Planning and Managing Soil and Water Resources in Drylands: Role of Watershed Management

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ABSTRACT

Through comprehensive watershed management, soil and water resources of drylands can be managed to sustain the productive capacity of the land and to better cope with water scarcity and the extremes of droughts and floods. The sparse and erratic nature of precipitation in drylands limits opportunities to enhance water yield from watersheds. Water supplies can be augmented in some instances through vegetation manipulation, water harvesting and other methods. Large scale reservoirs, upon which so many in drylands depend, benefit from sound watershed management that reduces sediment export from both uplands and riparian systems. The key to sustaining productivity of uplands and downstream areas is to manage land and water resources in concert with one another. Accounting for the economic value of water and the costs incurred to restore degraded watersheds (halt desertification) represents economic benefits of protecting soil and water resources. A comprehensive approach is necessary that promotes cooperation among stakeholders and that minimizes conflicts over land and water management. Implementing these ideas, which constitutes the watershed management approach, hinges on institutional and policy support.

INTRODUCTION

Soil and water resources provide the foundation for agricultural and natural resource development throughout the world. In many developing countries, expanding populations exert increasing pressure on land and water largely in efforts to enhance food production, and with little regard to long term impacts. In the wealthier countries, we often see human populations expanding in drylands because of favorable climates, but irrespective of water scarcity. In all cases, however, the wise use and management of soil and water resources are fundamental to achieving sustainable economic development.

Freshwater scarcity is a global problem (Postel 1989, Falkenmark 1989, Gleick 1993, Kundzewicz 1997, Vorosmarty et al. 2000) that is particularly acute in drylands, and that threatens our ability to achieve food security, alleviate poverty, and improve human health. The occurrence of droughts compounds water scarcity and often leads to excessive use of natural resources. Extended droughts results in famine in the poorest of countries. In contrast, many drylands can experience periodic excessive rainfall that can cause flash floods and consequently, loss of life and property. With few exceptions, water scarcity, and the extremes of droughts and floods impact rich and poor countries alike.

Land scarcity compounds the problems of water scarcity, making people more vulnerable to the extremes of droughts and floods and leading to widespread exploitation of natural resources. Accelerated soil erosion can accompany intensive human development and natural resource exploitation, whether it is urbanization or grazing and cropping on hillslopes. Surface and gully erosion exacerbate problems of low productivity, further diminishing soil resources which threatens the future productivity of the land. Water quality can become impaired, which when coupled with high sediment levels, constrains our ability to develop sustainable water resource management. Clearly, actions must be taken on many fronts to develop sustainable solutions and improved management of land and water in dryland environments.

Land use and water are inextricably linked together, but are not often managed in concert with one another. Watershed management offers the framework for achieving this integrated management approach to increase or sustain food and natural resource production while protecting the soil and water resources upon which this productive capacity depends (Brooks et al. 1997, Gregersen et al. 1987). Implicit in this approach is the recognition that land use in uplands affects the flow and quality of water reaching downstream areas; in contrast, water resource development (e.g., reservoirs, canals, and others) can affect the type and intensity of land use throughout a watershed. Transforming this recognition into effective solutions, however, is hampered by inadequate policies and an absence of institutions and organizational arrangements that are needed to achieve the integration and intersectoral cooperation upon which implementation depends (Kundzewicz 1997, Rosegrant 1997, Scherr and Yadav 1996). This paper considers the major issues facing natural resource management of drylands and discusses the opportunities to achieve more sustainable solutions through comprehensive watershed management. Although the focus will be more on the poorer areas of the world, where these issues are more pronounced, the principles and applications apply in all areas, regardless of economic status.

THE WATERSHED SETTING

Nowhere is there a greater need for comprehensive watershed management than in drylands. Understanding and coping with the linkages between land use and water is critical. Water should be viewed as the most valuable product of the land and the one resource upon which all other production depends. Whether the setting is the southwestern United States, with its expanding urban population, or an agronomically based country in sub-Saharan Africa, the specific objectives of management can vary, but the overall goals encompass the production of goods and services with the underlying dependence on developing and sustaining water resources. In discussing needs and opportunities for enhanced management of drylands, we must recognize and be able to work with the variable and often unpredictable precipitation and water yield characteristics that typify these regions.

Hydrologic Characteristics of Drylands

Drylands are characterized not only by low annual precipitation, but also by erratic precipitation that is subject to large temporal and spatial variability. While precipitation in many semiarid lands averages between 200-500 mm/yr, which is suitable for some crops, the extreme fluctuations in precipitation from year to year make such averages of little use (Heathcote 1983). That is, we cannot depend upon average precipitation values for planning agricultural and natural resource development, or urban expansi on. Within dryland regions precipitation can vary considerably from one location to another. In mountainous areas, orographic precipitation can result in high rainfall in upper elevations but with much lower precipitation in the valley bottoms. For example, annual rainfall in the Rif mountains of northern Morocco can reach 1,000 mm in the highest elevations, but annual rainfall is less than 250 mm a few kilometers away on the leeward side of the mountains (Tayaa and Brooks 1984). As a result, water yield enhancement strategies usually focus on higher elevation watersheds.

