BLUE PAPER

Water Storage in an Era of Climate Change:

Addressing the Challenge of Increasing Rainfall Variability

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Summary

Rainfall variability is a key constraint to agricultural production and economic growth in many developing countries. This is likely to be exacerbated in many places as rainfall variability is amplified (even where the total amount of rain increases) as a result of climate change. Changes in rainfall will also increase variability in groundwater recharge and river flow, thus affecting all water sources. Water storage, in its various forms, provides a mechanism for dealing with variability which, if planned and managed correctly, increases water security, agricultural productivity and adaptive capacity. As such, water storage can make an important contribution to safeguarding livelihoods and reducing rural poverty. However, ill-conceived water storage is a waste of financial resources and, rather than mitigate, may aggravate unpleasant climate change impacts. Systems that combine complementary storage options are likely to be more adaptable and acceptable than those based on a single storage type. More systematic planning and management is required to avoid the mistakes of the past and to ensure more effective and suitable storage systems for the future.

Introduction

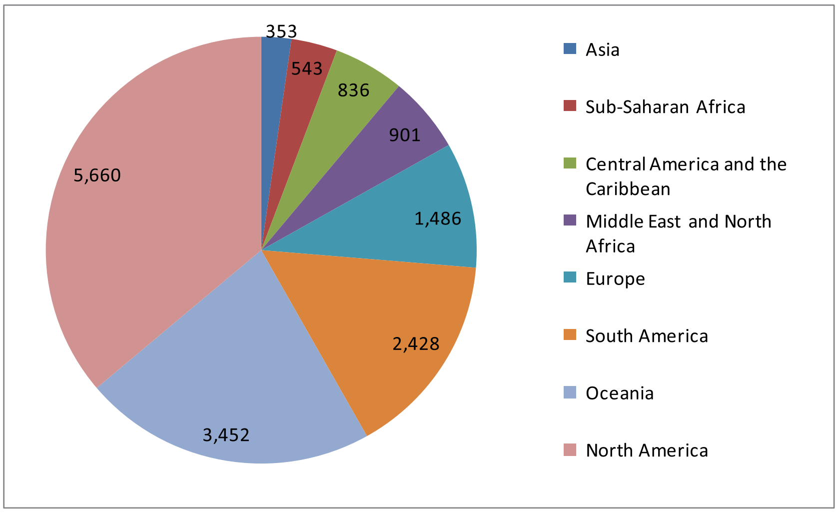
For many of the world's poorest people, rainfall variability is a major impediment to their livelihoods. The inability to predict and manage rainfall, and consequent runoff, variability is a key contributing factor to their food insecurity and poverty. Frequent periods with too much water are followed by periods with too little and intermittent water scarcity is often a direct consequence of rainfall variability. This is likely to be exacerbated by climate change.

In sub-Saharan Africa, by far the majority of agriculture (94%) is rain-fed. In Asia (which contains the highest proportion of irrigated agriculture in the world), 66% of agriculture is rain-fed. Rainfall in both regions is highly unpredictable with extreme variations, not just seasonally but also between years. Droughts occur frequently and agricultural yields are often constrained by insufficient water. Lack of predictability both in the amount and timing of rainfall makes rain-fed farming extremely tricky. For example, farmers have to make difficult choices about when to plant. Plant too early and, if the rain falters, the seeds may not germinate; plant too late and rain may cease before the crops have reached maturity. Pastoralists have to make similarly difficult choices about when and where to move their livestock for grazing and water. Where rainfall is less variable farmers do not face these dilemmas.

National economies, highly dependent on rain-fed agricultural production, are exceedingly vulnerable to fluctuations in rainfall. Although there are opposing views, there is little evidence that water scarcity by itself is a major factor limiting economic growth in most countries (Barbier 2004). However, in contrast, rainfall variability has been shown to be a significant factor that has an effect on economic growth (Brown and Lall 2006).

Under these circumstances, even relatively small volumes of water storage can, by safeguarding domestic supplies and supporting crops and/or livestock during dry periods, significantly increase agricultural and economic productivity and enhance people's well-being. For millions of smallholder farmers, reliable access to water is the difference between self-sufficiency in food and hunger. Water storage can also contribute to electricity generation and providing water supply to commercial and industrial enterprises. Consequently, it has an important role to play in poverty reduction, sustainable development and adaptation to climate change. Yet, despite greater rainfall variability than many other places, per capita water storage is lower in Africa and Asia than elsewhere in the World (Figure 1). Lack of water storage infrastructure is posited by some as a major constraint to economic development in many developing countries (Grey and Sadoff 2006).

Figure 1. Per capita water storage (in cubic meters (m^3)) in human-made reservoirs by continent.



Source: White 2005

Note: In Africa the lack of storage arises because relatively few (less than 2,000) large dams have been constructed. In contrast, in Asia many large dams have been built (about 18,000), particularly in China, but the high population means that per capita storage is low.

