

Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges

Malin Falkenmark

*Stockholm International Water Institute (SIWI), Hantverkargatan 5, SE 112 21 Stockholm, Sweden
(malin.falkenmark@siwi.org)*

The paper has its focus on water's key functions behind ecosystem dynamics and the water-related balancing involved in a catchment-based ecosystem approach. A conceptual framework is being developed to address fundamental trade-offs between humans and ecosystems. This is done by paying attention to society's unavoidable landscape modifications and their unavoidable ecological effects mediated by water processes. Because the coevolution of societal and environmental processes indicates resonance rather than a cause-effect relationship, humanity will have to learn to live with change while securing ecosystem resilience. In view of the partial incompatibility of the social imperative of the millennium goals and its environmental sustainability goal, human activities and ecosystems have to be orchestrated for compatibility. To this end a catchment-based approach has to be taken by integrating water, land use and ecosystems. It is being suggested that ecosystem protection has to be thought of in two scales: site-specific biotic landscape components to be protected for their social value, and a catchment-based ecosystem approach to secure sustainable supply of crucial ecosystem goods and services on which social and economic development depends.

Keywords: water blindness; blue versus green water; consumptive water use; ecosystem water determinants; incompatible imperatives; environmental sustainability

1. WATER AWARENESS: A KEY TO SUSTAINABLE DEVELOPMENT

Much has been written on sustainable development, ecosystem protection, biodiversity, etc., but without arriving at either a broadly accepted worldview or a successful implementation of such goals. One particularly interesting phenomenon in this debate is the very limited attention paid to the role of the water-related processes in the life-support system. Although water has the central function of the bloodstream of the biosphere (Ripl 2003), water tends in the general debate to be thought of with a strong technical bias. Thus the debate continues to be hampered by a sort of *water blindness* favouring a basically technical conceptualization of water. In line with such a view, water resources management is taken as various ways of controlling and governing direct water use and related waste flows, not as managing water's various functions in the landscape. At the same time, however, forests and rain-fed agriculture consume much larger amounts of water than irrigated agriculture (Rockström *et al.* 1999). In view of an increasing competition for water in water-scarce regions between different groups of water users, between land use and water stakeholders, and between humans and ecosystems, it has become essential to correct the misleading worldviews and complement conceptual deficiencies.

(a) *Breaking the poverty 'trap'*

This technical bias is broadly reflected in the difficulties in moving forward with socio-economic development and environmental protection. The different views even of what constitutes the environment—whether a biophysical reality or a socially constructed abstract phenomenon (Jones 2002)—are part of this enormous dilemma. The technical bias of water is mirrored for instance in the attention paid to water provision rather than to what happens to water after use (Lundqvist 1998). The human right to safe water (Gleick 1996) totally neglects the dependence—especially in poor, developing countries—on the existence of unpolluted water sources from which safe water can be provided. The technical bias is furthermore reflected in the remaining difficulties to see the water dimension of sub-Saharan Africa's dilemma (Falkenmark & Rockström 1993) and understand the very low crop yields achieved by the typical African farmer (Rockström & Falkenmark 2000). When water professionals discuss food production and water, they have irrigated agriculture in mind, although the crops do not mind what sort of water is available to the roots: whether infiltrated rain or applied irrigation water (Falkenmark *et al.* 2001). A clear confusion can be seen in recent efforts to understand water-deficiency-driven food import and virtual water flow (Earle & Turton 2002; Allan 2003).

Because the semi-arid tropics and subtropics are the regions with largest undernutrition and most rapid population growth (Dyson 1994), this retardedness in seeing the fundamental importance of water for poverty and

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hunger alleviation is not only depressing but even disastrous.

The link between environment and development has now been addressed at two high-level World Summits, Rio in 1992 and Johannesburg in 2002. It is being increasingly understood that environmental sustainability has to be seen as part of the development strategy. As pointed out by Jeffrey Sachs (2002)

without breaking the poverty trap of the poorest countries, we will not achieve environmental sustainability in large parts of the world....(A) tremendous amount of the local-scale biodiversity loss, watershed function, of deforestation, flooding, erosion of steep topographies, and so forth is driven by poverty populations moving into even more and more marginal lands. So the first place for environmental sustainability in my view is in the poorest countries—not to blame the poor but to help them solve the poverty trap.

The most fundamental task is, in other words, to clarify humanity's dependence on the planet's life-support system without which we would get no food, no fuelwood and timber, no wildlife, no pollination of our crops and other essential ecosystem services. Water, through its many different functions, plays multiple roles in the dynamics of ecosystems (Ripl 2003) and social systems. It has the function of determinant and life elixir of terrestrial ecosystems, as a carrier of nutrients, and as a habitat of aquatic ecosystems. In social systems, it has fundamental societal functions for human life-support, food production, energy production, as a transport medium, as a mobile dissolvent, in continuity-related propagation of impacts, as a microclimate moderator, as a global-scale energy carrier, etc.

(b) *Overcoming the inherited landwater dichotomy*

When water is discussed in connection with ecosystems, attention tends to go to aquatic ecosystems and wetlands, although the terrestrial ecosystems consume most of the water falling over the continents as shown by Rockström *et al.* (1999). In spite of these close land–water interactions, the conventional approach to water resources management addresses land and water separately (Falkenmark & Lundqvist 1997). Root zone water is seen only as a hidden attribute to land. Agricultural production ecology as seen by the Consultative Group on International Agricultural Research (CGIAR) refers 'production' to a process of energy accumulation, *not* the formation of new organic matter from two key components: carbon dioxide and water. The presence of water is in fact taken for granted in the same way as carbon dioxide. This perception may in fact reflect a climatic bias with its origin in the well-watered temperate zone.

Another illustration of this water blindness is the debate around global environmental change, in particular the ideas about carbon sequestration in poor tropical countries as a way for the rich countries in the temperate zone to come out of the climate change dilemma. What is referred to is the lack of attention to the involvement of water and therefore possible water constraints (Berndes 2002). The poor understanding of the relationships between plants and water is mirrored also in myths

(Calder 1999). One frequently cited putative truth is the statement that 'forests create water'. This very widespread perception reflects a large gap between ecologists and hydrologists, and between public perceptions and scientific understanding. It is true that trees facilitate rainwater infiltration but they are at the same time large water consumers in the sense that the roots may absorb the infiltrated root zone water, returning it as part of the plant production process back to the atmosphere.

Already in the late 1960s, the Soviet scientist M. I. L'vovich (1979) stressed the role that the vegetation plays in partitioning the incoming rainfall between the vapour flow and the remaining surplus that forms the liquid water flow and constitutes habitats for aquatic ecosystems. He showed, based on data from all the continents, that each biome has its own characteristic partitioning pattern. Recently, Eagleson (2002) has developed a theory for the bioclimatic optimality of trees. He has shown that studied tree species represent maximally productive canopies which make optimal use of both light and water: the two external inputs that drive and limit the productive process. Mature stands of the trees have, in other words, achieved just the right canopy structure to fit the equilibrium between carbon supply through open stomata and root-zone water availability to compensate for the parallel water vapour loss. His hypothesis is that this canopy adaptation is the result of a long-term development along the line of Darwin's principle of best fit.