Precipitation alone does not define the climatic character of drylands. Aridity describes the normal conditions of drylands that are the result of factors that create low levels of moisture availability (Heathcote 1983), which includes not only low annual precipitation amounts, but also high evaporation demands. Ratios of evapotranspiration to precipitation are generally large in drylands, exceeding 95% in some areas (Branson 1976). As a result, soil moisture is normally low during much of the year and is usually the controlling factor affecting vegetative growth. The exception is in oases or other riparian areas, such as in the southwestern United States, where evapotranspiration can exceed precipitation amounts because of locally available soil moisture (DeBano et al. 1996, Baker et al. 1998).

A distinction needs to be made between aridity, described above, and droughts. Whereas aridity is the normal condition of low available moisture of drylands, droughts result from periods of below normal precipitation that persist. Heathcote (1983) defines a drought as " . . . an unexpected shortage of available moisture sufficient to cause severe hardship human resource use . . . ," and points out that a drought can occur in any climate. Coping with droughts is particularly challenging in drylands, where water is normally of short supply.

As a result of low and erratic precipitation in drylands, ephemeral or intermittent streams are the norm rather than perennial streams. It is not uncommon for perennial streams to originate in higher elevation zones, or from springs or seeps at the toe of slopes in mountainous areas, and then become intermittent downstream from the source area. Transmission losses of water (i.e., water that infiltrates into the channel bottom) can however, result in a mounding of shallow groundwater below and near stream channels and in adjacent floodplains. Dense vegetative communities in these riparian zones, often dominated by phreatophyte vegetation (water loving plants, often deep rooted trees), are indicators of such conditions. Saltcedar (*Tamarisk spp.*), Mesquite (*Prosopis spp.*), and cottonwood (*Populus spp.*) are examples of phreatophytes which have been shown to transpire 1,000 mm to more than 2,000 mm of water per year from shallow water tables in the southwestern United States (Horton and Campbell 1974, Van Hylckama 1970). During periods of prolonged rain, or snowmelt runoff from high elevation zones, the water table can rise to the surface channel, only to retreat below stream channel bottoms during dry periods as a result of excessive evapotranspiration by phreatophytes. As a result, perennial streams in downstream valleys are rare as rainfall or snowmelt cannot be relied upon to sustain streamflow throughout the year.

Floods are not uncommon in drylands and can occur during the rare periods when there is prolonged and excessive rainfall or snowmelt runoff, or more frequently, from convective rainfall that brings localized but intense rainfall. Flash floods from high intensity rainfall are highly variable across the landscape and are common in the southwestern United States (Marti et al. 2000, and others). It is not uncommon for dry stream channels to become torrents within hours of convective storms that may have occurred several kilometers upstream. Furthermore, one stream channel can be flooding while another channel a few kilometers away can be completely dry. Such floods are the result of surface runoff or overland flow that occurs from watersheds with sparse vegetative cover and shallow, poorly developed soils with low infiltration capacities. Much, if not all, of the stormflow from flash floods that results from runoff into dry channels is lost to transmission losses and bank storage. As a result, the volume of streamflow often diminishes rapidly as the stormflow event moves farther downstream. Some of the transmission losses may recharge groundwater aquifers, but much of the bank storage and water that recharges shallow groundwater may be eventually lost back to the atmosphere via transpiration by phreatophytes.

Soil Erosion and Sediment Delivery

Soil erosion reduces the productivity of upland watersheds and the resultant sediment that reaches stream channels can adversely impact reservoirs, water conveyance systems, and water quality in downstream riparian corridors. Soil loss by the actions of water and wind is generally higher in drylands such as the southwestern United States than in the more humid east (Hendricks 1985, Brooks et al. 1997, Baker et al. 1998). Surface soil erosion accounts for much of the soil loss in the southwestern United States (Lopes and Ffolliott 1993, Lopes et al. 2001), but gully erosion is important in heavily degraded areas.

Intensive grazing and cultivation of marginal farmland occurs in many drylands of the world and have caused excessive soil loss from surface and gully erosion. Gully erosion is an indicator of advanced watershed degradation and can reduce the production potential of the land dramatically. When accelerated erosion occurs immediately upstream of a reservoir, the resulting sediment delivered to a reservoir can impact the function and life of the reservoir. Two examples are provided in Box 1.

Box 1. Examples of erosion and sedimentation from intensively used watersheds in two dryland countries of Africa.

Lesotho (from Stromquist et al. 1985)
The small country of Lesotho in southern Africa has historically been intensively grazed which has caused accelerated levels of soil erosion. Surface and gully erosion rates in a 4.9 km^2 watershed in Lesotho were documented with aerial photographs and ground measurements. Gully eroded areas increased by 260,000 m^2 between 1951 and 1980. Over that period gully erosion caused (1) a roughly 5% reduction in productive land area of the watershed, and (2) significant contributions of sediment to a downstream reservoir. The sediment delivered to a downstream reservoir was 300,000 t and 80,000 t, respectively from gully and surface soil erosion. The trapped sediment within the reservoir had a corresponding volume of about 267,000 m^3.

