

Integrated, watershed-based management for sustainable water resources

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Abstract Water scarcity is becoming a critical issue globally, driven largely by the demands of an exponentially growing human population and complicated by the impacts of climate change on the amounts and distribution of precipitation. It is also due to mismanagement as scarce water resources are being used simultaneously for irrigation, power generation, public and industrial water supply, flood reduction, and wastewater disposal without consideration of the cumulative impacts to the water resources themselves. This paper outlines eight ecologically based principles and associated guidelines as the basis for integrated and watershed-based management of the world's water resources.

Keywords water resources, watershed, integrated management, sustainable, ecological principles

1 Introduction

The problem of water scarcity is increasing throughout all countries across the globe. This scarcity is driven by a diversity of factors, foremost of which are the needs of an exponentially increasing human population that has doubled to seven billion people in the last half century (Gleick, 1998; Vorosmarty et al., 2000). Although drinking water is one of the basic needs for life, the greatest use of water, and more than three quarters of all water consumed, is for irrigation of crops that feed humans directly or indirectly via pastures for livestock (Scanlon et al., 2007).

Arguably, the second biggest factor contributing to water scarcity is the inherent variability in weather. Even the most highly trained meteorologist finds it difficult to predict with any certainty the amount, timing, or location of rainfall over the coming growing season or to predict

flood occurrence beyond a few weeks in advance. There is now global acknowledgement that this uncertainty is being exacerbated by climate change (IPCC, 2007). Although public attention has focused on the impacts to temperature and global warming, there will also be significant changes in the distribution, timing, and amounts of rainfall. Already there is clear evidence that trends in precipitation are increasing in some areas and decreasing in others (IPCC, 2007). Aside from direct changes in precipitation, immediate impacts of climate warming on water availability are already being experienced through the rapid melting and disappearance of tropical montane glaciers worldwide (Mizuno, 2004; Bradley et al., 2006). Summer snowmelt from glaciers has historically been a primary source of summer-time base flow in the Ganges, Mekong, Nile, and other major rivers. This flow is a critical source of water to millions of people in the downstream receiving countries (Viviroli et al., 2002). The underlying drivers of climate change and human population explosion will require international cooperation to slow their momentum and ultimately reduce their impacts.

However, there is a third driver behind water scarcity, that of water management, that is much more controllable, can be addressed at local and regional scales, and that is the subject of this paper. Water scarcity has been called “a crisis in management” since the Fourth World Water Forum in Mexico 2006. Throughout history, humans have used or impacted water bodies for a multitude of purposes, including irrigation, public water supply, fisheries, flood control, hydroelectric power generation, and wastewater disposal, and among others. These diverse uses have been conducted simultaneously on the same, limited water bodies usually without consideration of the cumulative impacts on the aquatic ecosystem itself and, arguably, never considering the protection of the biophysical processes that are critical to help sustain the water and its associated ecosystems.

This traditional and nonintegrated approach to water management relied heavily on engineering strategies to

address flooding and water supply via pipes, pumps, levees, ditches, channelization, and dams. Such engineering has been labeled as the “hard approach” (Gleick, 2003). As a result of these activities, increases in flooding, droughts, degraded water quality, loss of fisheries, and associated environmental problems have come back to haunt us. We now recognize that we need to manage resources more holistically and make them more ecologically sustainable using a “soft approach” (Gleick, 2003). Ideally, we need an integrated management framework for sustainable water resources, and by sustainable, we mean a dependable resource both in quantity and in quality over the long term. In order to achieve this, the management program must explicitly include strategies, a) which protect the processes that directly relate to maintenance of the water itself and b) which protect the fish, shellfish, waterfowl, wildlife, or plants that contribute to the self-sufficiency of local communities. Such sustainable management can be based on eight specific principles, synthesized, distilled, and translated from decades of research in the sciences of ecology, wildlife, and plant biology, biogeochemistry, wetland and landscape ecology, hydrology and soil science, among others. The remainder of this paper overviews these eight principles, translated into the associated management guidelines (underlined) to help inform water resource managers and planners.

2 Principles faced sustainable management

2.1 Principle 1: The most appropriate spatial scale to manage water is within watersheds and river basins

Historically, water has typically been distributed and allocated based on political boundaries of towns, states, countries, or other political entities. Perhaps, this is due in part to the fact that humans could not see where the rain clouds ended, and therefore, rainfall amounts were generally considered unknowable or unlimited. However, the discovery of the “watershed” concept only several decades ago has radically changed our perspectives and management approach (Chow, 1964). The watershed is the bowl into which rain falls and moves, with the mountains or hills defining the lip of the bowl (Fig. 1). The watershed therefore defines fairly precisely the total amount of rainfall that is available for use and highlights that it is a limited, finite, and roughly knowable quantity. This knowledge provides a powerful framework when thinking about feasible allocation and planning. Characteristics of the watershed also determine the processes that control the amount, rates, and quality of the water as it moves downhill and out of the basin. Thus, the sources and fates of pollutants can be better understood and managed. Using the watershed as the spatial framework, in complement

with political boundaries, is the first step to sustainable water resource management. The significance of the watershed as an organizing framework is evidenced by an exponential increase in the number of watershed organizations that have developed across the United States over the past two decades (Leach and Pelkey, 2001) by a recent federal requirement for certain funding programs to be watershed-focused (Hardy and Koontz, 2008), as well as the creation and/or strengthening of international basin programs, such as the Danube, Nile, and Mekong River Basin Commissions.

