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THE NEW BLUE AND GREEN WATER PARADIGM

Breaking new ground for water resources planning and management

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Water for food and hunger alleviation

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 concentrates on a fraction of the water for food challenge, namely irrigated agriculture that uses an estimated 25 % of the global water use in agriculture, and on industrial and domestic water supply, which correspond to less than 10 % of direct human water requirements (considering only water for food, domestic use and industry). The reason 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 vapour from the plant canopy. Furthermore, this productive flow of vapour, is accompanied by non-productive evaporative losses of water (from soil, ponded water, and intercepted water from foliage surface). Together, vapour 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 in the world by 2015, today amounting to a shocking 800 million people, is thus not only a tremendous agricultural endeavour, but also the world's largest water resource challenge. Hunger alleviation will require no less than a new Green revolution over the coming 30 years, particularly in sub-Saharan Africa. As stated by Conway (1997), the challenge is to achieve a green-green revolution, which compared to the 1st green revolution that lifted large parts of Asia out of an imminent hunger crisis in the 1960s and 70s, 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, as the focus will have to be on upgrading rainfed agriculture, which entails increasing the use of the portion of rainfall that infiltrates in the soil and is accessible by plants to generate vapour flow in support of biomass growth. This triply green revolution will require huge quantities of freshwater as vapour flow from the soil, through plants to the atmosphere. This raises the question of what eradicating hunger in fact will imply for water resources planning and management.

Two types of water involved in food production

The urgent need to focus on water investments in rainfed agriculture leads to the conclusion that conventional water resource perceptions are incomplete. This requires a widening of current agricultural water policy, which for decades has been squewed towards water for irrigation.

The conventional water resource planning and management focus is on liquid water or *blue water*. It served the particular needs of engineers quite well, involved in water supply and infrastructure projects. 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 vapour flow, dominated by consumptive water use by the vegetation. When analysing food production we therefore need to incorporate a second form of water resource, the rainfall that naturally infiltrates into the soil and which is on its way back to the atmosphere.

Figure 1 illustrates the new conceptualisation, 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 vapour water flow back to the atmosphere.

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 vapour flow or groundwater recharge/surface runoff . The place where the fate of *P* is determined is 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 *non-productive part* , or evaporation (E).

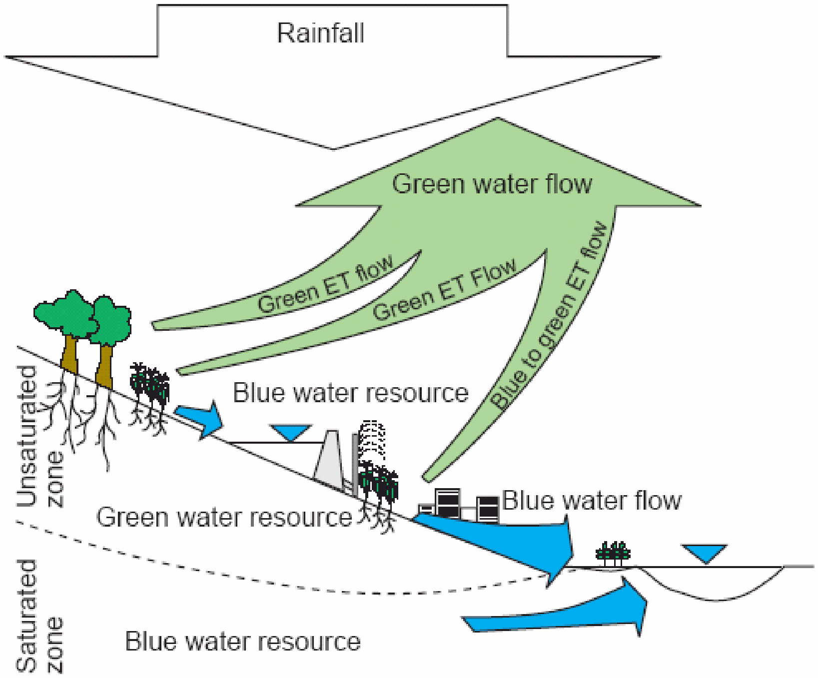

Figure 1. Conceptualisation of a widened green-blue approach to water resource planning and management. Rainfall, the undifferentiated freshwater resource, is partitioned in a green water resource as moisture in the unsaturated zone, and a blue water resource in aquifers, lakes, wetlands and impoundments (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 base flow from groundwater.