This report focuses on physical water storage. It argues for the need to rethink water storage in a future of rapidly rising population and increasing uncertainty related to climate change, and for better planning and management of the full range of water storage options available.

The Large Dam Dilemma

Large dams are often the first thing that comes to mind when "water storage" is mentioned. Mainly because of their considerable financial requirements, as well as the political opportunities that they represent, large dams (defined as those greater than 15 meters (m) high or with storage capacity exceeding 3 million cubic meters (Mm^3) for heights between 5 and 15 m (ICOLD 2003)) have often been the principal focus of water storage efforts in recent decades. Just under 50% of the 50,000 large dams constructed globally - since the 1950s - have been built to support irrigation. Many others have been built to provide hydropower and domestic and industrial water supply as well as to provide flood protection. In many cases a single dam supports many of these functions (ICOLD 2003).

Many large dams have brought significant social and economic benefits. The broad links between infrastructure development (including dams), increased agricultural productivity and economic growth have been documented (Hussain and Hanjra 2004; Hanjra et al. 2009). However, having a high per capita storage in large reservoirs is no guarantee of national economic development. For example, both Zambia and Zimbabwe have a greater per capita large reservoir capacity than the USA, and Ghana has a per capita large reservoir capacity three times higher than Australia (IRN 2006).

In common with all human development, large dams also have costs. For example, the Aswan High Dam built on the River Nile in the early 1960s has provided major benefits to Egypt. Nearly all of Egypt's agriculture (approximately 2.5 million hectares (Mha)) depends on irrigation in the Nile Valley and this in turn depends on the Aswan Dam. The dam protected Egypt from prolonged drought over nine years from 1979 to 1988 and, conversely, greatly reduced the impact of severe flooding in 1973 and 1988. The reservoir supplies the domestic and industrial water requirements of most of Egypt's 80 million people. However, the dam has also had negative environmental and social impacts. Because it traps sediment, silt deposition on the Nile floodplain is greatly reduced. The resulting loss of soil fertility on the floodplain requires the addition of some 13,000 tonnes of nitrate fertilizer each year. Furthermore, as a consequence of changes in flow regime, the fish catch in the Mediterranean has declined though, purely in economic terms, this is more than compensated for by the new fishery created in the reservoir. Thus, the dam has had both positive and negative impacts and though, in this case, the positive impacts outweigh the negative, this is not always the case.

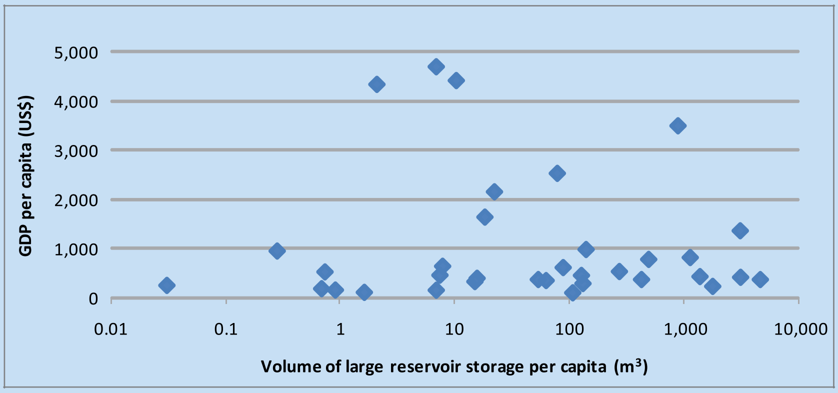
Largely because of the adverse environmental and social impacts that they can bring about, large dams are controversial. In 2000, the World Commission on Dams (WCD) concluded that "*pervasive and systematic failure to assess the range of potential negative impacts and implement adequate mitigation, resettlement and development programs for the displaced and the failure to account for the consequences of large dams for downstream livelihoods have led to the impoverishment and suffering of millions*" (WCD 2000) (Box 1).

As a result of the controversy, global investment in large dams dropped significantly in the 1990s, but it has risen sharply since 2000. The current position of the World Bank is that water resource projects provide the basis for broad regional development with "*significant direct and indirect benefits for poor people*" and that many of the adverse impacts of large dams can now be successfully avoided or mitigated (World Bank 2004). Many people disagree with this view and argue that, if the primary aim is poverty reduction, there are much more effective ways of spending limited financial resources (IRN 2006). There remains considerable acrimony over the construction of large dams.

Box 1. The continued controversy over large dams.

Although dams have brought benefits to many millions of people they remain controversial. This controversy arises from the fact that, too often in the past, the construction of dams has brought fewer benefits than envisaged and has resulted in significant social and environmental costs (WCD 2000). Historically, large dam projects have often failed to pay sufficient attention to environmental impacts and those, invariably poor, people adversely affected by their construction and operation. Globally, it is estimated that between 40 and 80 million people have been displaced as a consequence of the construction of large dams and, in addition, an estimated 472 million river-dependent people living downstream of large dams may have had their livelihoods adversely affected by changes in flow regimes (Richter et al. 2010). Many of these people, mostly unknown and voiceless, have not been adequately compensated and thus have literally "paid the price of development."