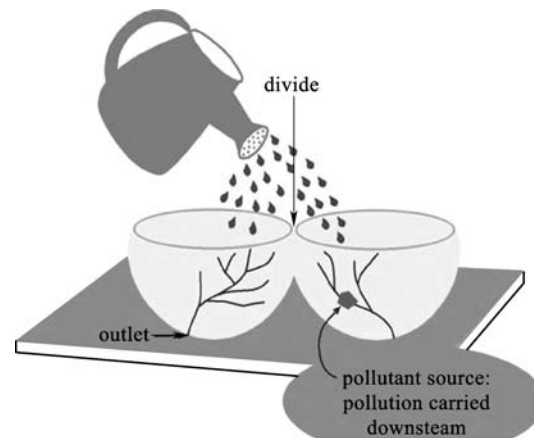


Fig. 1 A watershed acts like a bowl—it captures the finite amount of precipitation that feeds the streams and recharges groundwater. The watershed divide, or lip of the bowl, is defined by the ridge or mountain tops, with rainfall and snowmelt flowing down each side into adjacent, but separate, watersheds

2.2 Principle 2: Pathways of water movement through the hydrologic cycle interact with land uses along the way to determine the quantity and quality of water available for ecosystems and human communities

After rain falls and snow melts, the water will move through the watershed primarily along three different pathways (Fig. 2). Where the ground is relatively hard, most of the water moves as surface runoff or shallow interflow, downslope to the nearest stream or lake and then on to the ocean. If the soil is porous, then the water infiltrates into the ground and percolates down until it reaches bedrock or some other impermeable layer. The water then fills up the pore spaces, forming the saturated groundwater zone. This groundwater continues to build upward and then moves laterally, albeit more slowly, to discharge eventually in streams, lakes, and the ocean. Stream flow is thus a combination of both a) runoff, which is the immediate product of a storm event and drives the short-term fluctuations in water levels, and b) groundwater discharge that forms the base flow between rain events (Fig. 3). It has been estimated that although it varies regionally, on the average, 54% of all water flowing in U.S.

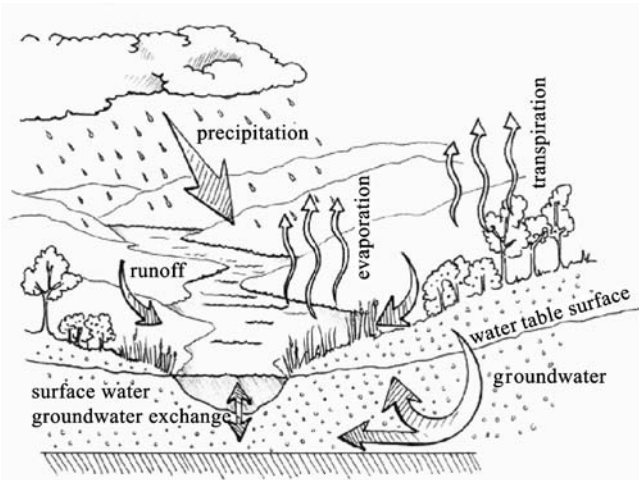


Fig. 2 After falling as precipitation, water flow follows the hydrologic cycle and is distributed among the three major pathways of runoff, groundwater, and evapo-transpiration through each watershed. (Figure by C. Cooley, reproduced with permission from NYSFOLA, 2009)

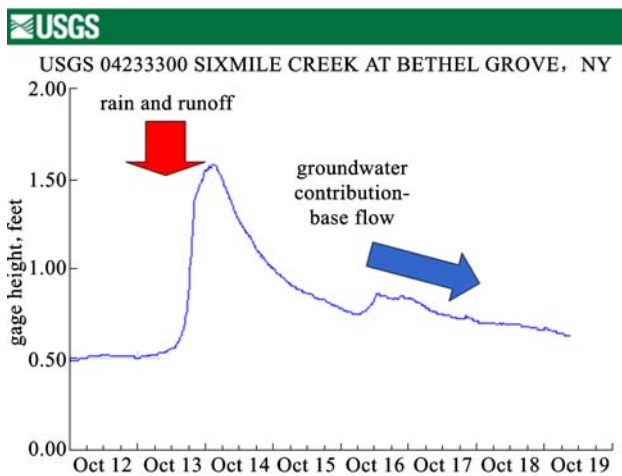


Fig. 3 Representative storm hydrograph or plot of water level changes through time, showing the rising water levels resulting from direct rain inputs and rapid runoff, followed by base flow that is contributed by groundwater discharging into the creek

ivers and streams is from groundwater (Winter et al., 1998). Evaporation of water vapor, from soil and water surfaces, combined with transpiration of water through plant leaves, forms the third part of the hydrologic cycle (see Fig. 2). This vapor contributes to clouds and the precipitation cycle is re-initiated.