Morocco (from Tayaa and Brooks 1984, Tayaa and Bazza 1992, 1993)
Mean annual precipitation averages less than 250 mm/yr in Morocco, but ranges from less than 50 mm/yr in the far south and southeast to more than 1,000 mm/yr in the highest elevations of the Rif, and the Middle and High Altas mountains. Nearly 90% of the country receives less than 250 mm/yr. Because of this uneven distribution of precipitation, reservoirs have been constructed near these high elevation zones to provide irrigation water for the drier areas.

Existing and planned reservoir projects, however, are threatened by excessive soil erosion in many parts of Morocco. Land use has a major effect on soil erosion and the resulting sedimentation rates to reservoirs, as illustrated below.

Characteristic	**Watershed/Reservoir**			
	Loukos	**Tleta**	**Nekor**	**Nakhla**
Area (km^2)	1,820	178	780	110
Average precipitation (mm/yr)	900-1,000	700	350	600
Percent area in				
Agriculture	47	48	45	32
Range	32	42	55	27
Forest	21	2	0	41
Reservoir capacity (x 10^6 m^3)	710	43	42	9
Sedimentation at reservoirs				
Average rate (t/ha/yr)	43	220	79-285	62
% of the total capacity	10	15	43	36

It is estimated that excessive soil erosion and sedimentation, as illustrated above, threatens the storage capacity of the 34 existing large reservoirs in Morocco. These projects have a total storage capacity of 10 billion cubic meters which provides irrigation water for 600,000 hectares and generates 660.4 MW of hydroelectric power. It is estimated that 50 million m^3/year is being lost (0.5 % of the total design storage capacity of the existing dams) corresponding to an average loss of 6000 ha of irrigated area each year. Under the prevailing sedimentation conditions, it is expected that 60 million Kwh of hydroelectric power and 40 million m^3 of drinking and industrial water will be lost by the year 2010. To date, a total of more than 820 million m^3 of the total storage capacity have been lost.

In addition to the impacts on reservoirs, excessive soil erosion in many parts of Morocco is causing the productivity of soils to decline. Annual loss of soil nutrients in agricultural areas located northwest of the Rif mountains is equivalent to $US20/ha/yr. This represents about 90% to 180% of what local farmers invest yearly in fertilizers.

Several lessons can be learned from the examples in Box 1. In the Lesotho case, once gully erosion begins, and if land use and structural changes are not implemented early on, land degradation proceeds rapidly with the potential for serious economic impact both on-site and downstream. The implications for watershed management would suggest that erosion from overgrazing led to both a loss of land production potential and shortened the economic life of the reservoir. Costly rehabilitation efforts involving both structural and vegetative measures would be needed to reverse these processes. From a watershed management perspective, preventing such losses in the first place through improved grazing practices can be (and should be) considered as an economic benefit, and thus a basis for justifying grazing management programs.

In the Moroccan example, land use and rainfall interactions dictate soil erosion and sedimentation rates. The highest rates of sedimentation correspond to the watershed with the most intense land use (and least forest cover), but with the lowest rainfall, averaging 350 mm/yr. Herein lies a dilemma for watershed management. With such low rainfall and severely overgrazed watersheds, opportunities to reduce erosion (estimated to be >250 t/ha/yr) and sedimentation through revegetation are limited. Costly structures would be required to accompany any vegetation program which takes a long time to materialize; furthermore, the ability to reduce grazing pressures during the rehabilitation period dramatically constrains rehabilitation in such areas where the rural poor are directly dependent on their livestock. As a result, reservoirs fill with sediment at an alarming rate. Where rainfall is greater, the potential is also greater for restoring the watershed. A watershed restoration program that controlled grazing and increased forest and fruit tree production on the Loukos watershed was shown to be economically justified with an internal rate of return of 15.9% (Brooks et al. 1982).

There is another aspect to sediment delivery at reservoir sites that needs to be addressed when considering watershed restoration measures. Sediment that is entrapped in streamflow is the product of upland erosion processes, streambank erosion, and channel scour. Streams are formed over geologic time in response to dynamic and complex fluvial processes and hydraulic factors. When watershed conditions change sufficiently to alter either the streamflow response or the amount and type of sediment that enters the channel, the stream will adjust and can become unstable, in some instances accelerating sediment delivery downstream (Rosgen 1994). Similarly, changes in the riparian plant community that alters streambank stability and that affect the velocity of flow through floodplains during flood events, all affect downstream flows and sediment regimes. Therefore, floods and sediment are linked together and are further linked to the condition of upland watersheds and their riparian plant communities. Flash floods are natural, episodic events that transport large quantities of sediment and debris. The extent to which land use on upland watersheds affects the magnitude and frequency of flash flooding, and the sediment and debris load that these floods carry, is not well understood in most drylands. We do recognize, however, the importance of riparian vegetation in helping to mitigate the effects of such events. Where riparian vegetation becomes patchy and less dense, it is less effective in dissipating streamflow energy and stabilizing streambanks (Medina 1996, Medina et al. 1996, DeBano and Baker 1999). Excessive livestock grazing, improper cultivation, improper tree cutting, roads, urban development, and so forth, all can accelerate runoff and the erosion processes that contribute to both watershed degradation and stream channel instability.

