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HEADING TOWARDS BASIN-LEVEL HYDROSOLIDARITY GOAL FOR LAND/WATER/ECOSYSTEM COORDINATION

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Introduction

Human interaction with the life supporting web of living matter has recently been assessed in the Millennium Ecosystem Assessment (MA 2025). The outcome of the assessment was summarised in four findings:

– over the past 50 years, ecosystems have been changed more extensively than ever before in human history;
– the changes have contributed to substantial gains for society, achieved however at growing costs in terms of degradation of many ecosystem services and increased risk of sudden non-linear changes;
– the degradation could grow significantly worse in the first half of the present century;
– reversing the degradation while meeting increasing human needs will involve significant changes in policies, institutions and practices.

This raises the question to what degree ecological changes can be repaired or avoided, and to what degree they must be seen as the unavoidable outcome of more or less aware trade offs.

The water cycle has the function of bloodstream of both biosphere and society (Falkenmark, 2005). People live on land where water is a key livelihood component. More or less irregular rainwater pulses rinse the land and generate runoff in aquifers and within river systems. During this movement, water has many parallel functions, Figure 1. Humans depend on clean water but pollute it during use. Since water is a unique solvant, it also tends to pick water soluble pollutants along its pathways, polluting the habitats of aquatic ecosystems in the rivers and coastal waters. The result is proceeding losses of biodiversity in these ecosystems.

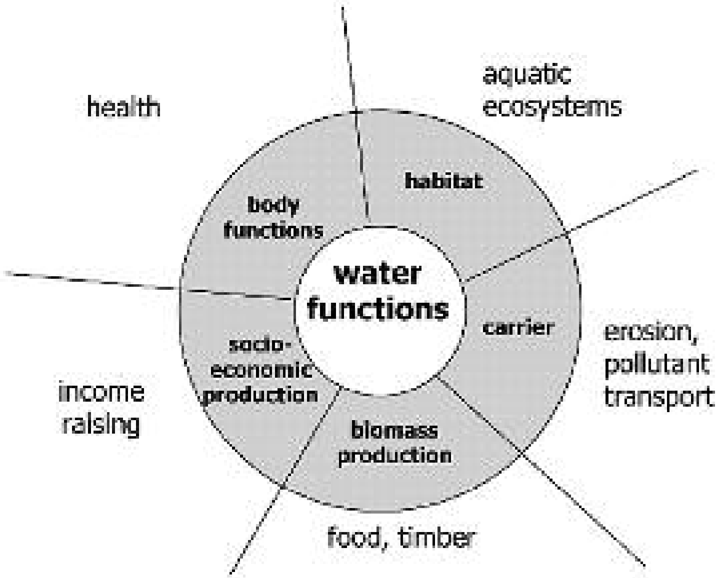

Figure 1. Five central functions of freshwater. From Falkenmark, 2005.

The focus of the Vatican Seminar is scientific frontiers regarding links between hydrology and ecology and the need for increasing disciplinary convergence. The current biodiversity loss makes a more science-based approach to humanity's water dependence urgent: while many river basins are already closed or closing (Smakhtin *et al.*, 2004, Falkenmark & Lannerstad, 2005), pollution continues to escalate, and aquifers are being overexploited, driving forces remain strong. A real dilemma is that the scientific and conceptual development needed to address these huge challenges has remained surprisingly slow. The Seminar aims at analysing scientific issues in terms of eco-hydrological links of relevance for future engineering and political problems. Especial attention is to be paid to the strong driving forces related to achieving the Millennium Development Goals (MDGs).

The aim of this paper is to clarify a number of interactions of hydrological and ecological phenomena in a river basin context. It will address the interpretation of the concept of ecosystem approach, building on the author's earlier studies on the links between water and ecosystems (Falkenmark & Folke, 2002, 2003; Falkenmark, 1997, 2003a, 2003b; Falkenmark & Rockström, 2004). It will analyse the water perspective of the MDGs and the particularities of the global hot spot regions. Integration opportunities in ecohydrological basin management will be discussed and conclusions drawn on the urgent need for better bridging of ecological and hydrological phenomena.