(c) *Combining human and ecological security*

A credible and transdisciplinary synthetic 'human ecology' (Lawrence 2001) will have to be developed in such a way that it incorporates water in its basic functions in the biosphere, and the close links between water, society and ecosystems, whether aquatic or terrestrial. Because uphill catchment vegetation is literally water consumptive, it influences the water feeding downstream wetlands and forms habitats for the aquatic ecosystems. Because humans and ecosystems share the same water, and that water moves within the modules of catchments, an integrated catchment management will be one way to address the joint management of water and ecosystems.

To support the growing world population, balancing will be needed between emerging societal needs and long-term protection of the life-support system upon which social and economic development ultimately depends. As will be shown in this paper, two main challenges are involved: first, that basic societal needs for water and water-dependent food and energy cannot be met without causing *unavoidable* water-mediated impacts on local ecosystems; second, that another set of impacts on ecosystems are principally *avoidable* in the sense that they are due to mismanagement, especially in terms of irrigation mismanagement, waste flows, and leaching of agricultural chemicals and other contaminants. The basic challenge is therefore how to balance landscape modifications linked to socio-economic development against their unavoidable ecological impacts. It will be essential to find out what minimum criteria have to be respected in terms of human needs and aspirations, criteria for ecosystem resilience, and the supporting governance system.

This paper will address water's key functions behind ecosystem dynamics and the water-related balancing

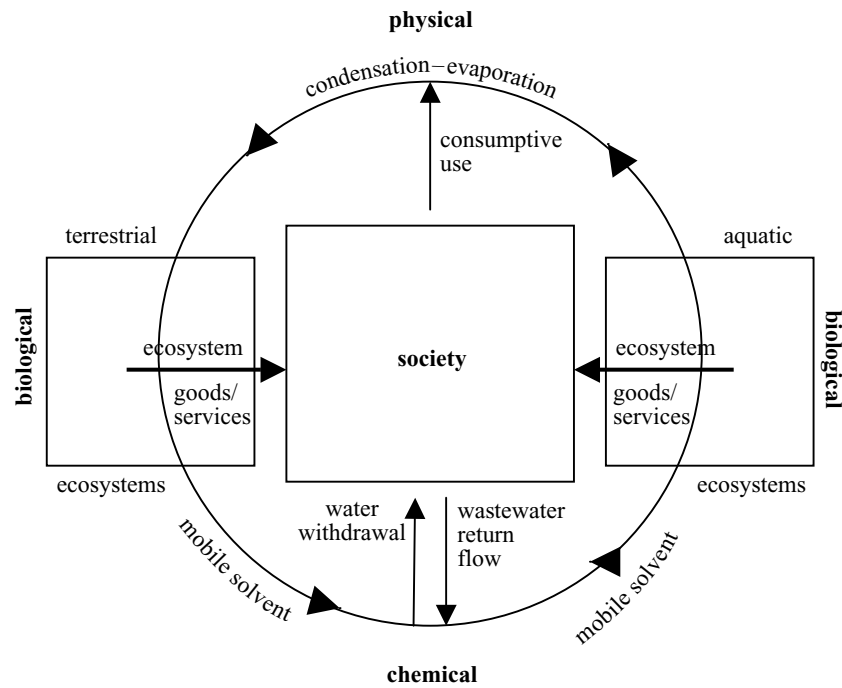


Figure 1. Water: the bloodstream of the biosphere. Schematic illustration of linkages between cycling freshwater, the terrestrial ecosystems feeding on it, the aquatic ecosystems thriving in the habitats formed by it, and human society withdrawing water from it, and after use returning it either as a (polluted) return flow or as a vapour flow.

involved in a catchment-based ecosystem approach. It will pay adequate attention to the consumptive water use by terrestrial ecosystems and compare current approaches with future challenges. It will finally arrive at conclusions in terms of challenges for the scientific community and for good governance.

2. HUMANITY AND THE LIFE-SUPPORT SYSTEM

(a) *The life-support system*

Humanity is totally dependent on a set of biological systems and processes, operating both in their own bodies, in the supporting ecosystems and in the biosphere (Lawrence 2001). From a biophysical viewpoint, human society is a subsystem of the biosphere, where water is a key element (Ripl 2003). Ecosystems may be seen as essential and dynamic 'factors of production' for social and economic development (Folke 1997). Ecosystems produce the bulk of both renewable resources and of the ecosystem services on which the wellbeing of human society is based. This means that human use of these resources and services is dependent on the existence, operation and maintenance of multifunctional ecosystems, in which hydrological flows constitute the bloodstream (see figure 1).

There is a whole group of largely water-dependent *ecosystem services* (Daily 1997) of decisive importance for the functioning of the life-support system: physical, chemical as well as biological (FAO 2000). Some ecological services are evident, others have remained mentally hidden. By a systematic approach they can be structured as follows (FAO 2000):

- (i) *physical* services such as phosphorus absorption in the soil; erosion and sedimentation of silt; interception of rainfall; facilitation of rainwater infiltration into the soil;

- (ii) *chemical* services such as oxygen production and carbon dioxide uptake in the photosynthesis process; denitrification; nutrient release through biodegradation; and
- (iii) *biological* services like plant matter production, pollination, seed dispersal, pest control and macropore-forming root penetration in the soil.

The world is continually changing as the systems involved are all dynamic and interacting: the ecological, the economic and the social systems (Lawrence 2001). Although it is therefore increasingly understood that humanity will have to live with change (Folke *et al.* 2002), sustainable development is about sustaining the potential and capacity for prosperous social and economic development. Because it relies on ecosystem services and support and will continue to do so in the foreseeable future, there is a need for approaches to ecosystems that are process-oriented with adequate stress on the biophysical interactions with water, the bloodstream of the biosphere.