THE CHALLENGE TO MANAGEMENT

Pressures on natural resources are intense in the drylands of the world. As populations of people and livestock increase, their demands for food, forage and other natural resources increase, thereby applying stress to drylands. Responding to such stresses and managing these ecosystems is constrained by inherent characteristics of sparse vegetation, shallow soils, low and undependable amounts of precipitation, and generally low productivity. In the developing world, overuse of drylands is expressed through overgrazing, depletion of fuelwood, and cultivation practices that are not suited for the climate or terrain. Even in the developed world, considerable stress is applied to the land through overgrazing, urban expansion, excessive use of off-road vehicles, and so forth.

In all drylands receiving intensive use, some common issues and problems arise, which need to be addressed through management. Foremost, drylands have commonly been viewed in the past as wastelands, not worthy of economic concern or political attention. Global concerns about desertification over the past few decades have focused more attention to dryland issues and the need for land use reform. Desertification is often used to describe areas that have become desert-like in their appearance as a result of human induced degradation. To some extent, emerging programs to combat desertification have helped generate the political and economic support that is needed to reverse land degradation. However, there are certain inherent characteristics of drylands that place limits on the potential for agricultural, natural resource and urban development. There are also conditions that make watersheds vulnerable to degradation, and that constrain our ability to restore or rehabilitate the land.

Water scarcity is a reality that must be dealt with before any type of development can be sustained. Opportunities for enhancing water supplies are discussed later, but there are other factors that need to be addressed in the planning and management of land and water resources so that the productivity of the land is sustained, and the soils and vegetation communities of dryland watersheds are not degraded. Any type of development of drylands should recognize that vegetative communities and soils are sensitive to intensive use and once degraded, many decades are needed to restore the production and hydrologic function of these ecosystems. Low and erratic precipitation prevents the rapid reestablishment of vegetation, leaving a degraded landscape exposed to water and wind erosion for long periods of time.

Although aridity typifies the general condition of drylands, it should also be noted that most dryland regions have "islands of abundant moisture" that can be found in higher elevation mountains (as in the southwestern United States), in oases, and in other riparian areas. Because of the presence of water, high productivity, and ecological values, riparian areas receive an inordinate concentration of human and animal use, many times leading to overuse and degradation. As a result, riparian areas have become a focal point of natural resource managers and developers in drylands (DeBano et al. 1996, Medina 1996, Medina et al. 1996).

Because of the favorable climate, many drylands are targeted for urban and agricultural development, all of which hinges upon the ability to develop and enhance water supplies. Many large cities and retirement communities have emerged in the driest areas of the southwestern United States. In contrast, large-scale irrigation projects likewise have emerged in the drylands of China, India and Pakistan. The sustainability of such efforts is becoming problematic as populations grow, demands for water increase, and conflicts over water use arise. In the past, engineering technologies have been relied upon that capture water in water abundant areas (or during periods of high precipitation) and then store and transfer water to areas (or during time periods) where or when it is needed (see Cech 2003 and Brooks et al. 1997). The following considers how land use and watershed management can complement efforts to enhance water supplies and cope with water scarcity.

ENHANCING WATER SUPPLIES OF DRYLANDS

An array of technologies exists to increase water supplies in an area, including cloud seeding, towing polar icebergs, desalinization of sea water, groundwater development, reservoir storage, evaporation suppression and vegetation management (Cech 2003, Brooks et al. 1997). New technologies are emerging but most are costly and sometimes have unwanted environmental impacts. A full discussion of all these technologies is beyond the scope of this paper. What is stressed here is the need for comprehensive to develop effective and efficient water resource development projects within the framework of sound watershed management. There is no simple solution. The management of uplands and riparian areas must be coordinated among stakeholders in a way that makes good economic and ecological sense. The following methods can be considered as complementary to the more the more common and larger scale reservoir storage and transfer technologies

Vegetation Management

Vegetation can be managed to either conserve existing water supplies or to increase the yield of water from a watershed for a given precipitation regime. Conservation of existing water supplies can be achieved through more efficient irrigation methods and by favoring crops with inherently low consumptive use. The second option is discussed in greater detail below, and can be used in conjunction with other nonvegetative measures as well. Discussions of improved irrigation technologies are beyond the scope of this paper. The selection of crops that have low water requirements will depend on the region and species that are adapted to the local conditions. Of course, any such crops must be acceptable to local people and must be economically viable. Therefore, a detailed discussion of specific species is not possible. In most areas, we do know that certain types of vegetation use water extravagantly and should be avoided. Eucalyptus trees are a good example of rapidly growing trees that have been planted in many drylands for purposes of increasing fuelwood supplies. The cost of growing such trees needs to be considered in terms of water consumption, that is, water that is lost that can otherwise be used for other purposes. It is not always clear whether any water savings from altering species will actually be realized. Genetic engineering may eventually lead to the development of crops with low consumptive use, although at this time the authors are unaware of any such research that has produced such plants.

