EDITORIAL

The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management

M. Falkenmark
Stockholm International Water Institute (SIWI).
E-mail: malin.falkenmark@siwi.org

J. Rockström
Stockholm Environment Institute (SEI).
E-mail: johan.rockstrom@sei.se

Water for Food and Hunger Alleviation

The production of biomass for direct human use—e.g., as food and timber—is by far the largest freshwater-consuming human activity on Earth. However, water policy and development concentrate on a fraction of the water for food challenge, namely, irrigated agriculture, which uses an estimated 25% of the global water used in agriculture, and on the industrial and domestic water supply, which corresponds to less than 10% of direct human water requirements (considering only water for food, domestic use, and industry). The reason that biomass production so strongly outclasses other water-dependent processes is that water is one key element involved in plant growth. Simultaneous with the photosynthesis process, when stomata in the foliage open to take in carbon dioxide, large amounts of water are being consumed as transpiration flow and released as vapor from the plant canopy. Furthermore, this productive flow of vapor is accompanied by nonproductive evaporative losses of water (from soil, ponded water, and intercepted water from foliage surfaces). Together, vapor fluxes as evaporation and transpiration, here defined as green-water flow, constitute the total consumptive water use in biomass production.

Addressing the millennium development goal (MDG) of halving the proportion of malnourished people in the world by 2015, today amounting to a shocking 800 million people, is thus not only a tremendous agricultural endeavor but is also the world's largest water-resource challenge. Hunger alleviation will require no less than a new Green revolution during the next 30 years, particularly in sub-Saharan Africa. As stated by Conway (1997), the challenge is to achieve a green-green revolution, which compared with the first green revolution that lifted large parts of Asia out of an imminent hunger crisis in the 1960s and 1970s, will have to be founded on principles of environmental sustainability. As suggested by Falkenmark and Rockström (2004), there is a third green dimension to a new agricultural revolution, since the focus will have to be on upgrading rain-fed agriculture, which entails increasing the use of the portion of rainfall that infiltrates the soil and is accessible by plants to generate vapor flow in support of biomass growth. This triply green revolution will require huge quantities of freshwater as vapor flow from the soil, through plants to the atmosphere. It raises the question of what eradicating hunger will in fact imply for water-resources planning and management.

Two Types of Water Involved in Food Production

The urgent need to focus on water investments in rain-fed agriculture leads to the conclusion that conventional water-resource perceptions are incomplete. This recognition requires a widening of current agricultural water policy, which for decades has been skewed toward water for irrigation.

The conventional water-resource planning and management focus is on liquid water, or *blue water*. It served the needs of engineers who were involved in water supply and infrastructure projects quite well. However, the blue water that has dominated the water perceptions in the past only represents one-third of the real freshwater resource, the rainfall over the continents. Most rain flows back to the atmosphere as a vapor flow, dominated by consumptive water use by the vegetation. When analyzing food production, we therefore need to incorporate a second form of water resource, the rainfall that naturally infiltrates into the soil and that is on its way back to the atmosphere.

Fig. 1 illustrates the new conceptualization, distinguishing between two types of water resources—the *blue-water* resource in aquifers, lakes, and dams, and the *green-water* resource as moisture in the soil—and two complementary water flows—the liquid blue-water flow through rivers and aquifers and the green vapor water flow back to the atmosphere.

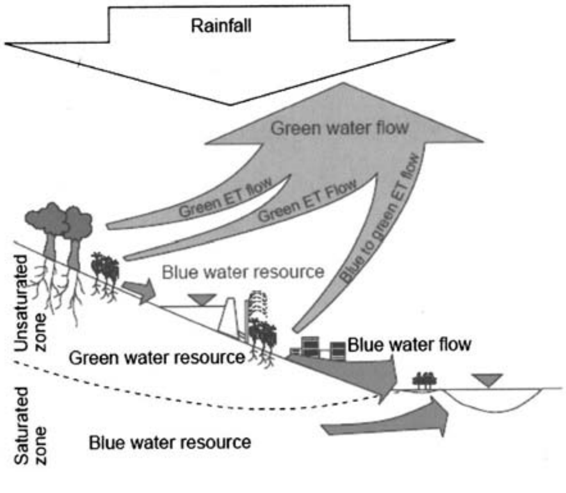

Fig. 1. Conceptualization of a widened green-blue approach to water-resource planning and management. Rainfall, the undifferentiated freshwater resource, is partitioned in a green-water resource as moisture in the unsaturated zone and in a blue-water resource in aquifers, lakes, wetlands, and impoundments (e.g., dams). These resources generate flows, as green-water flow from terrestrial biomass producing systems (crops, forests, grasslands, and savannas) and blue-water flow in rivers, through wetlands, and through base flow from groundwater.

