Rainwater Harvesting in the Water-scarce Regions of India: Potential and Pitfalls

M. Dinesh Kumar[1], Ankit Patel[1] and O.P. Singh[2]
[1] IWMI-TATA Water Policy Program, Hyderabad, India
[2] Benaras Hindu University, Varenasi, India

Introduction

India has a long tradition of water harvesting. Many of the traditional water harvesting systems have either fallen to disuse due to a variety of physical, social, economic, cultural and political factors that have caused their deterioration, and due to the decline of institutions that have nurtured them (Agarwal and Narain 1997), or have lost their relevance in the modern day context due to their inability to meet the desires of communities. While the first dimension of the decline in water harvesting tradition has been well researched and documented, the second dimension is much less understood and appreciated. The lack of willingness to appreciate the fact that different periods in history are marked by the genesis, rise and fall of new water harvesting traditions, is also very clear.

In the history of India's water sector, the past two decades are characterized by a boom in water harvesting. They are markedly different from the years of traditional harvesting in two ways; first, in terms of the context; and second, in terms of the purpose. As regards the context, the two decades are able to use recent advancements in soil, geosciences and hydro-sciences; and modern day techniques and technologies in survey and investigation, earth moving and construction; and management tools such as hydrological and hydraulic modeling. While the traditional years of harvesting represented the best engineering feats of those times, in terms of the water technology used for water harnessing and distribution (Agarwal and Narain 1997), and the volume of water handled, the modern water harvesting systems are at best miniature versions of the large water resource systems that used advances in civil engineering and hydrology. As regards the purpose, modern water harvesting systems are employed as resource management solutions, and not as resource development solutions. For instance, many water harvesting structures were built for improving aquifer storages and groundwater quality.

The limited Indian research on rainwater harvesting (RWH)/artificial recharge so far had focused on the engineering performance of individual structures (see Muralidharan and Athawale 1998). While a lot of anecdotal evidence on the social and economic gains is available, there is little understanding, based on empirical work, of: 1) the impacts of water harvesting activities on local hydrological regimes in terms of net water gain; 2) basin level impacts on the overall basin water balance; and 3) economic imperatives from a long-term perspective. Of late, researchers had raised questions of the possible unintended impacts of water harvesting (see Bachelor et al. 2002), and its economics (see Kumar 2004). One of the reasons for little or lack of empirical research on the hydrological and economic aspects of water harvesting systems is the lack of ability to generate accurate scientific data on various parameters, mostly hydraulic, hydrological and meteorological, governing the performance and impact of water harvesting. The problem mainly stems from the fact that these systems are very micro in nature, thereby making it difficult to obtain data on the variables from conventional sources. The analysis of water harvesting systems also misses the influence of the 'scale factor'.

Objectives of the Paper and Approach

The paper begins with the basic premise that scale considerations are important in analyzing the impact of water harvesting, i.e., one has to move from the local watershed level analysis to the river basin level analysis, and that basin level impacts are not always aggregates of local impacts. The paper first discusses the critical issues in rainwater harvesting from micro and macro perspectives. The macro level analysis is strengthened by primary data on hydrological variables collected from two small river basins. It then goes on to make practical suggestions for effective rainwater harvesting.

The paper would try and achieve the following: 1)] present the major typologies in water harvesting in India; 2) discuss the physical—hydrological and meteorological— and socioeconomic and purely economic considerations that need to be involved in decision - making with regard to water harvesting investments or analyzing the impact of RWH systems, and how these considerations limit the scope of water harvesting; and 3) make practical suggestions for improving the effectiveness of rainwater harvesting.

Critical Issues in Rainwater Harvesting

One of the most important underlying values in rainwater harvesting is that it is a benign technology (Bachelor et al. 2002) and cannot create undesirable consequences. Water harvesting initiatives are driven by firm beliefs and assumptions, some of which are: 1) that there is a huge amount of monsoon flow, which remains un-captured and eventually ends up in the natural sinks, especially seas and oceans, supported by the national level aggregates of macro hydrology; 2) that local water needs are too small and as such exogenous water is not needed; 3) that local water harvesting systems are always small and, therefore, are cost-effective; 4) since the economic, social and environmental values of water are very high in regions hit by water shortages, water harvesting interventions are viable, supported by the assumption that cost- effective alternatives that can bring in the same amount of water, do not exist; 5) incremental structures lead to incremental benefits; and 6) being small with low water storage and diversion capacities, they do not pose negative consequences for downstream uses.

Lack of Emphasis on Local Water Demand and Potential Supplies

Rainwater harvesting ignores a few critical parameters that govern the potential of rainwater harvesting systems (RWHS) in meeting local water demand, such as: a) the hydrological regime of the region/locality; b) the reliability of the supplies, governed by the reliability of rainfall; c) the constraint imposed by local geological and geo-hydrological settings on recharge potential; and d) the aggregate demand for water from various sectors within the local area.

Some basic hydrological phenomena, which make the abovementioned parameters very critical in deciding the scope of rainwater harvesting and groundwater recharging, are:

- For runoff harvesting, rainfall has to exceed a threshold to generate runoff, though the threshold would vary according to the nature of the soil and land cover of the area. The estimated runoff based on the regression equation arrived at from observed flows in the Hathmati subbasin of the Sabarmati Basin ($R=0.00193*X^{2.022}$) in western India (source: GOG 1994), shows that for the runoff to cross 100 mm, the minimum rainfall required is 682 mm. Whereas in the case of the Kabani subbasin of the Cauvery Basin, runoff starts when the rainfall crosses 366 mm.[1] However, the actual runoff rates would depend on how strong is the correlation between rainfall and runoff in a given basin, and this relation weakens if there is a major year to year change in rainfall intensity and pattern.

- Regions with lower mean annual rainfall experience higher variability and vise versa (Pisharoty 1990). Hence, in regions with lower mean annual rainfalls, rainwater harvesting as a dependable source of water is likely to be low.

- Generally, it has been found that a greater magnitude of annual rainfall means a larger number of rainy days and smaller magnitude of annual rainfall means fewer number of rainy days spread over the rainy season (Pisharoty 1990). The examples of Gujarat further illustrate this (see Kumar 2002b; Kumar 2004). Fewer rainy days also means longer dry spells and thus greater losses from evaporation for the same region.

- High intensity rainfalls are common in the semi-arid and arid regions of India (Garg 1987; Athawale 2003). Higher intensity of rainfall can lead to high intensity in runoff, occurring in short durations, limiting the effective storage capacity of rainwater harvesting systems to almost equal their actual storage size.

- High evaporation during the rainy season means losses from surface storage structures. It also means a faster rate of soil moisture depletion through both evaporation from barren soils and evapotranspiration, which increase the rate and quantum of soil infiltration. This reduces the generation potential of runoff. Among the seven locations in Gujarat for which ET_0 (reference evapotranspiration) data are available, ET_0 during monsoon (June to September) varies from a lowest of 543 mm in Vadodara to 714 mm in Rajkot. The ET_0 as a percentage of annual ET_0, varies from a

---

[1] The regression equation for Kabani estimated by the National Water Development Board, based on observed flows, was $R= 0.6363 N-233.7$ where N is the rainfall (mm) and R the runoff (mm).

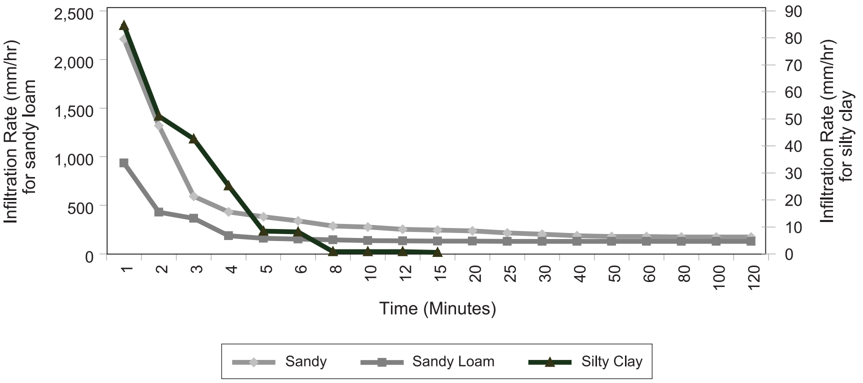
lowest of 33 % in semi-humid Surat to 37.3 % in Bhuj, Kachchh (source: authors' analysis based on data from IMD, Ahmedabad). In the case of Rajasthan, ET_0 during the monsoon ranges from 433 mm in the hill station of Mt. Abu to 967.7 mm in Jaisalmer in the Thar Desert. In percentage terms, it varies from a lowest of 32 % of the total annual ET_0 in Sawaimadhupur to a highest of 49.3 % in Anupgarh (GOR 1992). Among the 10 locations selected along the Narmada Basin in Madhya Pradesh, the values range from 429 mm to 600 mm, with ET_0 as a percentage of total ET_0 ranging from 31.3 % in Betul to 35 % in Mandla (source: GOMP 1972).

- Soil infiltration capacity can be a limiting factor for recharge. In sandy and sandy loam soils, the infiltration capacity of the recharge area can be sustained through the continuous removal of soils. But clayey soils have inherent limitations (see Figure 1). Results obtained from short-term infiltration tests carried out in dug wells in the Andhra Pradesh in two different soil conditions, showed that the infiltration rate becomes negligible (< 0.60 mm/hr) within 10 minutes of starting the test in the case of silty clay, whereas infiltration stabilizes at a rate of 129.1 mm/hour within the first 25 minutes in the case of sandy loam (NGRI 2000). If the infiltration rate approaches to zero fast, it will negatively affect the recharge efficiency of percolation ponds. As thin soil cover has a low infiltration (Muralidharan and Athawale 1998), the extent of the problem would be larger in hard-rock areas (ideal for percolation ponds) with thin soil cover. Dickenson (1994) based on several infiltration studies shows that the rate of infiltration declines to a minimum value within 4-5 days of ponding. This also will have adverse effects on the performance of structures built in areas experiencing flash floods and high evaporation rates, the solutions for which would be wetting or drying of pond-beds through the regulation of inflows.