(b) *Two main water flows to manage*

In the catchment, the land unit within a water divide, the rainfall is shared between terrestrial and aquatic systems, and between nature and human society. This is the areal unit in which a balancing between man and nature may be carried out, as it allows simultaneous attention to the functioning of its living landscape components in terms of biotopes, etc., to human interaction with both land and water, and to water's roles in generating environmental side-effects of human landscape modifications. All the rain falling inside the water divide constitutes the shared water resource of all water-dependent activities there, human as well as ecological. After reaching the land surface, the rainwater is partitioned into the vapour form *green water flow* and the liquid form *blue water flow*. The

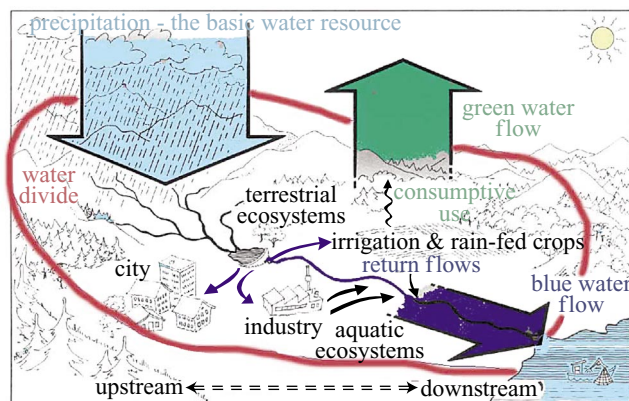


Figure 2. The catchment allows an integrated approach to all water-related phenomena at work within the water divide. All the rainfall within the water divide is being partitioned between the liquid blue water flow supporting society with direct freshwater services, and the invisible green water flow, supporting plant production in terrestrial ecosystems including rain-fed croplands. Water is withdrawn to supply cities and industries, returning the wastewater more or less loaded with pollutants. Water is also withdrawn to irrigated agriculture, from where the consumptive use part joins the green water flow whereas the return flow part returns to the river system loaded with salts and leached agrochemicals.

former consists of the total evaporation, composed of one non-productive part (evaporation from soil, water or canopy), and one productive part (water taken up by plants and returned to the atmosphere as transpiration). The rest moves as blue water flow in rivers and aquifers from uphill to downhill, and from land to water systems (see figure 2).

In spite of the introduction of green water in 1993 to incorporate soil water and plant water use in the discourse (Falkenmark & Rockström 1993), soil water continues to cause confusion. The past utilitarian and technical bias has kept attention directed towards *where* water is available for withdrawal. The evaporating water has been left to the expertise of hydrology and discussed as part of water balance considerations. The result has been a truncated approach to water which has become apparent through a set of 'arid zone surprises' in Australia and South Africa in terms of water consequences of land cover changes (Gordon *et al.* 2003). A second sign of the defectiveness that is now apparent is the earlier difficulties to understand food self-sufficiency limitations reflected in import of food, i.e. reliance on virtual water flows (Earle & Turton 2002; Allan 2003). The trickiness is due to the fact that crops are produced not only in irrigated agriculture but more so in rain-fed agriculture, where soil water is the main source.

Figure 3 aims at clarifying the conceptual water distinctions from two complementary perspectives, a water source related as opposed to a water flow related perspective:

- (i) the *source perspective* refers to where water is available to support beneficial use: as water *in rivers and aquifers* (blue water) but also as naturally infiltrated rainwater *in the soil* on its way to evaporate (green water); and
- (ii) the *flow/reuse perspective* indicates where water is

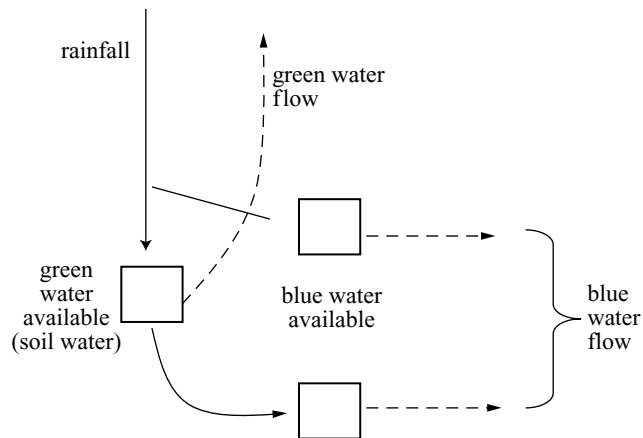


Figure 3. Green and blue water: the source perspective (squares) as opposed to the flow perspective (arrows).

going after use: as blue, liquid water flow available for reuse downstream or as green vapour flow, leaving the atmosphere as a result of consumptive use and *not* available for reuse downstream. The blue water flow is relevant from the perspective of downstream aquatic ecosystems.

The green water flow system mirrors the water consumption by forests, grasslands and rain-fed croplands. It sustains the terrestrial ecosystems as well as rain-fed crop production. The blue water system carries what is available for the human population. By water withdrawals, blue water may be 'harvested' by humans to support water-dependent human activities. Water is withdrawn and carried to settlements, cities and industries. After use, it goes back to the water system as a return flow of wastewater, often loaded with pollutants, unless far-reaching waste water treatment has been carried out. Blue water is withdrawn also to support irrigation. During use, part of that water—the *consumptive use*—will be transformed into green water flow, while the surplus (non-consumed part) forms a return flow of blue water. When agrochemicals are used and when run-off flow carries sediments from erosion, the return flow is loaded with leached agrochemicals and soil nutrients, causing eutrophication in the water system and the coastal waters where the blue water flow empties.

(c) *Ecosystems and their water determinants*

The concept 'ecosystems' is a biological construction referring to the interaction between groups of organisms involved in production, consumption and decomposition, respectively, and their bio-physical environment. The link to hydrology and water management is the *water determinants* of a specific ecosystem, i.e. the water characteristics that determine the habitats, the growing conditions, etc. Ecosystems are genuinely water dependent: some types are rainwater dependent like forests or bogs, others are groundwater dependent like groundwater-fed marshes and coral reefs, whereas others again are surface water dependent like recharge floodplains and shallow lakes (Mitsch & Gosselink 2000). Water-related ecological service providers may be related to either terrestrial ecosystems productivity or to aquatic system productivity. Both types of productivity have to be kept operational. At the same time

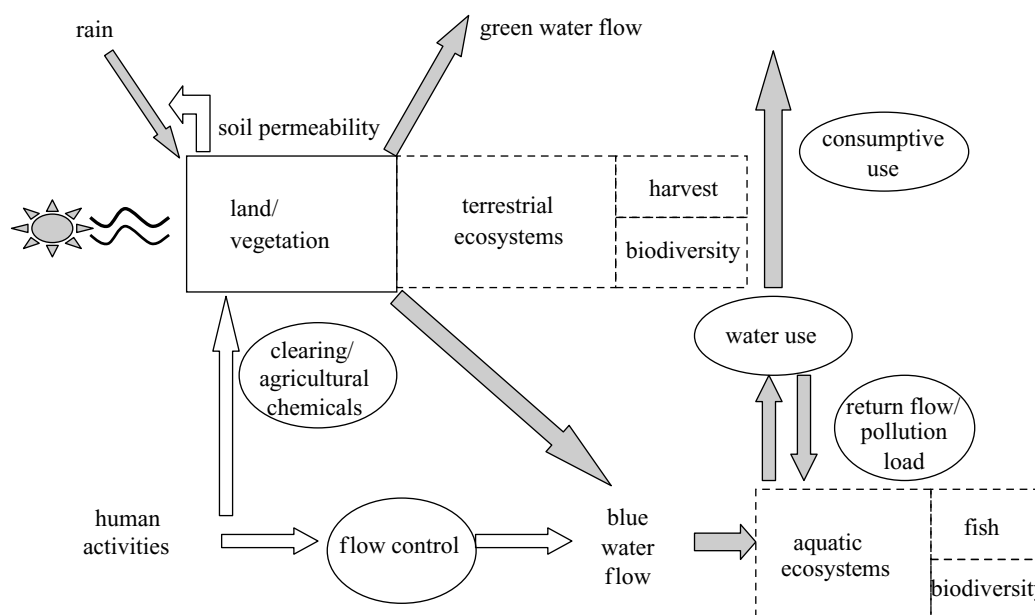


Figure 4. Ecosystems may be impacted from three different societal entry points: by land-use activities, by water use and introduced pollution load, and by flow control measures. The grey arrows denote water flow and the open arrows denote causal links.