Given that there is a finite amount of rainfall for distribution within each watershed, the water flowpaths that actually are followed represent a balance among the three main pathways of runoff, groundwater flow, and

evapo-transpiration. It is critical to understand how changes in land use have shifted this balance, seriously compromising the amounts and quality of available water (Fig. 4). In the northeastern U.S. and in similarly moist regions of the world, roughly where annual rainfall exceeds 80 cm annually, the predominant flowpaths are runoff and groundwater flow. However, prior to human development, forests and meadows covered much of the landscape. The vegetated canopies intercepted the rainfall, capturing it, holding some water, and reducing the impact of the falling raindrops. Soils, made porous by roots, animal burrows, and decomposing leaves and other organic matter, all allowed the precipitation to easily infiltrate and percolate downward. Thus, groundwater flow was the dominant pathway and runoff was relatively minor, except in the steepest terrains.

This balance has been shifted drastically wherever humans dominate the landscape (see Fig. 4). Humans have removed the forest canopies that intercepted the rain, burned off or eroded the soil organic matter, and compacted the soils with heavy traffic. In many places, impervious surfaces of rooftops, roadways, and parking lots now rapidly transfer water off-site to the nearest streams (Arnold and Gibbons, 1996), and networks of roadside and agricultural ditches are highly efficient conduits connecting impervious surfaces with the streams (Luce and Wemple, 2001; Duncan et al., 1987). As a result of these cumulative processes, the hydrologic balance within our developed watersheds has been shifted from groundwater-dominated to runoff-dominated pathways (Although investigations of rice paddy hydrology vary in their conclusions regarding the net impacts on infiltration versus runoff (Chen et al., 2002; Wu et al., 2001)). This shift has had a big impact on the associated stream and river systems. Increasing the rates and amounts of runoff has contributed to an increase in the frequency, rapidity, and magnitude of river flooding (Jones et al., 2000; Wang et al., 2001). Less intuitively, streams also dry out more quickly and local wells run dry more often during summer months (Finkenbine et al., 2000). This is because when more water is lost to runoff, then less is available to fill the groundwater reservoirs. Consistent evidence from the literature suggests that stream flooding, baseflow, and aquatic health are all impacted when only about 10%–15% of the watershed is covered with impervious surfaces (Meyer et al., 2004).

Working within a watershed framework, land uses can be optimized to increase precipitation capture and groundwater recharge and to reduce runoff. There are a diversity of best management practices (BMPs), such as the use of winter cover crops and contour tilling or no-till, that simultaneously increase rainfall infiltration and decrease soil erosion. Agricultural BMPs are scientifically validated techniques for reducing runoff and water pollution and are key components in the toolkit for watershed management.

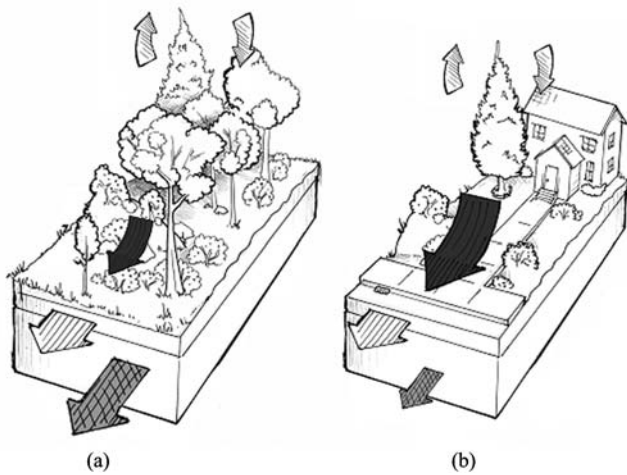


Fig. 4 Vegetated canopies and porous soils (a) capture precipitation that reduces runoff and maximizes infiltration and groundwater recharge, whereas impervious surfaces of developed landscapes (b) maximize runoff and minimize infiltration and recharge of groundwater. (Figure by C. Cooley modified from Center for Watershed Protection, and reproduced with permission of NYSFOLA, 2009)

Considerable effort has focused on training farmers in their usage. Forests can be restored or protected. Organic matter content of the soil can be increased by spreading mulch and allowing small woody debris to accumulate instead of removing it for fuel wood or other uses. Finally, parking lots, sidewalks, certain roadways, and other impervious surfaces can be replaced with more permeable materials in many locations.

2.3 Principle 3: Healthy wetlands, including floodplains, streamsidings, and lakeshores, perform various processes that translate into important ecosystem services for humans

Wetlands have been defined as the transitional zones between truly terrestrial and aquatic habitats. Legal definitions of what is, or is not, a wetland can vary but generally include some or all of the following three requirements: a) plant species composition is dominated by obligate or facultative wetland plant species (USDA Wetland Indicator Status <http://plants.usda.gov/wetinfo.html>), b) presence of hydric soils, and c) evidence of periodic flooding (Mitsch and Gosselink, 1993). Historically, wetlands have been misrepresented as waste places and drained to allow farming and development. However, after decades of research, wetlands are now recognized as unique and highly productive ecosystems occupied by a rich diversity of species, and many of which are restricted to these habitats. Wetlands and their biota perform diverse functions that translate into ecosystem services on which human societies depend:

1) The aboveground leaves, stems of wetland plants

intercept, slow down, and store rising stormwaters, thereby reducing flooding downstream.