- For artificial recharge, the storage potential of the aquifer is extremely important. The storage potential of an aquifer vis-à-vis the additional recharge is determined by the characteristics in geological formations, and the likely depth of the dewatered zone.

- In hilly watersheds, the area available for cultivation is generally very low, keeping agricultural water demand low. At the same time, the surface water potential available

Figure 1. Infiltration rate in the sandy loam and silty clay soil at the bottom of a dug well.



> for harvesting is generally high due to high rainfall and runoff coefficients. On the contrary, towards the valleys and plains, the area available for cultivation increases, raising agricultural water demand. At the same time, the surface water potential available for harnessing is generally low due to the lower rainfall, and low runoff coefficients owing to mild slopes, high PET and deeper soil profiles.

The implications of some of these factors on the potential of rainwater harvesting systems are analyzed in the following two sections.

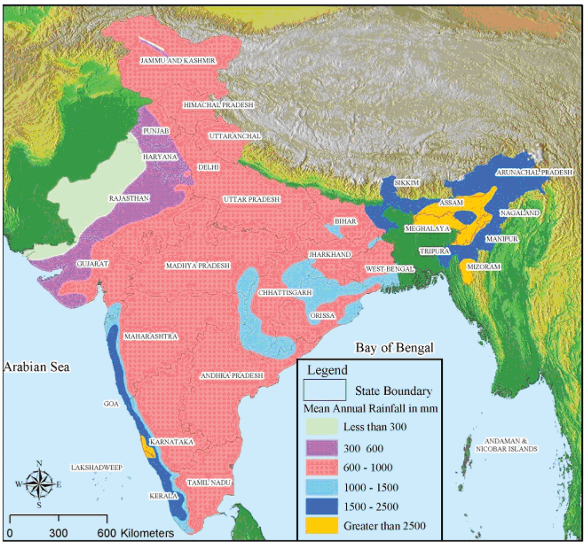
Limitations Imposed by Hydrological Regimes

Local water management interventions are often based on very little understanding of the local hydrological regimes, which govern the potential supplies of water for harvesting. They are rather based on the deep-rooted belief that the greater the size of the water impounding structure, the greater would be the hydrological benefit in terms of water storage and recharge. The best example is the participatory water conservation movement launched by the Government of Gujarat. The government implemented large-scale work for the excavation of thousands of village ponds, irrespective of the nature and size of catchments (Kumar 2002a). Part of the reason is the lack of availability of data on inflows, determined by stream-flows; and outflows, determined by evaporation rates, for small rainwater catchments. While runoff harvesting is most suited to areas with a high ‘runoff catchment area’ to ‘run on’ area ratio (Lalljee and Facknath 1994), this is also ignored. The higher the aridity, the larger would be the required catchment area to the cropped area required for the same water yield (Prinz 2002). Often, encroachment of catchments of water harvesting systems for crop cultivation is very rampant, reducing the runoff prospects.

The states, which have taken up rainwater harvesting and groundwater recharge programs on a large scale, are Gujarat (North Gujarat, Saurashtra and Kachchh), Rajasthan, Maharashtra, Tamil Nadu, Karnataka, Andhra Pradesh, Madhya Pradesh, Orissa and Chattisgarh. A major part of these regions is covered by six water-scarce river basin systems, namely, Sabarmati, the rivers of Kachchh and Saurashtra, Pennar, Cauvery, east-flowing rivers between Mahanadi and Godavari, east flowing rivers between Pennar and Kanyakumari, which have less than 1,000 m^3 of renewable water per annum (Gupta 2000: pp 116). Now let us look at the hydrological regime existing in these regions.

For this, we first examine the percentage area of each state falling under different rainfall regimes (<300 mm, 300-600 mm, and 600-1,000 mm, 1,000-1,500 mm, 1,500-2,500 mm and >2,500 mm); and different PE regimes (< 1,500 mm, 1,500-2,500 mm, 2,500-3,500 mm and >3,500 mm). It is understood that regions with relatively low rainfall have higher potential evapotranspiration due to relatively low humidity and greater number of sunny days (Pisharoty 1990). Lower rainfall, coupled with higher PE reduces the runoff potential and high evaporation from the impounded runoff, thereby increasing the dryness (Hurd et al. 1999) in the area. The analysis shows that Gujarat and Rajasthan have respectively 11 % and 42 % of area that fall under extremely low rainfalls (< 300mm); and 39 % and 32 %, respectively under low rainfall (300-600 mm). The other states by and large fall under medium rainfall (600 mm-1,000 mm) and high rainfall (1,000-1,500 mm) regimes. In the case of Maharashtra, MP, AP, Karnataka and Tamil Nadu, a lion’s share of the area (85 % and above) falls under the medium rainfall regime. And in case of Orissa and Chattisgarh, 45 % and 40 %, respectively, fall under high rainfall regime (see Map 1).

Map 1. Average mean annual rainfall.



As regards PE, the lion's share of the area in Gujarat and Rajasthan fall under high evaporation (2,500-3,000 mm); nearly 35-56 % of the geographical area of other states (except Orissa and Chattisgarh) falls under high evaporation regimes; the area of these states falling in the medium evaporation regime (1,500-2,500 mm) is in the range of 38-65 %. The entire areas of Orissa and Chattisgarh fall within the medium evaporation regime. Overall, a large section of the area (of the nine states considered) has medium rainfall, and medium to high evaporation. A significant portion of the area (of Gujarat and Rajasthan) has very low to low rainfalls and high evaporation (see Map 2 and Table 1).

Map 2. Average annual evaporation.

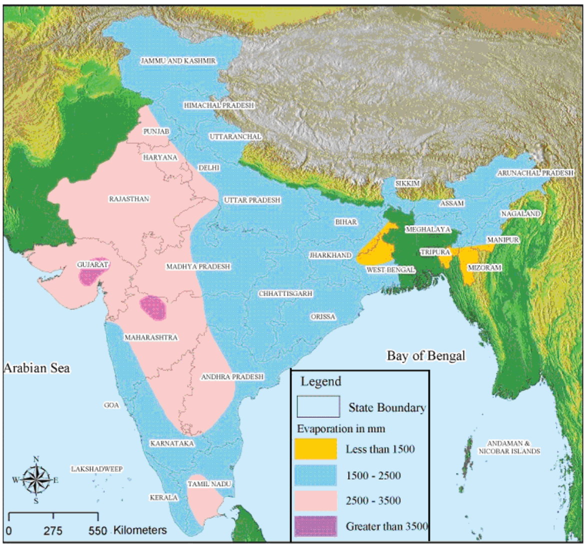


Table 1. Rainfall and PE regimes of states having water harvesting programs.

Name of State	% Area with rainfall in the range of						% of area with evaporation in the range of (PE)			
	<300 mm (very low)	300-600 mm (low)	600-1,000 mm (medium)	1,000-1,500 mm (high)	1,500-2,500 mm (very high)	>2,500 mm (extremely high)	<1,500 mm (low)	1,500-2,500 mm (medium)	2,500-3,500 mm (high)	>3,500 mm (very high)
Gujarat	10.88	39.08	47.27	2.77					88.53	11.47
Rajasthan	41.80	32.45	25.75						100.00	
Maharashtra			85.86	6.93	7.21			37.96	56.23	5.81
Madhya Pradesh			95.71	4.29				56.94	42.89	0.17
Andhra Pradesh			97.83	2.17				52.70	47.30	
Karnataka			88.01	3.65	5.67	2.67		62.82	37.18	
Tamil Nadu			96.52	2.98	0.50			64.56	35.44	
Orissa			54.01	45.99				100.00		
Chattisgarh			59.39	40.61				100.00		

Source: Authors' own estimates based on Pisharoty (1990) using GIS

In the next step, we analyze: the proportion of the geographical area from each of these regions/states falling under different rainfall variability classes like > 25 %, 25-30 %, 30-40 %, 40-50 % and 50 % and above. The higher the magnitude of PET during the monsoon, the higher will be the negative impact on hydrological variables such as surface storage and recharge. While it reduces surface storage through evaporation, the higher PET during the monsoon also means higher crop water requirement during the season and increased soil moisture depletion, leading to reduced recharge from rainfall. In barren soils, higher evaporation rates leads to faster soil moisture depletion perpetuating a higher rate of infiltration of the incoming precipitation and lower runoff.

As Table 2 indicates, a large percentage of the total geographical area of Gujarat and Rajasthan (72 % and 68 %, respectively) has high to very high (30-40 % and above) variability in rainfall. A significant part of the geographical area of the states three to seven in Table 1 (37 % to 92 %) experience medium variability in rainfall; the rest of the area experiences low variability. The entire Orissa and Chattisgarh experience only low variability in rainfall. In a nutshell, more than 50 % of the total geographical area of all the states put together experience medium variability; nearly 25 % experience 'high to very high variability'; and nearly 20 % experience 'low variability' in rainfall (see Map 3). They coincide with 'medium rainfall-medium to high evaporation', low rainfall to very high evaporation' and 'high rainfall to medium evaporation' regimes, respectively.