Precipitation P is, in other words, an undifferentiated form of freshwater, which can become either green or blue flow depending on whether it is partitioned in vapor flow or groundwater recharge/surface runoff. The fate of P is determined at the land surface and the unsaturated zone of the soil. The green-water flow has two components: the *productive part*, or transpiration (T), involved in biomass production in terrestrial ecosystems, and the *nonproductive part*, or evaporation (E).

Hunger Alleviation Seen through a Freshwater Lens

We estimate that global food production consumes (as green-water flow, here including both evaporation and transpiration, i.e., evapotranspiration) approximately 6,800 $\mathrm{km}^3/\mathrm{year}$ worldwide. Of this amount, 1,800 $\mathrm{km}^3/\mathrm{year}$ is consumed through allocation of blue water (withdrawals of liquid water in rivers, lakes, and groundwater) in irrigated crop production (which water planners generally refer to as the totality of water used in agriculture), whereas the remaining 5,000 $\mathrm{km}^3/\mathrm{year}$ is consumption of the green-water resource (soil moisture) in the world's rain-fed agriculture (practiced on 80% of the agricultural land). For developing countries, where the totality of global population growth and malnourishment is essentially concentrated, we estimate that 4,500 $\mathrm{km}^3/\mathrm{year}$ of water is used to produce current diets (SEI 2005).

To estimate future water for food, we have used the estimate of the Food and Agriculture Organization of the United Nations (FAO) of an adequate dietary demand of 3,000 kcal/day and have assumed that it will be attained by 2030 in developing countries. If 20%, or 600 kcal, of these originate from animal protein, the water requirement amounts to 1,300 $\mathrm{m}^3/\mathrm{year}$, assuming current water productivity. This amount corresponds to 3.6 tons of water per person per day and is 70 times larger than the amount taken as the basic need for household supply.

On the basis of water and diet analyses at the country level, we have carried out a recent assessment of the overall water requirements to eradicate hunger by 2030 in developing countries, which amounts to approximately 4,200 $\mathrm{km}^3/\mathrm{year}$. This total implies almost a doubling of the consumptive water use for food production from today's 4,500 $\mathrm{km}^3/\mathrm{year}$. If covered by irrigation only, it would involve more than doubling all the water withdrawals from rivers and aquifers today and would be absolutely unacceptable in view of the damage already caused by depleted rivers and degraded aquatic ecosystems.

Meeting the indicated water requirements must therefore be seen as a major environmental challenge: From where could such a huge amount of water be made available?

Minimizing Nonproductive Water Losses

We know that much of today's agriculture in the developing world suffers from large water losses. This statement holds true for both irrigated agriculture, where water-use efficiency tends to be of the order of only 30% (the ratio of consumptive water use by the irrigated crop to the water withdrawn from the source). Similarly, for rain-fed agriculture, losses of water in the on-farm water balance can be very high, particularly in low-yielding farming systems, which dominate in developing countries and where staple grain yields often amount to only 1 t/ha. For sub-Saharan Africa, only 10–30% of seasonal rainfall is used as productive green-water flow, that is, crop transpiration (T), for tropical grains (such as maize, sorghum, and millet), with up to 50% lost as nonproductive evaporation (E) from interception and soil evaporation. Significant volumes of rain leave farms as blue-water flow; as surface runoff (up to 30%), causing land degradation; and as deep percolation (up to 25%). Unless runoff flow evaporates during its journey downhill, it generates the blue-water resource downstream, which naturally is not a "loss" at a larger system scale.

However, only a small portion of rainfall is used productively, particularly in tropical rain-fed farming systems. The losses tend to be largest in the semiarid and dry-subhumid zone, that is, in savanna agroecosystems where most of the world's poorest countries are located. This outcome is highly worrying and presents a major challenge for water resource planners. The world's hot-spot countries with respect to poverty and hunger also correspond to the countries facing the largest inherent freshwater challenges because of water stress and extreme spatial and temporal variability. The opportunity lies in tapping the potential of a currently ineffectively used on-farm water balance, which requires innovative strategies to manage sudden excesses of water and frequent periods of deficit, the so-called dry spells.

In the savanna zone, rain-fed agriculture typically consumes (as green-water flow) on the order of 2,000–3,000 m^3/t grain (or 300 mm/t/ha). This low water productivity should be compared with the global average water consumption in grain production of between 1,000 and 1,500 m^3/t. The reason for this discrepancy is not explained by crop characteristics (generally C3 crops in temperate regions, such as wheat and barley, and C4 crops in tropical regions, such as maize and sorghum). Instead it is attributable to low yield levels and high evaporative demand, which together cause large evaporation losses, leading to large evapotranspiration flow but low biomass production (nonproductive E flow is a large proportion of ET flow).

