Harmonizing agricultural and environmental uses of water

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ABSTRACT

Development in general and especially agricultural development depends on development of water resources. The quantity of water available for development and the quality of this water much depend on the "environment", equated with natural ecosystems. Many of the natural functioning of ecosystems constitute life-support "services" to humankind, of which the renewal, storage and purification of the human-appropriated surface- and groundwater are most critical, especially in drylands where agricultural, rural and urban development are heavily dependent on irrigation and good quality water supplies. Biodiversity, the divergent array of plant, animal and microorganism species that is an integral component of ecosystems, is instrumental in the provision of ecosystem services. Many of these species are of realized or potential economic benefit - ecosystem "goods". An important service of ecosystems is the maintenance of these goods. Many ecosystem goods and services are not related to water, yet are essential for agricultural and other development: services such as soil conservation, flood prevention, pollination, pest control, decomposition and nutrient recycling, and goods such as progenitors and wild relatives of cultivated plants and potentially new cultivable species. Yet other ecosystem services and goods are not directly related to agriculture, but are vital for human survival and economic growth, such as the service of climate control through the maintenance of the chemical composition of the atmosphere, and goods such as peripheral populations of plant species expected to be resistant to global warming.

Water resource development often reduces the provision of ecosystem goods and services, either directly or indirectly. Directly, by damaging biodiversity of aquatic ecosystems, and by denying water from terrestrial biodiversity. Indirectly, through damage caused by agricultural development, that is enabled by water resource development. The damages of agriculture to biodiversity and ecosystem services are direct and indirect too. The direct ones are through

the irrigation-induced salinization and the use of pesticides and fertilizers; these not only harm agriculture, but also water resources. The indirect damages are through the appropriation of land by agriculture, land that otherwise would have harbored natural ecosystems, providing goods and services. Thus, water resource development has the potential, which is too often realized, to undermine the sustainability of its very development, and thus render the consequent agricultural development non-sustainable.

Agricultural development and the water resource development that drives it, as well as the welfare of humankind associated with these development efforts can be sustainable when an ample provision of ecosystem goods and services is guaranteed. This requires the conservation of biodiversity, which is instrumental in this provision. To achieve it, the benefits of proposed developments should be evaluated against the cost of lost biodiversity components and the consequent reduction of ecosystem goods and services. The valuation of biodiversity is therefore the prerequisite for harmonizing development with the environment. Recommended conservation measures include optimizing land allocation between natural ecosystems and agriculture; securing water resources for natural sustenance of terrestrial ecosystems; and allocating water resources, including when necessary treated wastewater, to aquatic ecosystems. Much research, especially in valuation methodologies, is required for successfully implementing these measures. Yet knowledge already available should be used to design and carry out development that allows the environment to guarantee the sustainability of that development.

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INTRODUCTION

Freshwater is a natural renewable resource exploited by humans for their domestic, agricultural, industrial and recreational uses. Most of these uses are essential for survival of individuals and societies, and in many cases water availability limits economic growth. Thus, humans *need* water, as well as other natural resources, to sustain their livelihood and economy. This has been known for centuries, but in recent decades the notion that humans *need* also the "environment" has evolved. At first, the environment has been viewed as a sort of luxury, to be concerned about only after other issues pertaining to survival and well being have been settled. But in recent years there is a growing recognition of the survival value of the environment. In this paper, it is proposed: (a) that much of the survival value of the environment for humans is in its role in renewal of the utilized freshwater resources - their quantity and quality; and (b) that in order to perform this role, the environment itself, just like agriculture and industry for example, requires water and should therefore be a legitimate water customer. Hence, in order to maintain the sustainability of water use for survival and economic purposes, it is necessary to protect the environment, partly by allocating to it a share of the very water it is instrumental in providing us. In the first part of the paper the concept of environment, ecosystem, ecosystem goods and services, and biodiversity, in relation to water use are presented. In the second part the environmental implications of water resource development and the consequent agricultural development are discussed. Finally means for mitigating the damages and striking a balance among environmental, agricultural and other objectives are recommended.

THE IMPORTANCE OF ECOSYSTEMS TO WATER SUPPLIES

Environment and ecosystems

Many people associate "environment" with forests, rivers, national parks and other outdoor entities. The term is also applied to the quality of "commons" such as air, soil, and water. Technically, "environment" is associated with the notion of the ecosystem. An ecosystem is a landscape unit comprising all its individual organisms and the physical and chemical attributes of that landscape, some of which affect, affected by, or interact with the organisms living in that landscape. The network of interactions between the components of the ecosystem results in its functioning. The functioning of an ecosystem is the sum total of processes taking place within it, such as energy transformations and cycling of matter. Ecosystems do not occur only in "nature"; cities are ecosystems too, human-managed ones. Human-managed and utilized ecosystems now constitute half of the ice-free earth (11% of which is covered by crops), the other half can still be regarded "natural" ecosystems. Much of the functioning of natural ecosystems – the involved organisms, processes, conditions – constitute (often marketable) "goods" and generate (mostly free) "services" useful to humanity (Mooney et al. 1995). Through the provision of goods and services, natural ecosystems contribute to the sustainability of ecosystems that are intensively managed by humankind and promote the sustainability of people's lives. When activities destroy or impair the ability of natural ecosystems to provide their goods and services, the goods and services must be replaced by artificial means. Experience has shown that the artificial replacements for natural ecosystem goods and services are usually very expensive and often inferior to the natural ones. Because natural ecosystems provide these goods and services at no immediate financial cost, they appear to be free and their value and importance are often underestimated or overlooked entirely (Perrings 1995). To take advantage of these crucial goods and services, they must be recognized, understood and protected (Constanza et al. 1997).

Ecosystem services

Some of the services of terrestrial ecosystems directly affect the sustainability of water resources and supplies. Other services for sustaining water supplies are provided by natural freshwater ecosystems. Both terrestrial and aquatic ecosystems also provide services not related to water, but critical to human survival and economic development.

Services provided by terrestrial ecosystems. Terrestrial ecosystems are instrumental in driving and maintaining the hydrological cycle. The vegetation cover of terrestrial ecosystems controls the movement of water from the atmosphere (rainfall) to the shallow soil layers, and from these layers to deeper portions of the soil profile and into the groundwater. This vegetation also regulates the single largest flux from the biosphere to atmosphere - the flux of water from the soil to the atmosphere (Schlesinger 1991).

The density of vegetation and the physical architecture of canopies and roots of all plants combined, interact with physical features of the ecosystem, to determine the fate of raindrops: either to penetrates the soil directly, to generate runoff to be stored at varying distances and depths, or to end up in lakes or in the ocean. Vegetation architecture also provides shade, which reduces evaporation from topsoil. One ecosystem service of prime significance especially in drylands is therefore the provision and conservation of soil moisture as well as controlling groundwater fluxes and aquifer recharge (Mooney et al. 1995, 1995a).

