

## Research



**Cite this article:** Falkenmark M. 2013  
Growing water scarcity in agriculture: future  
challenge to global water security. *Phil Trans R  
Soc A* 371: 20120410.  
<http://dx.doi.org/10.1098/rsta.2012.0410>

One contribution of 16 to a Theme Issue  
'Water security, risk and society'.

### Subject Areas:

hydrology

### Keywords:

water scarcity, green water, blue water,  
water crowding, global food supply,  
planetary freshwater boundary

### Author for correspondence:

Malin Falkenmark

e-mail: [malin.falkenmark@siwi.org](mailto:malin.falkenmark@siwi.org)

# Growing water scarcity in agriculture: future challenge to global water security

Malin Falkenmark

SIWI and Stockholm Resilience Center, Stockholm, Sweden

As water is an essential component of the planetary life support system, water deficiency constitutes an insecurity that has to be overcome in the process of socio-economic development. The paper analyses the origin and appearance of blue as well as green water scarcity on different scales and with particular focus on risks to food production and water supply for municipalities and industry. It analyses water scarcity originating from both climatic phenomena and water partitioning disturbances on different scales: crop field, country level and the global circulation system. The implications by 2050 of water scarcity in terms of potential country-level water deficits for food self-reliance are analysed, and the compensating dependence on trade in virtual water for almost half the world population is noted. Planetary-scale conditions for sustainability of the global water circulation system are discussed in terms of a recently proposed Planetary Freshwater Boundary, and the consumptive water use reserve left to be shared between water requirements for global food production, fuelwood production and carbon sequestration is discussed. Finally, the importance of a paradigm shift in the further conceptual development of water security is stressed, so that adequate attention is paid to water's fundamental role in both natural and socio-economic systems.

## 1. Introduction

Water security may be seen as tolerable water-related risk to society [1]. Water's social and productive potential meets human society in two main ways: on the one hand, as liquid (blue) water to meet hygienic, health and economic requirements (including irrigation), and, on the other hand, as the infiltrated rainwater in the soil (green water) that operates the production of food and other biomass. To be water secure, an individual

needs about  $1200 \text{ m}^3/\text{pyr}$  [2], but a strong economy can afford to import water-intensive commodities. A central question for humanity's future is therefore whether there is enough water in the global system to meet the demands of tomorrow's world population. Unless action is taken now, water insecurity is likely to become a key geopolitical issue that affects the entire global economic system [3]. This involves both harnessing water's social and production potential and limiting its destructive effects.

## (a) Water and agricultural development

Increasing agricultural water security through irrigation to complement soil moisture deficit has driven improved agricultural production in large regions of the world. In the post-World War II period, the Green revolution created marvels boosting food production, but turned out not to be sustainable. The outcome included unintended side effects such as depletion of river flow, river basin closure, groundwater depletion and severe water pollution. The side effects are of a scale that has in fact raised the question of what the planetary water circulation system can in fact endure without serious consequences for long-term water scarcity. Rockström *et al.* [4], in their first global analysis, suggested a planetary freshwater boundary which was expressed as a maximum consumptive water use based on an assessed maximum acceptable river flow depletion which was itself judged from the minimum river flow required for protection of aquatic ecosystems.

In spite of the Green revolution, large parts of dry climatic regions remained poor and hungry. In these areas, more international attention was drawn to the absence of water, i.e. droughts and desertification, rather than to the actual presence of water [5]. In the early 1990s, it had however been suggested to draw adequate attention to the *green water* in the soil as a fundamental component of the hydrological cycle [6]. This created an opportunity for a more complete approach to the assessment of the amount of water required for food production and human welfare. Today, increasing attention is being paid to rainfed food production, the dominant form of agriculture in the regions where most rivers are small and carry water only during the rainy season.

Thus, in many dry climate countries, the dominant form of water is the green water resource in the soil, i.e. infiltrated rain, and boosting crop production is therefore an issue of *green water security* which can be achieved only by overcoming the difficulties of rainfall variability and through the development of innovative ways to rely on local water through water harvesting for supplementary irrigation. Blue water, on the other hand, is an essential ingredient for industrial production processes. Today, awareness is expanding that blue water scarcity may cause disruption of water supplies, including in some cases the termination of business operations [7].

## (b) The most populated latitudes are water scarce

It is today realized that water is nothing less than the bloodstream of the biosphere [8]. It is therefore at the centre of human living conditions and a base for socio-economic development.

Kummu & Varis [9] have shown that the most populated latitudes are in fact those in which water is at its most scarce. In these regions, agricultural water use is more dominant than in other parts of the globe. In view of water's many parallel functions in nature and society, this regional dominance of water scarcity is of great relevance for water security analyses.

As many societal activities and processes are water-dependent, water scarcity has many faces of importance for water security: food security, human water supply, industrial production, hydropower production, nuclear power plant cooling, etc. Depending on the focus, water security can be looked at on different scales: local and regional scale for crop production, food security and different types of economic production; national and continental scale when the focus is on a country's hydroclimate, and remote links between areas feeding the atmosphere with moisture and those where that moisture subsequently precipitates [10].

This paper analyses water scarcity on different scales and related risks in terms of water insecurity: locally for an African farmer, nationally for country-level food security, at the scale of a river basin in terms of socio-economic development and on a continental scale to evaluate the sustainability of human living conditions. The paper analyses water scarcity originating from both climatic phenomena, societal driving forces at work, and from disturbances of rainfall partitioning between soil water recharge (green water) and run-off (blue water generation). The paper is an extension of an earlier paper [11] and draws heavily on the author's decades of engagement in water scarcity issues (see reference list).

## 2. Water scarcity typology

The key role played by freshwater in the biomass production process, and therefore for food production, implies that risks to water security arise not only from scarcity of liquid water (blue water), but also from scarcity of infiltrated rain in the soil (green water), which limits food production potential.