Hunger alleviation seen through a freshwater lens

Currently we estimate that global food production consumes (as green water flow, here including both evaporation and transpiration, i.e., evapotranspiration) approximately 6800 km^3/year worldwide. Of this, 1800 km^3/yr is consumed through allocation of blue water (withdrawals of liquid water in rivers, lakes and groundwater) in irrigated crop production (generally referred to among water planners as the totality of water used in agriculture), while the remaining 5000 km^3/yr is consumption of the green water resource (soil moisture) in the world's rainfed agriculture (practiced on 80 % of the agricultural land). For developing countries, where essentially the totality of global population growth and malnourishment is concentrated, we estimate that 4500 km^3/yr of water is used to produce current diets (SEI, 2005).

To estimate future water for food we have used FAO's estimate of an adequate dietary demand of 3000 kcal/p day, and assumed that it will be attained by 2030 for developing countries. Assuming that 20 percent, or 600 kcal, out of these originate from animal protein, the water requirement amounts to 1300 m^3/p year, assuming current water productivity. This 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.

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

To meet 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?

Minimising non-productive water losses

First of all we know that much of today's agriculture in the developing world suffers from large water losses. This holds true for both irrigated agriculture where water use efficiency tends to be of the order of only some 30 percent (the ratio of consumptive water use by the irrigated crop to the water withdrawn from the source). Similarly, for rainfed 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 ton/ha. For sub-Saharan Africa, only 10 – 30 % of seasonal rainfall is used as productive green water flow, i.e., crop transpiration (T), for tropical grains (such as maize, sorghum and millets), with up to 50 % lost as non-productive 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 deep percolation (up to 25 %). Runoff flow, unless it evaporates during its journey downhill, generates the blue water resource downstream, which naturally is not a “loss” at a larger system scale.

However, fact remains, only a small portion of rainfall is used productively, particularly in tropical rainfed farming systems. The losses tend to be largest in the semi-arid and dry-subhumid zone, i.e., in savanna agro-ecosystems where in fact the majority of the world’s poorest countries are located. This is highly worrying and a major challenge for water resource planners. The world’s hotspot countries in terms of poverty and hunger, also correspond to the countries facing the largest inherent freshwater challenges, in terms of water stress and extreme spatial and temporal variability. The opportunity lies in tapping the potential of a currently not so effectively used on-farm water balance, which particularly requires innovative strategies to manage sudden excess of water and frequent periods of deficit, so-called dry spells.

In the savanna zone, rainfed agriculture typically consumes (as green water flow) in the order of 2000-3000 m^3/ton grain (or 300 mm/ton/ha). This low water productivity should be compared to the global average water consumption in grain production of between 1000–1500 m^3/ton. 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 due to low yield levels and high evaporative demand, which together cause large evaporation losses, leading to large evapotranspiration flow but low biomass production (non-productive E flow 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/ton). As shown by Rockström (2003) there is a highly dynamic relationship between yield increase and water productivity, particularly in the low yield range between 1 – 3 t/ha, where higher yields result in large improvements in WP. The reason is vapour shift, where non-productive evaporation is shifted to productive transpiration, and that a larger proportion of the on-farm water balance actually flows as transpiration. In summary thus, maximising water productivity, or the amount of crop per drop of water, entails raising agricultural yields through management that (i) maximising rainfall infiltration, and (ii) minimising non-productive green water losses E. In other words maximising the fraction of P becoming beneficial, i.e. productive green water flow. As shown by Pretty and Hine (2001), there is ample evidence that rainfed 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 semi-arid and dry subhumid savannah zone to some 1500 m^3/ton.

Where to find the rest?

If such an increase in water productivity could be achieved, which corresponds roughly to a doubling of yield levels from current 1-2 t/ha to 2-3 t/ha, the water requirements would decrease by approximately 1200 km^3/yr from the 4200 km^3/yr mentioned above as the total required freshwater needs to alleviate hunger. This would reduce the total water requirements by 2030 to alleviate hunger to 3000 km^3/yr, which is a major reduction, while leaving a very sizeable volume unaccounted for.