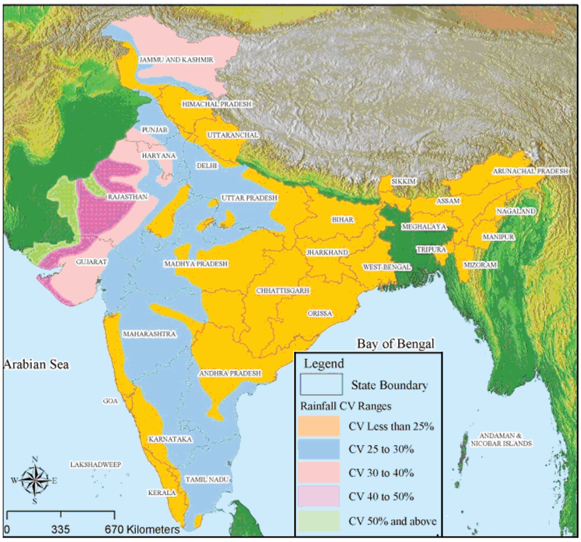
It can be seen from Maps 1, 2 and 3 that regions with high variability in rainfall coincide with those with low magnitudes of rainfall and high PE, which also have a high dryness ratio. In such areas, a slight variation in precipitation or PE can substantially magnify the water-stress on biological systems as compared to humid regions (Hurd et al. 1999). The higher the variability in rainfall, the lower would be the reliability of local water harvesting/recharge systems. This is because the chances of occurrence of low rainfalls and extremely low runoff would be higher

Table 2. Rainfall variability regimes of states having water harvesting programs.

Name of State	% area with rainfall variability in the range of				
	<25 % (low)	25 – 30 % (medium)	30 – 40 % (high)	40 – 50 % (very high)	> 50 %
Gujarat	0.24	27.12	44.30	17.11	11.22
Rajasthan	8.33	24.08	23.04	30.71	13.84
Maharashtra	37.67	62.33			
Madhya Pradesh	49.71	50.29			
Andhra Pradesh	62.64	37.36			
Karnataka	29.15	70.85			
Tamil Nadu	7.73	92.27			
Orissa	100.00	0.00			
Chattisgarh	100.00	0.00			

Source: Authors' own estimates based on Pisharoty (1990) using GIS

Map 3. Average coefficient of variation of rainfall.



under such circumstances, and at the same time, the demand for water would be high due to environmental stress caused by poor soil moisture storage, low runoff and high temperature.

In the third step, we analyze the average number of rainy days and their variability across regions (Table 3). We attempt to find out the percentage of geographical area in each region that falls under different rainy days (say <20 days, 20-30 days, 30-40 days, 40-50 days, 50-75 days, and 75 and above days). We also analyze the implications for the quantum of rainfall in each rainfall event and the maximum and minimum daily rainfalls under different rainfall regimes.

The analysis shows that Gujarat and Rajasthan fall in to the regions that experience fewer days of monsoon rains. To elaborate: nearly 21 % of Gujarat and 45 % of the Rajasthan state

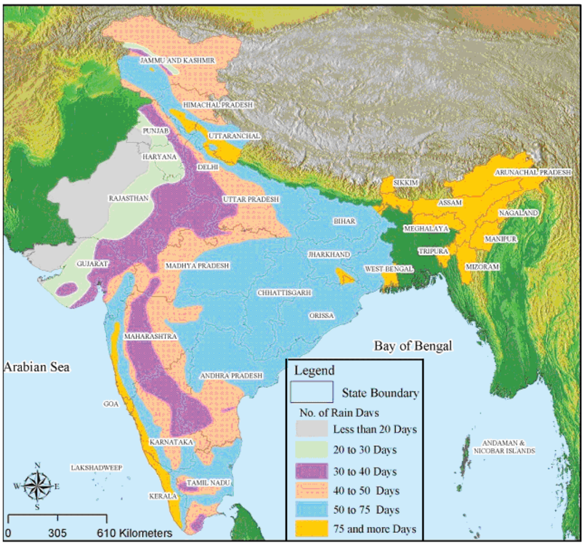
Table 3. Distribution of rainy days in states having water harvesting programs.

Name of State	% of area with rainy days in the range of					
	<20 days	20-30 days	30-40 days	40-50 days	50-75 days	>75 days
Gujarat	20.57	30.87	32.30	6.15	10.11	
Rajasthan	45.31	24.38	28.19	2.12		
Maharashtra			22.57	29.17	43.24	5.01
Madhya Pradesh			21.17	33.26	45.57	
Andhra Pradesh			12.17	29.80	58.03	
Karnataka			26.55	38.79	27.13	7.53
Tamil Nadu			9.35	35.78	54.86	0.01
Orissa					98.77	1.23
Chattisgarh					100.00	

Source: Authors' own estimates based on Pisharoty (1990) using GIS

receive less than 20 days of annual rains; nearly 51 % of Gujarat and 70 % of Rajasthan fall in areas which experience less than 30 days of rain in a year; nearly one-third of both the states receive 30-40 days of rain. As regards the states three to seven in Table 1, the area which receives 30-40 days of rain ranges from 9 to 27 %; 40-50 days of rain ranges from 29-39 %; 50-75 days of rain ranges from 27-58 %. The Western Ghat in Maharashtra and Karnataka receive heavy rains spread over many days (> 75). As regards Orissa and Chattisgarh, both states receive 50-75 days of rain in a year. To sum up, the regions that receive fewer days of rain (erratic rains) coincide with those experiencing low rainfall and high evaporation and high variability in rainfall. The regions that experience many wet days coincide with those which experience high and reliable rainfall and medium evaporation (see Maps 1, 2, 3 and 4).

Map 4. Average rainy days.



By synthesizing the results of the spatial analysis of rainfall, PE, rainfall variability and number of rainy days that are provided in Maps 1-4, the following trends can be established: a) the inter-annual variability in rainfall increases with reducing rainfall; b) the number of wet spells reduces with the lowering magnitude of rainfall; and c) the PE increases with the lowering magnitude of rainfall. The implications of these trends on the potential of water harvesting in a region needs to be understood. The potential for water harvesting is lower when lower rainfall, is coupled with higher potential evaporation and inter-annual variability in rainfall and fewer rainy days. This is due to the following processes. First, the runoff potential by and large would be low in low-rainfall regions with a high dryness ratio. Second, evaporation from surface storage would be high due to high PE. Third, the probability of occurrence of very low rainfalls, causing heavy reductions in runoff, would be high, with consequent hydrological stresses.

Limitations Imposed by the Socioeconomic System

Water harvesting arguments totally miss the water demand-availability perspective at the micro level. Ideally, the RWHS would work if the area which has uncommitted flows to harness has an ‘un-met demand’ or vise versa. This is unlike in large water resource systems where provisions exist for the transfer of water from ‘surplus’ areas to deficit areas.

The water demand of an area is determined by the agro-climate and existing socioeconomic system, which, in fact, gets adjusted by the natural resource environment of the village, the available technologies for accessing them and the institutional and policy environments over a period of time. Regions that were heavily into irrigated agriculture in the past, supported by good water endowments, institutional support and favorable policies, might continue demanding large quantities of water for irrigation even when they run out of water. This is because communities take quite some time to devise coping and adaptive strategies to manage with conditions of water deficits.

Studies in a village in Mandvi taluka of Kachchh, which is one of the most arid districts in India, showed that the annual water withdrawal from aquifers for irrigating crops is 25.42 MCM. The entire water requirement in the village was being met by groundwater, which is experiencing severe over-draft conditions (Kumar 1997). The total amount of rainwater falling in the village is nearly 10.14 MCM (source: based on data provided in Kumar 1997 on geographical area and the mean annual rainfall of Kachchh). With a surface water potential of 0.014 MCM/sq. km (IRMA/UNICEF 2001), the amount of runoff water that would be available for replenishment through natural and artificial recharge from within the village is only 0.40 MCM. The runoff is, therefore, a small fraction of the total consumptive use. This means that the village has to depend on exogenous sources of water for making water use sustainable. What is presented is representative of almost the entire peninsular of India excluding Kerala, central India and western India.

In a village named Manund, in the Patan District of North Gujarat, which has seen widespread pond de-silting, the total groundwater abstraction for agriculture alone was estimated to be 3.78 MCM (or 275 mm), with 35 deep tubewells pumping water at a rate of nearly 15,000 gallons per hour for nearly 1,500 hours a year (Kumar 2000b). The groundwater condition of the village is typical of the North Gujarat region. Against this, the total amount of rainfall over the village is only 7.56 MCM, with a mean annual rainfall of 550 mm over an area of 1,374 ha. The runoff that this amount of rainfall can generate is 63.8 mm as per the rainfall runoff relationship, with the total runoff being 0.877 MCM. But in practice, it is unlikely to get this amount of runoff, as farmers directly harness a significant portion of the runoff generated from the crop land, which falls in the catchment 'in situ' for crop production, unlike large basins which have a good part under virgin catchments. Kumar (2000) estimated the groundwater overdraft in the village as nearly 247.5 mm by considering the recharge as 5 % of the annual rainfall. Hence, even if the entire runoff generated is harnessed for recharge, it would amount to only 25.7 % of the overdraft.

On the other hand, there are many regions in India where the economic demand for water is far below what the natural endowment can provide. The entire Ganga-Brahmaputra Basin area can be put into this category. The region has an enormous amount of static groundwater, estimated to be 8,787.6 BCM, apart from having a high rainfall and cold subhumid climate that generate sufficient surface flows. Cheaper access to water might increase the demand for irrigation water slightly, but, there are significant limits to such access, imposed by the cold and humid climate and very low per capita arable land. The economic demand for water therefore, would continue to be below what the water endowment can provide (Shah 2001; Kumar 2003). Already, the irrigation intensities are high in thee Uttar Pradesh and Haryana. Though irrigation intensity in Bihar is low, the subhumid and cold climate reduces the irrigation requirement significantly. In most parts of this region, the issue is not the physical availability of water, but the ability of communities to access water for irrigation (Kumar 2003; Shah 2001). Water harvesting anyway does not offer any economic solution here for the poorer communities to facilitate their access to water.