### (a) Green water scarcity

Agricultural water security is highly susceptible to green water scarcity. Crop production critically depends on plant roots taking up soil moisture, transporting it up to the leaves to balance transpiration losses during the intake of airborne carbon dioxide associated with photosynthesis. Plant growth is thus a function of green water accessibility in the root zone. Under conditions of deficiency, blue water may be added through irrigation to achieve green water security. During the crop growing season, blue water accounts for only 16% of global consumptive water use, whereas green water accounts for 84% [12].

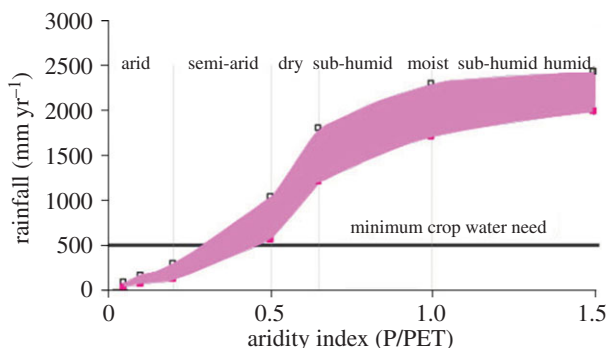
Green water can be scarce for several reasons [13]. Some reasons are climate- and soil related, whereas others are related to people's activities. There may be too little rain; most of the rain may evaporate leaving the soil dry; there may be problems with infiltration, for example soil crusting, so that rain quickly runs off; and the soils may have poor water holding capacity so that water percolates to recharge groundwater layers. Different categories of droughts cause different types of disturbances with different impacts on water security in terms of the required adaptation measures [5]: *intraseasonal dryspells* can be compensated by water harvesting and supplementary irrigation, whereas *interannual droughts* result in different degrees of crop failure which can be compensated for by irrigation. By contrast, climate change, and related situations of slow *aridification*, necessitate altered water policies like the Murray–Darling Cap—a policy limiting the water diversions [14].

### (i) Dry climate

Figure 1 shows the relationship between rainfall and the minimum crop water requirement. The diagram shows that conditions are especially critical where the crop water requirement line meets the precipitation curve. One vulnerable area is, for instance, the northern part of Tunisia, getting 400–750 mm yr<sup>-1</sup> [16]. This means that without irrigation to complement, yields would be fluctuating between total crop failure during drought years and good yields in years with plenty of rain.

### (ii) Droughts

For a long time, droughts remained more or less mixed up with desertification [5], so that the Millennium Ecosystem Assessment [17] found it crucial to distinguish between the two types of problem. In this paper, drought is seen as a climatic phenomenon, whereas desertification is a man-made problem. Bahri *et al.* [18] noted that Africa has a particularly high spatial and temporal variability in rainfall when compared with other continents and found a strong negative correlation between GDP growth and the highly erratic rainfall. The dilemma of southeast



**Figure 1.** Precipitation including  $\pm 1$  s.d. as a function of climate aridity. The zones where the precipitation and the crop water requirement meet are a critical zone when it comes to rainfed crop production (adapted from [15], IWMI).

Australia, during the severe multi-year drought period recently, was that it moved to the arid side of the precipitation curve in figure 1 and was therefore forced to reduce the allocation of water for irrigation, which met with great opposition from farmers [14].

### (iii) Dry spells

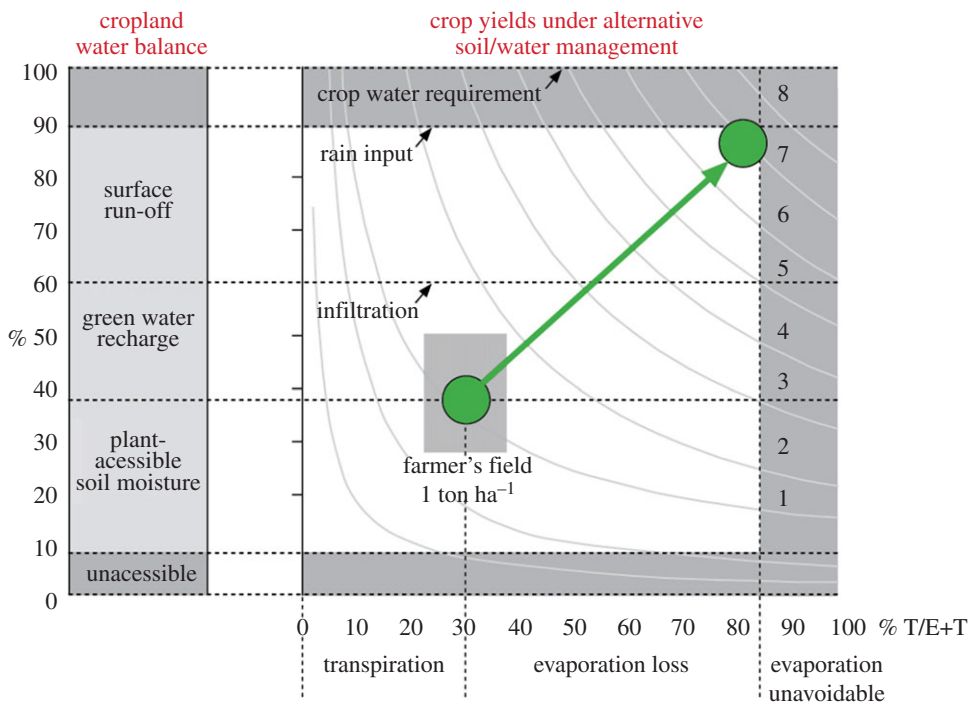
Dry spells are widespread phenomena in the dry climate regions; they are short periods of no rainfall, often not more than two to four weeks long, causing plant water stress and affecting growth [19]. Dry spells cause green water scarcity without necessarily causing reductions in seasonal or annual rainfall [20]. In field studies in the Sahel, Rockström [21] showed that dry spells disturb the root uptake capacity, which can result in large evaporation losses and therefore low yields [22].