Water and the Millennium Development Goals

Need for Additional Landscape Modifications

The scientific community has to base its future-oriented considerations on anticipation of the considerable changes related to water, land and vegetation. Such changes will be more or less unavoidable in order to *eradicate poverty* by income generating production activities (cash crop production, small scale industrial activities), to *alleviate hunger* by increased agricultural production among small scale farmers (SEI, 2005, Figure 2, see page 234), to expand *safe water provision* (a large number of additional raw water sources), and to organise *sanitation* (e.g. a large number of water-table vulnerable latrines).

Particularly the MDG-oriented activities aimed at eradicating poverty and hunger and securing societal water supply will necessarily involve modification of landscape components (Falkenmark, 1997). Examples are deepened wells and groundwater withdrawals, pipelines and surface water withdrawals, irrigation and consumptive/evaporative water use, clearing of additional agricultural land etc. Such landscape manipulations will influence water phenomena in the landscape and thereby alter abiotic conditions in terms of habitats of ecosystems, terrestrial as well as aquatic.

In altering abiotic conditions, thereby influencing ecosystems, it will be essential to secure *environmental sustainability*, defined as 'meeting current human needs without undermining the capacity of the environment to provide for those needs over the long term' (Melnick *et al.*, 2005). Environmental sustainability related constraints will have to be identified. It has to be clarified in what way landbased manipulations of vegetation, soil and water will have to be constrained, in other words define the degrees of freedom for MDG-driven landscape-related alterations. Abiotic alterations can originate both from *biophysical alterations* of landscape components, influencing evapotranspiration, groundwater recharge and runoff generation, and from *chemical alterations*, in particular introduction of pollutants directly through waste products disposed of to the atmosphere (leached out and carried back to the land by rainout or fallout), to the land (carried to the river by runoff), or as wastewater directly to the river. In addition, pollutants originate from agricultural chemicals, leached out to the river system.

Thus, it may be foreseen that MDG-driven modifications may influence the ecosystems both directly and indirectly. The alterations will vary between different MDGs. When *direct* and visible, they can be minimised and managed by for example a natural reserve approach through protection of particular landscape elements. When *indirect* and/or invisible, the response options are more uncertain. Some alterations may even generate moisture feedbacks, altering drought patterns, or the rainfall, influencing a rainforest. Specific considerations call for attention to the resilience of particular ecosystems, and how to avoid that they degrade into unwanted states.

Resilience protection refers to the fact that humanity, through its activities, tends to alter disturbance regimes with which organisms have evolved over time. There is therefore a need to secure enough 'elasticity' (resilience) of ecosystems to change in the surrounding conditions (storms, fire, drought, pollution events, or creeping pollution). What has to be protected is the capacity of the ecosystem to absorb continuous change *without loss of the dynamic capacity to uphold the supply of ecological goods and services.*

Hot Spot Regions

A fundamental factor to consider in analysing how to eradicate hunger is the hydroclimate. There is an unfortunate congruence between the zone where the majority of the hunger-prone countries are located and the zone with savanna climate (Figure 3, see page 234). Typical for this zone is that considerable challenges will have to be overcome:

- seasonal rainfall with intermittent dryspells, making the rainfall unreliable;
- recurrent drought years linked to large-scale fluctuations in the intercontinental water vapour flow system;
- high evaporative demand so that most of the rainfall evaporates, leaving only a limited fraction to generate runoff;
- often vulnerable soils with low permeability and low water-holding capacity which limits the amount of water available to the root system.

In that climate, rainwater partitioning is highly vulnerable to land cover change, altering the consumptive water use involved in food production and forestry. The result may be surprising effects on groundwater and streamflow. In vaste irrigation-dependent regions river flow is already over-appropriated beyond estimated needs of aquatic ecosystems (Smakhtin *et al.*, 2004). Overexploited groundwater, increasing water pollution and salinisation are other serious water-related problems that will demand great human ingenuity to be succsssfully coped with.