Manipulating vegetation on watersheds to increase water yields has been given considerable attention for several decades (Bosh and Hewlett 1982, Whitehead and Robinson 1993, Ffolliott et al. 2000, and others). Studies indicate that water yield can be increased when: (1) forest cover is reduced, (2) deep-rooted species are replaced with shallow rooted species, and (3) species with high interception and transpiration (ET) losses are replaced with species that have lower ET losses (Brooks et al. 1997, and others). Hibbert (1983) considered opportunities for increasing water yield from drylands in the western United States and concluded that the above manipulations of vegetation increase water yield only when annual precipitation exceeds 400 mm/yr, but increases are marginal unless annual precipitation exceeds 500 mm/yr. Before vegetation manipulation for water yield enhancement is implemented, several factors must be taken into consideration. First, there must be some means of capturing the water yield increase; reservoir storage should be both adequate to accommodate any increases in water yields and close to the watershed outlet. If water yield is increased during periods when reservoirs are full, there is little value in carrying out such management. As discussed earlier, stream channels in drylands characteristically have high transmission losses and ET rates of riparian vegetation can further diminish water flows from upland watersheds. Brown and Fogel (1987) determined that less than half of any water yield increases in the Verde River Basin of Central Arizona would actually reach the Phoenix area (about 150 km downstream) because of transmission and evaporative losses. Therefore, the best opportunities for this approach are in uplands where annual precipitation exceeds 500 mm/yr, and where watersheds can be dedicated for water supply purposes immediately above reservoirs. In marginal rainfall zones of between 400-500 mm/yr, some limited opportunities may exist to increase water yield by converting shrub lands to grasses, which improves grazing production as well. This concept was considered nearly 50 years ago in central Arizona (Barr 1956).

In addition to the above factors, implementing water yield enhancement strategies hinge on other considerations. Changing vegetative cover on a watershed can affect wildlife habitat as well as other uses of the land, such as outdoor recreation. Changes in erosion, sediment transport, and water quality must all be understood prior to implementation.

Vegetation manipulations for purposes of conserving groundwater were the focus of early work that considered the removal of phreatophytes in floodplains, or otherwise reducing their transpiration (Brooks and Thorud 1971). Because of the high transpiration rates of phreatophytes discussed earlier, there is considerable potential to salvage groundwater in areas where groundwater supplies are critical. Such possible benefits must be weighed against the value of such vegetation in terms of riparian values for flood control, channel stability, wildlife habitat, and so forth.

Clearly there are limitations in many dryland areas to enhance water yield through vegetation manipulations. Other technologies can be used to increase water yield or to complement other water conservation measures. Some are tailored more for local household or farm use, while others can be components of more comprehensive water management systems.

Water Harvesting

For centuries people have captured rainfall from rooftops that is stored in barrels for later household use. Likewise, but on a larger scale, small impervious catchments have been designed to efficiently produce runoff from rainfall as a means of increasing water supplies in drylands. Storage of the harvested rainfall is required, and such systems are normally used to augment existing water supplies or as an alternative to more costly methods of obtaining water. Water harvesting systems are small scale and best suited for watering livestock, small-scale subsistence farming, and/or local domestic use. Some water harvesting systems have been used for centuries and still have application in certain situations (Box 2).

Box 2. Water harvesting for multiple water use may be a source of inspiration for rural Moroccans (Tayaa, 2001)

Morocco’s expanding population and growing socioeconomic development is being constrained by water scarcity. In the past few decades, large investments have been made into developing Morocco’s water resources through the construction of large dams and multi-purpose reservoirs.

Until recently, little attention has been given to the role of rainwater harvesting as a means of enhancing domestic water supplies in rural areas. The past two decades have witnessed an expanding recognition and commitment to improve water harvesting systems in Morocco as well as several other countries of Africa. The application of modern hydrologic and construction techniques for water harvesting is being considered to play an increasing and important role in the highly populated dryland areas of Morocco. However, there are existing traditional systems that can serve as a source of inspiration to rural inhabitants and provide them with critical water supplies. For example, the traditional rainwater cistern system used in the drier areas of Morocco, is technically simple, inexpensive, and easily constructed with locally available materials. These systems can serve as feasible alternatives to more modern and expensive systems as a means of meeting the urgent demands for water by its rural population.

Action is now needed to integrate the traditional and modern water harvesting systems into the regional and national watershed and water resources development plans and projects.

Several different designs are possible, but generally at least 80-100 mm of annual rainfall is required (National Academy of Sciences 1974). Apron type water harvesting systems have an impervious catchment area, a storage facility and a water distribution system and have been widely used for providing water for livestock. Catchment areas can be a few square meters up to 1,000 m^2, and consist of natural rock outcrops, paved roads, or soils that have been treated to make them impervious. For livestock watering, storage tanks should be covered or situated where evaporation losses are minimal.

