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Research Report

Water Scarcity and the Role of Storage in Development

Andrew Keller
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and
David Seckler

International Water Management Institute

Research Reports

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Contents

Summary

One-third of the developing world will face severe water shortages in the twenty-first century even though large amounts of water will continue to annually flood out to sea from water-scarce regions. The problem is that the sporadic, spatial and temporal distribution of precipitation rarely coincides with demand. Whether the demand is for natural processes or human needs, the only way water supply can match demand is through storage.

There are four major ways of storing water—in the soil profile, in underground aquifers, in small reservoirs, and in large reservoirs behind large dams. Storage in the soil profile is extremely important for crop production, but it is relatively short-term storage, often only sufficient for a period of days. In this paper, the authors concentrate on the three kinds of technologies that store water for periods of months, in small reservoirs, or years, in aquifers and large reservoirs. These three technologies are compared from the hydrological, operational, and economic standpoints. Some of the environmental aspects of these options are also mentioned, but these aspects are very location specific and are not discussed in detail.

The two principle conclusions of this analysis are: 1) aquifers and small and large reservoirs all serve an indispensable role in water storage, and each technology has strong comparative advantages under specific conditions of time and place; and 2) where it is possible to do so, substantial gains can be achieved by combining all three storage technologies in an integrated system.

Water Scarcity and the Role of Storage in Development[1]

Andrew Keller, R. Sakthivadivel, and David Seckler

Introduction

By 2025, one-third of the population of the developing world will face severe water shortages (Seckler et al. 1998). Yet, even in many water-scarce regions, large amounts of water annually flood out to the sea. Some of this floodwater is *committed flow* to flush salt and other harmful products out of the system and to maintain the ecological aspects of estuaries and coastal areas (Molden 1997). However, in many cases, the floodwater is not fully utilized; and, of course, the floods themselves can do a great deal of harm. This problem is epitomized in India (see box on page 2) where annual precipitation is concentrated in the 4 months of the monsoon, and then in only a few hours of these months.

Because of the sporadic spatial and temporal distribution of precipitation, the only way water supply can be controlled to match demand is through storage. This is true whether the demand is for natural processes or human needs. In natural systems, precipitation may be intercepted by vegetation and temporarily stored on plant surfaces and on the soil surface. When water infiltrates the ground, it is stored in the soil and may percolate to groundwater storage. On the land, surface water is stored in watercourses, lakes, and other water bodies and in frozen form as snow and ice. Man can create and enhance water storage by such activities as water conservation tillage, constructing dams and dikes to impound water, and artificially recharging groundwater. Regardless of the method or type of storage, the purpose is to capture water when and where its marginal value is low—or, as in the case of floods, even negative—and reallocate it to times and places where its marginal value is high. Here, "marginal value" includes all of the economic, social, and environmental values of water.

As competition for water increases in many regions of the world, an increasingly higher proportion of normal flow of water is likely to be consumed, and the risk of shortages in periods of low flow will increase. For this reason, the need for additional storage as a proportion of the total water consumed will increase in the future.

In evaluating various kinds of water storage systems, it is useful to think in terms of three distinct hydrological situations in river basins (Seckler 1996; Keller et al. 1996; and Perry 1998):

- *Open basins* are those that have an excess of water, over and above all committed ecological and environmental requirements, flowing to the seas, saline aquifers, or similar *sinks*[2] during the low-flow seasons of the year. In open basins, the excess water has

[1]Andrew Keller originally presented the subject of this paper at the 1998 World Bank Water Week Conference, 15 December 1998, Annapolis, Maryland, USA, in a session on dams. The title of that presentation was "Water Scarcity and the Role of Dams in Development." For this paper, we changed the title, substituting the broader term "storage" for "dams," to reflect the importance of increasing storage, regardless of type, to address water scarcity.

[2]Flow to sinks is an economic as well as physical concept. Sometimes it can be prevented, but at an unacceptably high cost.

A meteorologist's view of India's water storage problems

"P. R. Pisharoty, one of India's leading meteorologists, points out that the nature of Indian rainfall is completely different from that of the middle latitude countries of Europe.

India receives some 400 million hectare metres (mham) of rain annually over a geographical area of 329 million hectares (mha). This, if evenly spread, would uniformly submerge the entire land surface to a depth of about 1.28 m. However, rainfall distribution varies widely across the land, both spatially and temporarily. Some areas like the Thar Desert receive less than 200 mm annually, whereas Cherrapunji in the Northeast receives as much as 11,400 mm each year. However, as Pisharoty emphasises, there is almost no area where rainfall is less than 100 mm annually, and even this is sufficient to meet local drinking water needs, provided it is harvested properly and where it falls.

