# Using indicators to inform the sustainable governance of water-for-food systems

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**Highlights:**

- Water-for-food governance requires integration of water- and food-centred knowledge
- Linking food consumption to water use requires multiple cross-scale indicators
- Climate-related extremes and effects complicate multi-level water-for-food governance

**Abstract**

As global demand for food increases and impacts of climate-related extremes become more severe new governance mechanisms have become relevant. Individual and collective efforts by actors in water-for food governance could all contribute to sustainably managing the locally scarce water resources that are mobilized to meet the world's demand for food. This review synthesises insights from agricultural water management, water resources management and socio-hydrology to contribute to a knowledge base for informing joint efforts by networks of actors teaming up for sustainable water-for-food governance. The interpretation of water-for-food indicator values is complicated by spatiotemporal variations, different interests and perspectives. However, incorporating these complexities is crucial for governing a globalized food system that depends on water resources of which the availability varies in space and time.

**Keywords**

Water resources management, agricultural water management, water-for-food indicators

# 1 Introduction

As the world population grows and diets change, total demand for food increases [1]. At the same time, in many regions the water available for crop production decreases as water needs from other sectors also tend to increase. Therefore, humanity needs to find solutions to meet its food demands such that its production remains possible without surpassing water availability and to sustain environmental flow requirements. Relevant ways to achieve this include a change in the types of crops cultivated and by sustainable intensification of agriculture (e.g. by modernization of agricultural systems) on existing agricultural lands [2-4], increasing virtual-water transfer by intensified international trade from places where water is still abundantly available to areas where demand is increasing [5-8] and changing food consumption itself [9,10].

To sustainably produce enough food, while accounting for environmental integrity and social equity, also in areas confronted with water crises (e.g. droughts, floods and storms), requires insight into the relationships between water systems and food production. Four common perspectives in studying the water-for-food research include those focusing on i) increasing water productivity (agriculture-centred), ii) reducing water footprints (water-centred), iii) achieving national food security, and iv) the local implications of water-for-food systems [11]. Agriculture-centred studies (e.g. perspective i) mostly focus on contributions to SDG Target 2.4 (resilient agricultural practices that increase productivity and production) while water-centred studies (e.g. perspective ii) rather focus on contributions to SDG Target 6.4 (increase water-use efficiency and ensure sustainable withdrawals). Agriculture-centred studies generally promote 'more-crop-per-drop' strategies (e.g., water productivity studies [12]) while water-centred studies generally promote 'less-drop-per-crop' strategies (e.g., water footprint assessments [13]) [14]. Such efficiency indicators have been proposed to be used for informing decision-makers in water-for-food governance from the local to the global level [15,16]. Differences between indicators with regard to what these indicators highlight may suit the different objectives of different actors in water-for-food governance, including both traditional water-governance-related actors and new supply-chain-related actors [17]. For well-informed decisions, these actors need timely, contextualized, and actionable information to support actors in their decision-practices, taking into account the local situation with regard to water shortages and specific environmental and socio-economic impacts, particularly in severely drought-affected regions. Towards achieving this, this paper reviews selected performance indicators to inform actors in sustainable water-for-food governance and discusses the related socio-hydrological complexities with regard to drought events and their impacts (Figure 1, Table 1).