### (iv) Man-made green water scarcity

Green water scarcity may also have man-made origin, for instance through soil mismanagement on the farmer's field, causing disturbances in local rainfall partitioning: the Sahelian situation illustrated in figure 2 clarifies the situation. Only a very limited part of the incoming rain is taken up and transformed into biomass, typically resulting in crop yields in the  $1 \text{ ton ha}^{-1}$  level only, far below the potential yield level for that particular hydroclimate. There is however enough water available for considerably higher yields, but not accessible to the plant because of low infiltration, disturbed water holding capacity of the soil, and low uptake capacity of the drought-damaged roots. By reducing these disturbances, yields could be considerably increased. Such agriculture is referred to as 'triply green' (green for productivity increase, sustainability and rainfed agriculture [24]). In a systematic series of case studies, ICARDA (International Center for Agricultural Research in the Dry Areas) has recently showed that with improved land and water management practices, yield gaps can be reduced to half in the Mediterranean region [25].

### (b) Blue water scarcity

Blue water may be scarce in relation to both societal water requirements (i.e. the water supply of household, industry and irrigation) and in relation to its role as habitat for aquatic ecosystems. The achievement of water security may be disturbed by the increasing pressure to be foreseen on the blue water availability, as climate changes and population increases in river basins with severe water shortages. In such locations, it will be increasingly difficult to find 'new' raw water to meet additional water needs. Risks relating to the scarcity of blue water involve competition for water and complexity of water management. As pressure increases, river basin closure will develop [26].



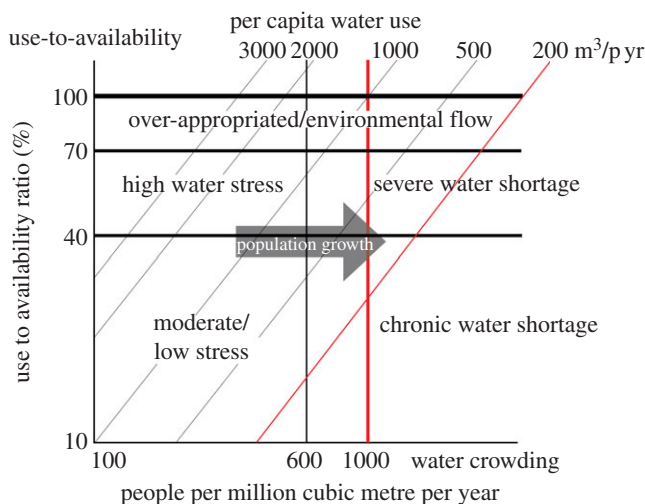
**Figure 2.** Effect on crop yield (green circles) of alternative water losses on a farmer's field outside Niamey, Niger. Right diagram shows crop yield in tonnes per hectare (rounded curves) as a function of possible levels of plant accessible soil moisture (vertical axis, per cent of crop water requirement). Grey rectangle shows actual situation ( $\approx 1 \text{ ton ha}^{-1}$ ) owing to large blue losses in terms as surface run-off and percolation to groundwater and large green losses as evaporation. If all losses would be avoided by improved soil/water management (and fertilizers), more than  $6 \text{ ton ha}^{-1}$  would be possible. Left column shows actual cropland water balance. Scale: per cent of crop water requirement (adapted from [22,23]).

Blue water may already be scarce, for climatic reasons. In dry climatic regions with high potential evaporation and monsoon climate, i.e. a limited rainy season, most of the rain may evaporate, leaving no surplus for run-off generation. The result is that water courses go dry except during rainstorms, forming the so-called ephemeral rivers. Only large rivers are perennial.

When societal water demands are high in relation to water availability, water is seen as scarce. This scarcity is reflected in user conflicts. Blue water scarcity has been studied from two complementary aspects: population-driven scarcity, in which it is implied that more and more people jointly depend on each unit of water (i.e. water crowding); and demand-related scarcity, a term which refers to a level of exploitation in which mobilization of even more of the resource becomes increasingly difficult and costly (i.e. water stress). Loucks [27] projects that the population in water-stressed countries will increase from less than one billion people in the mid-1990s to some four billion people in 2050. This situation is likely to involve considerable risks for water security.

### (i) Water crowding

Starting in the 1970s, attention has been drawn to the implications of the continuing population growth in the naturally water-poor latitudes [28]. In the mid-1980s, the author analysed population-driven blue water scarcity ('water competition level'), in today's vocabulary *water crowding*, (people per flow unit of 1 million cubic metres per year ( $\text{Mm}^3/\text{yr}$ ) of blue water availability [29]). She noted, based on published data available at that time, that on a country- or state-level, water management tended to get stressful around  $600 \text{ p}/\text{Mm}^3 \text{ yr}$  and difficult around



**Figure 3.** Two dimensions of blue water scarcity: population-driven shortage/water crowding (horizontal axis), and exploitation level/water stress (vertical axis), assuming environmental flow reserve of 30% of availability. Diagonal lines show *per capita* water use. A vulnerable zone is the area between the two characteristic lines 1000 p/flow unit and 200 m<sup>3</sup>/p yr. The boxes show number of people in millions living under different water scarcity conditions (adapted from [13]).

1000 p/Mm<sup>3</sup> yr. In a recent study, Kummu *et al.* [30] showed that water crowding is in fact a rather recent, post-World War II phenomenon in response to the continued population growth.

## (ii) Water stress, use-to-availability

Demand-driven scarcity refers to exploitation level, generally measured as use-to-availability, and is often referred to as *water stress* [9]. Rising water stress is equivalent to increasing difficulties to mobilize an even larger part of the water availability. This scarcity dimension was studied in the 1970s by the European scholar Balcerski [28], who explained water resources management differences at different levels of use-to-availability: at the 20% level, infrastructure investments are costly from a national economic perspective and have to be incorporated in a national economic planning. In the freshwater assessment [31], the UN set the withdrawal of 40% as the line distinguishing situations of high water stress. Later, the International Water Management Institute (IWMI) introduced the concept *economic water scarcity* for the low water accessibility, typical for many low-income developing countries lacking investment capacity for infrastructure development [15]. Unfortunately, the concept water stress remains vague and continues to cause problems and misunderstandings [11].