Another problem is that unlike a number of European countries, India does not receive rainfall all through the year. It is largely concentrated during four months of the year. But then too, rainfall does not occur daily; in most parts of the country, there is precipitation during not more than 50 days. On the days when rainfall occurs, it doesn't fall over a period of 24 hours. In fact, heavy showers are common. Most of the country receives rain for just about 100 hours each year. Pisharoty claims that a thumb-rule is that the number of hours of rain a place receives in a year is equal to the number of centimetres of rain it receives annually. Delhi, with an annual rainfall of 80 cm receives this in just 80 hours; Nagpur receives 100 hours of rain in a year, and Jodhpur receives rain for just 40 hours a year.

Moreover, Pisharoty stresses that half the annual rainfall is precipitated in just one-fifth of the total hours of rain in a year. Thus, if a town receives 80 cm of rain, half of it, that is 40 cm, falls in just 16 hours. In the country as a whole, half of the total annual rainfall is received in about 20 hours.

Pisharoty recalls that Ahmedabad, with 800 mm annual rainfall, once received 320 mm in six hours in a massive downpour. Parts of Rajasthan have in the past received twice their average rainfall in a period of just two days. This type of rainfall naturally generates a large runoff within short bursts of time, making it imperative to store this water if it is to be of use. Of the total rain that falls on the Indian subcontinent, only a small quantity percolates into the ground."

(Agrawal and Narain 1997)

no opportunity cost, its marginal value is zero or negative, and all that needs to be considered is the cost of utilizing more of the water relative to the benefits of doing so.

- *Closed basins* are at the opposite end of the spectrum. Here there is no excess water flowing into sinks at any time of the year.

This case represents a zero-sum game in physical terms. Additional water use by one party means reduced use by another party. Here the only options are to:

- reduce nonproductive evaporation and transpiration losses out of the basin, for example by reducing the non-beneficial uses by weeds, shrubs, and trees (as is being done in South Africa)

  - increase the total productivity of water by reallocating water from lower- to higher-valued uses
  - minimize effective water depletion due to salinization and pollution and losses to sinks
  - augment water supply with transbasin diversions or desalinization (Keller et al. 1998)

- *Semi-closed basins* represent the major opportunities for adding value to water through storage. In these basins, there is no excess outflow to sinks during the low-flow season, but there is excess outflow during the high-flow season. Thus, storing water and reallocating it between seasons can achieve potentially large increases in the value of water.

Two of the largest river basins, the Amazon and the Zaire, are open basins, but there are very few open basins left in the highly populated arid regions of the world. In China, for example, the Yangtze River, in the wet south, is open but the Yellow River in the arid north is closed. China is now creating transbasin diversions from the Yangtze River basin to the Yellow River basin to alleviate the problem of water shortage in the north. Other examples of completely closed rivers are the Colorado River in the United States and Mexico and the Cauvery in south India. Such large and important rivers as the Indus in Pakistan, the Narmada in India and the Ganges of Nepal, India and Bangladesh are semi-closed. The Ganges represents a classical problem of international waters, with the catchment areas and major new dam sites largely in Nepal, a major need for water in the low-flow season in Bangladesh, flood control storages in the head reaches, and a large demand for hydropower and irrigation in India. Development of the Narmada River (the Sardar Sarovar project) in India has become an international *cause celebre* because of concerns over resettlement and environmental issues, not withstanding its enormous economic and social benefits (Seckler 1992).

There are four major ways of storing water—in the soil profile, in underground aquifers, in small reservoirs,[3] and in large reservoirs behind large dams. Storage in the soil profile is extremely important for crop production, but it is relatively short-term storage, often only sufficient for a period of days. Here we concentrate on the three kinds of technologies that store water for periods of months, in small reservoirs, or years, in aquifers and large reservoirs. These three technologies are compared from the hydrological, operational, and economic standpoints. Some of the environmental aspects of these options are also mentioned, but these aspects are very location specific and are not discussed in detail. The two principle conclusions of this analysis are:

- Aquifers and small and large reservoirs all serve an indispensable role in water storage, and each technology has strong comparative advantages under specific conditions of time and place.

- Where it is possible to do so, substantial gains can be achieved by combining all three storage technologies in an integrated system.

[3]Structures less than 15 m high and embankment volume less than 0.75 mcm.

TABLE 1.
Comparative advantages, limitations, and key issues associated with groundwater, small reservoir, and large dam water storage.