Furthermore, because many other factors influence it, the role of dams in economic development is not simple. For example, in Sub-Saharan Africa, the relationship between the amount of water stored behind large dams and a country's level of development is inconclusive. Many relatively rich economies store relatively little water whilst many poor economies store relatively large amounts of water. The link between the construction of large dams and poverty reduction is even more intangible. This is not to say that large dams do not contribute directly and indirectly to economic development and poverty reduction (over the long-term), but proving the links is not trivial.



The relationship between water storage in large reservoirs and economic development for countries in sub-Saharan Africa. Note the log scale on the x–axis. (Source: storage data from the Food and Agriculture Organization of the United Nations (FAO), data on Gross Domestic Product (GDP) per capita from the World Bank).

The majority of the thousands of new large dams planned and under construction are in developing and fast-growing economies with rising demands for additional food and hydroelectricity. In Africa, the potential for water resources development is huge. The African Development Bank, the Commission for Africa and the New Partnership for Africa's Development (NEPAD) have called for increased investment in the water sector. Both the European Union and China are investing significantly in water storage infrastructure throughout Africa. For example, as a contribution to strategies for economic development, the Ethiopian, Ugandan and Sudanese governments are all commissioning large hydropower and irrigation dams in the Nile Basin (McCartney et al. 2009; Molden et al. 2010). In Asia, the need is primarily to revitalize existing, rather than build new, irrigation systems (Mukherji et al. 2009). Nevertheless, there is increasing pressure to build new water storage for both agriculture and hydropower. For example, in the Mekong Basin, all the riparian countries are planning to build large dams in the near future (Lee and Scurrah 2009).

Whether or not all, or only some, of the planned dams are built, there is an urgent need to enhance their benefits whilst minimizing the negative impacts. This requires much greater focus on environmental and social issues than has typically occurred in the past. Furthermore, it is important that much greater consideration is given to other storage options.

Water stored in reservoirs provides water for multiple purposes like agriculture, domestic use, fishing, livestock and hydropower. However, in some cases large amounts of water are lost through evaporation. The Chorra Bassa Dam on the Zambezi in Mozambique.

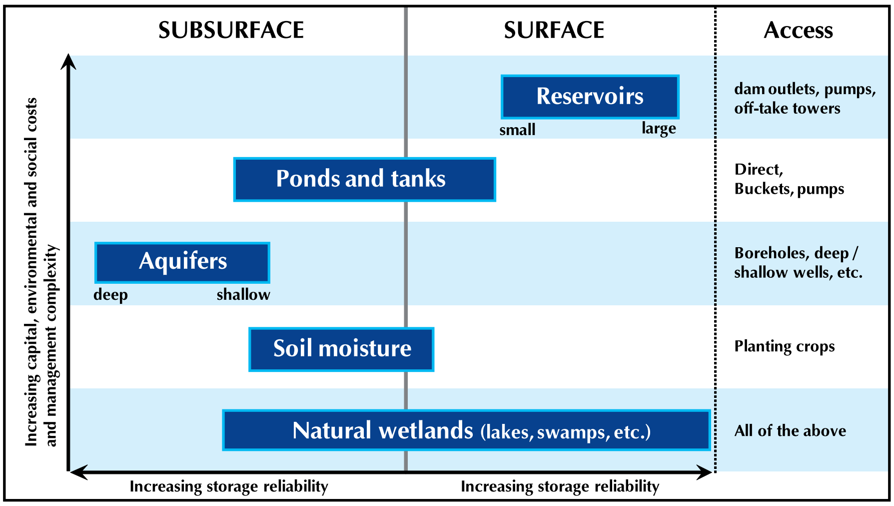
The Water Storage Continuum

Large dams are just one of a range of possible water storage options. Others include: natural wetlands, enhanced soil moisture, groundwater aquifers and ponds/small tanks. In fact, water storage can be considered a continuum of surface and subsurface options (Figure 2; Box 2). Each has an important role to play and, under the right circumstances, can contribute to food security and poverty reduction. However, obviously not all storage types are fit for all purposes. For example, enhancing soil moisture can benefit agriculture but will not contribute to hydropower production or industrial and domestic supply.

For each option, the way the water is accessed and who can access it varies. Some options are highly technical requiring modern tools and methods for construction and operation. Others are technically simpler and some have been around for millennia. Modes of management also vary considerably. In some cases, decision making and responsibility lies directly with farmers whilst in others relatively complex institutional arrangements are required. Hence, in any given situation, each type of storage has its own niche in terms of technical feasibility, socioeconomic sustainability and institutional requirements, as well as impact on public health and the environment.