## (iii) Combined water scarcity predicament studies

Figure 3 shows an analytical tool that links the two blue water scarcity coordinates to give an idea of the degree of blue water scarcity in a country or basin. Based on publicly accessible data [13], such diagrams can be used for preassessment and awareness raising by indicating principal differences in country or river basin exposure [19,26,32]. They make, for instance, possible getting an idea of the 'cost' in terms of additional water infrastructure needed to secure unchanged *per capita* water supply in times of population growth. Xia *et al.* [33] used the diagram to analyse the implications of climate change on the three water-scarce H-rivers in North China (Hai, Huang/Yellow and Huai).

When water demand increases, water managers traditionally consider the possibility of withdrawing more water from the river system. There is however a limit because aquatic ecosystems depend on river water as their habitat. Increasingly, a certain part of the river flow is today being reserved to protect aquatic habitats. In South Africa, this figure is of the order



of 20–30% [34,35]. When a river basin can supply water to meet withdrawal demands and maintain its ecological functions, it is considered an open basin [26]. A river basin is closing when allocations begin to impinge on ecological needs and closed when this limit is reached or breached [36]. Beyond the 70% level [37,38], a basin can be seen as closed in the sense that additional water commitments cannot be made—the basin would be overcommitted [26]. Many economically important river basins are closing or already closed, including the Amu and Syr Darya, the Indus, the Nile, the Colorado, Lerma-Chapala, Murray Darling and Yellow River Basin [38]. Typically, in these basins, large-scale irrigation development has been consuming vast quantities of water. The current predicament means that scope for additional irrigation is now quite limited.

Evidently, the extent of basin closure now raises a severe warning signal for future water insecurity. The rapid increase in water-stressed populations suggests that the world is approaching a threshold where increased water requirements cannot be met from already overcommitted river systems. When all the water in a river basin is already allocated, water management will have to be transformed and adapted to the actual water situation through allocation changes including, for example, withdrawal reductions, caps on irrigation, wastewater re-use and use of remote raw water sources for municipal water supply systems.

### 3. Water security risks

There is a strong linkage between poverty and lack of access to land and water, with the poorest having ‘the least access to land and water and are locked in a poverty trap of small farms with poor-quality soils and high vulnerability to land degradation and climatic uncertainty’ [39]. Water scarcity hinders water security in several ways, by complicating water supply for human health, food supply, energy supply and industrial production. Three examples are given: green water scarcity behind the African famine in the mid-1980s; blue water scarcity-related allocation difficulties in China and vulnerability to population change of large Asian river basins.

#### (a) African famine

The African famine in the mid-1980s offers an illustration of the former. Falkenmark & Rockström [19] suggested that this famine was the result of a set of disturbances to green water security. Natural factors, including the susceptibility of the region to interannual drought and the short growing season, were exacerbated by soil degradation and other human factors to generate man-made water scarcity. Irrigation could not help out owing to blue water limitations in the sense that small water courses go empty except during rain storms. This set of water-related challenges exposes clearly the vulnerability of the people living on rainfed and non-mechanized agriculture on the sub-Saharan savannahs. Rainfall variability is high, yields tend to be low, and water storage is lacking.

#### (b) Water supply problem

In figure 3, a vulnerable zone was defined by two characteristic lines: the 1000 p/flow unit and the 200 m<sup>3</sup>/p yr lines. Beyond the former, there is a situation of chronic water shortage, whereas 200 m<sup>3</sup>/p yr is a tentative threshold for water supply problems by indicating the level of non-wasteful water supply of municipalities and industry [40]. Today, more than 1 billion people are living in river basins in East and South Asia situated in that zone, pushed by population growth towards the 200-line. Beyond that line, even water supply for urban and industrial uses will be a complex task. All water below the slanting 200-line is needed for municipal and industrial water supply, and what is beyond the 70% horizontal line should be reserved for environmental flow to the benefit of aquatic ecosystems. As water crowding increases, the only amount of water left for irrigation is the shrinking amount between these two lines. Many river basins are already

there, for instance, the so-called three H-rivers in China [41]. To save water for irrigation in such situations, Chinese water managers have chosen to limit urban water allocation to only some  $90 \text{ m}^3/\text{p yr}$  [42].

### (c) River basin vulnerability

The vulnerability to change of the population living in a river basin depends on many factors, including the level of water appropriation, water-related hazards, and qualities of the governance system. Varis & Kummu [43] analysed such vulnerability in 10 major rivers fed from the Himalyan Mountains, based on a six-component index approach (governance/political instability, economy/purchasing power, social issues/multifaceted poverty, environment/human footprint, hazards/multiple hazard index and water scarcity/use-to-availability quotient). They found that the Indus and Ganges–Brahmaputra–Meghna basins as well as Helmand and Hari Rud Basins (in Afghanistan) are more at risk than even the two major rivers of the Aral Sea Basin, i.e. the Syr Darya and Amu Darya.

## 4. Long-term risks

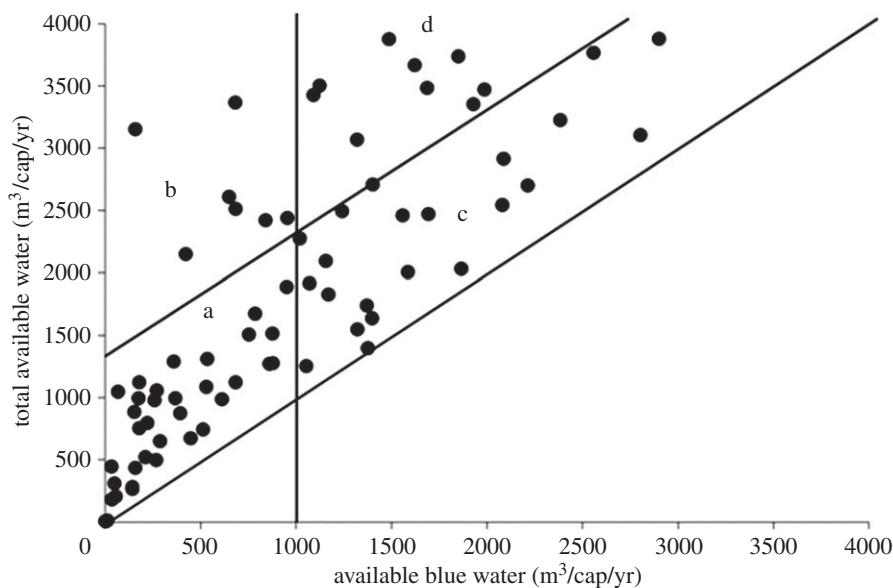
On the regional scale, both driving forces at work and ongoing land-use change will involve additional water security risks, both in terms of global food security complications and risks to the global water circulation system itself. Vicious positive feedback between water scarcity, food production constraints, undernourishment and poverty has tended to delay socio-economic development in water-scarce regions in Sub-saharan Africa [24,44,45].