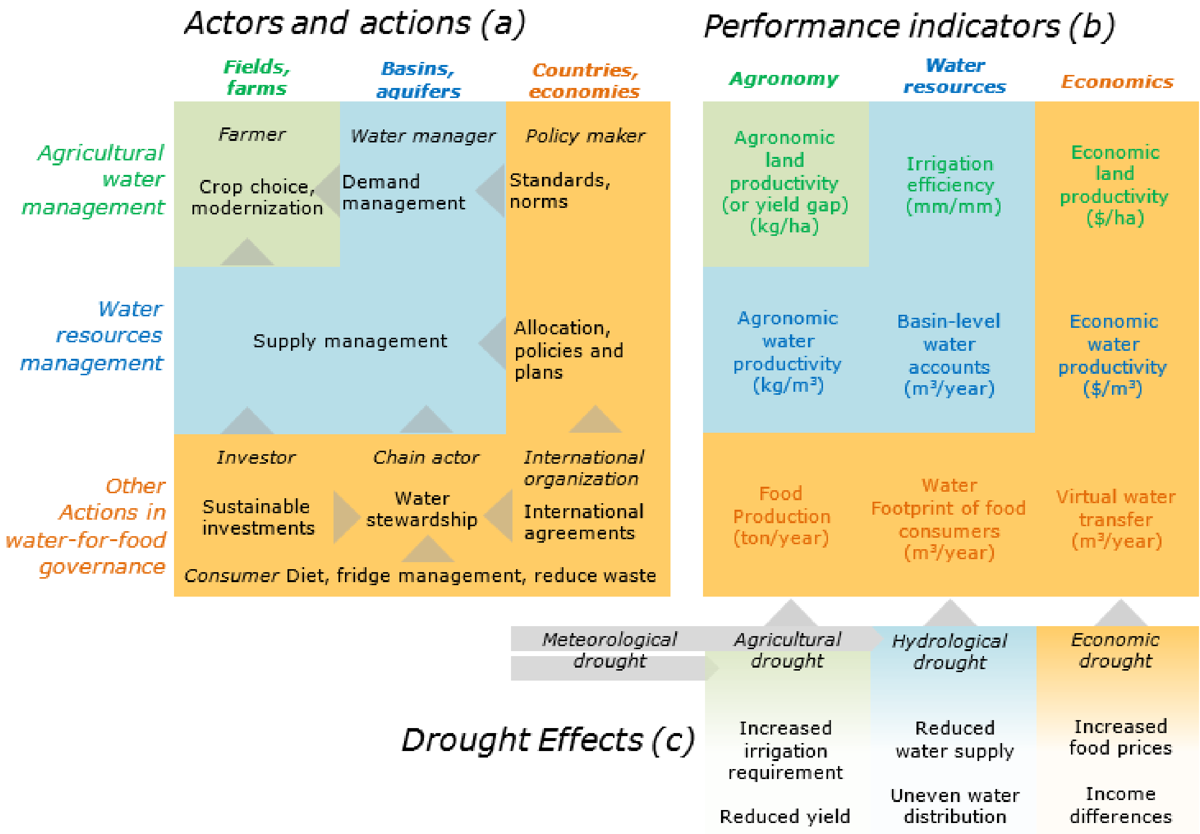


**Figure 1 Governing water for food can consist of a combination of supply-chain actions and water governance actions involving farmers, water managers and other actors operating from field-level (green), basin-level (blue) and country-level (orange) perspectives respectively. The arrows indicate how their actions could support each other to materialize as field-level or basin-level interventions (a). Several indicators exist to inform sustainable agricultural water management, sustainable water resources management and other supporting actions (b). At the same time, spatiotemporal variations due to climate-related extremes (drought events in this case) and their impacts complicate things further (c). See Table 1 for specifications and equations of the water-for-food performance indicators (b).**

**Table 1 Specifications and equations of the water-for-food performance indicators included in this review.**

| Indicator | Equation |
|---|---|
| Agronomic land productivity (kg/ha) | [harvested yield] / [area harvested] |
| Yield gap (kg/ha) | [crop yield potential] – [actual farm yield] [18] |
| (Classical) Irrigation efficiency (mm/mm) | [water beneficially used] / [water applied] * [100%] [19] |
| Economic land productivity ($/ha) | [agronomic land productivity] * [value/kg] |
| Agronomic water productivity (kg/m$^3$) | [product (harvested yield)] / [water consumed] [20] |

| | |
|---|---|
| Basin-level water accounts ($m^3$) | Basin-level overviews of the *Water resource base*, *Evapotranspiration*, *Biomass/agronomic water productivity*, and *Water withdrawal* [21] |
| Economic water productivity ($/$m^3$) | [agronomic water productivity] * [value/kg] |
| Crop production (ton/year) | [agronomic land productivity] * [harvested area] |
| Water footprint of people/nations ($m^3$/year) | [water consumed] / [product (harvested yield)] * [quantity consumed]<br>The food-related water footprint of an individual equals the volume of water needed to produce all food consumed by this individual [22]. |
| Virtual water transfer ($m^3$/year) | [water consumed] / [product (harvested yield)] * [quantity transferred]<br>[23] |

## Performance indicators to inform sustainable water-for-food governance

Indicators that relate water to food can be related to three actor groups:

1. Indicators for Agricultural water managers
2. Indicators for Water resources managers
3. Indicators for other actors (policy makers; investors, chain-actors and food consumers).