In any given location the impact of different types of storage on poverty can vary significantly with some options being much more effective in reducing poverty than others (Hagos et al. 2010). In other words, boreholes may have a greater impact than small reservoirs in some circumstances and *vice-versa* in others. It is not always clear why a particular option is successful sometimes and ineffective others. For example, in Ghana, some small reservoirs have led to diversification and more stable and reliable income for farmers whilst others, constructed nearby under seemingly almost identical conditions, have singularly failed to bring about significant change.

Figure 2. Conceptualization of the physical water storage continuum.



Box 2. Typology of different water storage options

Natural wetlands Lakes, swamps and other wetland types have provided water for agriculture for millennia both directly as sources of surface water and shallow groundwater, and indirectly through soil moisture. Consequently, wetlands span the surface/subsurface interface and provide water in many different ways. As a result of their important role in the provision of water, wetlands are increasingly perceived as "natural infrastructure" (Emerton and Bos 2004).

Soil moisture Globally, the total volumes of water stored within the soil are huge, but at any given locality they are relatively small and quickly depleted through evapotranspiration. Because of this, in recent decades there has been increased interest in various *in situ* rainwater management techniques that enhance infiltration and water retention in the soil profile. Widely referred to as soil and water conservation (SWC) measures, examples vary from place to place but the most promising include deep tillage, reduced tillage, zero tillage and various types of planting basin. The effectiveness of different measures depends a lot on soil characteristics and, particularly, on water holding capacity (Gregory et al. 2000).

Groundwater Groundwater is water stored beneath the surface of the Earth in aquifers. A major advantage of groundwater is that there is little or no evaporation and total volumes are often much greater than annual recharge. The amount of water that can be abstracted from a well in an aquifer is a function of the characteristics (particularly the permeability) of the rock. Some aquifers will yield only a few liters per day, whilst others can yield as much as several million liters. Methods for increasing groundwater recharge include pumping surface water directly into an aquifer and/or enhancing infiltration by spreading water in infiltration basins.

Ponds and tanks Ponds and tanks are cisterns or cavities (covered or uncovered, lined or unlined) built by individuals or communities to store water. They are often linked with rainwater harvesting and store relatively small (but often vitally important) volumes of water. Ponds and tanks fill either by surface runoff or through groundwater and differ from reservoirs by the absence of a dam. A common limitation is that they are usually shallow, with a relatively large surface area, so that often a significant proportion of the water is "lost" through evaporation.

Reservoirs Reservoirs are water impounded behind small and large dams constructed across streams and rivers. Small dams (often built simply by mounding earth) store relatively small amounts of water (a few hundred to a few thousand cubic meters) and often empty every year. Many small dams do not have outlets and water is simply removed by livestock drinking, pumping and as consequence of spilling and evaporation. They tend to be shallow with relatively large surface areas so that, in common with many ponds/tanks, a significant proportion (sometimes more than 90%) of the water may be lost through evaporation. Large dams (often rock-filled or concrete) store millions, sometimes billions of cubic meters of water. The water may be used for multiple purposes. Sometimes they are also used for flood control. Because they tend to be deeper with a relatively smaller surface area, in comparison to small reservoirs, they often have a higher yield relative to the inflow. Furthermore, some large reservoirs provide storage that is greater than the mean annual runoff and thus provide multi-year carryover of water.

FAO has identified better management of soil moisture and investment in small water storage as promising interventions for poverty alleviation (FAO 2008). Under the right circumstances, small-scale water storage interventions can contribute to both food security and increased economic prosperity at a local level. For example, field studies in various semi-arid environments have shown that crop yields can be stabilized and increased when seeds are sown not in furrows but in small planting basins which harvest water *in situ* (Twomlow and Hove 2006; Fatondji et al. 2007). Small tanks, ponds and reservoirs can also make important contributions to livelihoods and peoples well-being with significant potential both in Africa and Asia (Vohland and Barry 2009; Wisser et al. 2010).

None of the storage types is a panacea. All have strengths and weaknesses which depend, in part, on the inherent characteristics of the storage (Box 3) but are also affected by site-specific conditions and the way the storage is planned and managed. Consequently, each storage type needs to be considered carefully within the context of its geographic, cultural and political location.

With the exception of large dams past agricultural water storage development has mostly occurred in an ad-hoc fashion, largely through private, community and local initiatives, with minimal planning. In some cases (e.g., where reservoirs have silted, wells are dry and ponds have aggravated negative health impacts), it is likely that it is the lack of planning that has resulted in less than optimal investments. Even where there has been more central planning, despite good intentions, it has not always been successful. For example, it is estimated that, of around 4,000 rainwater harvesting ponds constructed in the Amhara region of Ethiopia between 2003 and 2008, the majority were non-functional in 2009 (AMU 2009). Failures were attributed to a range of factors, including: poor site selection, design and technical problems (e.g., failure of lining materials leading to seepage) and lack of commitment by communities for maintenance (Eguavoen 2009).