2) They also intercept moving water, absorbing the energy of waves and storm surges. This phenomenon was clearly demonstrated along the southern coasts of Asia, where swathes of destruction by the 2004 tsunami were reduced in those shorelines protected by expanses of mangrove forest (Danielsen et al., 2005).

3) Wetland vegetation filters out and traps suspended sediment and other debris, thereby improving water quality.

4) These vegetated habitats provide protective critical nursery areas for juvenile fish, for waterfowl, and other wildlife.

5) Belowground, plant roots bind and hold sediments, preventing erosion (Kiley and Schneider, 2005).

6) The soil matrix of organic matter, roots, and microbes also intercept and help filter out dissolved contaminants from groundwater, thus filtering and cleaning water before it discharges to a stream or lake. For example, dissolved nitrate, a common groundwater pollutant from fertilizer and animal wastes, will be effectively removed by denitrifying bacteria.

Costanza and coworkers have estimated that such ecosystem services provided by wetlands translate into several billion dollars annually around the world (Sutton and Costanza, 2002; Faber and Costanza, 1987). In recognition of these services, regulatory legislation has been enacted in many countries to protect their remaining wetlands and the 1971 Ramsar Convention on Wetlands of International Importance identified wetlands of global significance. However, overall, wetland loss continues to occur worldwide. It is critical to identify wetlands throughout watersheds and protect or restore them in order to achieve all the ecosystem services on which humans depend.

2.4 Principle 4: Plants and animals are adapted to, and dependent upon, the natural hydrologic regime of rivers and lakes

Human society has long recognized that periodic large-scale floods are both a blessing, because they reinvigorate the floodplain soils with nutrients and sediments, and a curse because of their unpredictability and resulting damage to lives, infrastructure, and livelihoods (Junk et al., 1989). However, a paradigm shift in the management of our flowing waters occurred with the recognition that there are actually natural patterns of flow in all rivers and water bodies that drive ecosystem health (Sanford et al., 2007; Poff et al., 1997). The fluctuations in flow are driven by the long-term climatic patterns in a region interacting with soils, topography, and vegetation. Although sparse, research consistently shows that there are predictable, natural patterns of flow in rivers of Asia, Australia, Europe,

and the Americas (Dettinger and Diaz, 2000). There are five key characteristics of the reoccurring extreme events, considering either floods or droughts, which define this natural regime. These key characteristics include a) timing within the annual seasonal cycle, b) frequency of the events, c) duration of each event, d) magnitude, and e) rate of change in conditions (Poff et al., 1997). Hundreds of research studies have now documented how plants and animals have adapted their life cycles to these predictable long-term patterns of water in their environment.

Unknowingly, humans have seriously altered the natural hydrologic regime of most water bodies, with significant impacts on the associated organisms and ecosystem services. Most obviously, water volumes can be depleted by direct and excessive withdrawals for public water supply and irrigation. Most dramatic examples include lake shrinkage of the Aral Sea (Kazakhstan, Uzbekistan), Dead Sea, and Lake Baikal (Russia), and reductions of river outflow to less than 20 percent of their original flows in the Nile River (Egypt), Colorado River (USA), and the Yellow River (China). Less obvious are the impacts to the hydrologic regime resulting from changing land use. As outlined in Principle 2, many alterations of the soil and vegetated cover of our watersheds have resulted in an increase in the runoff component of the hydrologic cycle. The rapid rates of water outflow are further magnified by a diversity of engineering practices that have been deliberately used over the past century to rapidly drain water and reduce flood damage, including channelizing, dredging, and straightening of rivers. Draining wetlands via ditches and underground tile pipes also reduces water retention in the landscape. These practices have cumulatively acted to increase the storm-related runoff component and deplete the between-rain groundwater component of flow in our rivers.

Finally, operations of flood control reservoirs have successfully reduced the magnitude and frequency of large scale flood events, and most also raise the baseline flow discharges (Chien, 1985). These hydrologic changes have been shown to reduce the width and extent of natural floodplains, lower productivity of water birds and other dependent biota, and also can impact wetland regeneration (Kozlowski, 2002; Stanford and Ward, 1979). Hydroelectric dams, operated primarily to maximize power generation, release large volumes of water at high flow rates for short time periods, followed by periods of zero flow (Moog, 1993; Cushman, 1985). The downstream reaches alternate between dewatered, hot and dry conditions to fast flowing, fully flooded conditions within each 24 h period. Few organisms are adapted to withstand, or escape from, these rapid rates of change and the dramatically different hydrologic conditions, and the result is that the native biota is usually extirpated. It is critical to protect, restore, or at least mimic, the natural hydrologic regime of rivers and lakes in order to sustain the wetland and aquatic ecosystems, their resident organisms, and the associated ecosystem services.

