TECHNICAL COMMENT

SUSTAINABILITY

Comment on "Planetary boundaries: Guiding human development on a changing planet"

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Steffen *et al*. (Research Articles, 13 February 2015, p. 736) recently assessed current global freshwater use, finding it to be well below a corresponding planetary boundary. However, they ignored recent scientific advances implying that the global consumptive use of freshwater may have already crossed the associated planetary boundary.

Steffen *et al.* (*1*) have updated an assessment of planetary boundaries for the stability of the Earth system. Among other proposed boundaries, a freshwater planetary boundary has been set at 4000 km^3 year^{-1}, and global consumptive use of blue water has been used as a control variable for its monitoring (*1*–*3*). Blue water refers to freshwater in lakes, rivers, and aquifers, and consumptive use of freshwater refers to the water amount used and not returned to runoff. Current global consumptive use of freshwater is then estimated to be about 2600 km^3 year^{-1} (*1*–*3*), based on forecasts for 2010 made in 1997 (*4*) and 2003 (*5*). This estimate is considerably below the proposed planetary boundary and therefore viewed as being in a safe operating space [figure 3 in (*1*)]. However, more recent scientific advances that include Destouni *et al.* (*6*) and that were ignored by Steffen *et al.* imply that current global consumptive use of freshwater has overpassed the corresponding planetary boundary.

The earlier estimates of consumptive use of blue water (*4*, *5*) included consumption by industry, municipalities, irrigated agriculture, and evaporation losses from water reservoirs (Fig. 1A). In these estimates, evaporation losses from reservoirs only included quantified losses from the actual water surface of the reservoir; the likely effect of increased evapotranspiration by raised groundwater levels around the reservoirs was assumed to be more or less counteracted by a corresponding decrease in evaporation from surface water downstream of the reservoirs (*4*, *5*). However, more recent studies have shown reservoir effects on atmospheric humidity and evaporative water flux from the landscape that extend up to 100 km from the reservoir borders (*7*). Furthermore, reservoirs related to hydropower or water storage have been found to, on average, increase the net total actual evapotranspiration from the hydrological basins that include the reservoirs; so far, such observations have been reported for Sweden (*6*), the contiguous United States (*8*), and southeastern Europe (*9*). Based

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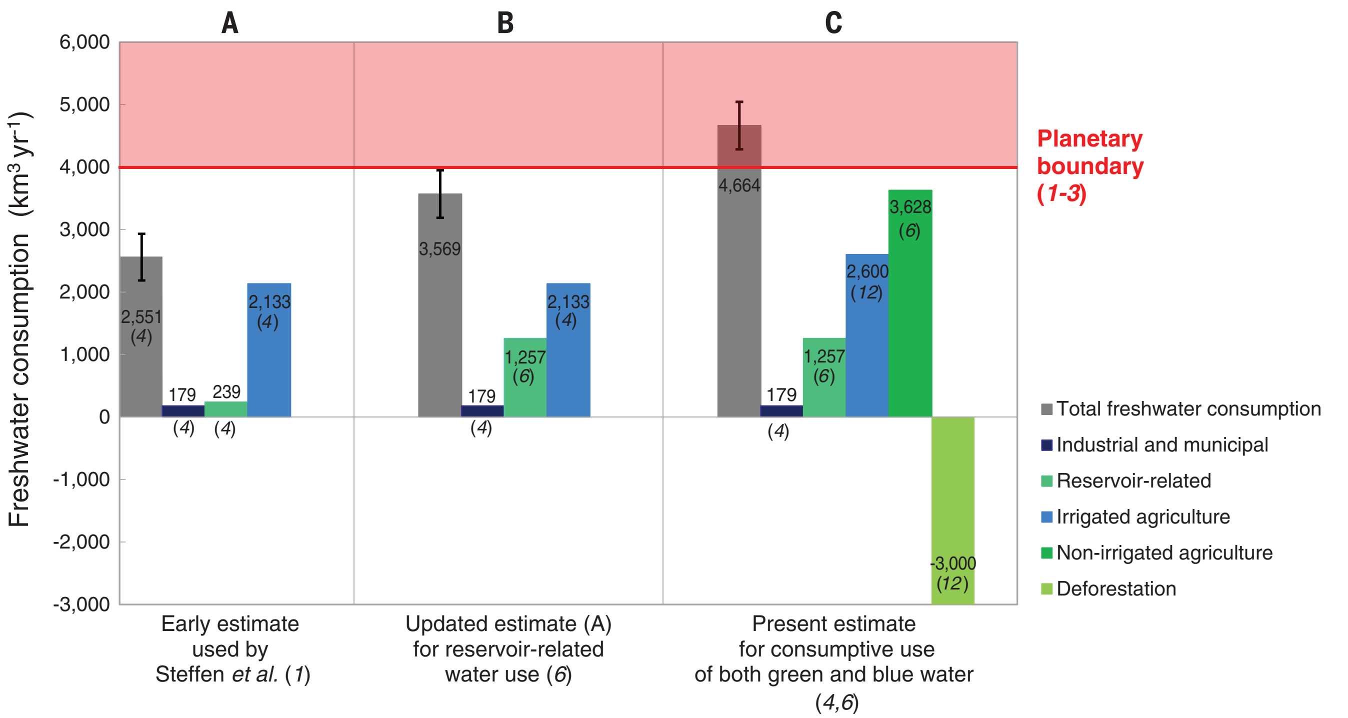