The overall effect of the vegetation on the water balance of an ecosystem, a watershed, a landscape unit or a region, also depends on the structure of its plant community. A plant community is composed of all the species populations that inhabit the ecosystem, each of them having a different aboveground and belowground architecture. The spatial combination of the individuals of all species in the community determines the overall architecture of the vegetation, and hence the effects of the vegetation on the water balance of the ecosystem and on the water balance of adjacent and even distant ecosystems as well.

The physical architecture of plants, together with their physiology and phenology interacting with local climate, determine the amount and timing of water transfer to the atmosphere via transpiration and soil surface evaporation. On a global dimension, this process is clearly a service. In dryland regions this may be a "disservice". The balance of this "service" - "disservice" is not known. For Israel, for example, Stanhill (1993) calculated that 10,000 years ago, when the dry subhumid part of the country (receiving 400 to 800 mm annual rainfall) was mostly a natural, scrubland ecosystem, the potential water yield (volume of rain falling in a given year on a given surface area, minus volume of water returned to the atmosphere from the same area and year) was 1,590 km^3/year. This is lower than the current 1,846 km^3/year, when most of the area consists of cropland, a highly managed ecosystem. Natural scrubland ecosystems appear to evaporate more soil water than intensively managed ecosystems in Israel. However, the positive contributions of natural ecosystems in recharging aquifers—to the water balance of a country, compared to the contributions of intensively managed ecosystems, must be calculated too, and weighed against the losses due to evapotranspiration from the same ecosystems.

Both these counteracting ecosystem services controlling the hydrological cycle also generate indirect water-related services. With relation to water input, the dryland ecosystems' vegetation and soil crust-forming photosynthetic microorganisms, lichens and mosses (Boeken & Shachak 1994) prevent topsoil water erosion and control floods. This maintains the water-holding capacity of the soil and conserves productivity. It also controls soil salinity by leaching, reduces flood damages, hinders the clogging of artificial water reservoirs with silt, and prevents sedimentation, turbidity and eutrophication that reduce water quality in natural as well as man-made water bodies. With relation to water output, vegetation-controlled evapotranspiration generates evaporative cooling that may ameliorate local climate.

The ecosystem's vegetation, so instrumental in the provision of water-related services, especially in drylands, requires sustainable water supplies for its own survival, on which the provision of the services depends. Unlike agricultural crops, natural vegetation does not require irrigation. But natural vegetation needs to receive its natural water supply. This can be curtailed by development projects that intervene with the natural patterns of surface runoff and groundwater levels in a way that may reduce water supply to natural vegetation.

The same ecosystem that provides water-related services, may also provide other services, related to air, to soil or to both. Denying water from such ecosystem is therefore detrimental not only to water quality and quantity but also to the atmosphere and the soil. For example, natural ecosystems are heavily involved in the maintenance of the gaseous composition of the atmosphere, thus regulating the global air temperatures and hence global and local rainfall and evaporation patterns. Soil is a universal substrate for terrestrial biological production. Weathering of rocks in the Earth's crust produces soils, and organisms directly affect this weathering and also mediate the effects of water and air on weathering. Thus, one important ecosystem service is production and maintenance of soil. Soil can be lost by wind and water erosion at a rate orders of magnitudes faster than it is generated. Normally, soil erosion is slowed down or even totally prevented by vegetation cover. The vegetation of drylands, though sparse, plays a similar role, which is augmented by the biological soil crusts (Boeken & Shachak 1994).

Terrestrial ecosystems also generate services directly beneficial to agriculture, such as pollination, seed dispersal and pest control. Agriculture in the vicinity of natural ecosystems benefits from the pollination and seed dispersal services provided by wild insects, birds and mammals inhabiting these ecosystems. Natural ecosystems are also instrumental in agricultural pest control, be it bats that roost in natural ecosystems but prey on agricultural nocturnal insect pests, or other insects and birds that prey on nocturnal or diurnal pests. Finally, In addition to the economic value of many species, both individual species and the biota as a whole can be an unparalleled source of inspiration, as in sighting a group of wild animals and observing their behavior in nature, or watching the seasonal changes of forests. Recreational and leisure uses of the plants and animals, often based on their inspirational values, are increasingly being translated to economic benefit, in the form of tourism, and especially "ecotourism."

Services provided by freshwater ecosystems. Human interference with freshwater ecosystems such as lakes and rivers may occur at very small spatial scales, but may have dramatic effects at landscape to regional scale because their influence is out of all proportion to their size. Freshwater ecosystems in general, and particularly in drylands, contribute specialized services to the areas around them and even to whole regions. Important freshwater ecosystems are wetlands, streams and lakes.

Wetlands are lands where the water table is usually at or near the surface, or lands covered by shallow water, that have physical, chemical, and biological features reflecting recurrent or sustained inundation or saturation (Cowardin et al. 1979; NRC 1995). Wetlands have long been recognized as providing a key role in absorption of materials harmful to aquatic systems (Mooney et al. 1995). This is partly because wetlands are characterized by the slow rate of water movement in them. The slow water movement promotes the deposition of suspended material and provides ample time for the complete biological mineralization of organic compounds and biodegradation of synthetic toxic chemicals (NRC 1992). The slow water movement also supports typical wetland vegetation, which further slows water movement, and reduces the depth of the wetland, thus contributing to its spatial expansion. This expansion provides a unique ecosystem service: water storage during floods and a slow downstream release. Wetlands therefore lower flood peaks and their detrimental economic and environmental effect, such as soil erosion (NRC 1992).

The most significant ecosystem service of streams is the natural treatment of wastewater. This service is performed by aquatic organisms, mainly microorganisms and invertebrates that are facilitated by the oxidizing properties of the stream current and its velocity. Other components of the food web, such as aquatic herbivores and predators, are instrumental in regulating the populations of these wastewater-treating species, and in this way become involved in the quality of the wastewater treatment service of streams. Another service is associated with riparian ecosystems. The vegetation on the banks of streams influences the rate of water flow with consequent effects on hydrology, sedimentation and stream channel structure.

Ecosystem services of lakes are water storage used for regulating human water supplies. Lakes too generate the service of wastewater treatment, though not as effectively as streams. Finally, Freshwater ecosystems, often instrumental in water supplies or fisheries, are highly valued for their inspiration and recreation value especially where such ecosystems are scarce, like in drylands.

All types of artificial open water bodies function as intensively managed ecosystems. These bodies include fishponds, wastewater treatment plants, water-carrying systems' open canals and reservoirs and other open-air reservoirs. Soon after construction such bodies are colonized by aquatic microorganisms, plants, and invertebrates, that are in turn preyed upon by waterfowl and insectivorous bats (Carmel & Safriel 1998). Thus, the water bodies, constructed for the sole function of water treatment or supply, become intensively managed ecosystems, with ecosystem functions shaped by the wild species that successfully colonize them. Like natural and less intensively managed ecosystems, constructed aquatic ecosystems provide the ecosystem service of promoting wastewater treatment. Many of these water bodies are also important habitat for birds, especially birds that migrate or that use them for wintering. Constructed wetlands for wastewater treatment can also provide wildlife habitat (U.S. EPA 1993).