2.5 Principle 5: The land-water interface is naturally dynamic and organisms are adapted to deal with these disturbance-dominated habitats and the associated unstable substrates

The shorelines of most freshwater and marine habitats are highly energetic and have dynamic and moving substrates of unconsolidated sediment. River channels naturally migrate back and forth across a wide floodplain or delta and coastal barrier islands experience washover and reformation in response to winter storms. The native shoreline plant species can rapidly recover when they are buried several meters deep under newly deposited sediment or torn apart by the water's energy (Brown, 1997). They can regrow from fragments of roots or stems. In turn, their leaves and stems help to slow down the currents and reduce the wave energies, and their below-ground root systems help to bind the sediment and resist erosion. Humans enjoy living along the water's edge but prefer stability and erect roads and hard permanent structures along the shorelines. In order to protect these structures and the associated human lifestyles, we engineer the shorelines to make them more stable using armoring, bulkheads, groins, and other structures. Thousands of kilometers of levees and bulkheads have been constructed along the Mississippi River in the U.S., along the Danube in Hungary, and along the Yangtze River, China, and groins, jetties, and bulkheads are used to stabilize most of the eastern U.S. coastline. Such stabilization degrades the natural resilience of the ecosystems, removes many of the native wildlife and plants, and makes the system more vulnerable when the next storm event occurs (Naiman and Decamps, 1997). Wide buffers of undeveloped and open space should be preserved along every freshwater or coastal shoreline to allow the natural ecosystem dynamics to occur. Such buffers will become even more important as an adaptive strategy to deal with increases in riverine flooding and coastal storm surge resulting from climate change. Acting as a global role model, the Netherlands has proactively adopted the Room for Rivers program as a core component of its climate change strategy.

2.6 Principle 6: Groundwater, although invisible, is integrally connected to the health of surface water ecosystems, including streams, lakes, and wetlands

With uncertainty in precipitation and growing demands on surface water in rivers and lakes, humans are increasingly relying on groundwater reservoirs, e.g., aquifers, as a stable source of water supply. Technological advances in well drilling make it easier to access these formerly unreachable reserves. However, humans have only recently begun to understand the processes that control aquifer replenishment, and few studies have investigated the interconnections between groundwater and above-ground organisms (Sebestyen and Schneider, 2004). Since

aquifers are “invisible” with uncertain boundaries, groundwater managers are more likely to allow higher rates of groundwater withdrawal than can be replenished. As a result, the groundwater reserve is gradually depleted, and the surface of the water, e.g., the water table, gradually lowers. In the mid-western U.S., overdraft has caused parts of the extensive Ogallala aquifer to decline by more than 50 meters. Similar examples of excessive overdraft and water table lowering have been documented in Jordan and the Middle East, in China, Africa, and elsewhere (FAO, 2003). There is a growing recognition that groundwater discharge is a critical component of lakes, streams, and wetlands (Winter et al., 1998). A few studies have documented that a by-product of groundwater overdraft is the drying-out of nearby streams and wetlands, with a loss of riparian vegetation, fisheries, and other wildlife (Patten et al., 2008). Additionally, the soil surface becomes more isolated from the moist soils below, with reduced water availability and increased stress to aboveground vegetation. Careful management of groundwater withdrawals is critical to prevent overdraft, and unanticipated and unwanted impacts on streams, wetlands, as well as terrestrial communities.

2.7 Principle 7: Arid and semi-arid regions are precisely adapted to naturally limited water and are therefore vulnerable to alterations in the hydrologic system

In arid and semi-arid regions of the world, rainfall is naturally limited, and the hydrologic balance is shifted toward evaporative processes. Most rainfall, when it occurs, quickly evaporates and little water makes its way, either as runoff or infiltration, to groundwater. In each region, the native plants and animals have strongly evolved to take advantage of the amount and timing of moisture when it is available. Where rainfall is limited in total amount to 50 cm/yr but relatively uniformly distributed year round, grassland-dominated biomes predominate. Grasses have numerous strategies to efficiently capture rain when it occurs, to intercept and trap water vapor and dew, to reduce transpiration losses, and to store moisture in the soil organic matter via litter build-up. In the case of savannahs, there are also scattered trees or shrubs that have very long roots extending tens of meters in depth in order to access deep groundwaters (Daly et al., 2000). Grasslands are so productive that they have historically supported huge herds of herbivores, e.g., bison and antelope of N. America, wildebeest, and other ungulates in Africa, despite the relative water scarcity. Elsewhere, rainfall is limited on a seasonal basis, and monsoonal seasons are followed by continuous dry spells lasting four months or longer each year. The associated plant communities, called tropical dry forests, are now recognized as hotspots of biodiversity, including many plant species that are drought-deciduous, as well as evergreen species that tap groundwater within riparian zones,

succulents, and cacti (Miles et al., 2006). Monsoonal ecosystems are found in India, SE Asia, South America, and throughout the tropics.

As the average annual rainfall of a region diminishes, grassland communities are replaced by deserts containing a highly diverse assemblage of cacti and succulents that have evolved waxy outer coatings, embedded stomates, CAM physiology, and numerous other strategies to maximize water storage and utilization efficiency. At the driest end of the terrestrial continuum, biological soil crusts (BSGs) may be the only living plant systems in the deserts. BSGs are complexes of algae, cyanobacteria, fungi, and mosses, which together form thin sheets that cement the mineral grains of the desert surface. They easily withstand extreme temperatures and extensive droughts (Belnap, 2003). Within minutes of becoming moistened, they revive and initiate photosynthesis.