Issues in Evaluating Costs and Economics

In the planning of large water resource systems, cost and economics are important considerations in evaluating different options. But unfortunately, the same does not seem to be applicable in the case of small systems, though concerns about economics of recharge systems in certain situations were raised by authors such as Phadtare (1988) and Kumar (2004).

Part of the reason for the lack of emphasis on 'cost' is the lack of scientific understanding of the hydrological aspects of small-scale interventions, such as the amount of stream flows that are available at the point of impoundment, their patterns, the amount that could be impounded or recharged and the influence area of the recharge system. Even though simulation models are available for analyzing catchment hydrology, there are great difficulties in generating vital data at the micro level, especially those on daily rainfall, soil infiltration rates, catchment slopes, land cover and PET, which determine the potential inflows; and evaporation rates that determine the potential outflows. Furthermore, for small water harvesting projects, implemented by local agencies and NGOs with small budgets, the cost of hydrological investigations and planning is hard to justify. Often, provision for such items is not made in small water harvesting projects.

That said, the amount of runoff that a water harvesting structure could capture, depends not only on the total quantum of runoff, but also on how it occurs. A total annual runoff of 20 cm occurring over a catchment of one sq. km. can generate a surface flow of 0.20 MCM, but the amount that could be captured for water harvesting depends on the pattern of rainfall events. As Garg (1987) points out, in arid and semi-arid regions in India, high-intensity rainfalls of short duration are quite common (source: Garg 1987 as cited in Athawale 2003: Figure 24). These runoffs generate flash floods.[2] If the entire runoff occurs in a major rainfall event, the runoff collection efficiency would reduce with the reducing capacity of the structures built. If large structures are built to capture the high-intensity runoff and thereby increase the runoff collection efficiency, the cost per unit volume of water captured would inflate. In fact, authors such as Oweis, Hachum and Kijne (1999) have argued that runoff harvesting should be encouraged in arid areas only if the harvested water is directly diverted to the crops for use.

Given the data on inflows and runoff collection efficiencies, predicting the impacts on the local hydrological regime is also extremely complex, requiring accurate data on geological and geo-hydrological profiles, and variables.

In lieu of the above described difficulties in assessing effective storage of RWHS, unit costs are worked out on the basis of the design storage capacity of the structures and the ‘rule of thumb’ about number of fillings. Shri Vivekananda Research and Training Institute, Mandvi, Kachchh, which had done pioneering work in the field of artificial groundwater recharge in India, often resorts to this rule of thumb to evaluate the cost-effectiveness of the recharge structures they built in Kachchh (see, for instance, Raju (1995)). The recent book by Dr. R. N. Athawale on rainwater harvesting in India though had covered a gamut of technical aspects on water harvesting in the different regions of India, does not deal with economic issues (see, for instance, Athawale 2003).

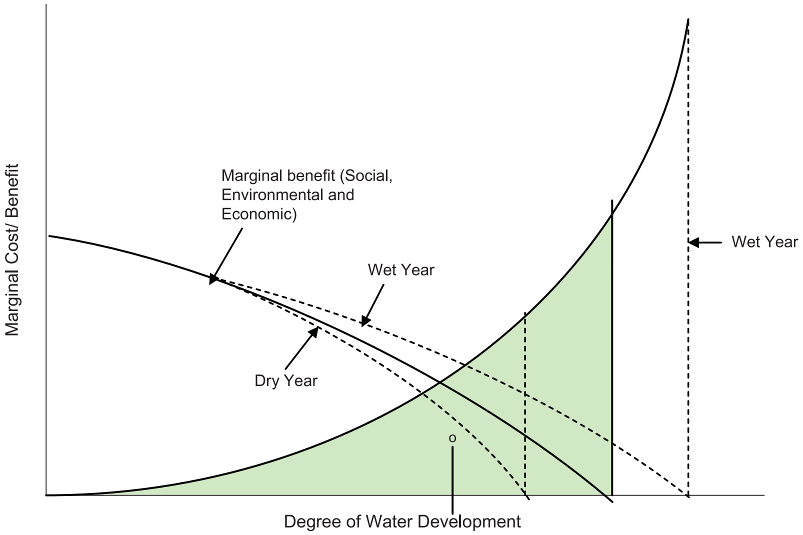
Scale considerations are extremely important in evaluating the cost and economics of water harvesting/groundwater recharge structures because of the hydrological integration of catchments at watershed and river basin levels. The cost and economics of water harvesting systems cannot be performed for individual systems in isolation, when the amount of surplus water available in a basin is limited. This is because incremental structures do not result in a proportional increase in hydrological benefits (Kumar 2000a), as interventions in the upper catchments reduce the potential hydrological benefits from the lower systems. What is important is the incremental hydrological benefits due to the new structure. A system in itself may be cost-effective and economically viable if evaluated independently, but, if evaluated as a part of a large-scale water-harvesting intervention at the level of river basins, the system may not be justifiable from the cost angle when compared against the additional benefit it brings in.

---

[2] Many parts of Kachchh, which records one of the lowest mean annual rainfalls (350 mm), experienced floods during 1992 and 2003 with many water harvesting (WH) structures overflowing. Flash floods occur even in some of the semi-arid and water-scarce basins such as Sabarmati and Banas (Kumar, 2002b).

In any basin, the marginal benefit from a new water harvesting structure would be smaller at higher degrees of basin development, while the marginal cost would be higher (see Figure 2). The reason being: 1) the higher the degree of basin development is, the lower would be the chances for getting socially and economically viable sites for building water impounding structures, increasing the economic and financial cost of harvesting every unit of water; and 2) with a higher degree of development, the social and environmental costs of harvesting every unit of water increases (Frederick 1993), reducing the net economic value of benefits. Therefore, the cost and economic evaluation should move from watershed to basin level. As Figure 2 indicates, the level at which basin development can be carried out depends on whether we consider the flows in a wet year or a dry year or a normal year. Nevertheless, there is a stage of development (marked by O in the chart) beyond which the negative social, economic and environmental benefits start accruing, reducing the overall benefits. Here, O is the optimum level of water resource development.

Figure 2. Marginal cost and benefits of water-harvesting with different degrees of basin development.



But, it is important to keep in mind that the negative social and environmental effects of over-appropriation of the basin’s water resources may be borne by a community living in one part of the basin, while the benefits are accrued to a community living in another part. Ideally, water development projects in a basin should meet the needs and interests of different stakeholders living in different parts. Therefore, the optimum level of water development should not aim at maximizing net basin level benefits, but rather optimizing the net hydrological and socioeconomic benefits for different stakeholders and communities across the basin, which amounts to basin-wide optimization. That said, in certain situations, the local economic benefits from RWH against the economic costs themselves may be questionable. But, such interventions could be justified if there are potential social benefits for changing patterns of water availability and use, in terms of increasing water availability to poorer farmers with low-capability landholdings. But such decisions should be based on the evaluation of alternative strategies to meet the local water needs of the poor.

Now, the ability to derive the economic benefits of recharge depends on where the recharged water ends up. In the regions underlain by hard-rock geology, the groundwater flow patterns are quite complex. Often, the benefits are that recharge structures extend up to a few kilometers downstream or upstream depending on the pattern of occurrence of geological structures such as lineaments, fractures and dykes (source: based on Muralidharan and Athawale 1998). Tracing the recharge water in such situations would require sophisticated studies involving isotopes. This is a common problem in the hard-rock areas of Saurashtra, Kachchh, North Karnataka and Tamil Nadu where large-scale water harvesting/groundwater recharge interventions are taken up through check dams, ponds and percolation tanks. Often the communities, for whom investment for recharge systems are made, do not get the benefit (Moench and Kumar 1993). In certain other situations, the recharge water could end up in saline aquifers.

The economics of RWH would also be a function of the incremental value of benefits accrued from the use of newly-added water. Apart from the recharge volume, the value of the use to which the additional water is put is extremely important in determining the incremental benefits, an issue often ignored in the project planning. Often, the benefits of RWHS are not clearly identified or understood. While the cost of water harvesting is significant, it is critical to divert the new water to high-valued uses. Phadtare (1988) pointed out that recharge projects would be economically viable in alluvial North Gujarat if the water is diverted for irrigation, as structures are expensive. Yield losses due to moisture stress are extremely high in arid and semi-arid regions and, that providing a few protective irrigations could enhance yield and water productivity of rain-fed crops remarkably, especially during drought years (Rockström et al. 2003). Therefore, the available extra water harvested from monsoon rains should be diverted to supplementary irrigation in drought years.

There are regions where human and cattle drinking become high priority demands. North western Rajasthan, which is arid and dominated by pastoral communities, named *Gujjars*, is one such example. The social and economic value realized from the use of water for human drinking and livestock use, respectively, would be much more than the economic value realized from the use of water in irrigating crops. In such situations, water should be diverted for such uses where the opportunity costs are low and net value products are high. But proper water use planning to realize the maximum value from the added water is largely missing in water harvesting efforts.