Integrated soil and water management—particularly focused on soil fertility management, soil tillage for improved rainfall infiltration, and water harvesting for dry-spell mitigation—can significantly improve yields and water productivity (WP) (m^3/t). As shown by Rockström (2003), a highly dynamic relationship exists between yield increase and water productivity, particularly in the low-yield range between 1 and 3 t/ha, where higher yields result in large improvements in WP. The reason is vapor shift, in which nonproductive evaporation is shifted to productive transpiration, and a larger proportion of the on-farm water balance actually flows as transpiration. In summary, maximizing water productivity, or the amount of crop per drop of water, entails raising agricultural yields through management that maximizes rainfall infiltration and minimizes nonproductive green-water losses E. In other words, maximizing the fraction of P becoming beneficial, i.e. productive green-water flow. As shown by Pretty and Hine (2001), ample evidence indicates that rain-fed crop yields can be doubled through innovations in soil, crop, and water management. Our estimate is that integrated soil and water management can improve water productivity in the semiarid and dry subhumid savannah zone to some 1,500 m^3/t.

Where to Find the Rest

If such an increase in water productivity—which corresponds roughly to a doubling of yield levels from the current 1–2 t/ha to 2–3 t/ha—could be achieved, the water requirements would decrease by approximately 1,200 $\mathrm{km}^3/\mathrm{year}$ from the 4,200 $\mathrm{km}^3/\mathrm{year}$ previously mentioned as the total required freshwater need to alleviate hunger. The total water requirements to alleviate hunger by 2030 would be reduced to 3,000 km^3/year, which is a major reduction, while leaving a very sizeable volume unaccounted for.

How far can blue water, that is, irrigation, go in covering this remaining net freshwater requirement to alleviate hunger by 2030? We know that many rivers in irrigation-dependent regions are overappropriated beyond the requirements of aquatic ecosystems (Smakhtin et al. 2004), and the projections of future water development for irrigation are lower than in the past, considering political, social, and environmental concerns that are related to large water infrastructure development. Our assessment, following the assumptions previously made by the International Water Management Institute (IWMI) suggests that irrigation might expand by a maximum of 20%, or some 500 km^3/year at the most (from the current 1,400 km^3/year to 1,900 km^3/year in developing countries), leaving 2,500 km^3/year to be covered by other green-water use in agriculture.

There are basically only two remaining alternatives to consider: capturing more local rainwater on current farmers' fields or expanding crop production into tropical forests and grasslands, appropriating water now consumed for plant growth in these natural terrestrial ecosystems. If yields roughly double over the next 25 years, approximately half the remaining 2,500 km^3/year would originate from increased water use on current cropland. The remaining 1,250 km^3/year would have to originate from horizontal expansion of agricultural land, which would correspond to approximately a 30% growth of agricultural land until 2030.

Water for Ecosystems

This analysis indicates very large water trade-offs among water for crops, for humans, and for ecosystems. Increasing water consumption on current cropland reduces blue-water availability for humans and ecosystems downstream, and expanding of agricultural land causes a loss of natural ecosystems. A new conceptualization of water for food is therefore required. Agriculture already covers some 25% of the land area of the continents and has—according to the Millennium Ecosystem Assessment—been the major driver years of severe degradation of ecosystem services, terrestrial as well as aquatic, during the past 50 years. When agriculture consumes even more water on current land—and moreover continues to expand (roughly at the same pace as during the past 50 years) into natural ecosystems, careful attention will have to be paid to ecosystems and their water relations: aquatic ecosystems and their blue-water dependence and terrestrial ecosystems with their green-water dependence.

Terrestrial ecosystems are interacting directly with runoff production: the larger the proportion of infiltrated rain that is consumed by plants and trees, the less remains to generate runoff or recharge groundwater. Considerable interest, for examples, is paid to the ways that forestry interacts with runoff formation: whether forest plantations increase or decrease blue-water availability, a debate often referred to in situations both of severe floods and of desertification phenomena (Calder 2004). Trees interact with rainwater partitioning in two main ways; by influencing soil permeability and therefore rain infiltration and by influencing root uptake of green water in the root zone.

Aquatic ecosystems dwell in blue-water habitats and suffer when these change either by the streamflow being depleted or its seasonality altered, for instance, by vanishing flood flows or by water-quality deterioration. Important advances have been made to define the environmental flow requirements of aquatic ecosystems in the percentage of the average flow that has to remain unappropriated and the inflood-flow events needed for proper ecological functioning (King et al. 2003).