Given a certain agricultural system and crop choice, agricultural water managers can manipulate the field water balance by selecting among alternative technologies for drainage, soil-water conservation and irrigation modernization [24]. In order to produce more yield without proportionally increasing water use, agricultural water managers (crop producers) can focus on enhanced agronomic management practices, such as pest control and mulching [2]. Obviously, crop producers' decisions to implement agricultural water management actions are affected by factors other than water-related ones alone, such as market prices, costs and availability of labour resources and social capital. Limiting water gifts, for instance by deficit irrigation, could jeopardize high yields locally [25,26]. Further, Implementing water-saving technologies could lead to downstream water shortage, known as the paradox of irrigation efficiency [27]. Agricultural water managers generally aim at increased crop production for maximizing Agronomic land productivity (Figure 1), i.e. closing the yield gap [kg/ha] [18,28]. If this requires to apply more water from a scarce resource, they may aim at increasing (classical) Irrigation Efficiency [%] [20], assuming that this also results in higher returns per unit of land, i.e. increased Agronomic [kg/ha] and/or Economic land productivities [$/ha]. These indicators are all included in the top-row of Figure 1.

Water resources management is traditionally studied at the local level, relevant to the management of local water resources such as aquifers, reservoirs, streams, irrigation systems [e.g. 29]. The nature of water systems at larger spatial scale-levels gives rise to difficulties in governing the common pool [30]. In water-stressed areas, scarce local water resources (blue water) are often used for supplementary irrigation of crops to compensate for the lack of rainfall (green water). Water management organisations can influence water allocation by combining water-supply management (e.g. installing reservoirs) and water-demand management (e.g. promoting micro-irrigation) strategies, to implement sustainable water management [31]. Relevant indicators for water resources management organizations concerned with water allocation (either through demand- or supply management) include Agronomic water productivity (WP) [kg/m$^3$] [2], Basin-level water accounts [m$^3$/year] [21], and Economic water productivity [\$/m$^3$] [32], see second row of Figure 1. The highest returns per unit of land (Agronomic and Economic land productivities) do not always coincide with the highest Agronomic and Economic water productivities [26,33]. Next to Agronomic and Economic water productivities there are also other ways to look at 'productivity'. A relevant example is the "social" or "pro-poor" water productivity [34] that looks at social benefits per unit water. In assessing the water-related performance of agricultural water management interventions it is important to distinct between the concepts of (classical) Irrigation efficiency (IE) on the one hand and (blue) Water Productivity (WP) on the other [20]. IE [%] refers to the relative share of the applied water (irrigation) which is beneficially used for crop production through evapotranspiration (ET). Agronomic WP [kg/m$^3$] refers to the output as a function of net water input (ET). Inconsistent use and misinterpretations of performance indicators at different spatial levels within water systems are common [20,35,36]. By reviewing field-level data-sets Zwart and Bastiaanssen [37] showed that agricultural WP for particular crops may vary substantially over space and time. WP values do not only vary substantially from one location to another (e.g. due to differences in climate, soil, and management practice), but even for one single location they may vary strongly from season to season and from year to year. This implies that the use of average values should be dealt with carefully. From the perspective of a farmer confronted with a water scarcity (or drought) situation it seems sensible to increase IE (for instance by installing micro-irrigation) if this leads to a reduction of the yield gap [kg/ha; 18,38]. Increased IE and a reduced yield gap often lead to an increase in ET and a reduction in the water surplus and thus reduced return flows [27,39]. However, whether an increase in IE and a reduction of the yield gap (i.e. a yield increase) also coincide with an increase in agronomic WP largely depends on the change in harvested yield relative to the total biomass, implying a change in the harvest index [26].