Ecosystem goods

Ecosystems require water supplies not only for securing the provision of the above-mentioned services, but also to maintain their "goods". The "goods" of ecosystems are the individual species -- irrespective of their ecosystem functioning and services. Humanity has derived food, fiber and other products by domesticating species that do not exist anymore in natural ecosystems, but many still have wild relatives or even progenitors in natural ecosystems.

While domestic species are endangered due to the erosion of their genetic variability, the wild relatives not only maintain variability but also continue to evolve in natural ecosystems in response to the changing environment. Thus these natural ecosystems constitute a repository of transferable genetic variability that can counteract the genetic erosion of the domestic species. Because this genetic diversity is the insurance against agricultural disasters, its loss through transformation of natural ecosystems to, for example, agricultural land, made feasible by water resource development, is counterproductive to the sustainability of this agricultural development.

Other wild plant species are collected for their herbal, aromatic, medicinal, and ornamental properties. Many wild plant species are critical for range-dependent livestock. Furthermore, the natural species pool is a repository of potential food and utility species for humans should current food species succumb to disease or to the effects of environmental disasters. The replacement of ecosystems harboring these species due to the expansion of irrigated agriculture is at the expense of alternative livelihoods and long-term food security provided by all these ecosystem goods. The fraction and magnitude of the biota of current and potential economic value have not yet been anywhere identified (Lawton 1991). All species and their different populations must be considered possible members of this economically important class, at least until a large part of the useful species are identified as such. Finally, because all these "goods" inhabit and are sustained by the ecosystems, of which they are part, an important ecosystem service is the maintenance of ecosystem goods.

The valuation of ecosystem goods and services

Although ecosystem goods refer to items given monetary value in the marketplace, whereas ecosystem services are valued, but rarely bought or sold (Christensen et al. 1996), attempts to value ecosystems goods and services are relatively recent. For example, Constanza et al. (1997) estimated the current economic value for the entire biosphere, of 17 ecosystem services and goods provided by 16 ecosystem types ("biomes"), at an average of US$33 trillion per year (compared to the global total gross national product of US$18 trillion per year). These are divided, in decreasing order of contribution (in trillion US$, rounded) between: nutrient cycling (17), "cultural" services (aesthetic, artistic, educational, spiritual and scientific values of ecosystems - 3), waste treatment (2), "disturbance regulation" (1.8), water supply (1.7), food production (1.4), gas regulation (1.3), regulation of hydrological flows (1.1), recreation (0.8), provision of raw materials (lumber, biomass for fuel, fodder – 0.7), climate regulation (including rainfall – 0.7), erosion control (0.5), biological control (0.4), habitats for locally harvested species and for migratory species (0.1), pollination (0.1), genetic resource (e.g. genes for resistance to plant pathogens, etc. – 0.1), and soil formation (0.05). By "biomes" per one hectare per year, aquatic ecosystems are very valuable. Wetlands are the most valuable (US$23,000), swamps and sea-grass come next ($19,000 each), and then come wetlands and lakes and rivers ($15,000 and $8,500, respectively). The most valuable service of wetlands is disturbance regulation and waste treatment (US$4,500 and US$4,200 per hectare per year, respectively) and for lakes and rivers these are water regulation and water supply (US$5,400 and 2,200 per year per hectare, respectively).

Though these figures are very crude and attract much criticism, their presentation helps make the point that because ecosystem services are largely outside the market and uncertain they are too often ignored or undervalued, leading to the error of constructing projects whose social costs far outweigh their benefits. Constanza et al. (1997) point out that as natural capital and ecosystem services will become more stressed and scarcer in the future, their value will increase. Furthermore, once significant, irreversible thresholds are passed for irreplaceable ecosystem services, their value may rise to infinity.

Biodiversity and ecosystem services

Living organisms, not necessarily those regarded as "goods" are intimately involved in the provision of ecosystem services. Thus, the provision of ecosystem services depends on the biota of ecosystems, or at least on a part of it. But there is more to it than just the *biota*. The provision of ecosystem services is believed to depend on *biodiversity*. "Biodiversity" (shorthand for biological diversity) refers to the quality, range or extent of *differences* between the biotic entities in a given set, such as a watershed, a lake or a stream (Heywood. & Bastge 1995). The 1992 United Nations Convention on Biological Diversity defines biodiversity as "*the variability among living organisms from all sources ... terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems'* (Anonymous 1992). In the following the significance of species as against the significance of their diversity, are discussed.

Species and biodiversity. To what extent species are instrumental in and essential for, the provision of ecosystem services? What are the losses in species and other biodiversity components that can be tolerated in this respect? The many examples of exotic species replacing indigenous species assemblages but apparently provide ecosystem services just as good, may suggest that most species of natural ecosystems are redundant from the viewpoint of ecosystem services (Lawton & Brown 1993). However, whereas the actual degree of redundancy present cannot yet be determined, there are some ecosystem services that automatically would be compromised by losses of species. This is because the extinction of one species may often lead to the extinction of others, directly dependent on the species that has disappeared. Each extinction event has the potential for generating cascades of further losses, some of which are bound to affect services.

Both a loss of a species and a loss in species diversity will detrimentally affect the provision of ecosystem services, but in different ways. The loss of an individual species will have its greatest impact when there are few species in the ecosystem, when the species lost is a dominant in that ecosystem, and when it differs strongly form other species in the ecosystem (Mooney et al. 1995). Species diversity, in contrast with individual species, is functionally important because it provides insurance against large changes in ecosystem processes and may enhance the efficiency with which resources are captured and transferred among species (Tilman 1996). Thus, diversity per se and the accompanying structural complexity of ecosystems impart resistance stability and resilience to allowing recovery from these disturbances that disrupt ecosystem processes, including processes that are important ecosystem "services" (Christensen et al. 1996). The differences among species in their responses to disturbances and environmental extremes and their indirect ecosystem effects, mediated by species interactions, make it unlikely that there is much, if any ecological redundancy in biodiversity over time scales of decades to centuries.

<u>Threshold relations between biodiversity and ecosystem services.</u> Are there threshold relationships between biodiversity and the rate of provision of ecosystem services that should not be passed? Such relationships are still hypothetical but plausible (Mooney et al. 1995). When biodiversity is relatively high, increase in biodiversity is expected to increase the rate of

provision of services. When biodiversity declines, the rates should decline. But when biodiversity is reduced to a certain low level, the rates fall abruptly to a very low level. Then, if diversity gradually recovers, rates recover in an extremely slower rate, until diversity reaches a threshold that returns the curve of biodiversity - services relationship to its initial shape. This threshold hypothesis is consistent with much evidence, and its practical implication is that costs of ecological restoration rise steeply if ecosystems must be forced across a threshold to restore them. Yet, there is considerable disagreement about the particular shapes of the curves and the locations of the thresholds, and whether particular species are crucial in determining the location of the thresholds (Mooney et al. 1995). In addition, it is not known what is the effect of removal of the many "unimportant" species, on the ecologically few species "important" in their direct ecosystem impact.