### (a) Global food supply

Rockström *et al.* [46] have analysed a country's food self-reliance potential as a function of green and blue water preconditions. The green–blue water framework in figure 4 gives a first indication of country situations. Total food water requirements were based on a generic food supply of  $3000 \text{ kcal/p d}$  (comprising 20% animal protein based on current supply levels in Mexico, Brazil and China; [47]) and water productivity of  $1300 \text{ m}^3/\text{p yr}$ , based on previous assessments for food-producing systems [24,48,49]. The diagram shows country-by-country diagnosis of green and blue water availability for food production by 2050, if restricted to current cropland area. Different country preconditions are indicated by the letters a, b, c and d. Class a countries (46% of the world population) may be expected to lack the water required for food self-reliance because they lack enough green water to depend on rainfed agriculture and suffer from chronic blue water shortage, complicating irrigation. Class c countries (21%) lack enough green water but are assumed to be able to compensate by irrigation. Class b and d countries have enough green water (respectively, 14% and 19%).

The diagram evidently indicates a considerable degree of foreseeable future carrying capacity overshoot. With plausible improvements in water productivity, the gross water deficit in water-short countries by 2050 might be limited to around  $2100 \text{ km}^3 \text{ yr}^{-1}$  [46]. Theoretically, this remaining water deficit would be met by increased food imports from water-rich regions [45]. Many water-scarce countries are however poor with limited import capacity, and the African farmer will have to survive in a global market dominated by distortions of Western subsidies [2]. Unless these water-scarce countries can find ways to secure economic development, the additional water requirement will have to be met by national solutions such as cropland expansion into grasslands, livestock intensification on pastures, lowered dietary expectations, food aid, etc. To stimulate economic development to generate purchasing power for complementary food import, it will be essential for these water-short countries to allocate water for the most beneficial uses [50].



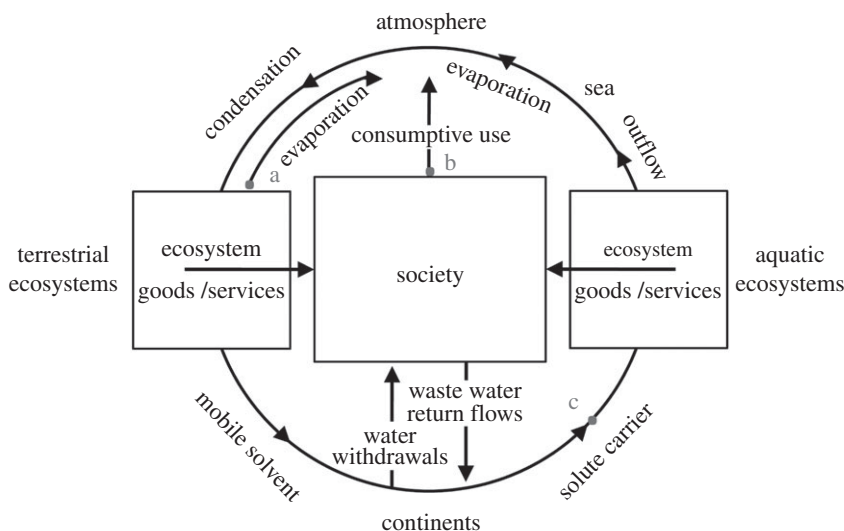


**Figure 4.** Country-by-country diagnosis of food water potentials on current croplands in water-scarce countries by 2050. Assumed water requirements based on 3000 kcal/p d, 20% animal food. Climate change according to the SRES A2 scenario of the IPCC, UN medium population projection. The horizontal axis shows available blue water with the vertical line indicating the chronic water shortage indicator 1000 p/flow unit; vertical axis blue plus green availability. The vertical distance below lower slanting line is blue availability; above it is green availability. Distance between the two lines indicates total water requirement for food production (current water productivity level) (adapted from [46]).

## (b) Gradual changes in rainwater partitioning

Hidden changes in the water cycle may involve slow changes in water security. The principal control on run-off generation is the partitioning of rain water at the ground level between green and blue water flows. This partitioning is easily disturbed by land-use change and can alter consumptive water use through evapotranspiration [51]. L'vovich & White [52] showed that the global-scale deforestation during the period 1680–1980 for development of agriculture reduced vapour flow and increased run-off generation by the order of  $2500 \text{ km}^3 \text{ yr}^{-1}$ . Gordon *et al.* [53] later found this to be, on the global scale, more or less compensated by increased consumptive water use in terms of irrigation, but noted that the two effects tend to dominate in different regions. The resulting river flow depletion is now widespread over 15% of continental land area—a phenomenon to which IWMI drew international attention at the World Water Forum in Kyoto in 2003, and which has generated a widespread call for higher water-use efficiency in irrigation. However, as the result would evidently be reduced return flow, river depletion might in fact be further exacerbated. The increasing scale of river depletion has, as earlier indicated, generated a call also for protection of suffering aquatic ecosystems by securing a minimum river flow (environmental flow), incorporating besides a certain average minimum flow, also a certain annual variability/flow regime [34,35].