In many places there is a dearth of information on existing storage, the benefits that they provide and their costs, including the impacts of scaling-up. For example, in both the Volta (West Africa) and the Olifants (South Africa) basins there are many thousands of small reservoirs but the exact numbers, let alone the volumes of water stored, are unknown (Johnston and McCartney 2010; McCartney and Arranz 2007). This is despite it being a recognized fact that, though they may increase the reliability of water supplies at the local level, the cumulative effect of large numbers of small reservoirs can be to reduce river flows, with potentially serious implications for downstream reservoirs (Meigh 1995; Liebe et al. 2009).

Even where data are available they are often dispersed and difficult to access. Furthermore, basic scientific knowledge required for planning is also often inadequate. For example, understanding of flow and sediment regimes (necessary for dam design), knowledge of aquifer extent and recharge (necessary for groundwater exploitation) and understanding of current climate variability (necessary for all storage types) are often insufficient for detailed planning. As a result, design failures are common, benefits are frequently suboptimal and, in the worst cases, investments aggravate rather than improve the well-being of local people. For example, the construction of rainwater harvesting ponds and wells in the Tigray region of Ethiopia has considerably increased cases of malaria with not only serious welfare, but also important economic, implications (Hagos et al. 2006).

Contributing to Climate Change Adaptation

As the challenges posed by global warming are increasingly understood, it is widely accepted that water is the principal medium through which the societal stresses of climate change will be manifested. Although the exact impacts remain uncertain, in many places, even where total rainfall increases, climate change will most likely increase rainfall variability. Without doubt those who will be most adversely affected are the poor, who already struggle to cope with existing variability. They will find it increasingly difficult to protect their families, livelihoods and food supply from the negative impacts of seasonal rainfall and droughts and floods, all of which will be exacerbated by climate change.

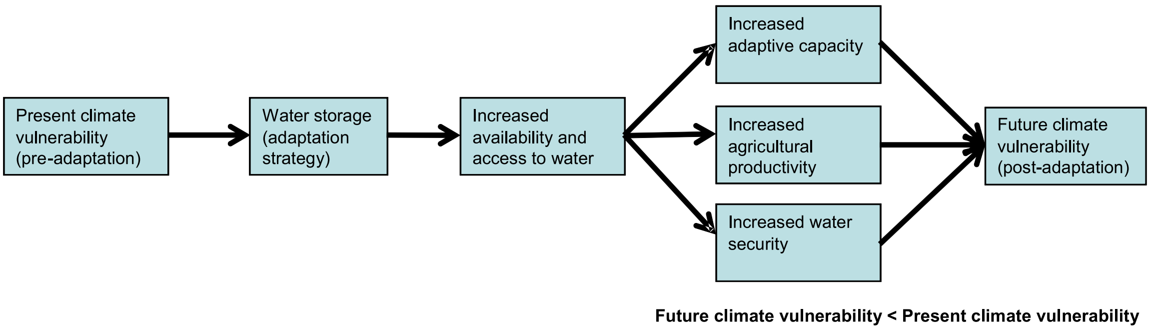
Box 3. Comparison of different water storage options

	Inherent benefits (pros)	Inherent risks (cons)	Possible risks from climate change	Possible social and economic implications
Natural wetlands	• Water storage is provided as an ecosystem service without the need for costly infrastructure	• Excessive utilization of water in, or upstream of, natural wetlands may undermine other ecosystem services.	• Reduced rainfall and runoff inputs resulting in desiccation • Higher flood peaks resulting in wetland expansion and flooding of fields/homes • Improved habitat for disease vectors	• Increased failure to provide community/household needs • Loss of water-dependent ecosystem services • Increased risk of waterborne diseases
Soil moisture	• Generally, low-cost options that can be implemented by individual farmers and communities	• Where landholdings are extremely small, farmers may be unwilling to use precious land for these interventions. • Limited storage - will not provide water for more than a few days without rain	• Reduced infiltration or waterlogging/ erosion resulting from modified ainfall intensities and durations • Depleted soil moisture arising from higher evaporative demand • Reduced soil quality (including water holding capacity) resulting from modified rainfall and temperature	• Decreased productivity – more frequent crop failures and reduction in yields
Groundwater	• Evaporation losses are low or non-existent • Multi-year storage that is largely decoupled from seasonal variability	• Detailed geological information is required to locate wells and and estimate yields • Depending on geology, may contain high concentrations of toxic chemicals (e.g., arsenic)	• Reduced recharge resulting from modified rainfall intensities • Reduced recharge resulting from land-cover modification and increased soil moisture deficits • Saline intrusion in near-coast aquifers	• Falling water levels make it increasingly costly to access groundwater • Poor water quality makes groundwater unsuitable for use
Ponds and tanks	• Generally, relatively low-cost options, implementable by communities and non-governmental organizations (NGOs).	• High evaporation losses • Water contamination (e.g., from water flowing in and livestock entering the water) • Risk of siltation • May provide breeding habitat for disease vectors	• Reduced inflow, resulting in longer periods between filling • Higher evaporation, increasing rates of pond/tank depletion • Infrastructure damage caused by larger floods • Improved habitat for disease vectors • Increased risk of eutrophication, salinization and siltation	• Increased failure to provide community/ household needs • Increased labor requirements and costs to repair structures • Increased risk of waterborne diseases
Reservoirs	• Large volumes of water stored, which can be used for multiple purposes • The only option that enables production of electricity and can offer protection from floods	• Significant capital investment • Often displacement of large numbers of people • Significant environmental and social impacts arising from changes to river flows • May provide breeding habitat for disease vectors	• Reduced inflow, resulting in longer periods between filling • Higher evaporation, increasing the rate of reservoir depletion • Infrastructure damage caused by larger floods • Improved habitat for disease vectors • Increased risk of eutrophication, salinization and siltation	• Increased failure to meet design specifications (irrigation and hydropower, etc.) • Increased costs due to the need to redesign infrastructure (e.g., spillways) • Increased risk of waterborne diseases