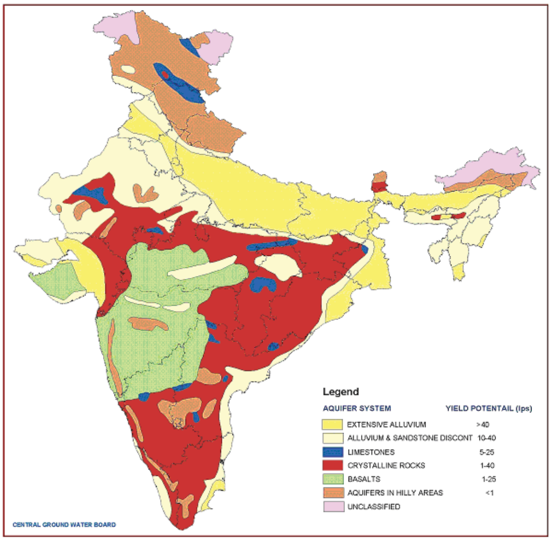
Lack of an Integrated Approach

In many river basins, the surface water systems and groundwater systems are often inter-connected. Any alterations made in one type of system could change the availability of water in the other type (Sohiquilo 1985; Llamas 2000). In many hilly areas, especially in the Western Ghats, the water levels rise steeply after the monsoon, and groundwater contributes significantly to the stream flows downstream during lean seasons due to the steep gradients for groundwater flow. In such cases, any water harvesting intervention to store water underground may not make much sense as the water stored would be rejected and appear as surface flows (Mayya 2005). On the other hand, in regions with deep water table conditions like in North Gujarat, the runoff directly moves into the groundwater systems of the plains through the sandy river bed as dewatering of the upper aquifers increases the rate and quantity of percolation (Kumar 2002b).

With two-third of the country's geographical area underlain by hard-rock formations, the storage capacity of aquifers poses a major challenge for artificial recharge. Most parts of water-scarce states, viz., Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, Orissa, Chhattisgarh and Tamil Nadu are underlain by hard rocks ranging from basalt, crystalline granite, hill aquifers and sandstone. A small area in Gujarat has extensive alluvium e.g., Narmada Valley and Cambay Basin (see Map 5). The hard rock aquifers have no primary porosity and have only secondary porosity. The constraints imposed by hard-rock geology in recharge efforts through percolation tanks are: high depth to the water table below and around the recharge structure due to the occurrence of recharge mounts and shallow bed rocks, which prevent the percolation of water (Muralidharan 1990 as cited in Muralidharan and Athawale 1998); and low infiltration capacity of the thin soils overlaying the hard-rock formations. Due to low specific yield (0.01-0.03), the sharp rise in water levels is observed in aquifers during monsoon, leaving little space for infiltration from structures. While harnessing water for recharge is extremely important during normal and wet years, the natural recharge in hard-rock formation is high during such years as it is a function of seasonal rainfall (based on regression equations shown in Figure 7 in Athawale 2003), further reducing the scope for artificial recharge.

In Saurashtra, in spite of the poor potential offered by low rainfalls, high variability, and high evaporation rates (see Map 1-3), significant recharge efforts were made. But, the biggest constraint in storing water underground during high rainfall years is the poor storage capacity or specific yield of the basalt formations. During good rainfall years, the aquifers get saturated

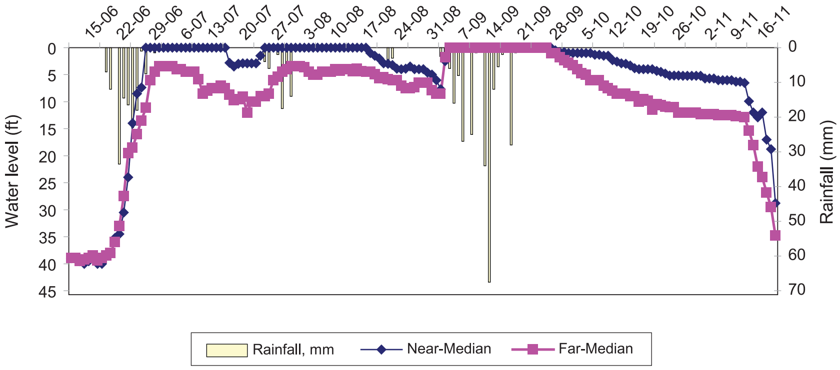
Map 5. Aquifer system in India.



with natural recharge immediately after the rains, leaving no space for entry of water from the recharge systems (Kumar 2000a). An estimated 20,000 check dams built in the region to capture the rainwater and recharge the aquifers are able to store only a small fraction of the surplus runoff. In such situations, proper water use programing is required to achieve effective utilization of the available surplus water, wherein water from aquifers is pumped out and used during the rainy season itself thereby creating storage space for the incoming flows (Muralidharan and Athawale 1990; Shah 2002).

The groundwater level fluctuation data obtained from the Ghelo River basin in Saurashtra illustrate this. The basin had experienced intensive water-harvesting since 1995. The data were collected from open wells located inside the basin periodically during and after the monsoon rains. The wells located close to the water harvesting structures and those away from the structures are demarcated. The water level fluctuation in the wells, in relation to the rainfall events, was analyzed and presented in Figure 3. The time series data shows that the wells close to water harvesting structures are replenished faster than those located away from the structures. But, these wells that are replenished faster start overflowing after the first major wet spell, while the second category of wells show similar trends only after the second wet spell. Another interesting observation is the steep rise in water levels in wells located both close to and away from the water harvesting structures soon after the first wet spell. This steep rise in water levels (in the order of 35-40 feet) is indicative of the poor specific yield of the aquifer in the area,[3] as the magnitude of cumulative rainfall that had caused this fluctuation is quite small (nearly 200 mm).

Figure 3. Water level fluctuation in wells in Fulzar, Ghelo River basin.



---

[3] The specific yield can be estimated as the ratio of the rise in water level (m) and the cumulative rainfall (m) that is responsible for the water level fluctuation, if we consider the lateral flows in groundwater as negligible and assume that pumping from the observation wells during the time of recharge is zero. The rise in water level is between 10.5 and 12 m and the rainfall is 0.2 m.

Trade-off between Local vs Basin Impacts in Closed Basins

Due to the lack of integration between plans for water harvesting at the local level and basin level water resource development, RWH often leads to over-appropriation of surface water in river basins. While the planning of conventional water development projects is based on dependable yields from the catchments, the subsequent plans for WH do not take into account the 'committed flows' for downstream reservoir/water diversion systems. Also, there is an increasing tendency to believe that because these structures are too small that they are benign (Batchelor et al. 2002), though present in large numbers in most cases. The primary reason for this is that the agencies that are concerned with small water harvesting (in the upper catchment) are different to those that are concerned with major head- works, and the two types of agencies do not act in a coordinated fashion at the basin level. The building of small water harvesting systems such as tanks and check dams are often the responsibility of the minor irrigation circles of the irrigation department or district arms of the rural development departments of the states concerned. This ad hoc approach to planning often leads to over-appropriation of the basin water, with negative consequences for large schemes downstream (Kumar et al. 2000).

The data collected from the Ghelo River basin shows that the inflow into Ghelo-Somnath Reservoir had significantly reduced after intensive water harvesting work was undertaken in the upper catchment. Figure 4 shows the catchment rainfall and runoff in the Ghelo-Somnath. Since 1995, the year that experienced intensive water harvesting work, the only time the reservoir overflowed was in 2005, when the recorded rainfall was 789mm. While reduction in runoff could be attributed to rainfall reduction as well, rainfall-runoff regressions were carried out for two time periods i.e., 1969-1995 and 1995-2005. The regression equations clearly show that the relationship between rainfall and runoff had changed after water harvesting interventions (see Figure 5). For the same amount of rainfall, the runoff generated is now low. Or in other words,

Figure 4. Ghelo-Somnath rainfall and reservoir inflows.

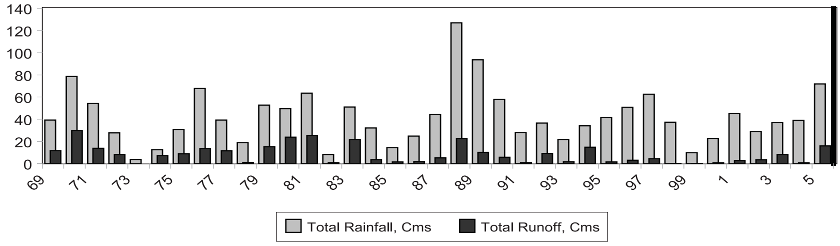
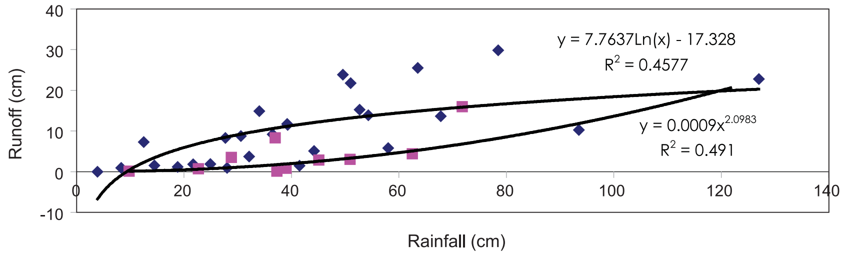


Figure 5. Impact of water harvesting on inflows in the Ghelo-Somnath Reservoir.



the amount of rainfall required for filling the reservoir had now increased from 320 mm to 800 mm. While this is theoretically true, the actual runoff received by the station might actually differ as there are many factors other than just rainfall magnitude, which determine the runoff rates. Though the curves intersect, at high magnitudes of rainfall, this is not a problem as such high rainfall does not occur in the basin, and the curve needs to be considered only for the rainfall regime of the basin.

Many large and important river basins in India, which are also facing water scarcity, are now ‘closed’ or do not have uncommitted flows that are utilizable through conventional engineering interventions. For example, the river basins of Pennar, Cauvery and Vaigai in the south (based on GOI 1999: pp 472-477), and Sabarmati and Banas in the west, and all the west-flowing rivers in Saurashtra and Kachchh in Gujarat, are closed (Kumar 2002). While the Krishna Basin too is on the verge of closure, basins such as the Godavari and Mahanadi in the east are still ‘open’ (based on GOI 1999: pp 466-469).