Thus, land uses involve a multitude of slow changes in the water cycle, not only in rainwater partitioning but also where atmospheric vapour fluxes either divert or meet, especially in areas where ocean vapour meets rising continental green water flow (evapotranspiration). When it comes to water use, slow changes occur when a consumptive use component is added to either river flow or groundwater flow, primarily by irrigation. Several of the resulting ecohydrological changes are well known from the sphere of global environmental problems, especially those originating from changes in the soil: desertification and salinization. Slow changes in the



**Figure 5.** The global water cycle and some basic functions: moisture feedback, point a; consumptive blue water use, point b; run-off depletion, point c (adapted from [54]).

atmosphere may come to disturb water security through its implications for generation of rainfall. Deforestation of tropical rainforests causes changes in the merging of oceanic vapour inflow and terrestrial vapour from transpiring forests, altering the regeneration of rainfall, and therefore the vegetation system (savannization). Rainfall effects may also appear as reduced precipitation in remote areas downwind [10].

### (c) Planetary boundary perspective

When discussing water security, it is interesting to note that, in recent years increasing attention has been paid also to the sustainability of the water circulation system itself ([4], p. 15f). They argue that ‘threats to human livelihoods due to deterioration of global water resources are threefold: (i) the loss of soil moisture resources (green water) due to land degradation and deforestation, threatening terrestrial biomass production and sequestration of carbon, (ii) use and shifts in run-off (blue water) volumes and patterns threatening human water supply and aquatic water needs, and (iii) impacts on climate regulation due to decline in moisture feedback of vapour flows (green water flows) affecting local and regional precipitation patterns’.

To avoid the risk of approaching green and blue water-induced thresholds (collapse of ecosystems, major shifts in moisture feedback and precipitation patterns and freshwater/ocean mixing), a planetary boundary for freshwater resources must be set, balancing enough moisture feedback to regenerate precipitation (cf. point a in figure 5) and enough blue water for aquatic ecosystems (point c). In estimating this boundary, the scholar group noted that, out of an upper limit of accessible blue water resources of some  $12000 \text{ km}^3 \text{ yr}^{-1}$  [55,56], a minimum has to be left uncommitted for instream purposes limiting the acceptable water withdrawals to some  $7500 \text{ km}^3 \text{ yr}^{-1}$ , but that a certain return flow is needed to avoid silting and salinization and limits the acceptable consumptive water use to  $4000\text{--}6000 \text{ km}^3 \text{ yr}^{-1}$  (point b)

Current consumptive blue water use is around  $2600 \text{ km}^3 \text{ yr}^{-1}$  [57]. As indicated earlier, future food water requirements are estimated to some  $2100 \text{ km}^3 \text{ yr}^{-1}$  [46], which leaves a quite limited margin for carbon sequestration, fuelwood production, etc., if adequate attention be paid to this fundamental water feedback to the atmosphere and its importance for sustainable precipitation patterns.

## 5. Discussion and conclusions

According to Grey *et al.* [1], water security should be understood as tolerable water-related risk to society. Accepting this interpretation, and realizing the importance of the water cycle to the biosphere, this paper has shown that scarcity of water involves numerous risk components on different scales. These risks include both blue water-related risks to human health, energy supply, industrial production, irrigation, etc., and green water-related risks in particular to food production. In terms of scales, risks both locally for the farmer and nationally for food security, river basin wise for sustainability of socio-economic development, and on a continental scale for sustainability of humanity's living conditions. Evidently, 'scarcity of water is one of the major global problems facing mankind at the moment and ... is likely to be an ever increasing problem in the future' [58].

Ways of reducing water scarcity risks vary between their type and scales, and might be thought of as components of a web of water security [59]. FAO stresses that there is a whole range of major strategies to cope with global water scarcity, including desalination of saline waters, re-use of wastewater, virtual water and food trade, increase in agricultural yields and improved water-use efficiency in agriculture including the use of biotechnology [60]. The latter involves a series of sequential steps related to both physical and biological processes, stressing that it will be more effective to 'make modest improvements in several steps than to concentrate efforts on improving efficiency of just one or two of the eight steps' further discussed in the FAO report.

*Blue water shortage*, on the other hand, tends to appear at late stages in socio-economic development. It is basically a phenomenon of the twentieth century, accelerating after World War II. A typical scenario is that water demands are increasingly overwhelming water availability (see the vulnerable zone in figure 3). Through consumptive water use the resource is getting depleted. River basin closure is a rapidly spreading phenomenon, where imprudent management may lead to rigidity traps. The way out includes water reallocation, wastewater re-use, desalination, etc. Blue water scarcity may also be a product of disturbances caused to rainwater partitioning in the water cycle: by land-use changes disturbing water infiltration processes but also by water-use changes, increasing the consumptive component of water use, reducing river flow and groundwater recharge.

Also a set of more long-term water scarcity-related risks have been highlighted. Risks causing more immediate concern are the risks in terms of *feeding a growing humanity*. The *per capita* water availability situation by 2050 has been exposed, distinguishing between green water deficiency and blue water deficiency. It was noted that some 46% of the world population could be expected to suffer from both green and blue water shortage for food production. Their food security will therefore depend on additional food import. Many of those countries are in sub-Saharan Africa and their purchasing power will depend on ability to secure economic development from low water activities.

The article has finally addressed the issue of long-term sustainability of the global water circulation system, in view of the parallel dependence of human civilization on secured rainfall and secured water availability for both societal water supply and healthy ecosystems, providing terrestrial biomass and aquatic products (fish, etc.). To achieve this, a balance between consumptive water use and the remaining so-called environmental flow has been suggested, maximizing the increase in consumptive water use beyond the natural level. This Planetary Freshwater Boundary has until now been tentatively defined only on the global scale. Research is ongoing to define also regional-scale values.

Finally, water's central role in the biosphere, and therefore the future of humanity and global sustainability in general, underscores the importance of a paradigm development when addressing water security risks that originate from different forms of water scarcity. The dramatic changes foreseen in water-scarce regions under continued population growth have to be analysed, so that the implications in terms of growing water insecurity can be addressed. The fact that growing populations in countries increasingly exceeding their carrying capacity for food production will have to import food from countries with water surpluses means an increasing

dependence in the next generation of expanded food trade. This brings attention to the need for a new water ethics, especially in view of the UN-declared human right to food. A new mode of stewardship will be necessary to overcome regional water insecurity.