Terracing in China. Rainwater replenishes soil moisture for crops and recharges underground aquifers.

Water storage (in all its forms) has a key role to play for both sustainable development and adaptation to climate change. By providing a buffer, water storage reduces risk and offsets some of the potential negative impacts of climate change, thereby reducing the vulnerability of people. Water storage can enhance both water security and agricultural productivity (Figure 3). However, all water storage options are also potentially vulnerable to the impacts of climate change (Box 3).

Figure 3. Water storage as an adaptation strategy to reduce climate vulnerability.



By modifying both water availability and water demand, climate change will affect the need, the performance and the suitability of different water storage options. In some situations certain storage options will be rendered completely impracticable whilst the viability of others may be increased. For example, climate change may have significant impacts on soil moisture. In arid regions, the percentage change in soil moisture can be greater than the percentage change in rainfall. Hence, longer dry periods may mean that soil water conservation measures fail to increase and maintain soil moisture sufficiently to prevent crop failure. Groundwater recharge may be reduced if rainfall decreases or its temporal distribution changes in such a way that infiltration declines. Many aquifers near the coast will be at risk from saltwater intrusion as a result of sea level rise. Ponds and tanks may not fill to capacity or the frequency of filling may be reduced so that they are unable to provide sufficient water for irrigation. Changes in river flows may mean that reservoir yields and, hence, assurance of water supplies decline. Storage in ponds, tanks and reservoirs may also be reduced more rapidly as a consequence of increased evaporation and/or greater sediment inflows. Furthermore, both large and small dams as well as ponds and tanks may be at increased risk of both eutrophication and flood damage. Natural wetlands also face a range of climate change related threats arising from changes in hydrological fluxes (i.e., surface water and groundwater flows, evaporation, etc.) as well as increased anthropogenic pressures resulting directly and indirectly from climate change.

In all cases the externalities associated with different storage types are also likely to be affected by climate change. For example, malaria transmission in the vicinity of some ponds, tanks and reservoirs may increase as a result of modified rainfall patterns and higher temperatures; though the extent to which this comes to pass is dependent on a large number of complex factors (including the effectiveness of malaria eradication programs), not just the creation of suitable vector habitat (Sutherst 2004; Gething et al. 2010). Impacts of dams on downstream river flows - and the livelihoods of people depending on those flows - may be exacerbated by climate change resulting in the need to release a greater proportion of water stored in reservoirs to maintain the riverine environment and ecosystem services on which people depend. These, and similar factors, will affect both the effectiveness and suitability of different storage options in any specific situation.

Furthermore, by introducing trends into hydrological behavior, thus invalidating the assumption of stationarity (i.e., the presumption that hydrological processes vary within an unchanging envelope of variability), climate change will greatly increase the difficulties of the already complex task of planning and managing water resources (Milly et al. 2008). For example, changes in flow regimes during the long lifetime of major water infrastructure, such as dams, will be large enough to fall outside the historic envelope of variability. Peak flows may increase and low flows may decline, affecting both the yield and the safety of dams. In some countries (e.g., Australia and the USA) consideration is being given to redesigning the overflow spillways of large dams to cope with the larger floods anticipated to arise as a result of climate change.

Rethinking Water Storage

Wise decision-making about water resource investments is uncommon. Evidenced-based planning is rare. Many governments leave the responsibility for small-scale interventions to community groups and NGOs. Whilst in itself this is not a problem, the lack of joined-up planning and the consequent inappropriate and ineffective interventions are. Past experience shows that well-planned storage can bring significant benefits in terms of food security, health and income, but ill-planned storage often equates to a waste of scarce financial resources and, even more seriously, deleterious environmental impacts and harmful consequences to the livelihoods and well-being of people.