it seems essential to distinguish between upland ecosystems involved in rainwater partitioning between the evaporating part, the floodflow part and the groundwater-forming part, and downstream ecosystems which can be seen as victims of both upstream water quality degradation, river depletion due to increase in consumptive water use, and seasonality changes.

To be able to decide on ecosystem conservation, the relevant water-related determinants have to be clarified. They indicate the way in which the ecosystems may be disturbed by water management or mismanagement. These determinants include water flow, water pathways, flow seasonality, water table and chemical composition. They may be impacted from three different societal entry points and mediated by water cycle linkages and by both direct and indirect water-related activities: both by land use, by water use and introduced pollution load, and by flow control measures. Figure 4 visualizes water-related causal chains between alterations of ecosystem goods (e.g. biomass harvest) and services (e.g. the role of biodiversity in pollination), on the one hand, and the causing human activities in the landscape, related to the supply of food, water and energy as well as the generation of income, on the other. Basically three entry points are involved in these modifications of ecosystem water determinants: flow control measures to fit flow to water demand seasonality; land cover changes influencing soil permeability and rainwater partitioning, and consequently run-off generation; water withdrawals and after use alterations in terms of consumptive water use and pollution load, respectively.

In the catchment, there is an important upstream/downstream dimension to be paid attention to in the trade-offs that have to be struck in an integrated water resources management (Falkenmark 1999). The upland part of a catchment or river basin hosts several *water-impacting* activities: land-use conversions, flow modifications, pollution load, etc. Together they influence the river flow and the seasonality and quality of the water

flowing into the downstream area. The downstream stakeholders are involved in several *water-dependent* activities: both direct water use for households, municipalities, industry, irrigated agriculture, etc., and ecological services within riparian wetlands, aquatic ecosystems and coastal ecosystems.

3. COEVOLUTION OF SOCIETY AND ENVIRONMENT

In understanding main phenomena behind the development of environmental problems and ecosystem degradation, it is important to have an idea of the main links between society and the landscape (Falkenmark 1997).

(a) *Unavoidable interferences and their side-effects*

Human activities are driven by political imperatives in terms of meeting societal demands for life-support: water, food, timber, energy and shelter. Societal leaders are expected to secure or at least facilitate access to these goods and services, fundamental for poverty eradication and human welfare. The provision of these services depends on interferences with the landscape that hosts the natural resources involved. There is a need for *biophysical interference* in both land (clearing, tilling, etc.) and water pathways (wells, pipelines, storages) (Falkenmark & Mikulski 1994). There are also the *chemical interferences*, originating from exhaust gases, solid refuse, wastewater and agricultural chemicals. One can even say that with human activities and socio-economic development goes waste production (Falkenmark & Lundqvist 2000).

Owing to particular water-related natural processes going on in the landscape, these interferences will be reflected in unintended side-effects. Three different water-related processes in the landscape are involved in the generation of side-effects of human landscape modifications:

- (i) the *partitioning* of the incoming rainfall at the ground surface, first between flood-flow-forming overland flow and infiltration into the soil, second between evapotranspiration and groundwater recharge;
- (ii) water's dissolvent capacity making it a *unique solvent on continuous move* above and below the ground, picking up everything that is water soluble and carrying it along; and
- (iii) water's mobility in the *water cycle with its continuity and integrity*, producing continuity-based chain effects in terms of onwards transport from the atmosphere to the ground and the terrestrial ecosystems, then onwards to the groundwater and the rivers, lakes and aquatic ecosystems, and then onwards again to the coastal waters and their ecosystems.

These links between social and environmental processes were analysed by Van der Leeuw *et al.* (2001) after studying land degradation in the Mediterranean region over a period of human activities during 20 000 years. They covered badlands, droughts and flash floods in Spain, salinization and water mismanagement in southern Greece, a mix of tectonic activity and human interactions with vegetation in northwestern Greece, and 7000 years of human activity in the Rhone valley in France. The outcome suggested that no single set of natural dynamics could be identified that was responsible for the land degradation. Rather, it was the result of a converging set of social processes, interacting with the surrounding environment, i.e. a coevolution of social and environmental processes (Norgaard 1994; Berkes & Folke 1998). Human reaction to environmental change was found to be less direct than other species because society has to become aware before it can consciously respond. They found the interrelationship to be more of resonance character than of cause-effect. The study also came to question the idea of sustainability in the meaning to continue living as we do forever, an idea which rests on the assumption that stability is natural and humanly achievable. The long-term perspective of the study, however, suggests this to be an illusion. Stability is probably an exception worth particular analysis. The consequence is that rather than assuming stability and explaining change, one needs to assume change and explain stability (see figure 5).

(b) *Resilience against disturbances*

Once it has been realized that human actions have become a major structuring factor of the dynamics of ecological systems or even the biosphere as a whole, the earlier worldview of nature and society as systems near equilibrium is now slowly being replaced by a dynamic view. Humanity, through its activities, tends to alter natural disturbance regimes with which organisms have evolved over time. Today's disturbances may be quite diverse: they may be natural like droughts, unnatural like contaminants, and combined ones like fires. There is therefore a need to secure ecosystem resilience (Holling 1986, 1996), i.e. *secure ecosystem capacity to absorb continuous change without loss of the dynamic capacity to uphold the supply of ecological goods and services* (Folke *et al.* 2002).

Without resilience, ecosystems would respond to gradual change by sudden switches to contrasting regimes, such change may be triggered by stochastic events like

storms, fire, drought or sudden pollution events. Resilience is a key property of both social and ecological systems. It provides the capacity to absorb change without losing functions and the self-organizing ability for repair, renewal and reorganization following change (Folke *et al.* 2002). When a social or an ecological system loses resilience, it becomes vulnerable to change that could previously be absorbed. A change of state takes place that may cause societal problems due to disruption of previous ways of life. As resilience declines, it takes progressively smaller external events to cause catastrophe. Reducing resilience in other words increases vulnerability.