Hydrologic-Ecological Interactions

Global Scale Interactions

Water circulates through the biosphere and thereby links atmosphere, terrestrial ecosystems, freshwater flows, and aquatic ecosystems. In this system, water has three fundamental global scale tasks (Ripl, 2003):
– distribute solar energy over the planet (by balancing evaporation and condensation);
– distribute water soluble substances (by balancing dissolution and crystallisation), in particular nutrients and vital minerals;
– provide one of the two key raw materials for the photosyntesis, the other being carbon dioxide from the atmosphere (by balancing splitting and reassemblage of the water molecule).

When striving towards environmental sustainability, the starting point is the interaction between the network of nested ecosystems and the social system (Figure 4, see over). Humans try to manage the complex of living organisms and their non-living surrounding – the ecosystem – since it provides essential goods and services on which human welfare is based. Human needs are driven by population growth and wealth expectations. In trying to meet those human needs, waste is introduced and various biophysical disturbances are produced, together degrading the life supporting web of ecosystems (Falkenmark, 2003b).

The life support system on the landscape scale has generally one single water source: the precipitation. All water-dependent human activities and ecosystems are enclosed in the water delivery system of the catchment. In its contacts with the land surface, the water input is partitioned between the naturally infiltrated *green water* in the soil and the surplus producing runoff in rivers and aquifers (*blue water*). Since the former evaporates and the latter forms liquid water flow, the distinction has been extended into vapor form green water flow and liquid form blue water flow.

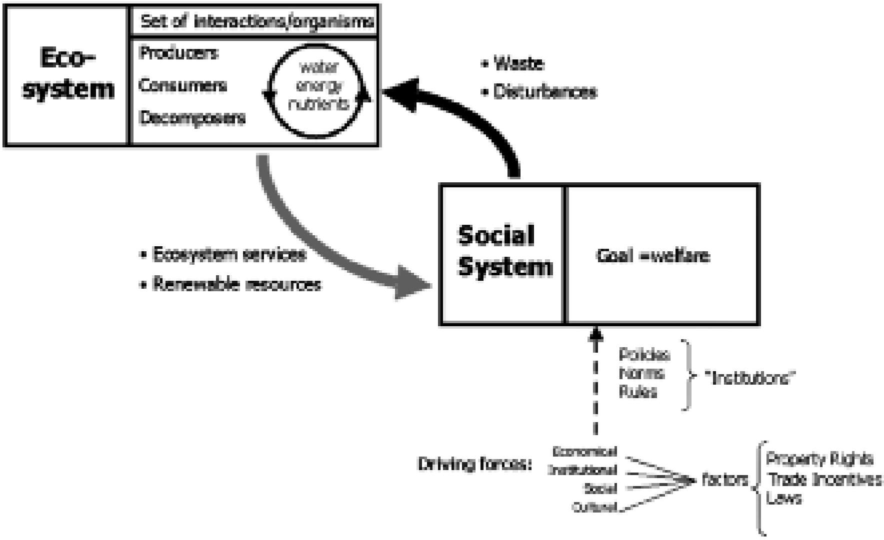

Figure 4. Humanity critically depends on ecological links between nature and society. Because driving forces are acting on the social system, ecosystem management is a question of living with change while securing long-term ecosystem productivity. From Falkenmark 2003a.

This division between green and blue water flows (cf. Figure 5, page 186) is useful in a closer analysis of water balance alterations, linked to terrestrial ecosystems, which are green water dependent, and aquatic ecosystems, which are blue water dependent. The green water flow system incorporates the consumptive water used by forests, grasslands and rain-fed croplands. The blue water system provides the water resource directly available to and 'harvested' by humans. Water is in other words being withdrawn from rivers and aquifers for use in the social system, and after use returned to the water cycle by two complementary pathways: as vapour flow after consumptive/vapourising water use, or as blue water return flow back to the river system, often carrying pollutants (Falkenmark, 2003b).

Both irrigation and deforestation are activities, altering vapour flows. Gordon *et al.* (2005) have studied the large-scale redistribution of global water vapour flows; they found that irrigation has increased the vapour flow by some 2,600 km^3/yr, which has been more or less compensated by an almost equal reduction from global scale deforestation. Different patterns were shown to dominate in different regions.