In today's globalized world water-for-food systems have an international dimension [17,40,41] which contrasts with the local level where water resources are governed. Thus, water governance today involves new actors, including remote private companies, investors, consumers, and governments aiming to increase food security [17,42]. All of them may interfere in the governance of local water resources, even if located far away. For productive dialogues and participation in governance or water stewardship [43], these actors need access to accurate, timely, and contextualized information on the possibilities to support sustainable agricultural water management and water resources management. Food consumers can indirectly influence the amount of water used in crop production as purchasers of imported goods by modifying personal diets [9,10], decide to select alternative products or reduce the amount of food waste they produce [44]. Policy makers, investors and chain-actors (traders and retailers) could indirectly influence agricultural water use by promoting sustainable food processing practices and trade flows. Governments could for instance improve access to infrastructure, resources and markets to promote reusing agricultural waste, initiate international trade agreements, introduce taxing, or subsidizing schemes, while chain actors could introduce standards, labels or benchmarks [45]. Such interventions could affect market prices of products and thereby affect consumed product volumes. The exact origins (places and time-periods of production) and the socio-economic and environmental effects of producing a particular good are very hard to determine [46]. It therefore also unclear how the introduction of certain policies (e.g. trade agreements, subsidies) then indirectly affect (e.g. alleviate) problems in areas where these products are produced, since for most consumer products it is unpractical to determine how they affect water scarcity situations in other parts of the world. Besides, water footprint or water productivity estimates [12,13], even if accurate, are not sufficient to support well-informed decision making on sustainable and fair trade in water-intensive goods, since these indicators do not contain any contextually relevant information on environmental and social impacts [46,47]. Relevant indicators for actions by these new actors in water-for-food governance include statistics on (national) Food production, Water footprints of food consumers [15,22], and Virtual water transfer [6,8], as included in the third row of Figure 1. Indicators that fit specific local contexts could help to demonstrate how proposed solutions may perform with regard to synergies and trade-offs, for instance, in relation to Sustainable Development Goals 2 (zero hunger) and 6 (clean water and sanitation). Specific local information would particularly be required for making strategic decisions with regard to supply-chain management and foreign trade policies. Another possible intervention involves the introduction of labels on consumer products. Such labels could show a water-related performance indicator (e.g. a Water footprint label to indicate crop water footprints), suggesting a direct relation between the act of consuming a particular product and its effect elsewhere. However, acquiring such information seems problematic since it is rather challenging to quantify effects in terms of impact indicators that make sense locally (e.g. local water scarcity or food security). Challenges towards using benchmarks and labels coincide with important lessons learnt from sustainability certification schemes [48] for which technocratic definitions of standards have resulted in general criteria that do not take into account local circumstances. Defective application of labels can even result in marginalization of smallholder producers, while only limited reductions in environmental damage and social harm are achieved [48].

## Socio-hydrological complexities with regard to drought and its impacts

Global food production is negatively affected by different types of climate-related disasters including droughts, floods and storms. Drought is particularly relevant as it simultaneously increases water demand and reduces water availability in some of the world's most populous water stressed regions in Africa and Asia [49]. Structural increases in water demand worldwide have expanded and worsened water scarcity and drought [50,51]. Droughts result from a complex interaction of meteorological anomalies (influenced by climate change), hydrological processes, and human influences [52], while human activities – such as irrigated farming and construction of dams – can be both a consequence and a cause of water scarcity and drought [27,53]. Meteorological drought leads to soil-moisture drought (i.e. agricultural drought) that causes reduced yields if the increased demand for irrigation is not met. With regard to hydrological drought, downstream populations are typically the most adversely affected by the overall reduced water supply [39,54], particularly during, but also following droughts [55,56]. In water-stressed socio-hydrological systems, human-environment interactions affect, or may even induce, hydrological drought and its socio-economic and environmental effects. People can both aggravate or alleviate related types of drought, including meteorological, agricultural (soil moisture), hydrological, (socio-)economic and ecological drought [52,57]. Examples of (socio-)economic effects of drought include price spikes and income differences across basins and regions [58]. Local interventions in the water system related to water use and supply do also affect basin-level hydrological processes, often leading to unintended consequences, both locally and elsewhere [27,53]. Therefore, it is crucial to incorporate the agro-hydrological dynamics and scale issues inherent in the interconnectedness of water resources systems and people and its socio-economic differentiated effects in water research [59]. Several indicators of drought and drought impacts exist [60,61] that can help to underline the effect of drought events for agriculture, water resources, the economy and the environment. But, although some indicators relate drought to water deficits for agriculture, they only indirectly link to food-crop production and food security.