	Groundwater storage	Small surface water reservoirs	Large dam reservoirs
Advantages	Little evaporation loss Ubiquitous distribution Operational efficiency Available on demand Water quality	Ease of operation Responsive to rainfall Multiple use Groundwater recharge	Large, reliable yield Carryover capacity Low cost per m^3 water stored Multipurpose Flood control and hydropower Groundwater recharge
Limitations	Slow recharge rate Groundwater contamination Cost of extraction Recoverable fraction	High evaporation loss fraction Relatively high unit cost Absence of over-year storage	Complexity of operations Siting High initial investment cost Time needed to plan and construct
Key issues	Declining water levels Rising water levels Management of access and use Groundwater salinization Groundwater pollution	Sedimentation Adequate design Dam safety Environmental impacts	Social and environmental impacts Sedimentation Dam safety

Kinds of Storage

Table 1 summarizes the comparative advantages, limitations, and essential issues associated with a quifers, small reservoirs, and large reservoirs.

Groundwater Storage

One of the major advantages of storing water in underground aquifers is that it can be stored for years, with little or no evaporation loss, to be used in drought years as a supplementary source of water supply. It also has the advantage that storage can be near or directly under the point of use and is immediately available, through pumping, on demand. The tubewell revolution that has swept through agriculture capitalizes on these advantages. For example, crop yields under tubewell irrigation in India are frequently two to three times greater than crop yields from irrigation by canal systems alone (see table 2).

Another great advantage of groundwater is that as water slowly percolates down into the aquifer it is usually purified of biological pollutants. Thus, groundwater is usually the best source of drinking water, especially in rural areas of developing countries where water treatment facilities are not available.

The critical issue facing many groundwater aquifers today is that the volume of water withdrawal exceeds long-term recharge, resulting in rapidly declining groundwater levels in many areas. Closely related to this is the key issue of managing groundwater access and utilization, because groundwater is a common property

[4]For aquifers with specific storage capacities of 10%, a typical value, a 2-meter decline in water level represents about 200 mm of actual water. Thus, where groundwater levels are falling 2 m per year, extractions are exceeding recharge by approximately 200 mm per year.

TABLE 2.
Average food grain yields, in tons per unirrigated hectare and per net irrigated hectare, by irrigation source in four Indian states.

State	Year(s)	Yield (tons per hectare)			
		Unirrigated	Groundwater	Canal	Tank
Punjab	77-79	1.08	5.46	3.24	–
	63-65	0.75	3.06	1.18	–
	50-51	0.37	1.75	0.94	–
Haryana	76-77 / 78-79	0.38	5.74	2.39	–
Andhra Pradesh	77-79	0.42	5.69	3.43	1.96
	57-59	0.47	3.11	2.27	1.35
Tamil Nadu	77-79	0.49	6.53	2.60	2.33
	64-66	0.61	4.00	2.14	2.08
	56-58	0.66	3.78	1.69	1.86

Source: Chambers 1988

concern with individual benefits and collective costs.

Declining groundwater levels are often on the order of 2 meters per year.[4] The extraction of water from aquifers in some districts of India (North Gujarat, Southern Rajasthan, Saurashtra, Coimbatore and Madurai Districts in Tamil Nadu, Kolar District in Karnataka, and the whole of Rayalasema Region in Andhra Pradesh) exceeds recharge by a factor of two or more. As these aquifers are depleted, the resulting cutbacks in irrigation could reduce India's harvest by 25 percent or more (Seckler et al. 1998, and Shah 1993). Groundwater levels in the Pishin Lara Basin, Pakistan have steadily declined approximately 2 meters per year since 1987 (Prathapar 1998). In China, groundwater levels are declining almost everywhere there is pump irrigation. Under much of the north China Plain, where nearly 40 percent of China's grain is harvested, water levels are dropping roughly 1.5 meters per year (Worldwatch Institute 1999).

Groundwater depletion also has serious equity implications since falling water tables take the resource out of reach of small and marginal farmers. Falling water tables can make wells for domestic water supply run dry. An especially dangerous aspect of falling groundwater tables is illustrated in Bangladesh, where toxic levels of arsenic are being found in the drinking water of millions of people. One theory is that falling groundwater tables have permitted oxidization and mobilizations of natural deposits of arsenic in these areas.

Other important problems of groundwater storage are water quality, the cost of pumping to extract groundwater, and the recoverable fraction of recharge. From a basin-wide perspective, nearly all of the groundwater recharge may be recoverable, but, from a more local perspective, there are some losses. Typically, groundwater recovery under artificial recharge averages 75 percent of the recharge volume (OAS 1997).

While falling groundwater tables are a major problem in many areas, many other areas suffer from the opposite problem of rising water levels, with waterlogging and salinization as a consequence (Prathapar 1998). Rising water tables also prevent effective sewage disposal in rural villages, with latrines overflowing and polluting the drinking water in wells.