Water harvesting has been widely practiced in sub-Saharan Africa. Such systems have been effective in augmenting rain-fed agriculture in areas with unreliable and erratic rainfall that normally occurs over short periods of 70-120 days per year (Rockstrom et al. 1999). For example, in Burkina

Faso and Kenya, catchments of 1-1.2 ha have been used to harvest rainfall to irrigate crops where annual rainfall averages 600-700 mm/yr, but potential evapotranspiration exceeds 1,500 mm/yr. Such applications can be crucial to subsistence farmers and pastoralists in many parts of the world. Economics, social factors, and careful consideration of alternatives should be taken into account before investing in water harvesting systems.

Box. 3. Traditional water detention and diversion practices in Morocco (Tayaa 2001).

Water diversions are traditional methods of using flash flood water to irrigate local crops in the drier parts of Morocco. These systems are well adapted to the local conditions and are used to irrigate areas close to or within the watercourse. In Morocco, more than 165,000 hectares are irrigated using these traditional water diversion practices. Three types of these water diversions are described below:

Lateral diversion: This technique consists of diverting a part of the flood water from an ephemeral watercourse or a gully to a conveyance channel which may at times provide water for several hundreds of hectares downstream. This system has been generally used in streams of relatively steep slope gradients (5 to 10%) and a large stable channel bed. The off-take is generally located at the base of a stream embankment. Several off-takes may be used to irrigate the same area.

Earth dike diversion: This is an improved version of the lateral diversion. The primary objective is to provide head for an off-take in order to irrigate greater areas. Its use is restricted to streams with relatively low slope gradients, pronounced banks and medium width. The dikes are constructed of primitive material such as gravel and sand excavation from the river bed.

Small retention dams: This practice is usually encountered in the Saharan zones where floods are less frequent and with limited runoff volumes. It consists of small earth or loose rock dikes (up to 1.5m height) constructed across the river and designed to store flood water for crop cultivation (mainly barley) in the river bed upstream of the dam and to recharge groundwater. It is practiced in wider rivers having lower slope gradients and appropriate bed material for cultivation. They are occasionally washed out and this insures, particularly for the diversion dams, a self cleaning of the sediment deposited upstream of the dikes. The reconstruction and maintenance require a tremendous effort in terms of labor supported totally by farmers, which is a way of keeping solidarity within the community.

Modern technology has been introduced into flood diversions, but is largely inspired from the traditional practices. With reinforcement, these structures provide better control of the diverted floods and protect the structure itself.

Water Spreading

Ephemeral flows of streams in drylands can sometimes be diverted onto gently sloping areas to enhance forage production or to irrigate crops in drylands (National Academy of Sciences 1974). Examples are presented in Box 3. Water spreading systems are best suited where upstream watersheds produce at least three or four runoff events immediately before or during the growing season. Stormflow is diverted from a channel and then with the use of a system of long, low earthen dams or dikes that are parallel to the contours of the land, water is spread onto a gently sloping land surface. The system is designed so that a series of cascading dikes splits the water received from upslope, so that water is spread over an increasing area in the down slope direction. The diverter can conduct all or just a portion of streamflow directly into the spreading system.

Even more so than with water harvesting, water spreading systems have limited applications. Economic considerations and the need for coordination and cooperation among upstream and downstream users of water are all critical to the implementation of water spreading.

COPING WITH HYDROLOGIC EXTREMES

Although water scarcity is pervasive in drylands of the world, and has been the focus of the preceding discussion, the role of watershed management in coping with the extremes of droughts and floods in drylands also deserves special attention. Droughts and floods are often referred to as unexpected and rare, and crisis management seems to be the term that best describes how many parts of the world cope with such occurrences. In planning for land and water management and human development in general, we should, however, recognize that such events do occur, and in fact they are not necessarily rare. What may be rare and unexpected is their magnitude and duration, not to mention the rarity of preparedness on the part of people affected by their occurrence.

Technologies abound that have been designed to help people cope with the extremes of too much or too little water, some of which has been discussed earlier (see Cech 2003 and Brooks et al. 1997). The weak links in actually coping with droughts and floods, however, are usually related to poor planning, the absence of a comprehensive, integrated approach to land and water management, and the means to coordinate and implement comprehensive programs. To begin with, planners and managers must recognize that droughts and floods will occur, and that people can do little to affect their occurrence. However, we can affect their impact on humans.