The Sabarmati Basin, for instance, having a drainage area of 21,678 sq. km., has a utilizable surface flow of 1,513.4 MCM allocated to Gujarat (Kumar and Singh 2001), whereas the total live storage capacity of irrigation schemes built in the basin, estimated to be at 1,470 MCM (GOI 1999), is still slightly below this. But the basin has many water diversion structures including weirs and a barrage. Actually, the dependable runoff upstream of the reservoirs/ diversion structures in the basin is far below the planned water utilization (estimated to be at 1,560 MCM as per Kumar and Singh (2001), leaving no spillover. At the aggregate level, the basin is over-appropriated. At the subbasin level, the scenario is different. Two of the subbasins, viz., Dharoi and Hathmati are heavily over-appropriated (Kumar et al. 2000). Still, one of the subbasins, named Watrak, has uncommitted flows (Kumar and Singh 2001), which eventually end up in the Gulf of Cambay.

It is hard to judge whether a basin is closed or open on the basis of the storage capacity of reservoirs and the dependable flows as many reservoirs also divert a lot of water during the monsoon season, increasing the effective water utilization to be greater than the live storage capacity. Figure 5 shows the ratio of total live storage of reservoirs (built, being built and proposed) in 17 major river basins in India against the dependable runoff in these basins. It shows that for many basins, the ratio is far less than 100 %, leaving the impression that there are much more uncommitted flows in the basin for future harnessing. But this is not correct. Take, for instance, the Narmada Basin. The total live storage volume of all terminal dams built in Narmada, i.e., Sardar Sarovar, is 5,800 MCM, where as the total water utilization from this reservoir is 11, 200 MCM. All the 30 large and 135 medium reservoirs together would divert a total of 30,588 MCM of water for irrigation and various other purposes (NWDA 2004). But the total live storage of these reservoirs would be much less, i.e., 23,790 MCM (GOI, 1999: pp 36). This is because a significant amount of water would be diverted from these reservoirs for kharif irrigation within the basin and outside, particularly from the Sardar Sarovar Reservoir. Again the estimates of the stages of development do not take into account the reservoirs having a live storage capacity of less than 10 MCM.

Trade-off between Economics and Hydrological Opportunity

Regions with semi-arid and arid climate experience extreme hydrological events (Hurd et al. 1999). As we have seen before high inter-annual variability in rainfall is a common phenomenon in most parts of these water-scarce regions. Rainfall variability induces a higher degree of variability in runoff. Such a high variability is found even in high rainfall regions as well as low rainfall regions. We take the example of the upper catchment area of the Cauvery Basin in peninsular India and one of the catchments of Sabarmati River basin in North Gujarat of western India.

In the Palanpur area of Banaskantha District in North Gujarat, which has semi-arid to arid climatic conditions, the rainfall records show a variation from a lowest of 56 mm in 1987 to a highest of 1,584 mm in 1907. The runoff estimated on the basis of regression equation developed for a subbasin, named Hathmati of the Sabarmati Basin in North Gujarat, which is physiographically quite similar to the Palanpur area of Banaskantha, shows that the runoff can vary from a lowest of 0.6 mm to a highest of 541 mm. But the occurrence of actual runoff could be different from this based on how other variables that are not considered in the regression viz., the intensity and pattern (over space and time) of rainfall, influence the runoff intensity. Thus the lowest runoff is close to one-thousandth of the highest runoff. Though what can occur at the subbasin level may not be representative of that in small upper catchments, the difference cannot be drastic. Even for the humid, high rainfall region of the Wayanad District in Kerala, the observed rainfall of the area range from 528 mm in the lowest rainfall year (2002) to 1,458 mm in the highest rainfall year (1994) in a 31-year period from 1973-2003.

When there is a high inter-annual variability in the runoff a catchment generates, a major planning question which arises is ‘for what capacity the water harvesting system should be designed’? When scarcity is acute, the highest consideration is given to capturing all the water that is available. If all the runoff that occurs in a high rainfall year is to be captured, then the cost of building the storage system would be many hundred times more than what is required to capture the runoff which occurs during the lowest rainfall, and, the system would receive water to fill only a small fraction of its storage capacity in the rest of the years. This could make it cost-ineffective. The issue of variability is applicable to the design of large head-works as well. But, in large systems, the water in excess of the storage capacity could be diverted for irrigation and other uses to areas that face water shortages during the same season, thereby increasing the effective storage.

In order to illustrate this point, we used the data generated from the Ghelo River basin in Saurashtra. The basin has a total catchment area of 59. 20 sq. km. It has a medium irrigation reservoir with a storage capacity of 5.68 MCM and that has been functional since 1966. The inflow data of the reservoir for the period 1969-1995 showed that the total runoff generated in the basin varied from zero, in the year which recorded a rainfall of 39 mm, to a maximum of 17.78 MCM in the year which recorded a rainfall of 1,270 mm. Today, the total capacity of water harvesting systems built in the upstream of the Ghelo Reservoir is 0.15 MCM. During the period from 1969 to 2005, the reservoir showed an overflow for 13 years with a total quantum of 60.936 MCM. Capturing one million cubic meters of runoff had to be captured in addition to the 5.89 MCM that would be captured by the medium irrigation reservoir, would cost around 0.09 X/m^3 of water, while capturing 3 MCM would cost 0.11 X/m^3 of water. If the maximum runoff observed in the basin, i.e., 17.785 MCM has to be captured, the total volume of water captured would be only 60.91 MCM, in which case the unit cost of water harvesting would be around 0.21 X/m^3 of water. Here, ‘X’ is the cost of storage structures for creating an effective storage space of one MCM. Here, again, we are not considering the incremental financial cost of the special structures for capturing high magnitudes of runoff, which cause flash floods.

Maximizing Local Benefits vs Optimum Benefits for Basin Communities

Generally, in any river basin, the upper catchments are rich in terms of their ability to contribute to the basin yields. This is mainly because of the unique physiographical features, and partly because of climatic conditions such as steep slopes, high rainfall in the mountains and high humidity, which provide a favorable environment for runoff generation. The upper catchments also provide a good source of base flows due to the forest cover, which causes favorable conditions for water storage and infiltration. On the demand side, these regions generally are less endowed in terms of the availability of arable land. Over and above, the demand rates for irrigation are generally low. On the other hand, the lower catchments are generally characterized by lower rainfalls and higher levels of aridity (rainfall deficit to meet ET demands) and better access to arable land, thereby increasing the aggregate demand for irrigation.

There are numerous examples for this and a few to cite are: the upper catchment of the Cauvery Basin in the south, the Narmada Basin in central India, the Sabarmati Basin in western India, the tributaries of the Indus River in north western India, the Krishna Basin in central India and the Mahanadi Basin in eastern India. Certain parts of the Kabani Subbasin of the Cauvery River basin have a cold and semi-humid climate, while certain other parts of this subbasin receive the second highest rainfall in India after Chirapunji, with the mean annual rainfall exceeding 4,000 mm. Irrigation demands in these regions are low owing to high precipitation and low reference evapotranspiration, and the low per capita availability of arable land**.** On the other hand, the lower parts of the Cauvery Basin in Tamil Nadu are hit by a scarcity of water for irrigation owing to lower rainfalls and high evapotranspiration.

We have defined agricultural water demand as a function of per capita net sown area and the ratio of ET_0 (reference evapotranspiration) and rainfall; and water availability as a function of rainfall. It is assumed that: a) higher the ET_0/R ratio, higher would be the irrigation requirement for a unit of land; and b) higher the per capita (rural population) net sown area, higher would be the aggregate demand for irrigation per capita. Table 4 shows the estimated values of two selected agricultural water demand variables, viz., ET_0/R and per capita arable land; and one water availability variable, i.e., rainfall. It also shows that the irrigation demand is much higher in the lower catchment areas, while water availability is higher in the upper catchments in all six of these important basins.

Major water resource/irrigation projects undertaken in the past, tap stream flows generated from the upper catchments but cater to either the lower parts of these basins or other less water endowed regions outside these basins (Verghese 2001 and 2002). The Bakhra Reservoir and Nangal diversion projects located in the high rainfall Shivalik Hills of Himachal Pradesh, essentially cater to the ravenous low rainfall and drought-prone regions of Punjab and scanty rainfall regions of Rajasthan (Verghese 2002). The Sardar Sarovar Dam harnesses water from ample rainfall areas in the Narmada Valley and takes it to the drought-prone areas of North Gujarat and Saurashtra, which are characterized by low and erratic rainfall (Verghese 2001). Similarly, the large reservoir projects in the Cauvery Basin transfer water to the drought-prone regions in Tamil Nadu and Karnataka. As such the water demand for irrigation is extremely low in the upper catchments.

Moreover, as irrigation water use efficiency and water productivity are likely to be high in areas with variability in rainfall and high drought- proneness (Rockström 2002), with transfer of water from the well-endowed regions to the poorly-endowed regions, the economic value of water in agriculture increases. The recent research carried out by IWMI in water-scarce and

Table 4. Comparison of agricultural water demand variables in upper and lower catchment districts of selected Indian river basins.