Loss of resilience in early civilizations has over time resulted in environmental degradation, sometimes so severe as to cause the downfall of whole societies. One example where human activities generated first the rise of the human society is Easter Island in the Pacific Ocean but later, owing to loss of ecosystem resilience, also the fall of that society (Redman 1999). This was a centralized and well organized society, driven by the urge to demonstrate power to neighbouring clans and led by a leader trying to outdo the next. Their activities were able to shift the ecosystem from a natural open forest system to a state of almost complete desertification. The main cause was extensive deforestation to harvest the timber required to transport huge stone statues from inland quarries to platforms along the coast where they were raised. Two hundred enormous statues still remain, with 700 more left in some stage of preparation in the collapsing ecosystem. Deforestation most probably resulted in increased wind and water erosion, increasingly degrading the soils which already from their natural state were inherently vulnerable to erosion and a consequent loss of essential ecosystem services.

Although resilience is a buffer to disturbance, this buffer is provided through functional roles of *biological diversity* which act as insurance in this context, and involves many organisms with mutually overlapping functions for restoring ecosystem capacity to generate essential ecological services (Peterson *et al.* 1998). A minimum composition of organisms has to be retained to secure the basic relationships between the primary producers, consumers and decomposers that mediate the flow of energy, the cycling of elements and spatial and temporal patterns of vegetation. For any ecosystem function to be sustained, freshwater provides the foundation for the processes involved: a foundation that has largely been neglected in the past (Falkenmark & Folke 2002). Loss of functional biodiversity reduces ecosystem resilience and threatens the function of the system and thereby economic activity and human welfare. Components that can re-establish ecosystems following disturbance are essential to protect. This includes three things: biological legacies, mobile links and support areas for those links (Lundberg & Moberg 2003). Water is fundamental for all these three reorganization components: biological legacies left in the area as cores for recovery like trees and seeds; mobile links like entering birds carrying seeds, or bats pollinating plants; and support areas for those links, like reserves or refugia in areas not hit by the same disturbance.

In a catchment-based adaptive management (Folke 2003), the golden rule will be not to allow any discernible ecosystem degradation to proceed too far, i.e. come too

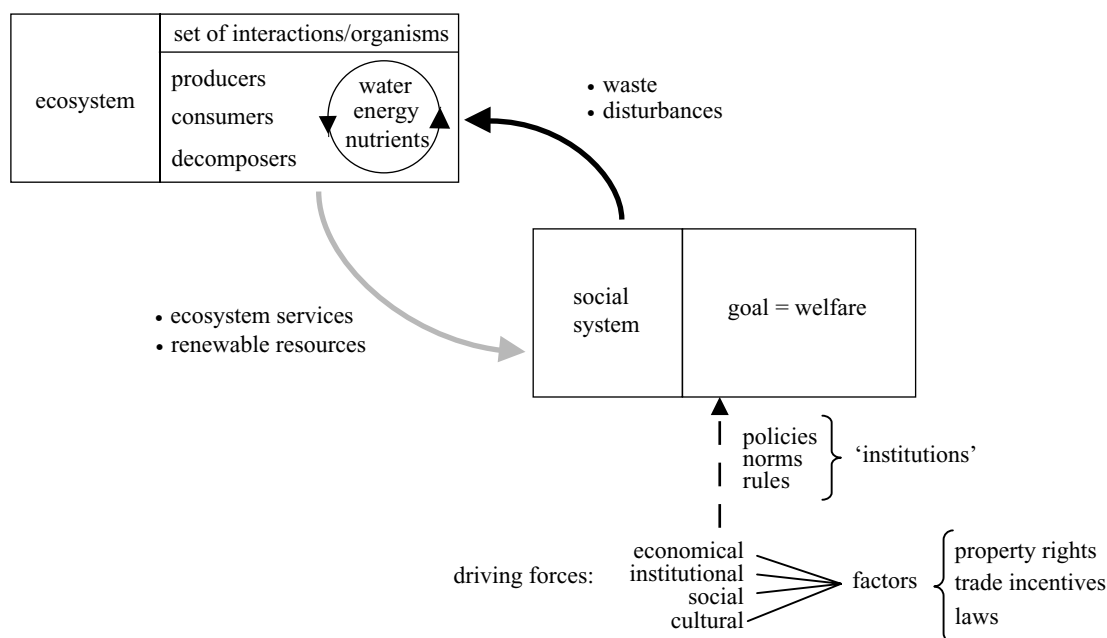


Figure 5. Humanity critically depends on ecological links between nature and society. Because driving forces are acting on the social system, ecosystem management is a question of living with change while securing long-term ecosystem productivity.

close to a collapse of the ecosystem state. The goal has to be to protect the basis for the life-support system of the region. The overarching aim is to protect the ecosystems from creeping changes that might make them flip into a different state with lower ability to produce ecological goods and services (Scheffer *et al.* 2001). At the present level of understanding, management has to focus on slow variables influencing the functioning of the particular ecosystem in question (Carpenter *et al.* 2001). These variables include land use, nutrient stocks, soil properties and biomass of long-lived organisms. Because both land use and soil properties are intimately linked to water processes and functions, water variables will have to be added at the next level of understanding, primarily water flow regime, green water flow and toxic water pollution.

4. REAL WORLD CHALLENGES

(a) *Two partly incompatible imperatives*

A fundamental problem in development of quality of life and economic welfare is evidently the previously discussed modifications of various phenomena in the landscape that such development involves, and the generated side-effects on local ecosystems and the services they generate for human wellbeing. The process has to proceed within environmental constraints, represented by water resource limitations and natural processes at work in the landscape. The implications are the development of environmental side-effects and goal conflicts.

The Millennium Declaration 2000, agreed upon in the United Nations by world leaders, involves a set of *human livelihood imperatives*, many of which are closely water-related: to halve by 2015 the population suffering from poverty, from hunger, from ill health and from lack of safe drinking water. A particularly crucial question will be the water-mediated implications for different ecosystems of the growing food and biomass needs for a growing humanity (Falkenmark & Rockström 2003). There is,

besides this socially oriented imperative, also a parallel *ecosystem imperative*. The awareness that ecosystems have to be respected is already widespread among water managers. From the shared dependence on water of the coevolving system of humanity and ecosystems follows that proper attention to ecosystems is increasingly being entered into water management (GWP 2003).

Real-world illustrations of direct and indirect water flow interferences in developing countries are closely linked to economic development. Efforts for improving human livelihoods often proceed without much attention paid to the management of ecosystem services. The frequent incompatibility of these two aspects is the origin of numerous controversial environment-related issues around the world and methods are badly needed for reconciliation of conflicting interests. There is, for instance, an evident link between inland activities for food production and income generation among poor communities in upland regions of the catchment, on the one hand, and poor communities in the coastal region, living on downstream wetlands or dependent on fishery in the coastal regions, on the other. A few examples may illustrate typical issues: one set related to *land cover changes* with effects on the green/blue water partitioning and higher-order effects on ecosystems; the other set related to *upstream water diversions* leading to river depletion and therefore effects on downstream water use and aquatic ecosystems.