Humans have impacted the natural water balance within these semi-arid and arid ecosystems in multiple ways. In many places, humans have replaced the complexes of native and drought-adapted species with monocultures in the form of crops or pastures, frequently with exotic species which require irrigation. Natural plant diversity is further diminished by overgrazing of livestock. However, such loss of plant diversity is actually reducing the natural resiliency of these ecosystems to droughts. Experimental studies by Tillman and other researchers demonstrate that high plant species diversity is a key factor contributing to resilience to drought in natural communities (Tilman and Downing, 1994). Using experimental plots, they found that different plant species successively gain dominance as a drought lengthens, thereby maintaining maximum overall plant biomass and support for the associated food webs. Biological soil crusts have also been impacted, in a different way. Although resistant to extended droughts, the dried-out dormant phase of BSGs is at the same time, highly vulnerable to pressure from livestock, vehicular, or human traffic (Belnap and Gillette, 1998). When the fragile crusts are broken apart, they quickly blow away, which makes the underlying mineral soils vulnerable to wind erosion, and the initiation of desertification. Finally, organic matter in surface soils of all these ecosystems plays a key role in trapping and storing moisture, thereby increasing water availability to plants and other organisms. However, various land practices are cumulatively reducing soil organic matter through water or wind erosion, through increased sun exposure and oxidation, and through human harvesting of leaves or lawn clippings for “aesthetically pleasing” lawns, and twigs and other debris for fuel wood. The cumulative result of all these impacts is that the natural and protective “skin” of the landscape is deteriorating and unhealthy.

Irrigation is a special issue associated with arid land management, which is seriously impacting both the quantity and quality of water worldwide. It accounts for roughly 70% of global water usage and volumes of irrigation water have increased in tight parallel with rising

human populations (Gleick, 1998). Furthermore, engineers and farmers typically assume that 50% of water derived from a source never actually makes it to the crop. Instead, a disturbingly huge amount of water is “lost” to evaporation or leakage underground. There are numerous additional impacts associated with the irrigation process that affect water quality, including increased erosion from exposed soils, and runoff of pesticides and fertilizers. It is particularly problematic when irrigation water evaporates from the soil surface, leaving behind dissolved ions as salt residue in the soil. This process continues until the soil becomes too salty for crops or native plants and the land must be set aside. The FAO estimates that more than one third of the world’s agricultural lands have been impacted by such soil salinization.

In all arid and semi-arid environments, sustainable water management depends first on careful selection of activities that work in concert with the natural communities, soils, and water availability. Restoring organic matter in soil, although it has been largely ignored in most restoration projects, can play a critical role to help trap and retain rainfall or dew condensation when it occurs. Maintaining areas of highly diverse and native plant communities will create a safe haven for pollinators, for wildlife, maintain root systems that hold the soil together, and provide a source of seeds and regenerating propagules adjacent to croplands or pastures. Livestock grazing needs to be carefully limited to avoid unrecoverable damage to the plants and soils, thus preventing the initiation of desertification. Irrigation practices need to be selected, which maximize water use efficiency, ranging from crop selection to lining of transfer canals and to the use of drip tubes or other more efficient irrigation practices.

2.8 Principle 8: Fresh, clean, pure water is the basis for all life

The world’s oceans contain some 1.4 billion cubic kilometers of water, but it is too salty for many life forms, including humans, to use it for life’s activities (Shiklomanov and Rodda, 2003). Indeed, pure water is only generated through the process of evapo-transpiration, naturally driven by solar heating or artificially through distillation processes. Precipitation is therefore close to being pure H₂O in chemical content, but after flowing through a watershed, the water picks up dissolved substances and sediments. It is human activities however that have polluted many freshwaters so much that they are no longer potable, even to toxic levels. We have done so inadvertently through runoff that carries sediment, manure, pesticides, and fertilizers into our waters. We have also polluted deliberately, when we use water as a mechanism for wastewater treatment and removal. This latter is somewhat surprising given how critical freshwater is to life.

As freshwater gets scarcer, we are beginning to rethink how we deal with pollution. Creation of the Clean Water

Act in the U.S. during the 1970s provided a powerful model for reducing contamination of water by nutrients, trace metals, pathogens, and other pollutants. It relied on a combination of science-based standards, extensive permitting, monitoring, and enforcement. Extensive tool kits of BMPs have also helped to reduce the nonpoint source pollution from our landscapes. However, continued efforts will be needed as new suites of pharmaceuticals, health care products, and industrial chemicals now flood into our waters, many unaffected by passage through wastewater treatment plants. Recent regulations by the European Union are providing a model for controlling these proliferating new substances. Research and technological solutions for cleaning polluted water, such as microfiltration and reverse osmosis, may be needed. It will also take education and incentives to change established human behaviors. For example, flush toilets using freshwater to carry away wastes may not be the best use of scarce water resources. However, the use of gray water or composting or electric toilet facilities will require effort to gain widespread adoption. Clean water is critical for both humans and ecosystems and requires a multitiered program of education, monitoring, permitting, technologically based treatment, and watershed management in order to address pollution that degrades and reduces freshwater availability.