The precautionary principle. The complexity of ecosystems and biodiversity means there will always be limits in ascertaining the role and significance of any species in any ecosystem service – direct effects and especially the indirect ones. Similarly, the effect of removal of the "unimportant" species on the ecologically few species "important" in their direct ecosystem impact and the effect of the already altered biodiversity to further changes in biodiversity are not known. We should be therefore conservative in drawing conclusions about the ecosystem impact of loss of a given species or level of biodiversity (Mooney et al. 1995). However, the Convention on Biological Diversity (Anonymous 1992) does specifically address the issue of scientific uncertainty with regard to biodiversity: "*Noting that where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimize such a threat*". This is because biodiversity may be irreversibly lost by the time its economic and survival value is proved and priced (Sagoff 1996).

It may therefore be prudent to apply the "precautionary principle" to policies for managing freshwater resources. This principle implies a high value-driven judgement about the responsibility borne by present generation toward future generations (Perrings 1991). Since current knowledge does not suffice, it is prudent to assume that while there is clearly redundancy in the role of species in delivering some services, there may also be an extinction threshold which, if crossed, will result in unacceptable deterioration of ecosystems services. Accordingly, the precautionary principle indicates that extreme care should be taken before labeling any species as "redundant" and hence its loss due to development projects can be tolerated. Since the precautionary principle entails a cost for human societies, decisions need to be made about how much the precautionary principle would have to be stretched or how much insurance different societies can afford to buy. These kinds of decisions will be greatly aided by a better understanding of the relationship between biodiversity and ecosystem services. Until then it may be asserted that threats to biodiversity are indicative of threats to the provision of ecosystem services, including those related to water supplies and to agriculture.

THE ENVIRONMENTAL CONSEQUENCES OF WATER DEVELOPMENT

In many regions, and especially in the drylands, water resource development allows for and promotes the expansion of agriculture and urbanization. This has two detrimental effects on biodiversity and on ecosystem goods and services. The first is a direct damage caused by the water resource development *per se*. The second is the indirect damage of water resource development, through the direct damages caused by agriculture, enabled by water resource development. The major damage of agricultural expansion is that this expansion is at the expense of natural ecosystems. The damage to natural ecosystems or their complete loss reduces biodiversity, thus the sustenance of ecosystem goods and the provision of ecosystem services are impaired. The amount of water-related services that is provided by the directly affected and by the remaining natural ecosystems, will not suffice to guarantee sustainability of the water supplies needed for the sustainability of the agricultural development. There is also a risk that the reduction in the spatial extent of natural ecosystems, brought about by water resource development, will cause a reduction in the provision of other services and goods, not directly related to water, but yet essential for human welfare and even survival. Thus, water resource development aimed at feeding (agricultural development) and housing (urban development) the growing population, may even reduce the welfare of this population a level lower than prior to the population growth, due to the damage to natural ecosystems and their biodiversity. This is because not only the new agriculture may fail and the urban development may suffer from water shortage, but the people involved will also be denied services and goods not related to water, yet critical. Even in cases whereby water resource development generates local sustainable water supplies, this development may still reduce the provision of other services that contribute to the sustainability of human life. Hence such water resource development can not be regarded a sustainable development at the regional and even at the country scale (Goodland 1991).

Direct effects of water resource development on ecosystems

In dryland regions large water development projects enable year-round intensive, pressure-irrigated agriculture as well as urban development. Such development projects are often associated with the management of river systems and lakes. These may revolutionize agricultural and rural development, often at the cost of ecosystem goods and services, many of them related to water supplies.

Lakes, wetlands, streams. Wetlands are often drained in order to reduce water loss by evaporation, to collect water for agricultural development and to increase land resources for agriculture. The effects of draining wetlands cascades to adjacent and remote ecosystems. Lakes are used to store water for human use, and to regulate their supply, thus affecting outlets of such lakes. The Rift Valley's Jordan River Basin management will serve as an example for direct detrimental effects of water management on freshwater ecosystems. The Hula, at the head of the Basin, was a large wetland, reduced in size by drainage and replaced by cropland, save a small section on which a nature reserve was reconstructed. The management of this wetland is a clear case of water resource development arousing a conflict between agriculture and ecosystem goods and services. Agricultural development in the "reclaimed" Hula lands has conflicted with the maintenance of water quality service of Lake Kinneret, the major water reservoir of Israel, located further down in the Basin. The transformation of the wetland ecosystem by cropland exposed the wetland peat to air. Decomposition of the organic matter caused accumulation of nitrates, and winter flooding led to the washout of nitrates through the Jordan River to the lake, thus initiating processes leading to the lake's eutrophication (NRC 1999). This conflict thus extends out of the agricultural development area, but there is also a local conflict between the economic benefit to the farmers cropping the Hula and the economic benefit of "inspirational services" provided by a recreated wetland in the drained wetland area. In spite of the drainage, a section of the newly created cropland area has become seasonally flooded, until recently part of the flooded area has been intentionally flooded for recreational purposes. These vicissitudes had dramatic effects on biodiversity, which suffered heavy losses (see later). The management-induced changes in water levels of the Kinneret jeopardize fisheries that depend on coastal breeding grounds. The Kinneret water management also caused a deterioration of water quality of the Jordan River descending from the lake, affecting aquatic and riparian biodiversity of this river. And at the lower reaches of the valley, the level of the Dead Sea dropped such that exposed salty deposits may be carried inland and affect terrestrial ecosystems.

Springs and ponds. Springs are often pumped and impounded within a sealed concrete construction, to prevent evaporation and to protect the pumps from vandalism. These practices affect both the riparian biodiversity along the stream, mostly of plants, and the aquatic biodiversity of the ponds and streams themselves. The effect of drying streams and obstructing access to ponds also cascades to the terrestrial biodiversity adjacent to the springs and streams, and ultimately even farther. In many drylands the rainy season generates ponds that completely dry out during the dry season. Some of these ponds have been created by ancient damming and quarrying, and were used for generations to water livestock in early summer. Such ponds harbor unique biodiversity, adapted in diverse modes to the ephemeral conditions, usually by having an amphibian lifestyle or leaving dormant propagules in the soil of the dried-up bottoms of the ponds. When wet, the ponds attract wildlife that come to drink or to prey on other animals. In many dryland countries such ponds are cut off from their runoff sources, drained and transformed to agricultural land. Other ponds become sinks for wastewater of high toxicity or high organic load, or drained intentionally or sprayed to control mosquitoes. Spraying of ephemeral ponds, and their spatial rarity, which prevents migration between them, have reduced their biodiversity. Implicating ponds as a mosquito threat is flawed since mosquitoes are controlled by the ponds' natural predators—tadpoles and predatory insects. These animals maintain mosquito populations at low levels. The use of pesticides to control mosquitoes aggravates the situation: their natural enemies are destroyed, and the mosquitoes evolve resistance to the pesticides. The most important ecosystem service of these pools is recreational, educational, and scientific, given the unique nature of their biodiversity and their dynamic ecology.