(i) *Land cover changes with effects on water and ecosystems*

Some examples from the past of this type of interference are the widespread deforestation of Australian woodlands by European immigrants that altered run-off generation and groundwater recharge, and caused water and dryland salinization and, as higher-order effects, ecosystem damage (Calder 1999; Gordon *et al.* 2003); the deforestation of Lake Malawi's catchment in the second half of the twentieth century, increasing outflow into Lake Malawi and causing a lake level rise that protected the surrounding

populations from an even larger lake level decrease during later droughts (Calder 1999); and regional afforestation in South Africa through spread of alien trees from commercial forest plantations and causing river depletion (Van Wilgen *et al.* 1998).

Many of today's plans for socio-economic development also involve land-cover changes: large-scale deforestation planned in the Puebla–Panama region, involving a massive infrastructure project including highways and rail links across Central America, which will threaten ecosystems and is strongly opposed by the indigenous population (S. Davila-Poblete, personal communication); a plan supported by the World Bank for afforestation in the Panama canal catchment, intended to increase run-off and thereby improve the navigation activities in the canal, however, predicted to reduce run-off even more (I. R. Calder, personal communication); and a Philippino foresters' proposal to re-afforest headwater catchments to Cebu city's raw water sources with the aim of counteracting ongoing salinity intrusion, however, predicted to worsen the problem rather than mediate it (Calder 1999).

(ii) *Water diversions with effects on downstream water use and ecosystems*

One of the most well-known examples from the past is linked to the economic development of the Aral Sea basin, based on irrigated cotton and wheat production, leading to severe river depletion and water pollution, with severe consequences in terms of massive effects on human health, especially mothers and children; and dramatic lake depletion, cutting the Aral Sea in two halves causing severe degradation of the lake ecosystem.

Two now actualized diversion plans are linked to the Okavango river, involving upstream economic development in Namibia and Angola with an out-of-basin transfer to the Windhoek region, modifying the aquatic ecosystems in the Okavango delta (Ashton 2002); and the water resources development of the mainstream Mekong river, altering the conditions, i.e. for seasonal fish migration and possibilities to spawn and feed in flooded areas, including the floodplain of Tonle Sap Great Lake, the vast wetlands in south Laos and the Vietnamese delta (Baran & Baird 2001).

(b) Two fundamental water–ecosystem challenges

Evidently, the water–ecosystem linkages are working in opposite directions for terrestrial as opposed to aquatic ecosystems. Whereas aquatic ecosystems are victims of river flow alterations, the management of terrestrial ecosystems may cause such alterations.

As already indicated, *terrestrial ecosystems* play a crucial role in the partitioning of the rainfall between the evaporating part and the run-off generation part. Changes in land cover affect the relative proportions of green to blue water flows and the proportions of fast-flowing surface storm run-off and slow-flowing groundwater recharge feeding rivers at downstream locations in a drainage basin. The impact on local water balance of degradation of land cover, e.g. deforestation, has been extensively documented, with substantial increases in long-term run-off and stormflow as typical results. Although the total run-off increases after deforestation, the principal source of increase is from savings in transpiration by the replacement of deeper-rooted trees by shallower-rooted low crops

(Calder (1999) and Bonell in GWP (1999)). Thus the largest increase is concerned with the delayed flow component of the stream hydrograph. In the tropical forest ecosystem, the surface soil hydraulic properties may be vulnerable to change through compaction on removal of the forest. The antecedent proliferation of macropores is lost because there is no longer the ability to incorporate biomass and associated biological activity of the forest.

A practical application of this understanding is the impressive Working for Water programme in South Africa (Van Wilgen *et al.* 1998). It involves 40 000 people for an anticipated 20 years in an effort to clear away a rapidly spreading alien vegetation of a tree species without natural enemies that were introduced earlier by forest companies. The twin goals of this megaproject are to gain an additional 10% in blue water flow and to recover the typical fynbos vegetation in the Western Cape.

Because, however, *aquatic ecosystems* are genuinely blue-water dependent, they are vulnerable to changes in river inflow and therefore to upstream river regulations, pollution loads and consumptive use. As groundwater is linked to the river, over-exploitation of groundwater resources can also affect aquatic ecosystems by reducing the river flow during periods of the year critical to instream ecology (Elliot *et al.* 1999 in Dunbar & Acreman 2001). Human activities include—besides overfishing and introduction of exotic species—toxic pollution, eutrophication, river depletion, etc. Especially vulnerable are aquatic ecosystems in the downstream part of a catchment as their habitats tend to accumulate the impacts from upstream disturbances.

5. FACING THE CHALLENGE

The previously mentioned ecosystem imperative has to be addressed on two parallel scales: the local scale referring to site-specific biotic landscape components of special social value; and the catchment scale which for ecological reasons has to be managed as an asset that delivers a bundle of water and ecological goods and services. Some of these services work in synergy, others are in conflict (GWP 1999).

(a) Protection of site-specific biological entities

Owing to interesting endemic species, valuable biodiversity, beautiful landscape or riverscape, etc., particular biological entities like a certain forest, a lake or a coastal wetland need to be protected in a catchment. Such entities may be terrestrial or aquatic. In the case of aquatic ones, it will be essential to secure acceptable habitat situations by avoiding water pollution that would degrade them, and influence fishery. Environmental flow will therefore have to be secured both in terms of flood episodes and uncommitted river flow of acceptable quality. Such ecosystem protection may be emotionally and/or ecologically motivated. In either sense, protection would basically mean to protect it from the risk of collapse or flip to a different, unwanted state (Folke *et al.* 2002). This would imply, for instance, to counteract a clear lake turning turbid; a cloud forest collapsing; a semi-arid rangeland turning from pasture to woody vegetation; a savannah agro-ecosystem flipping to a lower yield level due to soil mismanagement, or suffering from upwind deforestation through atmospheric moisture feedback.

(b) Catchment-based ecosystem approach

Ecosystems have to be addressed also on the catchment scale by managing ecological services and water in an integrated way. A catchment-based ecosystem approach can be central in adaptive management where dynamics, uncertainty and response to surprises are basic underlying ideas (GWP 2000). This means analysing the main types of ecosystem and the ecological services that they contribute, and to find out what has to be done to secure a sustainable supply of those services. The catchment has, in other words, to be managed in an adaptive way to protect resilience of the life-support system to surprises and shocks, and to avoid flips to a more vulnerable state. A particular challenge here is to identify resilience determinants to avoid ecosystem collapses. Here, the terrestrial ecosystems are of importance also as determinants of run-off production. Protecting them is basically an issue of putting constraints on land-use change. The more green water they consume, the less will be the rainwater surplus left for run-off production. They are important also for securing groundwater recharge and dry season flow.