3 Positive outlook for globally sustainable water resources

Chronic water shortages already affect nearly one third of the earth’s human population. Scarcity is expected to increase as continued population growth interacts with climatic changes in the amounts and distribution of precipitation. Convincing arguments have been made that water will outpace energy as the most limiting resource on the planet and that increasing scarcity will result in disease, famine, and eventually wars. However, taking a step back to gain perspective, the good news is that the earth as a whole is a “blue” planet. An inventory of the world’s water resources indicates that there are 35 million cubic kilometers of freshwater, an amount that is phenomenally huge, even considering that the bulk of this water is stored frozen in Antarctica and Greenland or in less-accessible underground aquifers (Shiklomanov and Rodda, 2003). Adopting the eight guidelines of an integrated and watershed-based approach to water resource management can be a major step forward in improving the availability of this water, and the health of humans and all the biota which depend upon it.

There is more good news. Numerous technological and sociological advances have occurred in just the past two decades that provide critically needed tools for improved water management. Satellite-based remote sensing and computer-based Geographic Information System analyses

help determine watershed divides and allow the monitoring of land use and crops across the Mississippi, Nile, Ganges, and Mekong basins, among many watersheds that encompass millions of square kilometers. Automated water monitoring equipment, groundwater tracer studies, and computer-based models provide powerful tools for understanding hydrologic processes in both surface and ground waters. There have also been advances in the process by which we manage water and other natural resources. The first advance was recognizing the importance of engaging private citizens and other stakeholders both in goal setting and in the implementation of best management practices. The second advancement was directly integrating mechanisms for monitoring, evaluation, and feedback of whether implemented strategies are actually working into the decision-making process. Through such “community-based adaptive management,” the potential for such debacles as the drying out of the Aral Sea are much less likely to occur (Precoda, 1991).

Perhaps even more important has been the invention of tools by which the world’s people can interact more rapidly and freely because, at the heart of the solution to water scarcity is a need for global cooperation. In the first part of the 20th century, the television, radio, ships, trains, and planes all helped people to learn about each other’s cultures either through images or visits. Most recently, this exchange has been increased via Email, through video conferencing, and the Internet. We can now make new information about best management practices or technological solutions accessible almost instantly, without lag times between publication and distribution of papers. Global communication can also take place in the international World Water Forums and other conferences that facilitate dialogue about water privatization, pricing, and other socio-economic issues. Friendships and empathy, which are critical to successful cooperation, are further developed through international student exchanges and through networks of scientists, nonprofit organizations, or other groups collaborating via the Internet. Such exchange builds bonds among watershed country members that need to be truly “neighborly” as water allocation and management decisions are made. Finally, interbasin transfer of water is already occurring but expanded, and still, sustainable transfer may be necessary to help assist communities in drought-stricken countries.

Numerous new challenges are on the horizon related to water scarcity. These challenges include such issues as how hydrologic and ecosystem processes will change on a planetary scale, how multinational corporations will interface with political entities in the governance of water resources, and how the true value of water can be determined when it is integral to every aspect of society including agriculture, industry, health, and energy production. Nonetheless, if we are to be successful stewards of the planet, then global collaboration and integrated,

watershed-based management will be the key to addressing water scarcity in the face of climate change.

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References

- Arnold C L Jr, Gibbons J (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association*, 62(2): 243–258
- Belnap J (2003). The world at your feed: desert biological soil crusts. *Frontiers in Ecology and the Environment*, 1(4): 181–189
- Belnap J, Gillette D A (1998). Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. *Journal of Arid Environments*, 39(2): 133–142
- Bradley R S, Vuille M, Diaz H F, Vergara W (2006). Threats to water supplies in the Tropical Andes. *Science*, 312(5781): 1755–1756
- Brown J F (1997). Effects of experimental burial on survival, growth, and resource allocation of three species of dune plants. *Journal of Ecology*, 85 (2): 151–158
- Chen S, Liu C W, Huang H C (2002). Analysis of water movement in paddy rice fields (II) simulation studies. *Journal of Hydrology*, 268: 259–271
- Chien N (1985). Changes in river regime after the construction of upstream reservoirs. *Earth Surface Processes and Landforms*, 10: 143–159
- Chow V T (1964). *Handbook of Applied Hydrology*. New York: A McGraw-Hill Publ
- Cushman R M (1985). Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. *North American Journal of Fisheries Management*, 5: 330–339
- Daly C, Bachelet D, Lenihan J M, Neilson R P, Parton W, Ojima D (2000). Dynamic simulations of tree-grass interactions for global change studies. *Ecological Applications*, 10(2): 449–469
- Danielsen F, Sorensen M K, Olwig M F, Selvan V, Parish F, Burgess N D, Hiraishi T, Karunakaran V M, Hiraishi T, Karunakaran V M, Asmussen M S, Hansen L B, Quarto A, Suryadiputra N (2005). The Asian tsunami: A protective role for coastal vegetation. *Science*, 310–643
- Dettinger M D, Diaz H F (2000). Global characteristics of stream flow seasonality and variability. *Journal of Hydrometeorology*, 1: 289–301
- Duncan S H, Bilby R E, Ward J W, Heffner J T (1987). Transport of road-surface sediment through ephemeral stream channels. *Water Resources Bulletin*, 23(1): 113–119
- Farber S, Costanza R (1987). The economic value of wetland systems. *Journal of Environmental Management*, 24(1): 41–51
- Finkbine J K, Atwater J W, Mavinic D S (2000). Stream health after