Pumping from aquifers, damming floodwater. Lowering the water table through pumping aquifers may pose risks to terrestrial biodiversity. Such pumping may detrimentally affect dryland tree formations (Ward and Rohner 1997) or reduce the discharge of springs thus transforming permanent spring pools into ephemeral ones, or curtail the flow of streams. Another common practice, especially in drylands, is damming runoff courses and constructing reservoirs. The objective of dams is to prevent runoff to be lost to the ocean or to land-locked saline lakes or marshes. The floodwater is stored in reservoirs or used to recharge aquifers or directly for irrigation. Unlike all other practices, which have a strong local effect (mostly on aquatic and/or riparian biodiversity), and a smaller regional effect on non-aquatic species, this management practice has a regional, whole-watershed effect, mostly on terrestrial biodiversity. The closer the dam is to the water divide, the larger the area of watershed affected. Dams and reservoirs can promote very successful agriculture, but also adversely affect downstream channels in various ways. Dams can reduce soil moisture in these channels and their immediate surroundings, adversely affecting the richest parts of dryland watersheds. In hyperarid dryland watersheds, the channel is the only element that has perennial vegetation. Installing dams in these drylands has a stronger effect on biodiversity than building them in less arid drylands of the region. Damming also reduces the subsurface runoff in the channel, which lasts longer than the surface runoff and is critical for the persistence of the channel vegetation. Finally, the reservoirs enrich the desert with water bodies that dramatically affect the behavior, population dynamics, and structure of the desert's annual plant communities. These changes may be exacerbated since the development of aquatic biota in the reservoirs often leads to introducing predatory fish to control mosquitoes. While the fish are ephemeral, they attract birds and thus generate instabilities in the bird population and in the ecosystem functions they perform. Other effects of runoff on wadi beds and their surroundings depend on those features of the flow that vary spatially and temporally, from flash floods causing severe erosion and loss of organisms to moderate currents that leach salts and deposit nutrient-rich soil.

Direct effects on aquatic biodiversity

The probability of extinction of a species population increases as its size decreases and as its isolation from other populations of the species increases. Dryland aquatic ecosystems are scarce and therefore isolated from each other, and often they are relatively small, resulting in high risks of extinction for the species that depend on them. The human intervention described above dramatically increase these risks. The Hula wetland in Israel is a good example.

The Hula wetland - losses of species. Dimentmann et al. (1992) showed that 585 (612, if doubted or insufficiently described records are included) aquatic animal species (excluding unicellular and parasitic species), were recorded in the wetland prior to drainage. Of these, 19 were represented by peripheral populations (for 14 and 5 species the Hula constituted the southern and the northern limit of the species' global distributions, respectively), and 12 (6 beetles, 2 dragonflies, a flatworm, a fly, a frog and a fish) were endemic to the Hula wetland. In spite of the reconstruction effort, 119 (20%) of the species, among them 11 of the 19 species represented in the Hula by peripheral populations, and 7 of the 12 Hula endemic ones, were not recorded in the Hula region as of the drainage. Namely, seven species, among them a frog and a fish, have become globally extinct. Furthermore, 36 of the species lost to the Hula, have not been recorded anywhere else in Israel, since the drainage. The birds are the best known group of the Hula, and the information of this group is highly reliable. Of the 36 species breeding prior to drainage, 10 ceased to breed after the drainage, but 5 of them were replaced by species that did not breed there prior to drainage. To summarize, the drainage of a wetland which is relatively small in global terms, resulted in a local loss of 119 species (plus 10 birds species that ceased to breed there), national loss of 36 species, and global loss of 7 animal species. On the other hand, 212 aquatic animal species new to the Hula have been recorded in the Hula region only after the drainage. Some of these might have existed prior to the drainage but escaped attention. But most of them are probably new colonizers, indicative of the changes in habitat extent and diversity, and in the quality of the water, following the drainage and subsequent reconstruction efforts.

The Hula wetland - other damages to biodiversity. The above section does not only document the mere loss of species. Rather, species whose center of distribution and origin is north (Europe), west (Mediterranean basin), east (Iraq, Iran) and south (Egypt, tropical Africa) of the Hula, all assembled into a unique community in the Hula. Thus, though most of the species also exist elsewhere, their combination, hence their interactions exist nowhere else. The ability of northern and tropical species to live together in the Hula has derived from the high diversity of aquatic habitats in the Hula, and the year-round discharge of springs with year-round stable moderate temperature, thus serving a refuge from extreme high summer and low winter water temperatures. Species belonging to each of these biogeographic categories have been lost due to the drainage, hence unique species interactions, probably related to unique ecosystem functions, were lost. Also, some dramatic nature phenomena, such as the upstream spawning migration into the Dishon stream of Lake Hula's three cyprinid fish, are forever lost, though the species themselves have not gone extinct. Finally, the Hula is located on the route of cross-desert bird migration hence its drainage may have detrimental effects on the functioning of both European and African ecosystems, of which the birds used to stage in the Hula are a significant biodiversity component, in summer (Europe) and in winter (Africa).

The loss of biodiversity due to the drainage of the hula is only a part of whole-country biodiversity losses in a dryland country like Israel in which water use is intensive.

Biodiversity losses in water use intensive dryland country - the case of Israel. Israel as a whole has thus far (1999) lost only one mammal, one frog, and one fern from its aquatic and riparian biota, many more species are at high risk. Moskin (1992) divided the 491 mammal, reptile, amphibian fish, fern, and monocotyledon plants (excluding grass) species of Israel into two categories: aquatic or riparian versus non-aquatic. In each category, he compared the number of species at risk of extinction using the International Union for the Conservation of Nature (IUCN) categories of "extinct," "endangered," and "vulnerable", with those not at risk of extinction (using their categories "rare," "insufficiently known," and "out of danger"). Whereas only 14 % of non-aquatic species were at risk, 35 % of aquatic species were at risk, representing a statistically significant difference that was seen in each of the taxonomic groups. For fish (only aquatic, of course), the proportion of species at risk was similar to those in non-aquatic species in other groups. Nathan et al. (1996) showed that, although waterfowl and raptors consist of only one-third of the regularly breeding birds of Israel, all but one of the 14 extinct bird species of Israel were waterfowl (7 species) or raptors (6 species, 4 of which were mostly wetland or riparian). These data suggest that further reduction in the size or water quality of aquatic ecosystems of Israel could cause the extirpation of more than 35 percent of their vertebrate and plant species (and probably a high number of invertebrate species as well). As discussed in previous sections, the number of species "necessary" to maintain ecosystem services or of potential economic value is not known; but the loss of 35 percent of species from aquatic ecosystems of a country seems likely to be significant in this respect.