As shown earlier, attention has to be paid to two basic categories of anthropogenic manipulation (cf. figure 4): change of water flows and change of land or vegetation. In the catchment approach, three key directions have to be incorporated in the emerging management system: *securing* water-related services to the population, *avoiding* ecosystem degradation, and *foreseeing* changes and variability. A fundamental way of approach must be to identify 'bottom lines' for ecosystems and their functions, terrestrial as well as aquatic. When balancing upstream against downstream interests, one has to identify downstream uncommitted environmental flows and minimum water quality (Wang 2002), and then to move segment-wise upstream.

(c) Integrated catchment approach by merging water, land use and ecosystem management

The social-ecological linkages evidently make it essential to learn how to strike a balance between socio-economic development and maintenance of the productive capacity of ecosystems. At the core of this issue is how effectively and purposefully humans manage to benefit from use of land and water resources. A dynamic approach will be essential to safeguard improved living conditions for the local population. Through improvements in technology, organization, management, land-use combination, etc., humans are evidently able to produce more desirable goods and services within the same (or even less) input of land and water. Such improvements may or may not involve more input of labour, better coordination among neighbours, etc. It has to be realized, for instance, that the idea of 'more crop per drop' is not necessarily equivalent to 'more crop per hour of work'. It therefore includes also a challenge of 'social acceptance'.

In this context, we need to better understand the *mosaic of ecosystems (in the sense biotic landscape components) in catchments* and how they affect and are affected by human activities, and how they are linked by water flows, and in particular the role of freshwater in securing the system capacity to sustain both the production of food and the protection of essential ecological services under conditions of change and uncertainty. We have, in other words, to

find out how to link water security, environmental security and food security, all of them closely related through the water cycle, but in the past treated as separate issues.

But there is also a *mosaic of hydronomic zones* to pay attention to (Molden *et al.* 2001), defined primarily from what happens to return flows after water use: whether they are recoverable and can be reused downstream, or whether not, because return flows go to sinks or stagnation zones or to the sea, or involve poor quality.

What has been argued in this paper is that the catchment functions as a *socio-ecohydrological system* (Falkenmark & Folke 2002) in which trade-offs must be identified and choices made intentionally. At the same time, broad social acceptance of the results of those trade-offs has to be secured, implementation made possible in terms of institutions, regulations and financing needed, and the implementation realized by securing adequate incentives and education efforts. In these efforts, complications will, however, emerge, i.e. continuous change in terms of further land-use and water-use modifications, driven by ongoing population growth, urban migration and increasing expectations. Moreover, response delays have to be accepted that will complicate the efforts: delays in both societal response, hydrologic response and ecosystem response (Meybeck 2001). Finally, triggering events will have to be expected in terms of intervening drought events, flood events and pollution episodes.

(d) Conceptual approaches

A few examples may be mentioned to illustrate recent efforts to address the necessary trade-offs between social and ecological aspects. In China, a policy switch is ongoing (Wang 2002) in the Yellow River basin from the fragmented and project-based management of the past towards a resource-based water management. Four major problems will have to be mastered: floods where water is seen more as a problem than a resource; severe water pollution; massive silt loads; and severe water shortage with drying up of a long downstream stretch. Minimum criteria will be developed for both water quantity and quality in the river, starting from the downstream end. By moving stepwise upstream from province to province, inflow and outflow to each stretch will be defined. The downstream 'bottom line' will be the minimum outflow necessary to keep the river mouth open to protect, i.e. its wetland preserve and avoid disappearance of birds; and to avoid sea water erosion and salt water intrusion into the groundwater. Each stretch will then be allocated an inflow from upstream and be responsible for leaving a certain outflow for the downstream neighbour with proper attention paid to both water quantity and quality. The idea is, finally, that highest priority should be given to water's ecological function while the priority relations between all the other water uses will have to be further debated.

When it comes to protection of aquatic ecosystems, a recent approach includes definition of a reserve, based on the environmental flow concept. The minimum flow needed to protect aquatic ecosystems and their ecological processes and biodiversity has been analysed by Smakhtin *et al.* (2003). In monsoon-driven river systems, where aquatic life is used to extended periods of low or no flow, the environmental flow requirements are assessed at only 30% of average flow. In regions with more stable flow,

ecosystems are more sensible to water shortage and 50% of the average flow is seen as the minimum requirement. South Africa, in its new National Water Act of 1998 has introduced a reserve of water to be given first priority and incorporating water for basic human needs (25 l d^{-1}) and for aquatic ecosystems, respectively. The latter is specified in terms of both quantity and quality, varying according to the management class of the river. In the 2002 draft National Water Resource Strategy, the quantity (environmental flow) has recently been estimated for different rivers to between 11% and 28% of the medium annual flow (South Africa 2002).

Australia has introduced the concept 'working rivers' (Whittington 2002). A healthy working river is managed to sustain at the same time an agreed level of work and river health. It refers to 'a managed river in which there is a sustainable compromise, agreed to by the community, between the condition of the natural ecosystem and the level of human use.... Working rivers will not look like nor will they function in the same way as pristine rivers. In general, the more work the river is made to do the less natural it becomes.... A different compromise may be struck between the level of work and the loss of naturalness, depending upon the values the community places on any river' (Whittington 2002, p. 3).

(e) *Four basic perspectives*

The basic challenge in a catchment can be summarized as managing the water flowing down a catchment while orchestrating for compatibility between land use/water, humans/ecosystems, upstream/downstream and present/future generations. The basic resource has to be seen as the precipitation caught within the water divide of the catchment, and partitioned between green water flows linked to consumptive water use by terrestrial ecosystems and by non-productive water losses, and the blue water flow available for societal use and forming habitats for aquatic ecosystems. The management has to incorporate four basic perspectives: the social, the ecological, the economic and the resource perspectives, respectively.

The *ecological perspective* involves attention to terrestrial ecosystems and their involvement in local run-off generation, and to aquatic ecosystems and their dependence on uncommitted environmental flows of adequate quality. When certain highly appreciated local ecosystems have to be protected, their particular water determinants have to be identified. The long-term resilience of the overall system has to be properly analysed and secured for the benefit of coming generations.

The *social perspective* involves meeting human needs in terms of safe household water, water-dependent food production, and—in view of present techniques deficiencies—water-polluting income generation activities. Securing societal acceptance of necessary trade-offs is essential by effective ways of stakeholder participation in planning and decision making. It also involves the challenge to motivate people to accept or abide to the laws of nature and to put in more (rather than less) effort to realize development aspirations.