Climate change necessitates a fundamental rethink of the way water resources, and particularly water storage options, are planned and managed. In all situations, maximizing the benefits and minimizing the costs of water storage options will, as in the past (but not commonly done), require consideration of a wide range of complex and interrelated hydrological, social, economic and environmental factors. However, in a departure from the past, planning needs to be much more integrated across a range of levels and scales with much greater consideration of the full range of possible options. To date, although there have been many studies on the effects of climate change on hydrological regimes, there has been very little systematic research into the potential impacts of climate change on different water storage options or how to plan and manage water storage under a changed climate. Despite the high levels of uncertainty it is important that climate change projections and scenarios are used to improve planning of all storage types.

Key to planning and management of water storage are determining current and future needs and making appropriate choices from the suite of storage options available. In any given situation this requires understanding of a range of biophysical and socioeconomic issues that influence the *need*, *effectiveness* and *suitability* of the different water storage options, both in isolation and within systems comprising several types. In the past there has generally been little explicit consideration of these issues, even for large dam construction. For other options, where planning is generally less formalized, needs are usually regarded as self-evident and alternative options are only very rarely considered. The impacts of different options on existing and future storage are seldom well thought out.

The details of climate change are unknown, so planning must allow for greater uncertainty. Future water storage must be more reliable and resilient and less vulnerable than in the past. All water storage options have strong comparative advantages under specific conditions of time and place. Hence, storage 'systems' that combine and build on complementarities of different storage types are likely to be more effective. Examples already exist that illustrate the value of such combined systems (Box 4).

Box 4. Examples of combined storage systems

Conjunctive use of a small reservoir and an aquifer: Complementarities also occur where surface storage, particularly in the form of micro-reservoirs, retards runoff and enhances groundwater recharge. With improved tubewell technology now available and within reach of small farmers, many storage reservoirs, which were previously used as irrigation tanks in the arid and semiarid tracts of India, have now been converted to recharge ponds, and tubewells have taken the place of irrigation canals. For example, Oosambadi Peria Eri is situated 10 kilometers (km) from Thiruvannamali in Tamil Nadu, India. This small reservoir has an 80-hectare (ha) command area, 53 farmer beneficiaries, and 60 wells, mostly dug. Prior to 1986, only one crop was grown. Even this crop could not be successfully irrigated without supplemental well water, because reservoir water, when directly used for irrigation, is sufficient only for about 70 days when the reservoir is full. In 1986, only four farmers in the command area did not own wells. It was decided by the Water Users Association that these four farmers would be provided with water at the common cost and that the reservoir water would be used only for recharging the aquifer. In 1986, the sluices of the dam were permanently closed. From then on, farmers have grown two crops per year. Conjunctive use of surface water and subsurface water has been practiced for the last 14 years. Similar switching over to conjunctive use has taken place in more than 16 minor irrigation reservoirs in the dry district of Coimbatore, Tamil Nadu.

Small and large reservoir combinations: This is nicely demonstrated by the "melons on a vine" irrigation schemes in China, Sri Lanka and other countries. In this case, a few large storage facilities supply water to numerous small tanks within a river basin. In this manner, small reservoirs act to dampen supply and demand mismatches from large reservoirs. In the Imperial Irrigation District in southern California, small regulator reservoirs of 500,000 m^3 save more than 12 Mm^3 of canal flows annually. In southern Sri Lanka, construction and linking of a large storage reservoir at Lunugamvehera with five small, existing, cascading reservoirs resulted in a 400% increase in crop production. In fact, cascading small reservoirs can significantly increase crop water use by capturing drainage, return flow and surpluses from upstream reservoirs.

(*Source:* Keller et al. 2000)

Enhanced climatic variability will have impacts on the effectiveness (i.e., technical performance) of water storage systems. A number of indicators have been developed by engineers to assess the effectiveness of large reservoirs. The most widely used are indicators of reliability, resilience and vulnerability (RRV), where reliability is a measure of the frequency of failure, resilience is a measure of the speed of recovery from failure and vulnerability is a measure of the average magnitude of failure (Hashimoto et al. 1982). They can be used to assess the effectiveness of either a single reservoir or a number of linked reservoirs. They can also be used under current climate conditions and, using outputs from climate change models, under possible future climate conditions. Similar indicators need to be developed for other storage options and combinations of storage options so that the effectiveness of storage systems can be deduced and quantified.

