources base.

CRediT authorship contribution statement

Petra Hellegers: Literature Review, Writing - Original Draft Preparation, Conceptualization, Investigation. **Gerardo van Halsema:** Co-writing and Editing, water balance analysis, Visualisations, Proposed Alternative Approach.

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Declaration of competing interest

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Appendix A. Annex A

Table A1
WUE ($/m^3) total and by sector, proportion of total water-use by sector and total water use (in billion m^3/year) in Switzerland, 2012–2017.
Source: Aquastat data.

Year	2012	2017
WUE	308.10	390.49
A_{we}	3.73	4.16
M_{we}	239.05	254.80
S_{we}	385.56	550.61
Pa	0.08	0.09
Pm	0.32	0.37
Ps	0.60	0.54
Total	2.00	1.73

Table A2
WUE (U$/m^3) total and by sector, proportion of total water-use by sector and total water use (in billion m^3/year) in The Netherlands, 2007–2017.
Source: Aquastat data.

Year	2007	2012	2017
WUE	59.37	61.67	44.21
A_{we}	53.71	61.01	56.98
M_{we}	15.02	14.27	8.96
S_{we}	401.86	429.61	455.79
Pa	0.01	0.01	0.00
Pm	0.88	0.88	0.92
Ps	0.11	0.11	0.08
Total	10.95	10.72	16.08

Table A3
WUE ($/m^3) total and by sector, proportion of total water-use by sector and total water use (in billion m^3/year) in China, 1992–2017.
Source: Aquastat data.

Year	1992	1997	2002	2007	2012	2017
WUE	2.21	3.73	5.61	9.91	14.76	20.99
A_{we}	0.30	0.47	0.62	1.42	1.85	2.05
M_{we}	7.17	10.06	12.35	19.29	28.97	38.88
S_{we}	16.08	17.72	22.57	34.38	55.75	82.78
Pa	0.79	0.72	0.67	0.63	0.64	0.64
Pm	0.15	0.19	0.22	0.25	0.24	0.22
Ps	0.06	0.08	0.11	0.12	0.12	0.13
Total	516.94	539.35	551.53	571.30	603.30	598.10

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