Name of Basin	Name of Upper Catchment District (UCD)	Name of Lower Catchment District (LCD)	Mean Annual Rainfall (mm) in		Mean Annual Potential Evapo-transpiration (mm) in		PET/R		Per Capita Net Sown Area(ha)	
			UCD	LCD	UCD	LCD	UCD	LCD	UCD	LCD
Sabarmati	Dungarpur	Ahmedabad	643.7	821.0	1,263.0	1,788.8	1.96	2.18	0.14	0.47
Indus	Shimla	Ludhiana	1,597.0	525.0	986.60	1,698.6	0.62	3.24	0.14	0.25
Narmada	Shahdol	Jhabua	1,352.0	792.04	1,639.0	2,127.0	1.21	2.69	0.35	0.35
Cauvery	Wayanad	Nagapattianan	3,283.0	1,337.0	1,586.9	1,852.5	0.48	1.39	0.18	0.13
Krishna	Raigarh	Guntur		1,029.0		1,785.9		1.74	0.13	0.22
Mahanadi	Raipur	Puri	1,388.0	1,440.0	1,667.0	1,667.0	1.20	1.16	0.18	0.06

Source: authors' own estimates based on Agricultural Statistics of India and FAO data on precipitation (R) and reference potential evapotranspiration (PET)

Notes: UCD: Upper catchment district; LCD: Lower catchment district

land-rich western Punjab and water-rich and land-scarce eastern Uttar Pradesh (UP) showed that the value of water realized from irrigation is much higher in Punjab than in eastern UP. The economic value of water was Rs. 14.85/m^3 in western Punjab, whereas in eastern Uttar Pradesh it was Rs. 11/m^3. Due to the scarcity of water, the farmers in Punjab make better economic use of water by choosing cropping systems that are economically more efficient and adopting agronomic practices in order to obtain higher yields, higher physical productivity and economic efficiency (Kumar, Malla and Tripathy 2006).

But, often water harvesting initiatives, especially those by NGOs, are driven by considerations other than economic efficiency, the most important of which are social equity and environmental justice. Impounding water in the upper catchments might serve the social objectives of meeting drinking water requirements.

As evident from the above illustrations, there is a clear trade off between meeting economic efficiency objectives and these developmental goals. Therefore, any water resource intervention in the upper catchment areas that reduces the downstream uses should be done with due consideration to the net change in the 'gross value product' of water in the basin due to the interventions. The 'gross value product' can be defined as the sum total of the incremental value product from the economic uses, environmental services and social uses that the basin's water resources meet. The amount of water to be captured upstream through RWH interventions should also be optimized to derive maximum regional social equity, environmental value and overall output from the economic uses of water. In basins where the available water resources are already committed (closed basins), the challenge is bigger as maximizing the gross value product might mean reallocating some water from a low valued use to a high valued use.

Major Findings

The following are the major findings that emerge from an extensive review of the research on water harvesting in India, and a macro analysis of the critical issues in rainwater harvesting from the point of view of hydrological opportunities, economic viability and socioeconomic impacts when scale considerations are involved.

- Macro level hydrological analysis shows that rainwater harvesting solutions offer extremely limited potential in terms of their ability to reduce the demand-supply imbalances and provide reliable supplies to water-scarce regions. The reason being: a) a significant part of these regions (states of Gujarat and Rajasthan) are characterized by low mean annual rainfalls, high inter-annual variability in rainfall, with high potential evaporation and a larger share of evaporation occurring during the rainy season, reducing runoff potential and increasing the occurrence of hydrological stresses; and b) another significant part is characterized by medium rainfalls, with medium inter-annual variability, but 'medium to high evaporation', making surface storage difficult.

- A large part of the water-scarce regions, which fall under the 'medium rainfall-medium to high evaporation' regime are underlain by hard-rock formations such as basalt, crystalline rocks and other consolidated formations, e.g., sandstones. The percolation tanks, which are the most preferred recharge structures, are likely to have low efficiency in these hard-rock areas and also in areas having silty clay and clayey soils. In high rainfall, and medium evaporation regions, which experience high reliability in rainfall, such as parts of Orissa and western Ghat, the overall potential and reliability of water supplies from RWHS would be high.

- Inefficient recharging in hard-rocks is due to a lack of integration of groundwater and surface water use. In these regions, the planning of recharge schemes should consider the surface water impoundment of all the available excess flows, than their direct recharge. This should be followed by water use programming to create an underground storage for incoming surface flows. However, this is not followed. The data on water level fluctuations collected from the Ghelo River basin in Saurashtra show that wells in the vicinity of check dams start overflowing during the monsoon due to lack of storage capacity in the shallow aquifer, which gets recharged.

- Many water-scarce regions have water demands that far exceed the supply, and being vulnerable to hydrological stresses, they would require exogenous water.

Economic evaluation of water harvesting/groundwater recharge systems poses several complexities due to the difficulty in quantifying the inflows, the storage and recharge efficiency, and the economic value of the incremental benefits, which are social, direct economic and ecological or environmental. Data for water harvesting structures constructed in the upper catchment shows a storage capacity of 0.15 MCM. At the same time, the estimated inflow reduction in the reservoir downstream (Ghelo-Somnath) was not found to be constant, but a function of the rainfall itself. The flow reduction is highest at below normal to normal rainfall regimes, whereas at higher levels of rainfall it appears to reduce.

- Scale considerations are extremely important in evaluating the cost and economics of water harvesting/groundwater recharge structures because of the integration of catchments at the level of river basins. The economics of water harvesting cannot be performed for structures based on their individual benefits and costs when the amount of surplus water available in a basin is limited; but on the basis of incremental benefits. Furthermore, the higher the degree of basin development, the higher will be the marginal cost and the lower will be the marginal benefit.

- There are many basins which cover significant areas in India that experience high inter-annual variability in the stream flows are many. In such basins, the trade-off between the hydrological impacts of water harvesting and the economic benefits is likely to be large. With the increasing storage capacity of RWH systems, the economic viability becomes poorer as the average cost of water harvesting per unit volume of water increases. The historical data on reservoir inflow obtained for the Ghelo River catchment illustrate this.
- In 'closed basins', there is an apparent trade-off between local benefits and downstream benefits. Upstream diversions reduce the prospects of storage and diversions systems in the downstream. Examples of closed basins are river basins in North Gujarat, Saurashtra, Kachchh, western Rajasthan and basins in peninsular India, such as Cauvery, Pennar and Vaigai. Narmada is another basin, which in the immediate future would join this category of river basins. The detailed hydrological data collected from the Ghelo River basin in Saurashtra also illustrate this.
- In many important basins, there is an apparent trade-off between maximizing the overall benefits for basin communities in terms of enhancing the gross value of product of water, and maximizing the local benefits of water harvesting. This is owing to the fact, that in these basins, water from well-endowed regions with low water demands is being diverted to poorly-endowed regions with high water demands, enhancing its social and economic value. Noteworthy examples are Indus in north-western India, Cauvery and Krishna in the southern peninsula, Narmada in central India and the Sabarmati Basin in western India.

Conclusions

In the most water-scarce regions of India, RWH offers limited potential. In many other regions, which have medium rainfalls but experience 'medium to high evaporation', the poor groundwater potential of the hard-rock that underlie these regions pose a constraint for recharging. This was illustrated by water-level fluctuation data in the wells of the Ghelo River basin in Saurashtra. The economic evaluation of water harvesting systems poses several complexities due to the problems in quantifying their hydrological impacts, and their various benefits. The economics of water harvesting cannot be worked out for structures on the basis of individual benefits, but on the basis of incremental benefits. In many water-scarce basins, there is a strong trade-off between maximizing the hydrological benefits from RWH and making them cost-effective. In many water-scarce basins, RWH interventions lead to the distribution of hydrological benefits rather than to their augmentation. This was also illustrated by the historical flow series data from the Ghelo River basin. There is an optimum level of water harvesting that a basin can undergo to optimize the gross value product of water vis-à-vis economic, social and environmental outputs basin-wide.

References

Agarwal, A.; Narain, S. 1997. *Dying Wisdom: Rise and Fall of Traditional Water Harvesting Systems*, Centre for Science and Environment. New Delhi, India: Centre for Science and Environment.

Athawale, R. N. 2003. *Water Harvesting and Sustainable Supply in India*, published for Environment and Development Series, Centre for Environment Education, Rawat Publications, Jaipur and New Delhi.

Batchelor, C.; Singh, A.; Rama, M.S.; Rao, M.; Butterworth, J. 2002. Mitigating the Potential Unintended Impacts of Water Harvesting, paper presented at the IWRA International Regional Symposium 'Water for Human Survival', 26-29 November, 2002, Hotel Taj Palace, New Delhi.

Badiger, S.; Sakthivadivel, R.; Aloysius, N.; Sally, H. 2002. Preliminary Assessment of a Traditional Approach to Rainwater Harvesting and Artificial Recharging of Groundwater in Alwar District, Rajasthan, paper presented at the annual partners' meet of IWMI-Tata Water Policy Research Program, Anand, February 19-20.

Boughton, J. C.; Stone, J.J. 1985. Variation of Runoff with Watershed Area in a semi arid Location. *Journal of Arid Environment* Vol. 9, pp13-25.

Down to Earth. 2004. Water Woes in Wet Kerala, Cover Story, *Down to Earth*, May 31, pp 26-33.

Evans, J. P.; Jakeman, A.J. (undated) Development of a Simple, Catchment-Scale, Rainfall-Evaporation-Runoff Model, Centre for Resource and Environmental Studies, The Australian National University, Canberra ACT 0200: http://earth.geology.yale.edu/~je84/mystuff/research/ems_paper.pdf.

Frederick, K. D. 1993. *Balancing Water Demand with Supplies: The Role of Management in a World of Increasing Scarcity*, Technical Paper 189, Washington D. C: World Bank.

Garg, S. K. 1987. *Hydrology and Water Resources Engineering*, Khanna publishers, Delhi, pp.110-181.

Government of Gujarat. 1994. Integrated Plan of Sabarmati River Basin, Draft Report prepared by Gujarat State Water Resources Planning Group, Gandhinagar, Gujarat.