How far can blue water, i.e., 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, taking into consideration political, social and environmental concerns related to large water infrastructure development. Our assessment, following the assumptions earlier made by IWMI (the International Water Management Institute), suggest that irrigation might expand by a maximum of 20 percent, or some 500 km^3/yr at the most (from current 1400 km^3/yr to 1900 km^3/yr in developing countries), leaving 2 500 km^3/yr 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 coming 25 years, approximately half of the remaining 2500 km^3/yr would originate from increased water use on current cropland. The remaining 1250 km^3/yr would have to originate from horizontal expansion of agricultural land, which would correspond to approximnately a 30 % growth of agricultural land until 2030.

Water for ecosystems

This analysis indicates very large water trade-offs between water for crops, humans and for ecosystems (increasing water consumption on current cropland reduces blue water availability for humans and ecosystems downstream, and expansion of agricultural land is a loss of natural ecosystems). A new conceptualisation of water for food is thus required. Agriculture already covers some 25 percent of the land area of the continents and has according to the Millennium Ecosystem Assessment been the major driver over the past 50 years of severe degradation of ecosystem services, terrestrial as well as aquatic. When agriculture will have to consume even more water on current land, and moreover continue to expand (roughly at the same pace as over the past 50 years) into natural ecosystems, careful attention will have to be paid to ecosystems and their water relations: aquatic ecoystems 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. There is for instance considerable interest paid to how 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 over the past years to define environmental flow requirements of aquatic ecosystems both in terms of percentage of the average flow that has to remain unappropriated and the floodflow 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 – not only a question of water allocation between irrigation, industry and municipalities, but involving difficult decisions of how to balance green and blue water for food, nature and society. This 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 becomes the freshwater resource, and not stable runoff. A key new component of water governance will be to provide water for human activities, while paying attention to safeguarding water of vital ecosystems, aquatic as well as terrestrial, not only as a means of preservation of ecological functions, but as a strategy for resilience building when faced with extreme events such as floods and droughts.

The importance of investments to upgrade rainfed 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 rainfed agriculture is not adequate when addressing the challenge of water to feed humanity in the future. Irrigated agriculture is in fact practically always supported by some infiltrated rain. Key strategies to upgrade rainfed agriculture involve investments in supplemental irrigation to bridge dryspells. Both types of crop production in other words involve both green and blue water to meet crop water requirements, although in different proportions. If water resource focus is shifted from runoff to rainwater management, the rationale for a sectoral divide between irrigation and rainfed agriculture fades away.

A redefinition of integrated water resource management (IWRM) is required, both in terms of focus (generally perceived in terms of allocation of blue water resources) and scale (generally perceived in terms of water resource management at basin scale). The focus should be redirected, from a blue water perspective, towards considering the full water balance as “manageable”, including vapour flow, or green water flow. As rainfed 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 relevant scale of the farmer .

It is often argued, that the freshwater crisis can be solved through virtual water trading, i.e. produce food in regions with excess of freshwater and export it to water scarce regions, which already occurs particularly in arid countries (e.g., the Middle East). Certainly, food trade will continue to play an important role in meeting growing demand for food. Our analysis, however, is based on the current situation, with a very small portion world food production being traded on the international market (5-10%), 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, i.e., put emphasis on integrated *land* and water resource management (ILWRM). It is well known, as highlighted above, that a land use decision is also a water decision. Currently, IWRM plans are implemented at country level, in line with the plan of implementation from the World Summit for Sustainable Development (WSSD) in Johannesburg, 2002. It is urgent that the

"L" in IWRM is incorporated in strategic planning of water for livelihoods and sustainability, as evidence clearly point out that the freshwater legacy of the past is definitely inadequate to face the challenges ahead of us.

References

Calder, I.R., 2004. Forests and water – closing the gap between public and science perceptions. Water Science and Technology 49(7): 39 - 53

Conway, G., 1997. The doubly green revolution. Food for all in the twenty-first century. Penguin Books, USA. p 334.

Falkenmark, M., and Rockström, J., 2004. Balancing Water for Man and Nature: The new approach to ecohydrology. EarthScan, UK

King, J.M., Brown, C.A., and Sabet, H., 2003. A scenario-based holistic approach to environmental water flow assessments for regulated rivers. Rivers Research and Application, Vol. 18.

Pretty, J., and Hine, R., 2001. Reducing food poverty with sustainable agriculture: A summary of new evidence. Final report from the "Safe World" Research Project, University of Essex, UK. p 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

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

Smakhtin, V., Revenga, C., and Döll, P., 2004. Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive Assessment Research Report 2. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. p 22