- urbanization. *J American Water Resources Assoc*, 36: 1149–1160
- Food and Agriculture Organization of the United Nations (2003). *Groundwater management: the search for practical approaches*. Water Reports 25. ISBN: 92–5–104908–4
- Gleick P H (1998). *The World's Water: 1998–1999*. Washington D C: Island Press
- Gleick P H (2003). Global freshwater resources: soft-path solutions for the 21st century. *Science*, 302(5650): 1524–1528
- Hardy S D, Koontz T M (2008). Reducing nonpoint source pollution through collaboration: policies and programs across the U.S.States. *Environmental Management*, 41(3): 301–310
- IPCC (Intergovernmental Panel on Climate Change) (2007). *Contribution of working group 1 to the 4th assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press
- Jones J A, Swanson F J, Wemple B C, Snyder K U (2000). Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology*, 14(1): 76–85
- Junk W J, Bailey P B, Sparks R E (1989). The flood-pulse concept in river-floodplain systems. In: Dodge D P, ed. *Proceedings of the International Large River Symposium*. Canadian Special Publication of the Fisheries Society, (106): 110–127
- Kiley D, Schneider R (2005). Riparian roots through time, space, and disturbance. *Plant and Soil*, 269 (1–2): 259–272
- Kozlowski K (2002). Physiological-ecological impacts of flooding on riparian forest ecosystems. *Wetlands*, 22(3): 550–561
- Leach W D, Pelkey N W (2001). Making watershed partnerships work: a review of the empirical literature. *Journal of Water Resources Planning and Management*, 127(6): 378–385
- Luce C H, Wemple B (2001). Introduction to special issue on hydrologic and geomorphic effects of forest roads. *Earth Surface Processes and Landforms*, 26: 111–113
- Meyer J, Miltner R J, White D, Yoder C (2004). The biotic integrity of streams in urban and suburbanizing landscapes. *Landscape and Urban Planning*, 69: 87–100
- Miles L, Newton A C, DeFries R S, Ravilious C, May I, Blyth S, Kapos V, Gordon J E (2006). A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, 33: 491–505
- Mitsch W J, Gosselink J G (1993). *Wetlands* (2nd edition). New York: Van Nostrand Reinhold
- Mizuno K (2004). Glacial fluctuation and vegetation succession on Tyndall Glacier, Mt. Kenya. *Mountain Research and Development*, 25 (1): 68–75
- Moog O (1993). Quantification of daily peak hydropower effects on aquatic fauna and management to minimize environmental impacts. *Regulated Rivers*, 8: 5–14
- Naiman R J, Décamps H (1997). The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics*, 28: 621–658
- Patten D T, Rouse L, Stromberg J C (2008). Isolated spring wetlands in the Great Basin and Mojave Deserts, USA: Potential response of vegetation to groundwater withdrawal. *Environmental Management*, 41(3): 398–413
- Poff N L, Allan J D, Bain M B, Karr J R, Prestegard K L, Richter B D, Sparks R E, Stromberg J C (1997). The natural flow regime. *BioScience*, 47(11): 769–784
- Precoda N (1991). Requiem for the Aral Sea. *Ambio*, 20: 109–114
- Sanford S E, Creed I F, Tague C L, Beall F D, Buttle J M (2007). Scale-dependence of natural variability of flow regimes in a forested landscape. *Water Resources Research*, 43(8): W08414. doi:10.1029/2006WR005299
- Scanlon B R, Jolly I, Sophocleous M, Zhang L (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research*, 43: 363–365
- Sebestyen S, Schneider R (2004). Seepage patterns, pore water, and aquatic plants: Hydrological and biogeochemical relationships in lakes. *Biogeochemistry*, 68(3): 383–409
- Shiklomanov I A, Rodda J C (2003). *World Water Resources at the Beginning of the Twenty-first Century*. Cambridge: Cambridge University Press
- Stanford J A, Ward J V (1979). *Stream regulation in North America*. In: Ward J V, Stanford J A(eds.). *The Ecology of Regulated Streams*. New York: Plenum Press, 215–236
- Sutton P C, Costanza R D (2002). Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. *Ecological Economics*, 41: 509–527
- Tilman D, Downing J A (1994). Biodiversity and stability in grasslands. *Nature*, 367: 363–365
- Viviroli D, Weingartner R, Messerli B (2002). Assessing the hydrological significance of the world's mountains. *Mountain Research and Development*, 23 (1): 32–40
- Vorosmarty C J, Green P, Salisbury J, Lammers R B (2000). Global water resources: vulnerability from climate change and population growth. *Science*, 289: 284–288
- Wang L, Lyons J, Kanehl P, Bannerman R (2001). Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management*, 28(2): 255–266
- Winter T C, Harvey J W, Franke O L, Alley W M (1998). *Ground Water and Surface Water A Single Resource*. U.S. Geological Survey Circular 1139
- Wu R S, Sue W, Chien C, Chang J, Lin K (2001). A simulation model for investigating the effects of rice paddy fields on the runoff system. *Mathematical and Computer Modelling*, 33 (6–7): 649–717