Sustainable water-for-food governance depends on collective efforts by multiple actors. To build such collective action (for instance in the context of existing water governance structures or along supply-chains of consumer-products [17]), actors need to account for the ways that others make decisions and to reconsider how to use indicators and models to support decision-making processes [62]. Existing large-scale assessments of water scarcity and drought [e.g. 56] lack the spatiotemporal agro-hydrological and socio-economic detail so essential for understanding changes that take place during and following periods of drought, and how these further impact water scarcity patterns [51]. This surprising lack of theoretical knowledge on human influences on drought and the knock-on impacts of droughts hampers progress in water-for-food governance. In some cases, periods of drought push socio-hydrological systems into states where the impacts of drought persist for long time periods [39,55]. To better understand how meteorological drought propagates into agricultural drought (i.e. soil-moisture drought), and hydrological drought and how it leads to environmental impacts and socio-economically differentiated effects, we need to better grasp how social and spatiotemporal patterns of water use, demand, and availability emerge and evolve [52,53].

## Examples of using multiple indicators to evaluate interventions

Different water-related indicators provide information at field-, basin- and country-levels to actors with particular interests associated with often only one of these spatial scale levels. Their actions may have unintended consequences. Here, we provide three examples of interventions with their possible effects in terms of different indicators. In addition we discuss how the effect of drought may affect the scores for specific indicators.

Example 1 (Figure 2) Micro-irrigation technologies are intended to save water (from an agricultural water management perspective) but are often of limited effectiveness, and sometimes have the adverse impact of reducing water availability for others downstream [27,36], particularly during drought. In this example relevant indicators that are directly affected are Agronomic and Economic Land productivities, Irrigation efficiency and Basin-level water accounts. The effect of drought can particularly increase the irrigation water requirement, which is likely to be compensated by increased supply in areas where blue water resources are still available. This could then lead to aggravated hydrological drought in downstream areas.

Example 2 (Figure 2) Reservoir development is a form of water supply management. Water managers install reservoirs based on policies targeting at water resources development. Reservoirs can compensate to some extent for growing water demand [63] but may also intensify the effects of droughts [53,55,64]. Reservoir effects [53] may lead to increased supply-dependencies and water demand, possibly affecting Agronomic and Economic land productivities and Food production. Obviously the effects of a reservoir may unfold very differently for those water users in the direct vicinity of the reservoir than for those that are located more remotely (downstream). Moreover, reservoir networks can lead to skewed distributions of water storage and thereby aggravate hydrological drought [55]. The effect of drought can particularly affect the uneven distribution of available water resources further.

Example 3 (Figure 2) If large numbers of people become vegetarians, this could have the following effects in terms of the indicators in Figure 1: Reduced Water footprints of consumers could lead to changes in Virtual-water transfers (e.g. due to reduced international trade feed ingredients livestock and livestock products itself), modified Basin-level water accounts and changes in the economic land productivities of particular crops of which demand changes. Obviously, drought can affect food production which can also affect food prices, which may then affect consumer choices and farmer incomes as well.