The problems of rising and falling water tables are among the most important issues in water policy. Declining groundwater levels in many metropolitan cities such as Mexico and Bangkok, and in many parts of Japan cause land subsidence. It is commonly thought that groundwater withdrawal should be decreased to the sustainable rate of natural recharge. In some cases, this is correct, but the problem is that this reduces production from this valuable resource. It is much better to artificially recharge the aquifers with excess water wherever possible. However, much more research and development are needed in the field of artificial recharge before this will be a widely used technology. The problem of rising water tables is more tractable, in most cases, using well known but often expensive drainage techniques. Care should be taken to prevent the problem of rising water tables in the first place, for example, by not irrigating highly saline areas unless an acceptable drainage plan is in place.

Small Reservoirs

Here we use the standard definition of small dams as structures less than 15 meters high and with an embankment volume generally less than 0.75 million cubic meters (BOR 1987 and ICOLD 1998). Included within our discussion of small surface reservoirs are small tanks and micro-storage facilities such as dug cisterns and farm ponds.

Small reservoirs have the advantage of being operationally efficient. They are flexible, close to the point of use, and require relatively few parties for management. Because of these attributes, they can be responsive to demands, the supply to demand mismatch can be small, and managerial and institutional issues are easier to handle. Because of their limited storage capacity, small reservoirs respond rapidly to precipitation runoff, often refilling several times a year. Thus, the actual amount of water delivery from a small reservoir can be several times its one-time storage capacity. The great operational benefit of small storages is their rapid response times. Like groundwater systems, they can respond to rainfall on fields, thus maximizing effective rainfall and minimizing operational losses. Small reservoirs often serve multiple uses such as bathing, washing, animal husbandry, and aquaculture in addition to irrigation. Small reservoir storage is ideal from the standpoint of operational efficiency, but generally less effective than groundwater or large dams for water conservation.

The high surface area to volume ratio of small reservoirs leads to high evaporation loss. Micro-storage facilities lose, on average, 50 percent of their impoundments to evaporation in arid and semi-arid areas (Gleick 1993 and Sakthivadivel et al. 1997). Other limitations are that their small storage volume does not allow for seasonal or annual carryover and, in addition, there are the cost and safety problems of handling overflow during extreme storm events.

The seepage and percolation “losses” from small tanks in Sri Lanka account for 20 percent of reservoir volume (Tasumi 1999) against 5 percent of reservoir volume in large dams. These small reservoirs can act as percolation tanks, recharging aquifers and retarding runoff. Since seepage “loss” can be both an advantage and disadvantage of small reservoirs depending on perspective, it is not listed in table 1; from a basin-wide hydrologic standpoint, it is generally an advantage. In fact, in India, small reservoirs that have high percolation rates, “percolation tanks”, are often preferred because of their contribution to groundwater recharge.

Perhaps the greatest threat facing existing reservoirs, both large and small, is sedimentation. While highly variable, it is estimated that 1 percent of the total global freshwater surface storage capacity is lost each year to sediment (Palmieri 1998).[5] This does not seem like much until it is realized that the world needs to increase the amount of storage by 25 percent just to stay where we are over the next 25 years!

Often small dams are built without adequate climate and hydrologic analysis. Due to small catchment areas and large variation in rainfall some small tanks in Sri Lanka, for example, do not get sufficient water 3 out of 10 years. Inadequate hydrologic analysis can also result in insufficient spillway capacity and lead to dam failure due to breaching of the embankment.

An issue facing large and small dams alike, but primarily small dams, is dam safety. Of 8,818 high-hazard, non-federal dams inspected by the United States Army Corps of Engineers, one-third (2,925) was determined to be unsafe (FEMA 1996). It is unknown whether the fraction of dams outside of the United States with safety problems is greater or less than this.[6]

Contrary to common opinion, it is very difficult to construct safe small dams. First, in order for them to store as much water as possible, it is desirable to have a large catchment area. But large catchment areas have large runoff, exceeding storage capacity in extreme storm events. The water must therefore be spilled over or around the dam. However, it is very expensive to build concrete and steel spillways, and many small dams, especially in developing countries, do not have them. Consequently, water spillage can breach the dam. In addition, small dams often are constructed in the dry season when there is inadequate soil moisture and water to properly compact soil during construction. Consequently, water seeps through the dam creating "pipes" that can breach a small dam from within.