Indirect effects of water use - agriculture and environment

The steady increase in the extent of global irrigated agricultural land (from 139 million hectares in 1961 to 249 million hectare in 1994, Brown et al. 1997) and of urbanization reflects a significant increase in water use, made possible by an intensive water resource development. Agriculture, urban development, and the infrastructure connecting them (e.g., roads and pipelines) adversely affect biodiversity in two ways: through the loss of natural ecosystems by land transformation, and the loss of biodiversity in natural ecosystems resulting from their fragmentation, especially by infrastructure. Two other effects are restricted to agriculture: the damage to species in adjacent and nearby ecosystems caused by airborne pesticides, and the contamination of aquatic ecosystems and aquifers by pesticide and fertilizer runoff.

Direct effect of land transformation - loss of natural ecosystems. Newly developed agricultural land means newly lost natural ecosystems. The specific contribution of transformed lands to aquifer recharge and how it may have changed since their transformation to agricultural lands is often not known. But such indirect effects of water use on natural ecosystems may be the most undesirable effects on water supplies, more undesirable than the direct effects of water use on natural ecosystems. The dimensions of the loss of this service (recharge) depend on the geomorphological properties of the transformed watershed, its geographical placement with respect to regional aquifers, the diversity of ecosystem types in the landscape involved, and the type and structure of its natural vegetation. The degree of loss also depends on the properties of the development, that is, on the agro-technological practices and type of crops. Furthermore, large-scale replacement of natural ecosystems by agricultural systems results in reduced structural and landscape diversity. This reduces the resilience of the developed region to episodic high rainfall events. The large-scale removal of complex perennial vegetation and its replacement by agriculture also causes regional changes in albedo, evaporation, and cloud formation and rainfall distribution. Reduced landscape and structural diversity around water bodies leads to changes in chemical, physical and biotic characteristics, and also a higher probability of irreversible system change following episodic storm events (Mooney et al. 1995a).

Indirect effect of transformation - reduction in overall biodiversity. The reduction of natural ecosystems also causes local extinction of populations and of species, many of which are ecosystem goods, regardless of the loss of ecosystem services. The persistence of a population is a function of its size, among other things. Population size is often a function of the area available for that population. The chances of extinction of a population dramatically increase when its available area, hence its size, is reduced below a species-specific threshold (NRC 1995a). Similarly, in general, as the area of a natural ecosystem decreases below an ecosystem-specific threshold, the number of species inhabiting it decreases (Soulé 1986). It is usually not known how many species' populations have been lost through reduction in the sizes of natural ecosystem following the transformation of these natural ecosystems to agricultural one, made possible by water resource developments.

Direct effects of agriculture - pesticides, fertilizers and trace elements. Agricultural development encompasses an increasing use of pesticides and fertilizers. Especially when applied from the air, the effect of pesticides on natural ecosystems adjacent to agricultural land is evident. Insecticides and herbicides are often concentrated at each link of food webs, sometimes at up to lethal concentrations in top trophic levels. Top-down effects on ecosystems may be highly significant, hence pesticides cause much concern. Pesticides are also transported by runoff, and thus affect aquatic ecosystems and contaminate ground water. Fertilizers too are applied in large quantities in the study area, often in the irrigation water. Fertilizers reach aquatic ecosystems, where they can cause eutrophication, and they also contaminate ground water. Thus, water drawn from lakes, rivers, and aquifers for agriculture contaminates and alters ecosystem functioning. Again, such indirect effects of water use may be environmentally more significant than their direct effects. Because dryland ecosystems are limited not just by water but also by nutrients, the enrichment of fertilizers "escaping" from desert agriculture may dramatically change the functioning and structure of these ecosystems. The experience of irrigated agricultural development in the Joaquin Valley in California (Anonymous, 1989) suggests that harmful trace elements, especially selenium, are abundant in agricultural drainage water, and these can be further concentrated in the food web, damaging biodiversity and humans.

Water and agriculture related to desertification and climate change

Desertification. Transformation of natural ecosystems to agricultural ones occurs nowadays mainly in drylands. Dryland development is often expressed in the transformation of rangeland (grassland, scrubland or woodland) to cropland. There are two detrimental effects of this transformation: reduced quantities of the remaining range, and soil salinization. Rangeland transformation requires removal of large tracts of indigenous vegetation to make room for cropping, thus reducing the geographic extent and the overall population size of the plant species concerned. This in turn threatens the species' long-term persistence; the greater the population and the larger the geographic extent, the lower the risks of local or regional extinction. Clearing large areas of indigenous vegetation puts plant species in the remaining areas at risk of extinction. Thus, the transformation of rangeland to cropland may reduce the quality of the remaining range, encourage overgrazing, and bring about topsoil erosion.

The second detrimental effect -- soil salinization -- results from the heavy dependence of dryland cropping on irrigation. Due to the high evaporation rates in drylands and since water scarcity does not allow using large quantities of water for leaching soils, dryland irrigation brings about soil salinization. Rates of salinization may vary according to irrigation practices and land uses, but eventually soil salinity reaches a threshold value at which the cropland can no longer be maintained, and is abandoned. Such croplands, when abandoned due to salinization, are likely to be colonized by halophyte vegetation, rather than restored by the original rangeland biodiversity. Thus, either due to loss of topsoil or due to salinization or both, land degradation may reach the point of irreversible degradation or its plant diversity, a component of biodiversity, may never be restored. This extent of land degradation is labeled "desertification". Desertification, currently affecting some 30% of global land, may thus be easily driven by water resource development aimed at dryland agricultural development.

Desertification often has roots, typically a large external disturbance (Puigdefabregas 1995) that began some years, or even decades, before crises manifest themselves (e.g., the Dust Bowl in the United States in the 1930s and the Sahel crisis in the 1970s). For this reason, it is important to worry about and try to prevent desertification by avoiding non-sustainable use of water, before it manifests itself by loss of biodiversity and the consequent impaired provision of ecosystem services such as aquifer recharge, leading to a reduced sustainability of water supplies.

Climate change. It is predicted that a 1-2°C global increase in temperature by 2030 to 2050 due to the global increase in atmospheric concentration of "greenhouse" gases, will result in climate changes in regions affected by desertification, that will cause higher evaporation, decreased soil moisture and desertification (Watson et al. 1998). The change of the global atmosphere is due to human-induced release of "greenhouse gases", of which carbon dioxide is highly significant. Climate change can be mitigated by promoting sinks (processes which remove a greenhouse gas from the atmosphere) and generating or maintaining "reservoirs" (greenhouse gas storage). Global plant life provides the sink service and the global biota, of which plants constitute the largest fraction by mass provides the reservoir service. The causes for desertification are the same as those causing a reduction in the global sink and reservoir services and the results of desertification include the inability to restore these services. When rangeland is transformed into cropland, the vegetation cover of the agricultural crop may be even greater than that of the natural vegetation. But this does not necessarily mean that the carbon sink increases. Many crops are annual, and are harvested for use after a few months. There is often a time lapse between harvesting one crop and sowing the next. During this period the bare soil is exposed to wind erosion or water erosion, reducing fertility. This continual process will eventually lead to abandonment, and hence, to a complete loss of its carbon sink. Thus, desertification exacerbates climate change and is exacerbated by climate change.