Interactions in the River Basin

As already stressed, human needs for food, water, energy, minerals etc. cannot be met without manipulating the life support system with its natural resource base and its incessant biomass production processes (Falkenmark, 1997, 2003b). These interventions involve alterations of three key water processes, crucial for the generation of ecosystem impacts: water partitioning at the land surface, influenced by land use change; water as a carrier of pollutants to the ecosystems, linked to waste production and use of agricultural chemicals; and consumptive blue water use (mainly in irrigation), involving a blue-to-green redirection.

Since ecosystems are water-dependent they are easily impacted when water's activities in the life support system are being disturbed. The manipulations mentioned aim at meeting human needs, but are through the biosphere bloodstream system translated into ecological side effects, most of them mediated by water multifunctionality. The resulting environmental degradation influences the capacity of ecosystems to produce goods and services.

In analysing possible countermeasures against ecosystem degradation, it is useful to distinguish whether the causes in terms of manipulations are *avoidable or unavoidable*. The former (erosion, pollution etc.) include uncautious land use changes, containable waste loads, use of toxic chemicals that will escape to the life support system etc. The latter (biologically controled consumptive water use etc.) include consumptive/evaporating water use linked to the photosynthesis process (Falkenmark & Lannerstad, 2005).

In meeting the ecological side effects of the alterations needed to meet societal needs, there are principally two alternative approaches involved (Falkenmark, 2003a):

- for the former type *minimisation*;
- for the latter type *striking of trade offs*.

In managing the trade offs it is useful to distinguish also between *known trade offs* and *unknown trade offs*. The former call for analysis, ability to balance different interests, stakeholder involvement etc. The latter have to be met by clarifying resilience conditions and by an adaptive management, that is flexible and supported by monitoring of slow indicators that can provide early warning about unacceptable ecosystem change.

Ecosystem Approach

A fundamental tool often referred to for the response to unacceptable effects of hydrology-ecology interactions is the so-called *ecosystem* *approach*. Since ecosystems may be of very different scales this concept is somewhat unclear. The concept may be interpreted on different scales (Falkenmark, 2003a).

It may on the one hand be seen in a local scale, and refer to *living components in the local landscape* that are of particular interest from societal and/or scientific perspectives, such as iconic sites (a certain local forest with high biodiversity, a beautiful lake, a groundwater-dependant wetland with particularly high biodiversity due to the shifting mix of groundwater seepage and inundating surface water, etc.). It may also be understood on the overall catchment scale, and refer to the conglomerates of ecosystems, internally linked by water flows into a *catchment ecosystem.* This is the way that GEF has used the concept when stressing the need for 'land-water integration in a catchment-based ecosystem approach' (GWP, 2000). When looked at in this scale, we might think of the catchment as a biological fabric linked by flows of water and nutrients.

In a good ecosystem governance, environmental sustainability will as already indicated have to remain in focus, implying that the life support system may not be undermined (Melnick *et al.*, 2005). This means that ecological bottomlines have to be defined. What this would mean in terms of terrestrial ecosystems remains rather unclear. In terms of aquatic ecosystems, such bottomlines have been formulated in terms of minimum residual streamflow ('environmental flow', Tharme, 2003), referring to the minimum seasonal flow to remain in the river. Also water quality must evidently be a key component of such minimum flow characteristics.

Thus, the concept ecosystem approach will differ depending on what ecosystem is under scrutiny. Whereas for an ecosystem in the sense of a local landscape component, iconic site, or downstream aquatic ecosystems, focus has to be put on the water determinant of that particular ecosystem, it is less clear what should be meant by a catchment-based ecosystem approach.

But the concept ecosystem approach is even more complex. At the recent international symposium in South Africa on 'Good ecosystem governance', it became clear that the concept 'ecosystem approach' tends to have basically *two interpretations*: a biophysically based one in line with the approach in this paper, and a rhethoric, socio-politically based one with very unclear meaning, referring back to the WCED report in 1977.

INTEGRATION OPPORTUNITIES IN MANAGEMENT

The water-related linkages in a catchment provides a basic rationale for the integrated, basin-wide approach taken within IWRM, Figure 5. Currently, attention is being paid to the need of expanding the approach from blue water only, to incorporating also the consumptive water use linked to plant production and green water. Land use needs in other words to be included by entering an L for 'land' into the integrated approach, turning IWRM into ILWRM (Duda, 2003).