## References

1. Grey D, Garrick D, Blackmore D, Kelman J, Muller M, Sadoff C. 2013 Water security in one blue planet: twenty-first century policy challenges for science. *Phil. Trans. R. Soc. A* **371**, 20120406. (doi:10.1098/rsta.2012.0406)
2. Allan JA. 2010 Prioritizing the processes beyond the water sector that will secure water for society—farmers, fair international trade and food consumption and waste. In *Rethinking water and food security. Fourth Botin Foundation Water Workshop*, pp. 93–106. Leyden, The Netherlands: CRC Press.
3. Rio+20. 2012 Water security for a planet under pressure. Transition to sustainability: interconnected challenges and solutions. Rio+20 Policy Brief no. 1. Planet under Pressure, 20–29 March 2012, London.
4. Rockstrom J *et al.* 2009 Planetary boundaries: exploring the safe operating space for humanity. *Ecol. Soc.* **14**, 32.
5. Falkenmark M, Rockström J. 2008 Building resilience to drought in desertification-prone savannas in Sub-Saharan Africa: the water perspective. *Nat. Resour. Forum* **32**, 93–102. (doi:10.1111/j.1477-8947.2008.00177.x)
6. Falkenmark M. 1995 *Land-water linkages—a synopsis. Land and water integration and river basin management*, pp. 15–16. Rome: FAO Land and Water Bulletin.
7. WWF. 2011 Assessing water risk. A practical approach for financial institutions. WWF Report D 2011, World Wildlife Fund and DEG KfW Bankengruppe, Berlin, Germany.
8. Ripl W. 2003 Water: the bloodstream of the biosphere. *Phil. Trans. R. Soc. Lond. B* **358**, 1921–1934. (doi:10.1098/rstb.2003.1378)
9. Kumm M, Varis O. 2011 A world by latitudes: a global analysis of human population, development level and environment across the north-south axis over the past half-century. *Appl. Geogr.* **31**, 495–507. (doi:10.1016/j.apgeog.2010.10.009)
10. Key PW, van der Ent RJ, Gordon LJ, Hoff H, Nikoli R, Savenije HG. 2012 *Biogeosciences* **9**, 733–746. (doi:10.5194/bg-9-733-2012)
11. Falkenmark M. 2013 Water security—the multiform water scarcity. In *Water security: principles, perspectives and practices* (eds BA Lankford, K Bakker, M Zeitoun, D Conway). London, UK: Earthscan Publications.
12. Liu J, Yang H. 2010 Global agricultural green and blue water consumptive uses and virtual water trade. In *Rethinking water and food security. Fourth Botin Foundation Water Workshop*, pp. 23–32. Leyden, The Netherlands: CRC Press.
13. SIWI. 2007 *On the verge of a new water scarcity: a call for good governance and human ingenuity*. SIWI Policy Briefs. Stockholm: SIWI.
14. Lundqvist J, Falkenmark M. 2010 Adaptation to rainfall variability and unpredictability. *Water Resour. Dev.* **26**, 595–612. (doi:10.1080/07900627.2010.519488)
15. Molden D *et al.* 2007 *Water for food, water for life: a comprehensive assessment of water management in agriculture*. London, UK: Earthscan.
16. Chahed J, Besbes M, Handame A. 2010 Water scarcity and food security: a global assessment of water potentiality in Tunisia. In *Rethinking water and food security*, pp. 33–52. Fourth Botin Foundation Water Workshop. Leyden, The Netherlands: CRC Press.
17. Millennium Ecosystem Assessment. 2005 *Millennium Ecosystem Assessment. Ecosystems and human wellbeing: a framework for assessment*. Washington, DC: Island Press.
18. Bahri A, Sally H, McCarteny M, Namara R, Awulachev SB, von Kppen B, van Rooijen D. 2011 Integrated water shed management: towards sustainable solutions in Africa. In *Water for food in a changing world* (eds A Garrido, H Ingram). Abingdon, UK: Routledge.
19. Falkenmark M, Rockström J. 2004 *Balancing water for humans and nature: the new approach in ecohydrology*, p. 247. London, UK: Earthscan.
20. Barron J, Enfors E, Cambridge H, Moustapha AM. 2010 Coping with rainfall variability: dryspell mitigation and implication on landscape water balances in small-scale farming systems in semi-arid Niger. *Water Resour. Dev.* **26**, 543–559. (doi:10.1080/07900627.2010.519519)