Large Reservoirs

By 1997, there were an estimated 800,000 dams in the world, 45,000 of which qualify as large dams. More than half of these large dams were constructed in the past 35 years. In 1997, an estimated additional 1,700 large dams were under construction (WCD 1998). The aggregate design storage capacity of the world's large dams is about 6,000 km^3 (LeCornu 1998). This compares with total water withdrawals of 3,800 km^3 (Gleick 1998). Considering loss of storage due to sedimentation, lack of filling, etc., perhaps one-half of the design storage (or the total withdrawals of about one year) is actually achieved. However, given that a large percentage of withdrawals is from recycled water, the aggregate design storage capacity of 6,000 km^3 seems to us to be an incredibly high amount.

It is interesting to note that of all the registered large dams in the world only 5 percent is in Africa where most of the severe economic water scarce countries are located. Fifty-five percent of the large dams is in North America and Europe, where, largely because of this, there are not likely to be severe shortages (LeCornu 1998, and Seckler et al.1998).

Large surface water reservoirs have the advantage of greater yield relative to the available inflow than small reservoirs, and their yield is generally more reliable. This is because of lower evaporation loss fractions in large reservoirs due to their greater depth. Because of their depth, many large reservoirs can store water for multiyear carryover to weather droughts. In monsoonal climates, large reservoirs store excess flows in the wet season for use in the dry season.

Other advantages of large surface storage facilities include their relatively low cost per

[5]We note that some have serious reservations about the validity of this sedimentation figure. While we were unable to validate the number, we believe that if correct, it is alarming and important to point out.

[6]Many of the "unsafe" dams in the US were rendered so by changes in the applicable design standards—especially the switch to probable maximum flood (PMF) for spillway capacity. In addition, many dams in the US were built privately with less control of standards than is often the case outside the US.

unit of utilizable water (see table 5) and multipurpose qualities—e.g., hydropower and irrigation. According to the Secretary General of the International Commission on Large Dams (ICOLD), 30 percent of the world's registered large dams is multipurpose (LeCornu 1998).[7]

An emerging new use of large reservoirs in the United States is "mimicry" of the natural hydrograph to mitigate environmental impacts associated with water development. By releasing artificial flood flows from large storage dams, the hydraulics of the natural river system can be imitated and the dynamic conditions of an environmentally healthy system recreated with less water than under virgin conditions.

Large dam reservoirs are more complex to operate than small reservoirs and groundwater systems from the standpoint of meeting the needs of individual users. Because they command large areas, they are often far from the points of use. This distance, measured as the water travel time from the dam to the point of use at around 3 km per hour,[8] can be weeks long. Therefore, large dam operations cannot be responsive to individual demands that deviate from their expected values and so there is potential for large mismatches of supply to demand. For example, water released from the High Aswan Dam on the Nile in Egypt takes 10 days to reach irrigated areas in the Nile Delta. If there is an unexpected rainfall event in a portion of the Nile Delta that temporarily reduces the demand for irrigation, the water released at Aswan will likely be spilled directly into the Mediterranean Sea unused. On the other hand, unexpected rises in demand may not be met, causing water stress to crops. The flexibility of large storage structures is further reduced when they are multipurpose and potentially conflicting demands (for example, hydropower generation and irrigation) exist. Other factors limiting the flexibility of large dam operations are the many parties and levels involved in their management and countless institutional prerequisites.

Reservoirs that are sited upstream of major demands have maximum operational flexibility to shift water among competing uses, for example, taking advantage of rainfall in one area to conserve water for use at another location or time. Where reservoirs are too far downstream in relation to basin demands, surplus flows may become unusable. The Oum er R'bia in Morocco is a case in point, where storage available in the upper catchment is insufficient to meet the demands of irrigation facilities in the area, while excess water accumulates in large downstream reservoirs with limited potential uses further downstream.

An important general issue facing large dams is their social and environmental impacts. The intense social and environmental debate over large dams led to the establishment of the World Commission on Dams, which started its work in May 1998. The Commission's report is due by June 2000 (WCD 1998).

Many of the negative impacts associated with large dams occur because they are constructed on-stream where they obstruct fish passage, inundate important aquatic and riparian habitats, dislocate historic communities, etc. Consequently, many of the new dams being planned and constructed, particularly in the United States (for example, the recently completed Los Vaqueros Dam in California), are for off-stream storage.

In the United States, beginning in 1997, decommissioning of large dams has exceeded their construction rate.[9] Between June 1997 and July 1998, the Secretary of the United States

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[7]We believe this number is an anomaly of the reporting in the ICOLD dam registry and that the percentage of multipurpose large dams is likely much greater than 30.

[8]Based on an allowable critical flow velocity in earthen channels of around 1m/s. Lined sections may have twice this flow velocity. Where gradients are shallow, such as in Egypt's Nile Delta, flow rates are much slower.

[9]Most of the recently decommissioned dams in the United States are hydropower dams, which, besides having adverse environmental impacts, suffer from dam safety and other issues and are not economical to repair or upgrade.