The *economic perspective* involves the challenge of how to best to allocate water to yield the best overall results. It also involves attention to benefit–cost relations, financing challenges, cost coverage to secure operation and

maintenance of water in infrastructures, incentives to encourage implementation, and guidance from the values of water in different functions.

The *resource perspective*, finally, implies that attention has to be paid to both blue and green water and the partitioning of the rainfall between these two flows. Blue water is the one that is directly manageable, but at the same time influenced by land-use and land-cover changes (cf. Gordon *et al.* 2003). At the focus will be blue water accessibility; consumptive use and return flows along the river; how much blue water can be mobilized and put to societal use along different water stretches, while respecting the need for uncommitted environmental flow in the river. The management efforts will have to include preparedness for a policy switch when a basin goes from being open to being closed (Molden *et al.* 2001), in the sense that there remains no blue water surplus available for beneficial consumptive use.

6. CONCLUSIONS

What has been shown in this paper is that the overall problematique boils down to finding ways of meeting at the same time immediate societal needs through proper management of ecosystem services, and long-term ecosystem needs to secure social and economic development. The societal needs generally call for manipulation of landscape components in terms of water pathways and land cover. Owing to water's consequence-producing functions, side-effects of such manipulations will be unavoidable and involve disturbances of water-dependent ecosystems. At the same time, ecosystem functions in the water cycle have to be taken into account: terrestrial ecosystems are on the one hand water-consuming but may on the other hand facilitate groundwater recharge, thereby securing dry season flow; aquatic ecosystems are on the one hand blue-water dependent and therefore vulnerable to change when river flow, seasonality and/or water quality are altered, but are on the other hand interacting with certain water pollution components, partially reducing water pollution problems. The real challenge is to find out what is the 'best possible manipulation', not the 'least possible manipulation'.

It follows from the above discussion that freshwater management has to be integrated with the management of ecosystem dynamics. This is equivalent to finding ways and means to merge water management, land-use management and ecosystem management (terrestrial as well as aquatic) within a socio-ecohydrological catchment management: with full awareness of the different ethical dilemmas involved. Because land use and terrestrial ecosystems are green-water dependent whereas societal water needs and aquatic ecosystems are blue-water dependent, and the blue and green water flow branches are the result of the partitioning of incoming precipitation, the ultimate resource is the precipitation over the catchment. Adequate attention has to be paid to the fact that water is deeply involved from many different perspectives through its many parallel functions:

- (i) as societal support: health, socio-economic production, food/timber production and energy production;

- (ii) in ecological services, both in terrestrial and aquatic ecosystems;
- (iii) in environmental threats from floods, droughts, diseases; and
- (iv) in its function as a 'silent destroyer' through erosion/sedimentation and solute transport.

The ecosystem approach will have to be taken on different scales: both on the catchment scale by attention to fundamental links between terrestrial ecosystems upstream and aquatic ecosystems downstream; and on the local scale by protection of particular biotic landscape components in view of their value, such as a lake, a wood or a wetland. At the present level of understanding, the ecosystem approach to catchment management is a rather lofty concept that will have to be further developed to facilitate constructive use on the catchment scale. The catchment contains a mosaic of smaller-scale ecosystems, defined by the abiotic character of the surroundings which shift as one moves from the water divide down to downstream floodplains and delta areas. Ecosystems with different localization are internally linked by the water flow through the catchment.

The basic criterion for a catchment-based ecosystem approach is that it will have to incorporate efforts to protect the production of essential ecosystem goods and services on which the welfare of the society is based. In doing this, one has to remember that there are *many entry points for human ecosystem interference*: both directly through interference with local flows and pathways, and indirectly through interference with soil permeability and vegetation, but also through moisture feedback from distant green-water disturbances, influencing rainfall. Water has to be addressed as the shared bloodstream in the catchment system in the ensemble of all its different functions: as life-support flows, in the water partitioning functions, the lift up/carry away function and the cycle-based transport continuity function.

(a) *Conceptual modernization*

What has now to be developed includes a set of challenges: the ability to define, value and socially accept trade-offs; to define ecological 'bottom lines'; to realistic social and ecological criteria that can be respected; and to develop sustainability principles based on an understanding of what resilience will demand.

The water-ecosystem relations at large represent an area with more advocacy than scientific understanding and conceptual clarity, full of folklore and myths that hinder rational decision making (Calder 1999). The scientifically best developed area in relation to freshwater management is *aquatic ecosystems*, their value and what key determinants should be entered into water management, e.g. uncommitted environmental flows, flood-mimicking dam releases, etc. Misleading simplifications, however, tend to remain, especially regarding *wetlands*—biologically defined phenomena characterized by their soil anoxia and resulting vegetation—which may, however, be of very different hydrological origin in terms of the water that keeps the wetland wet, and consequently their links to water management.

An area of equal relevance in terms of close water-ecosystem interactions, but where the water perspective has

attracted much less attention, is *terrestrial ecosystems*, especially forests. Perceptions that forests are good for the environment and water resources are deeply ingrained in public awareness and have even 'become enshrined in influential policy documents' (Calder 1999). After thorough analysis of a set of 'mother statements' in terms of assumed environment/hydrology benefits and scientific evidence they were found to be at best marginal and at worst negative instead of positive. The previously indicated land/water dichotomy is reflected in the lack of attention, in global change research and to the involvement of green-water flow in the carbon sequestration process. This water blindness is all the more remarkable because, as shown by Berndes (2002), a large-scale expansion of energy crop production (in line with scenarios developed by the International Institute of Applied Systems Analysis and World Energy Council) would lead to *an additional green-water flow appropriation of the same order of magnitude as the current water consumption by croplands, whether irrigated or rain-fed*.

Thus, the research community will have to address several *conceptual challenges*. Focus has to be moved from water withdrawals to what happens to water after use, to ecosystems' water determinants and to their hydrological functions (consumptive water use, influence on groundwater recharge, water quality modifying functions). Finally, water-related determinants of resilience have to be identified and water's involvement in resilience erosion and the collapse of ecosystems, such as salinization of fertile soils, collapse of cloud forests, shrub development of savannahs, or eutrophication of lakes, identified.

In catchment-based ecosystem management, two complementary focuses will have to be introduced in terms of scale: on the one hand, where focus is on site-specific ecosystems in the sense of living landscape components (a lake, a wetland, a forest, etc.) in need of being protected and how to best protect their particular water determinants; on the other hand, the challenge of catchment-based balancing of non-compatible perspectives of human support versus ecological protection in the sense of protection of ecosystem productivity and functions.

Whereas in the former ecosystems, humans are seen as perturbators, they are seen as part of the ecosystem in the latter. The scientific community should activate itself in developing a synthesized human ecology which pays adequate attention to the multitudes of roles and functions of water, the bloodstream of the biosphere. Moreover, to facilitate a mutual understanding between ecologists and water managers, ecologists need to be more limpid and specific when using the extremely broad concept 'ecosystem'.

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