21. Rockström J. 2003 Water for food and nature in drought prone tropics: vapour shift in rainfed agriculture. *Phil. Trans. R. Soc. Lond. B* **358**, 1997–2010. (doi:10.1098/rstb.2003.1400)
22. Rockström J, Falkenmark M. 2000 Semi-arid crop production from a hydrological perspective. Gap between potential and actual yields. *Crit. Rev. Plant Sci.* **19**, 319–346.
23. Rockström J. 1997 On-farm agrohydrological analysis of the Sahelian yield crisis. PhD dissertation, Department of Systems Ecology, Stockholm University, Sweden.
24. Rockström J, Lannerstad M, Falkenmark M. 2007 Assessing the water challenge of a new green revolution in developing countries. *Proc. Natl Acad. Sci. USA* **104**, 6253–6260. (doi:10.1073/pnas.0605739104)
25. Pale M *et al.* 2011 Assessment of wheat yield gap in the Mediterranean: case studies from Morocco, Syria, and Turkey. *Comprehensive Assessment of Water Management in Agriculture*, ICARDA, Syria.
26. Falkenmark M, Molden D. 2008 Wake up to realities of river basin closure. *Water Resour. Dev.* **24**, 201–215. (doi:10.1080/07900620701723570)
27. Loucks DP. 2011 Optimizing water for life. In *Water for food in a changing world* (eds A Garrido, H Ingram), pp. 171–196. Abingdon, UK: Routledge.
28. Falkenmark M, Lindh G. 1976 *Water for a starving world*. Boulder, CO: Westview Press.
29. Falkenmark M. 1986 Fresh water—time for a modified approach. *Ambio* **15**, 192–200.
30. Kumm M, Ward PJ, de Moel H, Varis O. 2010 Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environ. Res. Lett.* **5**, 034006. (doi:10.1088/1748-9326/5/3/034006)
31. UN (CSD). 1997 Comprehensive Assessment of the Freshwater Resources of the World. Economic and Social Council, fifth session, 5–25 April. E/CN.17/1997/9/. New York, NY: United Nations.
32. Falkenmark M. 1997 Meeting water requirements of an expanding world population. *Phil. Trans. R. Soc. Lond. B* **352**, 929–936. (doi:10.1098/rstb.1997.0072)
33. Xia J, Qiu B, Li Y. 2012 Water resources vulnerability and adaptive management in the Huang, Huai, and Hai river basins of China. *Water Int.* **37**, 523–536. (doi:10.1080/02508060.2012.724649)
34. Smakhtin V. 2008 Basin closure and environmental flow requirements. *Int. J. Water Resour. Dev.* **24**, 227–233. (doi:10.1080/07900620701723729)
35. Falkenmark M. 2003 Water management and ecosystems. Living with change. TAC, Report No. 9. Global Water Partnership, Stockholm.
36. Seckler D. 1996 The new era of water resource management: from ‘dry’ to ‘wet’ water savings. IWMI Research Report 001. IIMI Research, Colombo, Sri Lanka.
37. Molden D, Sakthivadivel R, Samad M, Burton M. 2005 Phases of river basin development: the need for adaptive institutions. In *Irrigation and river basin management: options for governance and institutions* (ed. M Svendsen), pp. 19–29. Wallingford, Colombo: CABI, IWMI.
38. Molle F, Wester P, Hirsch P. 2007 River basin development and management. In *Water for food, water for life: a comprehensive assessment of water management in agriculture* (eds D Molden *et al.*). London, UK: Earthscan.
39. FAO. 2011 *The state of the world’s land and water resources for food and agriculture. Managing systems at risk*. Rome: Food and Agricultural Organization.
40. Lundqvist J, Gleick P. 1997 Sustaining Our Waters into the 21st Century. Stockholm Environment Institute. Stockholm. Background document to the Comprehensive Assessment of the Freshwater Resources of the World report. (WMO, 1997).
41. Falkenmark M, Xia J. 2012 Urban water supply under expanding water scarcity. In *Wastewater treatment: source separation and decentralization* (eds TA Larsen, KM Udert, J Lienert). London, UK: IWA Press.
42. Xia J, Zhang L, Liu C, Yu J. 2007 Towards better water security in North China. *Water Resour. Manag.* **21**, 233–247. (doi:10.1007/s11269-006-9051-1)
43. Varis O, Kumm M. 2012 The major Central Asian river basins: an assessment of vulnerability. *Water Resour. Dev.* **28**, 433–452. (doi:10.1080/07900627.2012.684309)
44. Grey D, Sadoff C. 2007 Sink or swim? Water security for growth and development. *Water Policy* **9**, 545–571. (doi:10.2166/wp.2007.021)
45. Falkenmark M, Lannerstad M. 2010 Food security in water short countries—coping with carrying capacity overshoot. In *Rethinking water and food security* (eds L Martinez-Corina *et al.*), pp. 3–22. Fourth Botín Foundation Water Workshop. Boca Raton, FL: CRC Press.



46. Rockström J, Karlberg L, Falkenmark M. 2010 Global food production in a water-constrained world: exploring green and blue challenges and solutions. In *Water resources planning and management* (eds Q Grafton, K Hussey). Cambridge, UK: Cambridge University Press.
47. Lannerstad M. 2009 Water realities and development trajectories: global and local agricultural production dynamics. PhD thesis, University of Linköping, Sweden.
48. Rockström J, Gordon L, Folke C, Falkenmark M, Engwall M. 1999 Linkages among water vapor flows, food production, and terrestrial ecosystem services. *Conserv. Ecol.* **3**, 5.
49. Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D. 2009 Future water availability for global food production: the potential of green water for increasing resilience to global change. *Water Resour. Res.* **45**, W00A12. (doi:10.1029/2007WR006767)
50. Sagardoy J, Varela-Ortega C. 2010 Present and future roles of water and food trade in achieving food security, reducing poverty and water use. In *Rethinking water and food security*, pp. 109–143. Fourth Botin Foundation Water Workshop. Leyden, The Netherlands: CRC Press.
51. Dadson S, Acreman M, Harding R. 2013 Water security, global change and land-atmosphere feedbacks. *Phil. Trans. R. Soc. A* **371**, 20120412. (doi:10.1098/rsta.2012.0412)
52. L'vovich MI, White GF. 1990 Use and transformations of terrestrial water systems. In *The Earth as transformed by human action: global and regional changes in the biosphere over the past 300 years* (ed. BL Turner II). Cambridge, UK: Cambridge University Press.
53. Gordon LJ, Steffen W, Jönsson BF, Folke C, Falkenmark M, Johannessen A. 2005 Human modification of global water vapor flows from the land surface. *Proc. Natl Acad. Sci. USA* **102**, 7612–7617. (doi:10.1073/pnas.0500208102)
54. Rockström J, Falkenmark M, Lannerstad M, Karlberg L. 2012 The planetary water drama: dual task of feeding humanity and curbing climate change. *Geophys. Res. Lett.* **39**. (doi:10.1029/2012GL051688)
55. de Fraiture C *et al.* 2007 Looking ahead to 2050: scenarios of alternative investment approaches. In *Water for food, water for life: a comprehensive assessment of water management in agriculture* (ed D Molden), pp. 91–148. London, UK: Earthscan.
56. Postel SL. 1998 Water for food production: will there be enough in 2025? *BioScience* **48**, 629–637. (doi:10.2307/1313422)
57. Shiklomanov IA, Rodda JC. 2004 *World water resources at the beginning of the 21st century*. Cambridge, UK: Cambridge University Press.
58. FAO. 2008.
59. Zeitoun M. In press. The global web of national water security. *Glob. Policy*. (doi:10.1111/J.1758-5899.2011.00097.x)
60. Ruane J, Sonnino A, Steduto P, Deane C. 2008 *Coping with water scarcity: what role for biotechnologies?* Rome: Food and Agricultural Organization.