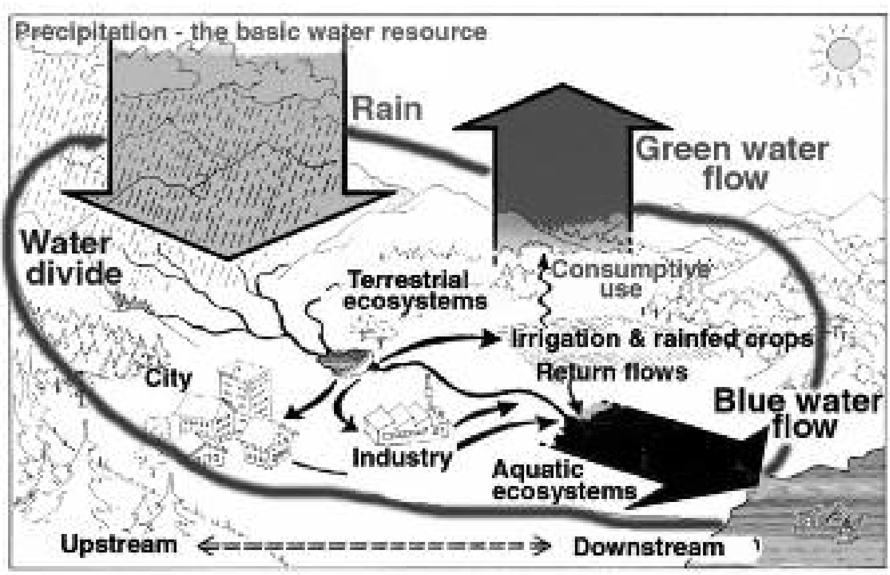

Figure 5. The catchment allows an integrated approach to all water-related phenomena at work within the water divide. All the rain falling within the water divide is being partitioned between humans and nature, between land use/terrestrial ecosystems and water use/aquatic ecosystems, and between upstream and downstream uses and phenomena. From Falkenmark, 2003a.

Water is thus increasingly being seen as a resource to be shared between human society and ecosystems. It is both the bloodstream of the biosphere, and a fundamental base for a multitude of human activities, and therefore a common denominator of the two systems. But these complementary functions are not always compatible: consumptive water use removes water from the catchment and therefore withholding it from the aquatic ecosystems. Pollution load degrades the habitat for aquatic ecosystems and therefore contributes to biodiversity loss. According to the comparison, within the Living Planet Index study, of the biodiversity loss in three major types of ecosystems during the last 30 years (marine ecosystems, freshwater ecosystems and forest ecosystems), the biodiversity loss was largest in the freshwater ecosystems. This is of course a natural consequence of their lying in the bottom end of river basins, cumulating all the human influences to the water arriving from upstream.

The goal for a good governance can be described as reaching an *eco-hydrosolidarity*, where the rainwater input to a catchment is wisely orchestrated between all different water-dependent and water-impacting activities and ecosystems. An introductory analysis will have to clarify the water-related links between major land uses, water uses and ecosystem services (Falkenmark & Rockström, 2004). The crucial resilience capacity of the ecosystem to absorb change without loss of stability must be established. There has also to be a broad realisation of the fact that a land use decision is also a water decision, and that all ecosystems are genuinely water-dependent.

A pragmatic approach taken in Australia is the concept 'healthy working river', defined as the negotiated compromise 'struck between the level of work and the loss of naturalness, depending upon the values the community places on any river' (Whittington, 2002). This type of approach is currently under discussion also for the Yellow River in China.

CONCLUSIONS

It has been stressed that water is a permeating phenomenon in the landscape with a circulation governed by biological and physical laws and moving by gravity through river basins, linking human activities with ecosystems, land based activities with streamflow and groundwater, and upstream activities with downstream opportunities and systems. However, science fragmentation inherited from the time of the 17th century philosopher Descartes, adds to the difficulties of a science-based coping with the looming water crisis.

The *urgency* of an effective bridging between hydrology and ecology is evident from the fact that the overappropriation of streamflow has already gone very far, involving 15 percent of the global land area with a gross population of 1.5 billion.