Department of Interior, Bruce Babbitt, symbolically took his sledgehammer to six large dams (Babbitt 1998). In response to the dam busting furor, the International Commission on Large Dams (ICOLD) has prepared a position paper on dams and the environment (ICOLD 1998). The ICOLD paper discusses sustainable development of water resources and the role of dams and reservoirs

Comparison of Large and Small Reservoirs

Both large and small reservoirs are appropriate technologies under specific conditions of time and place. Table 3 provides a means of examining these issues by comparing the massive High Aswan Dam (HAD) and its reservoir, Lake Nasser, on the Nile in Egypt with the more than 17,000 small tanks in Sri Lanka.[10]

Several observations may be made from the figures in table 3:

- The storage capacity behind HAD is 168.9 km^3, three times Egypt's annual allocation from the Nile, and sufficient to meet 3 years of total water needs for all of Egypt. HAD literally saved Egypt from the disasters that afflicted most of Africa during the great drought of the late 1980s.

- In comparison, small reservoirs are used primarily to meet water demands within a period of a few months. The storage capacity behind HAD is over 240 times the aggregate capacity of all 17,000 minor tanks in Sri Lanka. HAD commands 3.4 million irrigated hectares compared to around 700,000 ha in Sri Lanka, and supplies water to meet the domestic and industrial needs of 60 million people.

TABLE 3.
Contrast of characteristics of the High Aswan Dam and it reservoir, Lake Nasser, with a typical minor tank in Sri Lanka.

Characteristic	High Aswan Dam	Typical minor tank in Sri Lank
Storage capacity	168.9 km^3 (16.89 million ha-m)	4.1 ha-m
Surface area	6,500 km^2 (650,000 ha)	5.0 ha
Net irrigated area	2.648,000 ha	5.0 ha
Storage fraction of area times depth	0.29	0.4
Annual evaporation loss	14 km^3 (1.4 million ha-m)	2.0 ha-m
Annual evaporation depth	2.7 m	1.0 m
Dam height	111 m	2 m
Crest length	3,830 m	170 m
Embankment volume	44,300,000 m^3	2,600 m^3
Travel time to command area	10 days to 60% of total command	Few hours
Command area	3.4 million irrigated hectares	<10 ha

[10]HAD statistics are from Gleick 1993 and the minor tank numbers are derived from Sakthivadivel et al.1997.

- The ratio of HAD's Lake Nasser surface area to Egypt's irrigated area is about 5:1; the ratio with small tanks is near 1:1. This means that the evaporation from the small tanks exceeds that of the area they irrigate.

- The dispersion of area inundated by small tanks may be better, in terms of environmental impact, than the concentrated inundation that occurs with large reservoirs. On the other hand, small tanks often submerge the best agricultural lands.[11]

- The high operational flexibility of small tanks and high overall effectiveness of cascade systems (noted below) can provide substantial benefits over large reservoirs.

The point in comparing these two surface storage systems is that they are both very different yet appropriate technologies in their respective settings. Small dams could not collectively capture the surplus flows of the Nile as effectively as the High Aswan Dam. On the other hand, a single large water impoundment with the combined capacity of all the small tanks in Sri Lanka would not be effective in servicing all the associated small irrigation systems.[12] This is not to say that there is no room for improvement in either case or that either is optimally designed or sited to maximize the capture of flows that would otherwise be lost to the sea.

Complementarities

It is important to consider complementary opportunities among different types of storage systems to improve conservation and productivity of water. Water conservation per se may not increase water productivity because of inefficient operation and mismatches with crop water requirements. Table 4 presents the characteristics of storage types for providing the needed conservation and operational efficacies. Among the alternatives available, combinations of storage systems are most likely to produce superior results. The suitable combinations of storage types depend on a number of factors, including topography, hydrology, and the existence of suitable aquifers.

TABLE 4.
Characteristics of storage structures.

Storage type	Conservation potential	Operational flexibility	Adequacy	Reliability
Large reservoir	H	L	H	L
Small reservoir	L	H	L	L
Groundwater storage	H	H	L	H
Large and small reservoirs combined	H	H	H	L
Large and small reservoirs combined with groundwater storage	H	H	H	H

Notes: H = High; L = Low; Adequacy = Sufficiency of yield to meet needs of command area; Reliability = Assuredness of water deliveries.

[11]Small tanks (by definition) only submerge a few feet up the sides of a valley—the rest is valley floor. Large dams flood a lot of non-valley floor area that is usually less productive land.

[12]Note that there are several large storage facilities in Sri Lanka.