Fig. 1. Estimates of current global consumptive use of freshwater relative to the proposed planetary boundary (red line). Bars show consumptive use in net total (dark gray) and by sector (other colors). (**A**) Early estimate used by Steffen *et al*. (*1*). (**B**) Present update of the estimate in (A) based on a more recent quantification of the hydropower-related net increase of evapotranspiration and associated consumptive water use (*6*). (**C**) Present synthesis of complementary sector estimates for consumptive use of both blue and green water (*4*, *6*). Original source of each estimate is shown in brackets. The error bar range in all panels (~760 km^3 year^{-1}) represents the uncertainty range of consumptive use of blue water (*4*), calculated as the product of a minimum uncertainty due to problems with national-level statistics of freshwater withdrawal of 1300 km^3 year^{-1} (*10*) and a corresponding ratio of water consumptive use to water withdrawal of 0.58 (*4*) (error bars of ± 380 km^3 year^{-1} around the expected global consumptive use).

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on quantified relations for basin-average net evapotranspiration increase associated with hydropower developments in Swedish hydrological basins, the global net consumptive use of freshwater related to hydropower reservoirs was estimated to be 1257 km^3 $year^{-1}$ (*6*). This is about 1000 km^3 $year^{-1}$ greater than the earlier global estimates of reservoir-related water consumption (*4*, *5*) (Fig. 1A).

Like other global estimates of consumptive freshwater use, the hydropower-related estimate of 1257 km^3 $year^{-1}$ is also uncertain because it is based on the global implications of findings for one region. However, this estimate may be more conservative than exaggerated because it does not take into account evaporative water losses related to nonhydropower reservoirs used only for flood regulation, irrigation, and/or municipal or industrial water supply. Furthermore, the underlying regional relations are for the relatively cold climate of Sweden, where evaporative water losses are generally lower than in warmer world regions.

Taking account of this, likely conservative, reservoir estimate brings the total consumptive use of freshwater to 3569 km^3 $year^{-1}$ (Fig. 1B). Independently quantified problems with national-level statistics further imply an uncertainty range of at least 1300 km^3 $year^{-1}$ for estimates of global freshwater withdrawals (*10*). A global average ratio of water consumption to water withdrawal of 0.58 (*4*) translates into an uncertainty range of at least 760 km^3 $year^{-1}$ for water consumption (error bars of ± 380 km^3 $year^{-1}$ around the expected global consumptive use of freshwater in Fig. 1B). Hence, the freshwater planetary boundary may have already been reached just by accounting for this uncertainty level and the more recent estimation of reservoir-related net evapotranspiration increase, in the global consumptive use of freshwater (Fig. 1B). The importance of this reservoir-related update also puts into question the omission by Steffen *et al.* of any reservoir-related freshwater use in their newly introduced freshwater control variable for subglobal freshwater boundaries.

Furthermore, blue and green water fluxes are interlinked (*2*), which implies that consumptive use of freshwater also relates to green water and its human-driven changes. Green water is defined as the precipitation on land that does not run off but adds more or less temporarily to water storage and eventually evaporates or transpires through plants. Several studies have shown that human-driven changes in land and water use alter the net total evapotranspiration flux from land to the atmosphere (*6*, *8*, *11*–*13*), as well as the amount of soil moisture feeding this flux (*14*). A recent study found that landscape drivers, rather than atmospheric climate change, were needed to explain evapotranspiration changes occurring during the 20th century in at least 74% of investigated basins worldwide (*15*). By fundamental water balance, such green water–related evapotranspiration changes also affect runoff changes and therefore the consumptive use of blue water (*6*, *11*, *15*).

Globally over the past century, deforestation is estimated to have decreased evapotranspiration by ~3000 km^3 $year^{-1}$ (*12*). In contrast, over the same period, the expansion and intensification of the globally most prevalent nonirrigated agriculture, as well as the development of irrigated agriculture, are estimated to have increased evapotranspiration by a net total of 6228 km^3 $year^{-1}$ [3628 km^3 $year^{-1}$ for nonirrigated agriculture (*6*) and 2600 km^3 $year^{-1}$ for irrigation (*12*)]. Destouni *et al.* (*6*) synthesized estimates of human-driven changes to global consumptive use of freshwater over the 20th century (Fig. 1C), considering the various effects of nonirrigated (*6*) and irrigated (*12*) agriculture, hydropower (*6*), and deforestation (*12*). The net total sum of these human-driven evapotranspiration changes along with the water use by municipalities and industry (*4*) amounts to a global consumptive freshwater use of 4664 km^3 $year^{-1}$ (Fig. 1C), which is greater than the proposed freshwater planetary boundary.

In their update and message of apparent calm for freshwater, Steffen *et al.* neglected the above-discussed recent advances in understanding and quantifying consumptive freshwater use. The present freshwater synthesis should be considered in future references to the freshwater planetary boundary to raise general awareness on the current levels of freshwater consumption and to direct efforts for reducing the uncertainty in global and regional assessments of this consumption.

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