In spite of this urgency, the concept ‘ecosystem approach’, although having been around for several decades, still remains unclear. There are two interpretations:

– one biophysical, demanding attention to the protection of the resilience against change that might lead to the ecosystem flipping towards a lower state where some of the ecological services provided may not be available any more;
– one socio-political, based on WCED-originating rhethorics with focus on environmental impacts and supported by international, unidimensional conventions.

A *basin-level eco-hydrosolidarity* will have to involve an ecosystem approach, with proper attention to the linkages between ecosystems and different human activities, performed by the water flows above and below the land surface, from the water divide to the mouth. Such an approach will have to be based on current understanding of water/humans/ecosystem linkages.

It will be essential to further develop the mode of research of human interaction with the life support system from monodisciplinarity to interdisciplinarity. It is urgent to proceed from advocacy-oriented ecological studies and from focus on the intricacies of different local ecosystems to the clarification of possible trade-off-based pathways on the route towards an ecologically sustainable future, based on realistic assumptions of basic human rights as expressed by the MDGs, and proper awareness of the many different functions of water in the life support system.

It will be essential to give much more focus to near-future problems to complement the massive amount of longer term climate-change research. It is only when superimposing the water-related changes, linked to human driving forces, and the altering climate that we get an idea of the real challenges during the next few decades (Vörösmarty, 2000). The SEI-study on the water implications of meeting the MDG goal of eradicating hunger shown in Figure 2 is thought-provoking (SEI, 2005): to alleviate hunger, *massive amounts of additional water will be needed for consumptive water use linked to food production*.

Further delays in linking ecology and hydrology are unacceptable: their price will have to be paid in terms of even further degradation of ecosystems and loss of biodiversity, even in terms of human lives. Attention is therefore needed to *ethics of science*, as discussed by Lubchenko (1998) and to the social contract of science, interpreted as the *duty to address priority issues*.

REFERENCES

Duda, A.M. (2003), Integrated management of land and water resources based on a collective approach to fragmented international conventions, in: *Freshwater and welfare fragility: syndromes, vulnerabilities and challenges,* Theme issue, Philosophical Transactions, Biological Sciences, vol. 358, n. 1440, pp. 2051-206, The Royal Society, London.

Falkenmark, M. (1997), Society's interaction with the water cycle: a conceptual framework for a more holistic approach, *Hydrological Sciences,* 42:451-466.

Falkenmark, M. (2000), A European perspective on sustainable consumption of freshwater: Is gettting rid of pollutants realistic and affordable? In: *Towards Sustainable Consumption. A European Perspective*, The Royal Society, London.

Falkenmark, M. (2003a), *Water management and ecosystems: Living with change,* TEC Background Papers n. 9, Global Water Partnership, Stockholm.

Falkenmark, M. (2003b), Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges, in: *Freshwater and welfare fragility: syndromes, vulnerabilities and challenges*. Theme issue, Philosophical Transactions, Biological Sciences, vol. 358, n. 1440, pp. 2037-2050, The Royal Society, London.

Falkenmark, M. (2005), Water usability degradation, Economist wisdom or societal madness, *Water International,* 30:136-146.

Falkenmark, M. and Folke, C. (2002), The ethics of socio-ecohydrological catchment management: towards hydrosolidarity, *Hydrology and Earth System Sciences*, 6(1):1-9.

Falkenmark, M. and Rockström, J. (2004), *Balancing Water for Humans and Nature. The New Approach in Ecohydrology*, London: Earthscan Publications.

Falkenmark, M. & Lannerstad, M. (2005), Consumptive water use to feed humanity – Curing a blindspot, *Hydrology and Earth System Sciences*.

Gordon, L. *et al*. (2005), Human modification of global water vapor flows from the land surface, *Proceedings, National Academy of Sciencies*, USA, 102:7612-7617.

GWP, (2000), *Towards water security: A framework for action,* Global Water Partnership, Stockholm.

Lubchenko, J. (1998), Entering the century of the environment: A new social contract for science, *Science*, 279, 491-496.

MA (2005), *Millennium Ecosystem Assessment Synthesis Report*, Island Press, Washington DC.