Government of India. 1999. Integrated Water Resource Development: A Plan for Development, Report of the National Commission for Integrated Water Resources Development Vol. I, Ministry of Water Resources, Government of India, New Delhi.

Government of Madhya Pradesh. 1972. *Master Plan for Development of Water Resources of The Narmada in Madhya Pradesh*, Volume –II, Statements, Government of Madhya Pradesh.

Government of Rajasthan. 1992. Effect of Rainfall and Potential Evapo transpiration on Groundwater Levels of Rajasthan, Groundwater Department, Jodhpur.

Gupta, R. K. 2000. Regional Water Transfer and Human Rights: Some Reflections on Sardar Sarovar Project, *ASIAN Journal* (Formerly Journal of Transportation and Infrastructure, 7 (4) pp: 112-127.

Hira, G. S.; Khera, K.L. 2000. Water Resource Management in Punjab under Rice Wheat Production System, Department of Soils, Punjab Agricultural University, Ludhiana.

Hurd, B.; Leary, N.; Jones, R.; Smith, J. 1999. Relative Regional Vulnerability of Water Resources to Climate Change, *Journal of the American Water Resources Association*, 35 (6): 1399-1419.

Jakeman, A.; David, J.; Post, A.; Beck, M.B. 1994. From data and theory to environmental models, *Environmetrics*, 5, 297-314.

Kolarkar, A. S.; Murthy, K.; Singh, N. 1983. Khadin-a method of harvesting water for agriculture in the Thar desert, *Arid Environment*. 6: 59-66.

Kumar, M. D. 1997. Water Use Study for Coastal Saurashtra and Kachchh, report submitted to the Water Resources Development and Management (WARDEMA) Project, Rajkot, VIKSAT, Ahmedabad.

(2000a) Dug-well Recharging in Saurashtra: Are the Impacts and Benefits Over-stretched? *Journal of Indian Water Resources Society*, July.

(2000b) Institutions for Efficient and Equitable Use of Groundwater: Irrigation Management Institutions and Water Markets in Gujarat, Western India. *Asia-Pacific Journal of Rural Development*, Vol. X (1), July.

(2002a) Integrated Water Management in the face of Growing Demand and threatened Resource Base in North Gujarat: Constraints and Opportunities: A Pilot Project to protect North Gujarat's Groundwater Ecology and Agriculture Economy, paper presented at the annual partners' meet of the IWMI-Tata Water Policy Research Programme, Anand, February 19-20.

(2002b) *Reconciling Water Use and Environment: Water Resource Management in Gujarat, Resource, Problems, Issues, Strategies and Framework for Action*, report submitted to Gujarat Ecology Commission for the Hydrological Regime Subcomponent of the State Environmental Action Programme supported by the World Bank.

Kumar, M. D. 2003. Food Security and Sustainable Agriculture in India: The Water Management Challenge, Working Paper 60, International Water Management Institute, Colombo, Sri Lanka.

Kumar, M. D. 2004. Roof Water Harvesting for Domestic Water Security: Who Gains and Who Loses? *Water International*, 39 (1): 43-53.

Kumar, M. D.; Chopde, S.; Mudrakartha, S.; Prakash, A. 1999. "Addressing Water Scarcity: Local Strategies for Water Supply and Conservation Management in Sabarmati Basin, Gujarat," in M. Moench, E. Caspari and A. Dixit (eds.) *Rethinking the Mosaic: Investigations into Local Water Management*. Kathmandu and Boulder: Nepal Water Conservation Foundation and Institute for Social and Environmental Transition.

Kumar, M. D.; Ballabh, V.; Talati, J. 2000. Augmenting or Dividing: Surface water Management in the Water Scarce River Basin of Sabarmati, IRMA Working Paper 147, Institute of Rural Management, Anand.

Kumar, M. D.; Malla, V.J.; Tripathy, S. 2006. Value of Water in Agriculture: A Comparative Analysis of Water Scarce and a Water Rich Region, *Water International*, paper accepted.

Lalljee, B.; Facknath, S. 1999. Water Harvesting and Alternative Sources of Water for Agriculture, PROSI Magazine, September 1999.-N 368-Agriculture.

Llamas, M. R. 2000. La Inserción De Las Aguas Subterráneas En Los Sistemas De Gestión Integrada, Paper presented at *II Congresso Ibérico Sobre Planeamento E Gestão De Água*, 9-12 November 2000, Oporto.

Moench, M.; Dinesh Kumar, M. 1993. Local Water Management Initiatives: NGO Activities in Gujarat, VIKSAT-Pacific Institute Monograph, VIKSAT, Ahmedabad.

Molle, F.; Mamanpoush, A.; Miranzadeh, M. 2004. *Robbing Yadullah's Water to Irrigate Saeid's Garden Hydrology and Water Rights in a Village of Central Iran*, Research Report 80, International Water Management Institute, Colombo, Sri Lanka.

Muralidharan, D.; Athawale, R.N. 1998. Artificial Recharge in India, base paper prepared for Rajiv Gandhi National Drinking Water Mission, Ministry of Rural Areas and Development, National Geophysical Research Institute.

National Geo-physical Research Institute. 2000. Geo-hydrological Investigations in M. C. Tanda Watershed, Anantapur District for Formulation of Suitable Artificial Recharge Strategies, interim report, September.

Oweis, T.; Hachum, A.; Kijne, J. 1999. Water Harvesting and Supplementary Irrigation for Improved Water Use Efficiency in Dry Areas. SWIM Paper, Colombo, Sri Lanka.

Pandey, D. N.; Gupta, A.K.; Anderson, D.M. 2003. Rainwater harvesting as an adaptation to climate change, Review Article, *Current Science*, 85 (1), 10 July.

Patel, A. S. 2002. Impact of Groundwater Recharge Activities in Saurashtra, paper presented at the annual partners' meet of the IWMI-Tata Water Policy Research Programme, Anand, February 19-20.

Phadtare, P.N. 1988. Artificial recharge of groundwater, paper submitted in the meeting of the working group on Water Harvesting, NCL, Pune, August 5, 1988.

Phansalkar, S.; Verma, S. 2004. “Improved Water Control as a Strategy for Improving Tribal Livelihoods,” Review of Agriculture, *Economic and Political Weekly*, XXXIX (12).

Pisharoty, P. R. 1990. Characteristics of Indian Rainfall, Monograph, Physical Research Laboratories, Ahmedabad.

Prinz, D. 2002. The Role of Water Harvesting in Alleviating Water Scarcity in Arid Areas, Keynote Lecture, Proceedings, International Conference on Water Resources Management in Arid Regions. 23-27 March, 2002, Kuwait Institute for Scientific Research, Kuwait (Vol. III. 107-122).

Raju, K. C. B. 1995. Rainwater Harvesting for Groundwater Recharging: The Experience of SVRTI in Moti Rayan Village, Kachchh in Moench, M. (Ed.) *Groundwater Management: Supply Dominated Focus of Government and NGO Efforts*, Monograph, VIKSAT, Nehru Foundation for Development, Ahmedabad.

Rangachari, R.; Sengupta, N.; Iyer, R.R.; Banergy, P.; Singh, S. 2000. Large Dams: India’s Experience, Final Report, prepared for the World Commission on Dams, Cape Town, South Africa, Secretariat of World Commission on Dams.

Rockström, J.; Barron, J.; Fox, P. 2003. Water productivity in rain-fed agriculture: Challenges and opportunities for smallholder farmers in drought-prone tropical ecosystems. In Jacob Kijne and others (Eds.) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Sahuquillo, A. 1985. Groundwater in Water Resource Planning: Conjunctive Use, *Water International,* 10 (1985) 57-63.

Sakthivadivel, R.; Fernando, N.; Brewer, J. 1997. *Rehabilitation Planning for Small Tanks in Cascades: A Methodology Based on Rapid Assessment*, Research Report 13, International Irrigation Management Institute, Colombo, Sri Lanka.

Seckler, D. J. 1996. *The New Era of Water Resources Management: From Dry to Wet Water Savings*, Research Report # 1, International Irrigation Management Institute, Colombo, Sri Lanka.

Shah, T. 2001. Wells and Welfare in Ganga Basin: Public Policy and Private Initiative in Eastern Uttar Pradesh, India, Research Report 54, International Water Management Institute, Colombo, Sri Lanka

Shah, T. 2002. Decentralized Water Harvesting and Groundwater Recharge: Can these Save Saurashtra and Kachchh from Desiccation, paper presented at the annual partners’ meet of the IWMI-Tata Water Policy Research Programme, Anand, February 19-20.

Sharma, A. 2002. Does Water Harvesting Help in Water-Scarce Regions? A Case Study of Two Villages in Alwar, Rajasthan, paper presented at the annual partners’ meet of the IWMI-Tata Water Policy Research Programme, Anand, February 19-20.

Sivapalan, M.; Kalma, J.D. 1995. Scale problems in hydrology: Contributions of the Robertson Workshop, *Hydrological Processes*, 9 (3-4): 1995.

Verghese, B. G. 2001. Sardar Sarovar Project Revalidated by Supreme Court, *International Journal of Water Resources Development*, Vol. 17 (1), 79-88.

Varghese, B. G. 2002. Water and Energy for Future India, paper presented at the International Regional Symposium on Water for Human Survival, 26-29, November, 2002, Hotel Taj Residency, New Delhi.

Wood, E. F.; Sivapalan, M.; Beven, K. 1990. Similarity and scale in catchment storm response. *Rev. Geophysics*, 28, 1-18.

Zhu, Z.; Giordano, M.; Cai, X.; Molden, D. 2004. Yellow River Basin Water Accounting, International Water Management Institute, Colombo, Sri Lanka.