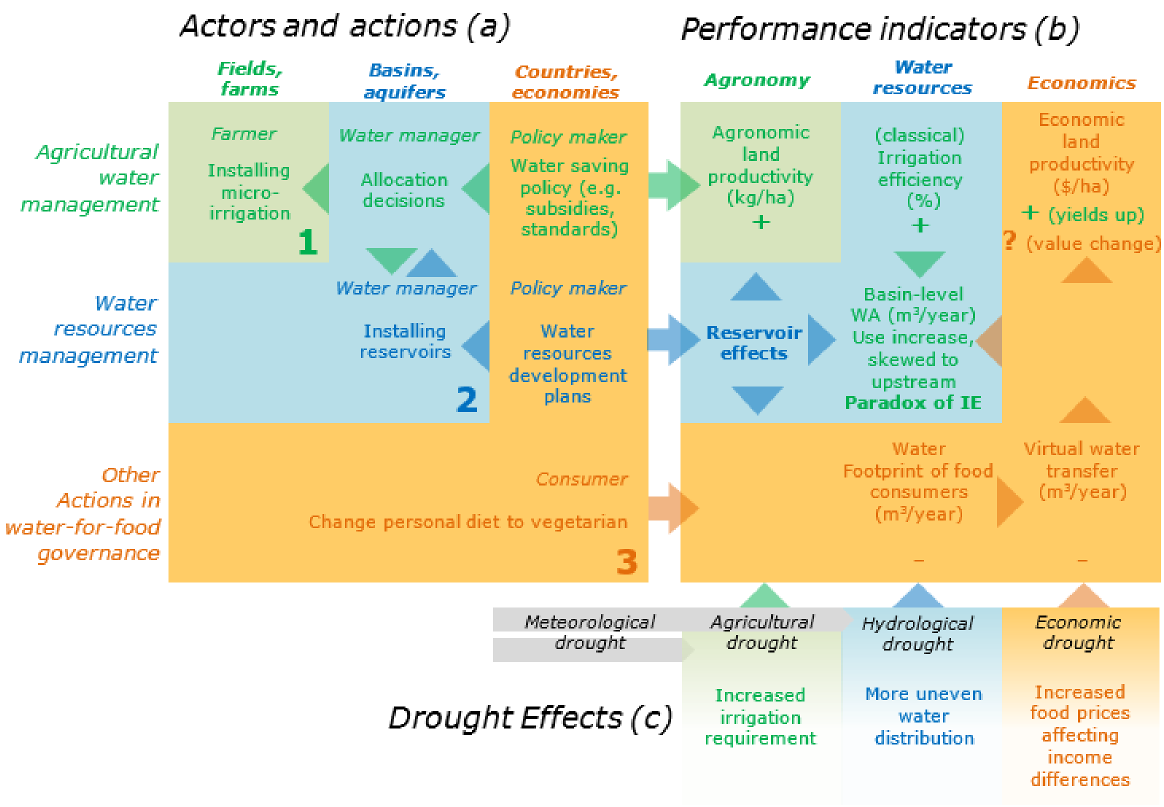


**Figure 2 Three examples of the effects of actions by actors in water-for-food governance reflected as reflected in performance indicators: Farmers installing micro-irrigation (1), Water managers installing reservoirs (2), Food consumers adopting a vegetarian diets (3).**

## Conclusions

Actors need coherent information on human influences on agro-hydrological processes, and the relationships between these processes and trade and consumption of food products. Towards adequately informing collective efforts in governing water for food first requires information, concepts and indicators that can inform a constructive dialogue between water-governance actors all the way from crop producers, water managers, and governments to retailers and eventually food consumers. Such information and indicators involves details on the links between local food-production (and water use) and water availability and environmental health in particular local contexts.

Providing actionable knowledge in the context of specific objectives requires contextualized assessments to move beyond agriculture-centric or water-centric conclusions and assumed single-crop realities [12,13]. If the purpose of a decision is to mitigate drought impacts, the performance of a planned intervention needs to be evaluated in the context of the environmental and socio-economic impacts of drought, which mostly vary strongly in space and time and are affecting different ecosystems and different groups of people differently. If actors aim to increase national food-security, the performance of a planned intervention needs to be evaluated in the context of factors affecting the food-security in some place and time (or in relation to a particular group of people), including the availability of water resources and its effect on food crop production and food prices.