Climate-change related ecosystem service of semi-arid drylands. The semi-arid drylands are most prone to desertification, since their relatively high productivity as compared with that of arid drylands, is tempting for populations that are in need but easily cross the threshold from exploitation to over-exploitation. But the semi-arid drylands may have a unique ecosystem service of value for mitigating detrimental effects of climate change on ecosystems. This service is the maintenance of "goods" - plant species with high within-species, genetic diversity. These species have their core populations in "non-desert" regions, but their peripheral populations, those with high within-species diversity, inhabit the semi-arid drylands, often at the transition between "desert" and "non-desert" drylands. Due to their genetic diversity, these populations are likely to persist in the semi-arid drylands when climate changes, whereas the populations of the same species inhabiting the core distribution areas and not endowed with such diversity, will go extinct. The semi-arid populations of these species therefore have the potential for restoring services of ecosystems off the drylands, that will be damaged by the expected global warming (Safriel et al. 1994). This semi-arid biodiversity that may be instrumental in securing ecosystem services under prevailing global warming and climate change, may be lost when non-sustainable water resource development makes the semi-arid drylands desertification-prone.

MEANS OF MITIGATING ENVIRONMENTAL DAMAGES

What is being done and what should be done to mitigate detrimental effects on natural ecosystems and their biodiversity, as they are caused by current and future water resource development? How to optimize sustainability of water supplies with the provision of ecosystem goods and services? Mitigation activities are of four types: restoration of damaged aquatic ecosystems; securing allocation of water for aquatic ecosystems, thus guaranteeing their ecosystem services for the future; development and implementation of a system for environmental impact assessment of planned major water management projects; and development of national and regional planning policies that integrate water resource development, agricultural development, and the functioning of natural ecosystems, to guarantee overall sustainability.

Restoration of freshwater ecosystems

Water allocation to natural ecosystems. Insufficient knowledge exists with regard to the quantity and quality of water required by natural ecosystems for maintaining their biodiversity and providing their services. Where there are legal allocations of water "for nature" these are determined as compromises rather than based on ecosystem's needs. In Israel for example, between 0.2 to 2.0 percent of mean annual total renewable water is allocated to protected natural ecosystems (NRC 1999). This may not suffice, and alternatives should be sought. A notion prevailing for a long time has been that aquatic ecosystems should be rehabilitated by elimination of all effluents, ensuring flow of freshwater only. But the grim prospects of severe water shortages make it clear that in many countries rivers will dry up completely if the discharge of high-quality effluents back to them is not permitted when freshwater allocations are unavailable. The notion of using wastewater to help support biodiversity is based also on the belief that natural ecosystem can "serve themselves" by processing the wastewater.

Use of wastewater for ecosystem rehabilitation. Many data have been accumulated, for example, along the course of the Yarkon River in Israel, to evaluate the treatment capacity of this river. For the month of June 1994, for example, self-purification during the passage of water through measured sections of the river was evident in reductions of 0.1 to 0.5, 0.5 to 0.6 and 0.2 microgram/liter/second respectively in biological oxygen demand, chemical oxygen demand, and ammonium concentration—a high rate of self-purification, typical of an eastern Mediterranean climate (Rahamimov 1996). To increase the self-purification potential of the Yarkon, small dams have been constructed and the slowed-down stream above them is artificially oxygenated. An Israeli National River Administration was established in 1993 and charged with coordinating the restoration of river ecosystems, including the use of wastewater for this purpose. Though the main motivation for such action is recreation, the rehabilitated rivers promote biodiversity and provide ecosystem services. These restorations require water allocation of wastewater of specified quality, as well as freshwater allocation. This freshwater is not necessarily water lost to agriculture, because most of the allocation can be impounded at the lower reaches of the rivers, and the fraction lost by seepage recharges aquifers.

Optimizing land allocation for balancing development with biodiversity

The risks of loss of biodiversity and hence ecosystem services can be reduced by striking an optimal balance between land allocation for development and for biodiversity. Remote sensing and geographic information systems (GIS) technologies are now available to carry out this mission by means of the following steps.

1. Taking stock of current land uses, classed by development (e.g., urban areas, industrial areas, rural settlements, agriculture, and infrastructure) and biodiversity (e.g., protected areas, open areas not legally proclaimed as protected, rangelands, and some types of extensive agriculture). Thus, a first GIS map layer can plot current development and existing biodiversity.
2. Allocating value to the various types of existing biodiversity (e.g., the value of indigenous woodland of a given succession stage, or ecological succession series, of a semiarid watershed) and to different sizes of each of these types.
3. Assessing the value of existing biodiversity areas identified in step 1 using the values obtained in step 2. For highly developed sections of the region under consideration, the biodiversity areas will be scattered patches of natural ecosystems within a matrix of development, with the size of each patch and its distance from adjacent patches contributing significantly to its value. In less-developed areas, patches of development will be interspersed within a matrix of protected natural ecosystems, and size and distances to similar patches will less affect the value of each type of patch. Values can be expressed as colors or color tones in a second GIS map layer.
4. Estimating the dimensions and identifying the areas required for additional, forecasted water-driven development. The economic benefits of water resource development of each of these areas can then be assessed and expressed in a third GIS layer.
5. Overlaying the third map layer on the second layer is the first step in an iterative process leading to optimization. Given that ecosystems can not be recreated, optimization will entail

adjusting the development areas such that, for example, low-benefits development areas will not be over laid on high-value biodiversity areas.

The major undertaking is step 2 above, namely the valuation of biodiversity and ecosystem services. The required knowledge for doing that is insufficient and needs much research. However, since demand for such evaluation grows faster than the pace of the required research it is necessary to use existing knowledge, and improve the valuation as knowledge accumulates.

Valuation of terrestrial biodiversity

The biodiversity of an area can be valued by three criteria: its ability to provide ecosystem services; the number of species considered realized or potential "goods" and the number of those instrumental in the provision of services; and its ability to absorb anthropogenic disturbances without loss in its ecosystem services (resistance), along with its potential for rehabilitation following disturbance (resilience; Safriel 1987). Each of these criteria can be quantified by applying current knowledge, paradigms, or prevailing notions, as follows.

Provision of ecosystem services. Water-related ecosystem services depend on the property of the ecosystem and its placement within the watershed. Concerning properties, working hypotheses are that the larger the number of vegetation layers, the greater is the infiltration potential and the smaller the risk of soil erosion and intense surface runoff; and the larger the number of species, the greater the number of vegetation layers. Concerning placement, the higher the elevation of an ecosystem within the watershed, the greater the value of its services. For example, loss of woodland at the top of a watershed, where rainfall is more abundant, will generate more destructive floods, with a greater loss to aquifer recharge, than similar loss at the bottom of the watershed. Ecosystems can therefore also be scored according to their elevation above the bottom of the watershed.