Land and water scarcity affects human behavior and to some extent constrains our ability to cope with extreme hydrologic events. In most drylands, people become concentrated near stream channels, and in the adjacent riparian or floodplain areas. Such areas are, of course, the most prone to flooding. Even though floods may not occur every year in ephemeral streams, we know that they will eventually occur and the nature of flash floods gives little time for humans to escape their destructive power. In mountainous terrain, steep stream channels can become charged with sediment over time, which can become debris torrents when high intensity rains occur. Such debris torrents are extremely destructive to the downstream areas that lie in their path. One or more of the following approaches can be taken to cope with floods and debris torrents: (1) flood and debris torrent control with the use of engineering structures such as dams, levees and diversions, (2) flood warning programs that give people advanced warning of an impending flood so that they can leave the flood prone areas, and (3) zoning of hazardous areas that restricts human activity in areas susceptible to floods and debris torrents. Given that the first option is costly and can provide only limited protection, and flood warning systems in areas subjected to flash flooding is unrealistic, zoning of hazardous areas (e.g., flood plain management) is considered to be the most viable option in most cases. This approach recognizes that where people and their dwellings become concentrated in areas that are prone to hazards of flooding or debris flows, disasters will occur.

Policies and institutions must be in place that provides incentives for people to avoid hazardous areas. Delineating flood-prone areas can be facilitated with GIS-based terrain analysis (Gupta and Joshi 1990, Sidle 2000). Similarly, methods of delineating flood plains and zoning are well known (Bedient and Huber 1988). However, incentives are needed to change people's behavior in such hazardous areas; an example is the Federal Flood Insurance program (USA) which links insurance rates to the degree of hazard.

Coping with droughts is more problematic and requires that many contingencies be considered. Two perspectives are needed, one to prepare for droughts and the other to deal with droughts after they occur. Efforts to increase water supplies in drylands and that can carry over supplies for several years have been the goal of many water resource projects. Reservoirs, water transfer systems, etc. all have some merit in developing dependable water supplies for periods of water shortages. Once droughts occur, water conservation programs can become accelerated by means of reducing consumption. However, communities that already have strict water conservation programs in place may find that once the drought occurs, there may be no buffer in the system; that is, there are no additional water conservation actions that can be implemented without incurring severe hardship. In many instances, programs can be established that incrementally reduces water use on an established priority basis at the outset of droughts. Restrictions on water use can become prioritized based on established criteria for a region. Those uses, which have the least adverse impact on people, become restricted early on and progress into uses that have greater impacts. In any event, coping with droughts requires the necessary policies and institutions that can implement a combination of water conservation measures and drought contingencies. Options, unfortunately, seem to be more restricted in the poorer countries, where the effects of droughts are more dramatic.

A watershed management approach can play an effective role in coping with the types of hydro-meteorological extremes discussed above. In the process of planning and implementing agricultural, water resource, and other natural resource projects, a watershed approach brings into the process the explicit recognition of the linkages that exist between land use and water and between upstream and downstream areas. Land use that leads to loss of vegetative cover, soil disturbance and overall watershed degradation can exacerbate flooding and debris flows and can constrain the ability of local inhabitants to cope with droughts. The benefits of soil and water conservation through watershed management are expanded upon below.

IMPLEMENTING WATERSHED MANAGEMENT

Dryland watersheds present unique problems and challenges to planners and mangers of land and water resources. They are more fragile than watersheds with more abundant rainfall and dense vegetation. They have a limited potential for production that is largely due to inadequate precipitation and poor soil conditions. Once disturbed, these watersheds take longer to recover. For the most part, water scarcity dictates the types and extent of land use that takes place, yet we see land development occurring in some drylands as if water was abundant. In moving toward sustainable development and use of resources on these lands, the biophysical realities of these systems must be recognized, but equally important, the necessary policies and institutional arrangements must be in place to mobilize human activities on the land in ways that are compatible with these biophysical realities.

Freshwater benefits to downstream areas naturally accompany sound management of upland and riparian areas. Preventing watershed degradation should, therefore, be realized as beneficial; avoiding losses that would occur from exploitation of resources on the land is equally beneficial as increasing the productivity of an already degraded land. In contrast, management can be targeted to specific watershed objectives, such as enhancing the quantity and quality of water yield above a reservoir. In either case, benefits can be masked by: (1) the location and diffuse nature of land use practices and their effects, (2) the scale of activities relative to overall watershed size, and (3) the length of time needed for benefits to become realized. Changes on the land can have incremental effects, which individually may not be apparent, but when viewed over the watershed and over time, can have more serious cumulative effects. This complexity has blurred the vision of decisionmakers in many parts of the world, has constrained economic assessments, and overall weakened commitments to watershed management. To overcome this problem, the economic costs and benefits of comprehensive watershed management must become better known.

Economic Considerations

Watershed improvements for land and water management purposes require economic justification. A watershed perspective provides clarity in determining the economic importance of water-related ecosystem services (e.g., increasing water yield, improving water quality, reducing sediment delivery to a reservoir) attributed to changes in land use. To date, comprehensive economic analyses that consider the *full range* of these services or benefits from watershed improvements are lacking. Inadequate monitoring and evaluation of watershed projects explain part of this void. Other reasons include (1) the difficulty in determining the values of many of the services or benefits, particularly those that are not traded in the market place, and (2) water subsidies. Water is heavily subsidized in many parts of the world, including drylands, and is often treated as a free good. Water scarcity is now causing people to become more realistic in determining the true value of freshwater, as discussed below.