Globalization and international trade in food products has brought along new groups of actors (including remote private companies, investors, consumers and national governments) of which some are willing to make positive contributions to sustainable governance of local water systems. The actors at different levels can improve governance with help of multiple water-for-food indicators that contribute to social equity and ecological integrity. To adequately inform these (groups of) actors in sustainable water-for-food governance [17] using a suite of multiple water-for-food indicators is more suitable than a single one-size-fits all indicator. This is particularly relevant since the contextual relativism (due to water stress, drought, and the socio-economic setting) in an area in which food is produced is of utmost importance for the actual impact of water-for-food interventions.

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Papers of particular interest, published within the period of review, have been highlighted as:

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| **11. Vos J, Van Oel P, Hellegers P, Veldwisch GJ, Hoogesteger J: Four perspectives on water used for global food production and international trade: incommensurable objectives and implications. Current Opinion in Environmental Sustainability 2019, (accepted manuscript). |
| The paper gives an overview of four research perspectives on water in global food production and trade. These four perspectives are: (1) Increasing water productivity for export crop production, (2) Reducing water footprints, (3) National food security and import dependency; and (4) Local values and implications of water used in export food production. |
| *17. Hoekstra AY, Chapagain AK, Van Oel PR: Progress in Water Footprint Assessment: Towards Collective Action in Water Governance. Water 2019, 11:1070. |
| This introduction to a special issue on Water footprint assessment calls for collective and coordinated action at different levels and along all stages of commodity supply chains to promote more sustainable, efficient, and equitable water use. It stresses that research is needed the potential roles of |

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| different players along supply chains in making production and consumption patterns more sustainable. |
| *16. Vanham D, Hoekstra AY, Wada Y, Bouraoui F, de Roo A, Mekonnen MM, van de Bund WJ, Batelaan O, Pavelic P, Bastiaanssen WGM, et al.: Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress". Science of The Total Environment 2018, 613–614:218-232. |
| This paper argues that SDG indicator 6.4.2 could be improved by looking at seven essential elements of a the water balance. They recommend to consider net water abstractions, to incorporate EFR, and to be explicit about green or green-blue water scarcity and on water quality. |
| **20. Van Halsema GE, Vincent L: Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. Agricultural Water Management 2012, 108:9-15. |
| This paper shows different relevant performance indicators for field and basin levels, and the use and abuse of definitions and applications of concepts of irrigation efficiency, water use efficiency and water productivity. The paper argues that water management decisions are best informed by using IE and WP at the irrigation scheme and catchment level, respectively. |
| *27. Grafton RQ, Williams J, Perry CJ, Molle F, Ringler C, Steduto P, Udall B, Wheeler SA, Wang Y, Garrick D, et al.: The paradox of irrigation efficiency. Science 2018, 361:748. |
| This paper shows that to mitigate global water scarcity, increases in irrigation efficiency must be accompanied by robust water accounting and measurements, a cap on extractions, an assessment of uncertainties, the valuation of trade-offs, and a better understanding of the incentives and behavior of irrigators. |
| *46. Yang H, Pfister S, Bhaduri A: Accounting for a scarce resource: virtual water and water footprint in the global water system. Current Opinion in Environmental Sustainability 2013, 5:599-606. |
| This paper argues that limitations and shortcomings remain in virtual water and water footprint studies with regard to policy relevance, data accuracy, methodological approaches and conceptual consistency. The paper calls for efforts from the scientific community to tackle these problems in order to enhance the usefulness for water resources management and governance across geographical levels. |
| **53. Di Baldassarre G, Wanders N, AghaKouchak A, Kuil L, Rangecroft S, Veldkamp TIE, Garcia M, van Oel PR, Breinl K, Van Loon AF: Water shortages worsened by reservoir effects. Nature Sustainability 2018, 1:617-622. |

This paper argues that there are two counterintuitive dynamics with regard to reservoirs: supply–demand cycles and reservoir effects. Supply–demand cycles describe instances where increasing water supply enables higher water demand, which can quickly offset the initial benefits of reservoirs. Reservoir effects refer to cases where over-reliance on reservoirs increases vulnerability, and therefore increases the potential damage caused by droughts.