Challenge for Tomorrow's Water Planners

The water-resource challenge of the future is more complex than previously portrayed—it is not only a question of water allocation among irrigation, industry, and municipalities but involves difficult decisions for balancing green and blue water for food, nature, and society. It will change the role of water-resource planners and managers. Water resources planning and management will have to incorporate land-use activities consuming green water and its interaction with blue water, generating surface runoff and groundwater recharge.

The ultimate task is to manage the partitioning of rainfall for humans and ecosystems across spatial and temporal scales. Rainfall not stable runoff, becomes the freshwater resource. A key new component of water governance will be providing water for human activities while paying attention to safeguarding the water of vital ecosystems, aquatic as well as terrestrial, not only as a means of preserving ecological functions but as a strategy for resilience building when faced with such extreme events as floods and droughts.

The importance of investments to upgrade rain-fed agriculture, particularly in terms of water productivity, raises the need for a conceptual change in our view of water development in agriculture. The conventional dichotomy between irrigated and rain-fed agriculture is not adequate when addressing the challenge of water to feed humanity in the future. Irrigated agriculture is in fact almost always supported by some infiltrated rain. Key strategies to upgrade rain-fed agriculture involve investments in supplemental irrigation to bridge dry spells. Both types of crop production, in other words, involve both green and blue water to meet water requirements for crop, although in different proportions. If the water-resource focus shifts from runoff to rainwater management, the rationale for a sectoral divide between irrigation and rain-fed agriculture fades away.

A redefinition of integrated water resource management (IWRM) is required, both in focus (generally perceived in terms of allocating blue-water resources) and scale (generally perceived in terms of water-resource management at the basin scale). The focus should be redirected from a blue-water perspective toward considering the full water balance as "manageable," including vapor flow, or green-water flow. Because rain-fed agriculture will have to continue bearing the largest burden of generating food for growing populations in developing countries, the scale of focus should more prominently focus on the smaller catchment or watershed scale, which corresponds better to the scale relevant to the farmer.

It is often argued that the freshwater crisis can be solved through virtual water trading, that is, food can be produced in regions with excess fresh water and exported to water-scarce regions, which already occurs, primarily in arid countries (e.g., the Middle East). Certainly, food trade will continue to play an important role in meeting the growing demand for food. Our analysis, however, is based on the current situation, with a very small portion of world food production (5–10%) being traded on the international market and the low purchasing power among communities in countries facing the largest growth in food demand.

A necessary conceptual advancement of IWRM, is to incorporate land use, that is, to emphasize integrated *land* and water resource management (ILWRM). A land-use decision is also a water decision. Currently, IWRM plans are implemented at the country level, in line with the plan of implementation from the World Summit for Sustainable Development (WSSD) in Johannesburg in 2002. It is urgent that the "L" in IWRM be incorporated in strategic planning of water for livelihoods and sustainability, since evidence clearly shows that the freshwater legacy of the past is definitely inadequate to enable us to face the challenges ahead of us.

References

Calder, I. R. (2004). "Forests and water—Closing the gap between public and science perceptions." *Water Sci. Technol.*, 49(7), 39–53.

Conway, G. (1997). *The doubly green revolution: Food for all in the twenty-first century*, Penguin Books, New York.

Falkenmark, M., and Rockström, J. (2004). *Balancing water for man and nature: The new approach to ecohydrology*, EarthScan, U.K.

King, J. M., Brown, C. A., and Sabet, H. (2003). "A scenario-based holistic approach to environmental water flow assessments for rivers." *Rivers Research and Application*, 19(5–6), 619–639.

Pretty, J., and Hine, R. (2001). "Reducing food poverty with sustainable agriculture: A summary of new evidence." *Final Rep. from the "Safe World" Research Project*, Univ. of Essex, U.K., 133.

Rockström, J. (2003). "Water for food and nature in the tropics: Vapour shift in rainfed agriculture." *Phil. Trans. R. Soc. Land. B*, 358, 1997–2009.

Stockholm Environment Institute (SEI). (2005). *Sustainable pathways to attain the Millennium Development Goals—Assessing the key role of water, energy and sanitation*, Stockholm Environment Institute, Stockholm, Sweden, 96.

Smakhtin, V., Revenga, C., and Döll, P. (2004). "Taking into account environmental water requirements in global-scale water resources assessments." *Comprehensive Assessment Research Rep. 2*, Comprehensive Assessment Secretariat, Colombo, Sri Lanka, 22.