Conjunctive use of groundwater and small reservoir water

Oosambadi Peria Eri is situated 10 km from Thiruvannamali in Tamil Nadu, India. This small reservoir has an 80-hectare 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 reservoir were permanently closed. From then on, farmers have grown two crops, paddy and another crop. 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.

A number of combinations already exist and work satisfactorily. The combination of small and large reservoirs is nicely demonstrated by the "melons on a vine" irrigation schemes in China, Sri Lanka, and other countries. Here, 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 million cubic meters annually of canal flows that otherwise spill to the Salton Sea; this results in an annual 25:1 water conservation to storage volume ratio. In southern Sri Lanka, construction and linking of a large storage reservoir at Lunugamvehera with five small, existing, cascading reservoirs resulted in a 400 percent 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.

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.

These successful experiments indicate that combinations of big and small reservoirs along with effective aquifer management can provide efficient solutions for conserving water and increasing its productivity. Hitherto, this concept has not been effectively put into practice from the planning stage, although it has been practiced in many areas of the world. With water becoming scarce, use of such integrated planning for conserving water could lead to higher water productivity while maintaining environmental and ecological balance.

Costs

The typical low, median, and high costs (in 1998 US dollars) of various water supply technologies are presented in table 5. The lifetime delivery costs reflect the present value capital, operation, and maintenance costs over the economic life of the technologies divided by the total volume of water they produce and deliver.

The surface storage capital costs differ greatly between the low and high ends. This is due to the wide variability in dam construction costs associated with site conditions, dam types, construction methods, spillway requirements, etc. We found some large dams that cost as little as US$1.00 per 1,000 m^3 of storage[13] and others that were more than US$15,000 per 1,000 m^3. Rather than give these extremes, we present in table 5 typical low- and high-end costs. As expected, the distribution of surface storage costs is positively skewed; that is, the average cost of storage is greater than the median. The median cost of storage in table 5 is estimated at 2.5 times the typical low-end cost, whereas the average cost of storage is closer to four times the low end.

It very well could be that dams can no longer be built for the low-end costs listed in table 5 given current dam safety requirements and the costs of mitigating negative environmental

TABLE 5.
Water supply costs (1998 US dollars).[a]

Technology	Storage capital costs (US$/1,000 m^3)			Lifetime delivery costs (US$/1,000 m^3)			Source
	Low	Median	High	Low	Median[b]	High	
Large storage projects (storage and conveyance costs only)	110	270	1,600	2	5	32	Keller for this paper
Medium and small storage projects (storage and conveyance costs only)	130	320	2,200	7	17	110	Keller for this paper
Micro-storage projects (storage costs only)	160	390	2,500	7	17	110	Keller for this paper
Dug storage	500	800	1,200	22	35	60	OAS 1997
Artificial groundwater recharge				190	210	230	Gleick 1993
Groundwater development and pumping				20	40	110	Keller for this paper
Diversion projects (interbasin)				190	200	400	Gleick 1993
Conservation practices				40	105	300	Keller et al. 1998
Recycling wastewater (secondary treatment)				120	170	220	Gleick 1993
Reverse osmosis (for brackish water)				160	350	540	Gleick 1993
Recycling wastewater (advanced water treatment)				260	460	660	Gleick 1993
Desalinization of seawater				600	1,200	2,000	Keller et al. 1998

[a]The costs obtained from Gleick 1993 were indexed to 1998 US dollars using appropriate construction cost trends from BOR 1998 and RSMeans 1998. The storage costs of small, medium, and large reservoirs were computed by applying BOR 1969 cost estimating guidelines to dam statistics obtained from the BOR web site (1999) and from Gleick 1993. Indexed dam cost figures from the western US (BOR 1969) and the State of Tamil Nadu, India (Sakthivadivel 1999) were used as a check.

[b]Median cost is taken as 2.5 times the low-end cost for large, medium and micro projects.

[13]These extremely low-cost dams are generally concrete arch or gravity dams. An example of such a low-cost (US$1.00/1,000 m^3) dam is the Kariba Dam in Zambia and Zimbabwe, which resulted in one of the world's largest reservoirs (by volume, right behind HAD's Lake Nasser). However, we note that Kariba had high environmental and social costs associated with it, which are not reflected in the dollar cost of the dam. (Kariba is a case study of the International Commission on Dams.)

impacts. The cost of Los Vaqueros Dam, a key component in the first major water project to be built in California in the past decade, was US$346 per 1,000 m^3 of storage (commensurate with the median cost of large dams given in table 5). The dam cost, however, represented only 10 percent of the total project costs, which were large because of efforts to minimize environmental impacts.[14]