Species of economic value. The following groups of species can be ranked by their realized or potential economic value, the top rank being most valuable: (1) progenitors of cultivated species; (2) wild relatives of cultivated species; (3) non-cultivated species currently collected for nutritional, medicinal, ornamental, aromatic, energy production, and industrial purposes; (4) high-quality forage species; (5) low-quality forage species; (6) species represented by peripheral populations, hence with high genetic diversity; (7) species already identified by IUCN revised criteria under the categories of vulnerable and rare (including species whose economic significance is not yet known, but whose extinction would prevent the discovery of their significance); (8) species of inspirational and recreational value (which often translate to economic benefits); (9) species of scientific interest (which also have economic value, including through scientific discoveries); and (10) species that provide or manipulate habitats for other species (Jones et al. 1994). An ecosystem can be scored by the number of its species in each of the above categories, multiplied by the rank of the category.

Resistance and resilience. Resilience and resistance are positively (but not linearly) correlated with area. The risk of extinction is reduced with greater population size, population size increases with area, number of species increases with area, and the large perimeter-to-surface ratio of small areas makes their species highly vulnerable to surrounding development. Rehabilitation of biodiversity and ecosystem services following disturbance is faster when there are sources of immigrants. These sources are other areas with protected biodiversity, so their significance increases, as they are closer to the disturbed area. The penetrability of the surrounding areas for propagules interacts with their distance: the greater the penetrability of the areas, the farther the propagules can travel. For example, for many species, an extensive surrounding agricultural area is more penetrable than a surrounding urban region. To conclude, the most valuable ecosystem is one with highest number of species, many of which are of potential economic significance, and an ecosystem of a large size, connected by a corridor to another similar natural ecosystem.

Valuation of freshwater biodiversity

In many countries, and especially in drylands, freshwater ecosystems are relatively small in size. Therefore, in valuing biodiversity, a higher score should be attributed to areas that contain freshwater ecosystems, or to each aspect of a freshwater ecosystem, compared to a terrestrial ecosystem otherwise having the same scores. Thus, the value of a freshwater ecosystem of a given number of species will be higher than that of a terrestrial ecosystem of the same number of species and the same size. The following identifies some guidelines for valuing freshwater ecosystems.

In their provision of ecosystem services and number of species, freshwater ecosystems can be ranked by their spatial extent. Also, the higher the elevation of a freshwater ecosystem within a watershed, the greater the value of its services. Freshwater ecosystems also affect biodiversity of adjacent terrestrial ecosystems, by providing water for terrestrial vegetation, and water and food for terrestrial fauna. With respect to species' economic value, the category of forage species in the previous list of terrestrial ecosystems should be replaced by species of fisheries significance. Special features of freshwater ecosystems that confer resistance and resilience, apart from features described for terrestrial ecosystems, are the distance of the ecosystem from polluting sources, which should be great, and the existence of corridors, such as streams, between isolated water bodies. Using these sets of rules, it should be possible to evaluate biodiversity, and use this evaluation as a tool to determine the extent of desirable water resource development, such that this development is sustainable.

Recommendations

This paper has shown that maintaining and enhancing ecosystem goods and services will help—not hinder—the sustainability of water resource development and its effects on the sustainability of agricultural development. The paper has also shown that it is prudent to treat biological diversity as instrumental in the provision of ecosystems' goods and services. Maintaining ecosystem goods and services therefore entails protecting biodiversity. The two points above require that, in plans for providing and allocating water resources among various uses in any country or region, a balance is needed among environmental, economic, and other objectives when they do not lead to the same priorities for water use.

Two types of recommendations follow. The first outlines the scientific information needed to better understand the relationships among ecosystem goods and services, ecosystem structure and functioning, and biodiversity, and also the information needed to assess the balances and tradeoffs among various objectives. The second set of recommendations outlines ecologically based methods for improving the sustainability of water supplies, based on scientific information already in hand.

Research recommendation. Much research into the interactions between agriculture, biodiversity and ecosystem services is required. The major charges are listed below.

1. Identify and quantify the services provided by each ecosystem type, distinguishing between water-related services, and other services. Study and quantify the optimal and minimal water (quantity and quality, in time and space) and land (size and spatial pattern) allocations for each of these ecosystems to sustain the provision of each of their services.

2. Determine which of the ecosystem types within the landscapes play landscape-relevant keystone roles and research means to maintain natural processes, and hence biodiversity at the landscape and regional scale, while meeting the human demands of these landscapes.

3. Identify species that are endangered or at risk of becoming endangered, assess the contribution of each to water-related ecosystem services, identify the causes for the endangerment of these species, and explore means to reduce the risks.

4. Compare local water losses from evapotranspiration of natural and moderately managed major ecosystems to water gains from each of the ecosystem services, including increasing infiltration and reducing surface runoff and its associated topsoil erosion.

5. Assess biodiversity components of current and potential economic significance, especially in aquatic ecosystems and climatic transition zones inhabited by peripheral populations, and determine the water allocation, as well as the extent of land and its spatial configuration, required for their conservation.

6. Conduct long-term studies to evaluate the effects of damming storm water on biodiversity at the lower reaches of watersheds, especially in dryland regions, and use the results to prescribe amounts of water that must be released to reduce damages to downstream biodiversity components.

7. Evaluate the amount of water lost through appropriation of natural watersheds by agriculture and urban development, to generate guidelines for land use allocation in areas still not developed and planned for changes in their current land use.

8. Study the rate of extinction of species populations owing to fragmentation, transformation and reductions in size of natural ecosystems, and use the results to provide guidelines for water management and related development projects.

9. Evaluate the amounts of water allocated to protected areas and other supports of biodiversity that go to recharging aquifers after these uses.

10. Study the role of natural ecosystems in treating wastewater of various qualities, the degree to which freshwater allocated to natural ecosystems can be replaced by treated wastewater, and the technologies appropriate for this substitution.

11. Conduct the research required to define improved criteria for evaluating the significance of biodiversity in providing ecosystem goods and services.

<u>Operational recommendations.</u> Even though knowledge is still overly lacking, some generic guidelines can already be provided. These are:

1. The sustainability of water-driven agriculture requires that the natural ecosystems be treated as one of the legitimate users of water resources identified for development.

2. Because water resource development and the further development it promotes can damage biodiversity, and may therefore risk the provision of ecosystem services, agricultural and other development should be carried out so that the gains of water resource development clearly outweigh lost ecosystem services.

3. Precise objectives should be set for all aquatic, riparian, and other water-dependent sites, specifying the type of biodiversity components to be maintained and the type of ecosystem service the site can provide and whose continuance should be ensured. These objectives should be used to determine the minimal required allocation of water quantity and quality. Indicators, benchmarks, and monitoring programs for each water allocation site should be developed to review and update the allocations.

4. In future land use planning, as in water resource planning, the benefits of proposed developments should be evaluated against the cost of lost biodiversity components and reduction of ecosystem services.

5. When climatic transition areas (rich in within-species diversity), as well as other areas rich with progenitors and relatives of domestic crops are targeted for water-driven development, it

would be prudent to consider setting aside within them protected areas sufficiently large to serve as repositories of genetic resources.

6. The costs and benefits of avoiding, reducing, or mitigating the effects of fragmentation of natural ecosystems should be considered when planning water development and allocation and the additional development they promote.

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