A new perspective on the global water economy is now emerging in which freshwater is viewed more as an economic commodity rather than a publicly managed resource (Anderson, 2002). For example, in southern California (USA), farmers pay $10/acre-ft ($8 per 1,000 cubic meters) for irrigation water that has been supplied from reservoirs located in the northern, water rich parts of the state. In contrast, the City of Santa Barbara pays $2,000/acre-ft ($1,600 per 1,000 cubic meters) for its drinking water through the process of desalinization of ocean water. Here, water has more value than many of the crops being irrigated, resulting in some farmers willing to sell their water to municipalities. In such instances, there may be sound economic justification for managing watersheds strictly for water supply purposes. Such economic reality faces hurdles in developing countries, where water has often been treated as a free good because of long-standing practices and religious beliefs (Rosegrant and Cline 2002). In all cases, however, more efficiency-oriented water allocation and innovative pricing policies can provide the incentives needed to support watershed management for water supply purposes. In contrast, policies that continue to treat water as a free good, or that heavily subsidize water, will continue to promote waste in developing and developed countries alike.

Institutional and Policy Considerations

More effective and efficient management of land and water resources to improve human welfare requires more than just technical knowledge. Technical information provides a foundation from which upstream-downstream linkages can be assessed and economic analyses performed. Transforming such information into management requires effective participation by stakeholders to develop a consensus and provide incentives for implementation (Eckman et al. 2000). A policy environment must be created that supports rather than hinders the integration of land and water management.

Watershed and political boundaries rarely coincide; as a result, the necessary coordination of land and water management depends upon functional organizations that can resolve transboundary issues and water use disputes. The lack of effective watershed-level organizations led to the formation of more than 1,000 watershed districts in the United States during the 1990s to deal with upstream-downstream issues (Lant 1999). Internationally, the Nile Basin Initiative established a basin-wide partnership of nine riparian countries to help resolve transboundary issues and to deal with inequities of water distribution in the basin (Baecher et al. 2000). More than 80% of the flow in the Nile River originates in mountainous Ethiopia, a river upon which downstream Sudan and Egypt are heavily dependent. Without cooperation and coordination of both land use on watersheds and water development projects within the basin, disputes and conflicts could erupt. In all situations, a strategy is needed that promotes coordination and cooperation among the stakeholders in a watershed. Policies are needed that provide the incentives to these stakeholders to achieve comprehensive and sustainable soil and water management of dryland watersheds.

CONCLUSIONS AND RECOMMENDATIONS

Water scarcity is a global problem that is particularly acute in the drylands of the world. As such, global attention on water management issues and solutions is needed. Finding solutions presents difficult challenges because options are often limited for increasing water supplies in most drylands. Furthermore, land and water use should be managed together to sustain or enhance productivity of the land and effect better watershed management. A multifaceted approach is suggested here to cope with water scarcity on one hand and extremes of too much water on the other. Supportive technologies exist in many cases, but implementation requires appropriate policy and institutional support to engage stakeholders and agencies in efforts that lead to sustainable solutions. Specific recommendations include:

1. Special attention should be focused on the management of mountainous, forested watersheds in drylands. These are the highest freshwater yielding areas in drylands, but can also be the source areas for torrents and flash floods.

    - Watersheds above reservoirs that receive annual precipitation of more than 500 mm/yr can be managed to enhance water yield through vegetation manipulation. Water yield of municipal watersheds can be augmented through forest management in which species of high consumptive use are replaced with those of low consumptive use, or where forest stands are periodically thinned and harvested.

    - Reducing people's exposure to the hazards of flash floods and debris torrents can be accomplished through combinations of zoning of hazardous areas within which human activities are restricted, and to a more limited extent, the use of engineering structures and improved watershed conditions.

2. Water has economic value that needs to be more explicitly recognized in justifying and developing watershed management programs. There are costs associated with producing water and there is value in preserving its source areas and in protecting water quality. By reducing water subsidies and treating water more as a commodity rather than a free good, economic incentives may support more efficient and effective water and watershed management for the following purposes:

    - Preventing land degradation in drylands and rehabilitating degraded watersheds, particularly those upstream from and in close proximity to reservoirs, thereby reducing sediment delivery to reservoirs.

    - Managing and preventing degradation of riparian areas in drylands. Their production potential needs to be considered together with their value in maintaining ecological values and stream channel functions.

    - Providing compensation to watershed inhabitants for vegetative changes and other land improvements that enhance water yield or that result in reduced downstream losses.

3. A watershed perspective needs to be incorporated into the planning and management of water in concert with the management of upland forests, grazing lands, agricultural areas, and urban centers. This perspective is needed at the local level as well as at the highest levels of government to promote sustainable solutions to land and water resource problems.

4. A policy and institutional environment are needed that provide the incentives and the organizational structure or cooperation at the local watershed level and up to the river basin level, to achieve land and water management objectives. Intersector dialogue and cooperation are necessary to achieve management objectives and to resolve inequities in terms of who pays and who benefits from changes in upland and downstream resource use

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