Melnick, D. *et al.* (2005), *Environment and human well-being: a practical strategy,* UN Millennium Project, Earthscan, London.

Ripl, W. (2003), Water: the bloodstream of the biosphere. In: *Freshwater and welfare fragility: syndromes, vulnerabilities and challenges,* Theme issue, Philosophical Transactions, Biological Sciences, vol. 358, n. 1440, pp. 1921-1934, The Royal Society, London.

Smakhtin, V., Revenga, C. & Döll, P. (2004*), Taking into account environmental water requirements in global-scale water resources assessments*. Comprehensive Assessment Research, Report 2, IWMI, Colombo, Sri Lanka.

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

Tharme, R.E. (2003), A global perspective on environmental flow assessment. Emerging trends in the development and application of environmental flow methodologies for rivers. *Rivers Research and Application*, 19:397-441.

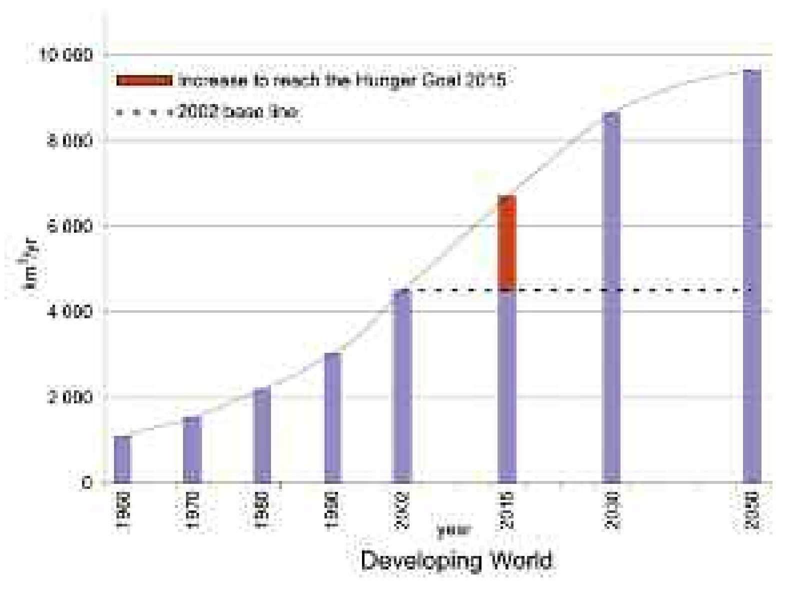

Figure 2. Consumptive water use for food production in 92 developing countries 1960 to 2002 and future requirement to fulfill the Hunger Goal Target 2015 of halving the number of undernourished and to eradicate hunger 2030 and 2050. From SEI 2005.

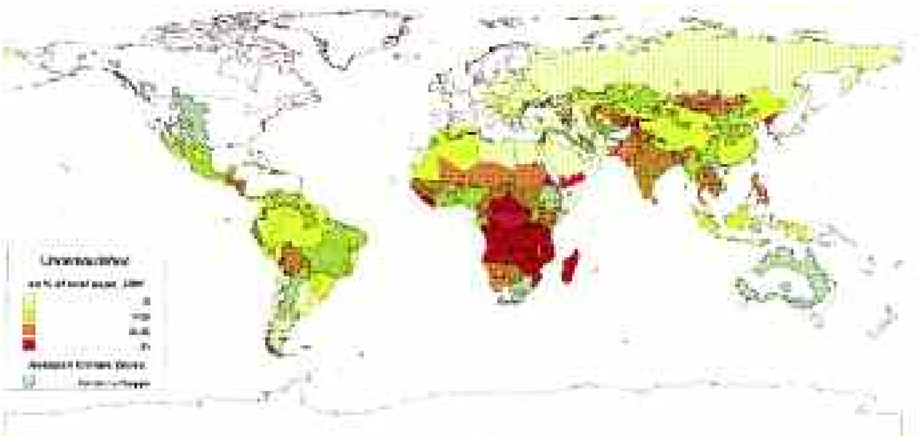

Figure 3. Most of the poor countries with large hunger eradication challenges are located in the zone with savanna and steppe type hydroclimate. From SEI 2005.