The storage capital costs in table 5 are the cost of the storage facility per 1,000 m^3 of gross reservoir capacity plus the associated cost of the conveyance system. For the storage capital costs to be comparable to the other water supply technologies listed in table 5, these costs must be adjusted to account for all the usable water a reservoir will "produce" over its life. To do this, one has to divide the storage costs in table 5 by an estimate of how many times its capacity a reservoir will release water over its life. This is affected by the mean annual inflow to a reservoir relative to its storage capacity, the rate of sedimentation, and the evaporative loss fraction. For example, the combined large dam storage capacity of the Colorado River system in the western United States is approximately four times the mean annual flow of the river. Thus, on average, Colorado River storage cycles once every 4 years. So, in the course of 100 years, a reservoir on the Colorado River will regulate and release 25 times its storage capacity. However, losses in capacity due to sedimentation[15] and losses of water due to evaporation reduce the total release volume to approximately 20 times storage capacity over 100 years.

In monsoonal climates, storage is only a small fraction of the mean annual flow. (For example, Tarbela Dam on the Indus River in Pakistan has a live storage capacity less than 10 percent of its mean annual inflow.) Since these reservoirs are filling and releasing during the wet season, they may realize 1.5 times their usable storage capacity per year. However, sedimentation will reduce their relative yield by 50 percent over a 100-year life of a typical reservoir. Thus, the yield of a large dam reservoir in a monsoonal climate might be 75 times its usable storage capacity over the course of 100 years.

If we assume that on average medium and large dam storage projects deliver 50 times their storage capacity and small dams 20 times (due to shorter lives and greater evaporation fractions than larger reservoirs), the effective cost per 1,000 m^3 delivered to a 50-hectare command is US$2.00 to US$32.00 for large dams and US$7.00 to US$110.00 for medium and small dams.

We have also added cost estimates for alternative sources of water supply. The conservation practices listed in table 5 include programs targeted at real water savings. Water saved by such activities is transferable to other uses or is available for expanded use within the project area without adverse consequences downstream. An example of a water conservation practice is canal lining where the seepage from the unlined canal is lost to non-beneficial evaporation or to a saline sink. The median cost for conservation practices listed in table 5 was derived from the water conservation agreement between the Imperial Irrigation District (IID) and the Metropolitan Water District (MWD) of southern California. Under the terms of this agreement, MWD paid for conservation at IID in exchange for the water saved (Keller et al. 1998).

The costs of desalination of seawater given at the bottom of table 5 include all approaches, of which multistage flash distillation and reverse-osmosis are the most common (Gleick 1998). The low-end desalination costs are engineering estimates for cogeneration/reverse-osmosis desalination (Keller et al. 1998).

[14]The Los Vaqueros Project was winner of the 1999 Outstanding Civil Engineering Achievement award; largely because of the way it addressed environmental concerns (Hunt 1999).

[15]Note that the effect of sedimentation on total reservoir yield for reservoirs with capacities two or more times their mean annual inflow is relatively small compared to losses due to sedimentation in reservoirs with capacities smaller than their mean annual inflow.

The technologies presented in table 5 vary widely in scale and, therefore, to make the costs comparable, we have included the conveyance cost associated with delivering water from the facility to within 50 hectares of its point of use in the storage capital cost. For large surface storage projects, we estimate the cost of conveyance facilities to range between US$100 and US$600 per 1,000 m^3 of gross reservoir capacity. For medium and small-scale surface storage projects, the costs in table 5 include US$80 to US$500 per 1,000 m^3 of gross reservoir capacity. For waste-water recycling, interbasin diversion, reverse osmosis, and desalinization, the costs include US$0.00 to US$10.00 for conveyance of 1,000 m^3 of developed water. The delivery costs in table 5 include no conveyance costs for micro-storage and dug storage, groundwater development and recharge, conservation practices, and distillation, as these technologies are generally scaled to the 50-hectare command area or are additions to existing systems.

Conclusion

Under all but the most optimistic scenarios, there is a dearth of freshwater storage. If climate change as a result of global warming manifests, the need for freshwater storage will become even more acute. Increasing storage through a combination of groundwater and large and small surface water facilities is critical to meeting the water of the twenty-first century. This is especially so in monsoonal Asia and the developing countries in the tropics and semitropics. As an immediate first step, we must assess the major river basins of the world, whether they are open, closed or semi-closed. The productivity of water as presently used must also be assessed to determine the extent to which increased demands for irrigated agricultural production can be met by increasing water productivity, and the extent to which increased demands will require increased consumption of water. The uncommitted discharges from those basins that are open or semi-closed must then be determined, and plans made to effectively capture and put this water to use. Combinations of small and large storage and surface water and groundwater recharge are generally the best systems where they are feasible. In monsoonal Asia, research and development are needed on how to manage water under monsoonal conditions.

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