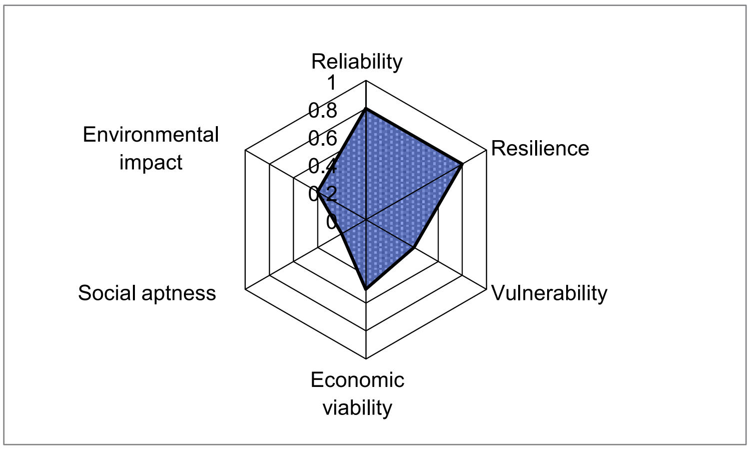
It is important to note that in systems combining multiple storage types, in some circumstances particular types will fail but others will not. In interconnected systems, failure to supply water may occur only when concurrent shortfalls occur in more than one storage type. Furthermore, there are often trade-offs between RRV terms. For example, a storage type that is resilient (i.e., quick to recover to normal operation) is likely to be vulnerable to failures of large magnitude. Conversely, a storage type that is reliable (i.e., infrequent operation failures) maybe less resilient (Moy et al. 1986). In some instances, climate change may increase the overall effectiveness of certain storage types but decrease the effectiveness of others. What is of real interest is the overall effectiveness of the whole system (Fowler et al. 2003). From the perspective of *effectiveness*, an ideal storage system is one that is highly reliable, highly resilient and has low vulnerability.

Beyond assessments of technical effectiveness it is necessary to consider the suitability of different storage systems. This largely relates to the socioeconomic factors affected by storage options and thus requires consideration of a large number of factors including economic viability (i.e., broadly the ratio of benefits to costs), social aptness (i.e., broadly the ratio of beneficiaries to the total number of people affected) and environmental impact (i.e., broadly the extent to which the environment is disturbed). From the perspective of *suitability*, an ideal storage system is one that is highly cost-effective, highly socially apt and has little impact on the environment. However, just as with effectiveness there are likely to be trade-offs between suitability terms, and climate change is likely to increase the overall suitability of certain storage types and decrease it for others. In contrast to effectiveness, there are as yet no generally accepted indicators for these factors, even for large dams. However, research is being carried out and some possible indicators have been suggested (van der Zaag and Gupta 2008; Kahinda et al. 2008).

When considering storage systems for climate change adaptation it is important to combine a mix of storage types in order to bolster elements of both effectiveness and suitability. However, the best combination of storage options will vary depending on local biophysical and socioeconomic circumstances. There will rarely be an ideal combination and, in most instances, trade-offs between characteristics will need to be considered. Because there are always trade-offs, assuming a mechanism can be found for appropriately weighting and normalizing the different indicators, radar diagrams may provide one way of viewing effectiveness and suitability indicators (Figure 4).

While there is no doubt that providing more and diverse storage infrastructure is an imperative for securing reliable supplies of water for agriculture and other uses, it should also be remembered that with increased uncertainty, higher demand and greater competition, water storage should only be one component of a multi-pronged approach for adapting agriculture to climate change. Future water resources management must also include reallocation of water between users and increasing water productivity wherever possible.

Figure 4. A radar diagram illustrating how key characteristics of a storage option might be displayed in a manner that shows trade-offs between them (McCartney et al. Forthcoming).



Conclusions

Rainfall variability is an important factor in development and translates directly into a need for water storage. In Africa and to a lesser extent Asia, existing variability and insufficient capacity to manage it, lies behind much of the prevailing poverty and food insecurity. These continents are predicted to experience the greatest negative impacts of climate change. By making water available at times when it would not naturally be available, water storage can significantly increase agricultural and economic productivity and enhance the well-being of people.

In the past, water resource planning has tended to focus on large dams but dams are just one of a range of possible water storage options. Other options include natural wetlands, groundwater aquifers, ponds and small tanks. The storage type to be used in any given location must be fit for purpose. Each of these options can, under the right circumstances, make important contributions to poverty reduction. However, none is a panacea. All have costs as well as benefits and in any given location the poverty reducing impact of different water storage options varies.

To date, there has been very little systematic analysis of alternative storage options and the role that these alternatives may play in poverty reduction and climate change adaptation. With the exception of large dams, in most places past storage development has occurred in a piece-meal fashion, largely through local initiatives and with minimal planning. It is generally characterized by absent or poor data management, insufficient communication with local stakeholders and water resource authorities, and lack of any integrated planning. In some cases the lack of information and planning has resulted in less than optimal investments.

Future population growth, in conjunction with climate change, will increase the importance of water storage in many developing countries. However, as water resources are increasingly utilized and climate variability increases, planning will become even more difficult. Without greater understanding of which types of storage are best utilized under specific agroecological and social conditions and in the absence of much more systematic planning, there is the risk that many water storage investments will fail to deliver the intended benefits. In some cases they may even worsen the most disagreeable impacts of climate change.

Current research aims to better understand water resources and storage under different social and ecological conditions. This will provide insights into potential climate change impacts on water supply and demand; the social and environmental impacts of different storage options; the implications of scaling-up small-scale interventions; and the reasons for success/failure of past storage schemes. Systematic methods for evaluating the suitability and effectiveness of different storage options are being developed to assist planning and facilitate comparison of storage options, individually and within systems.

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