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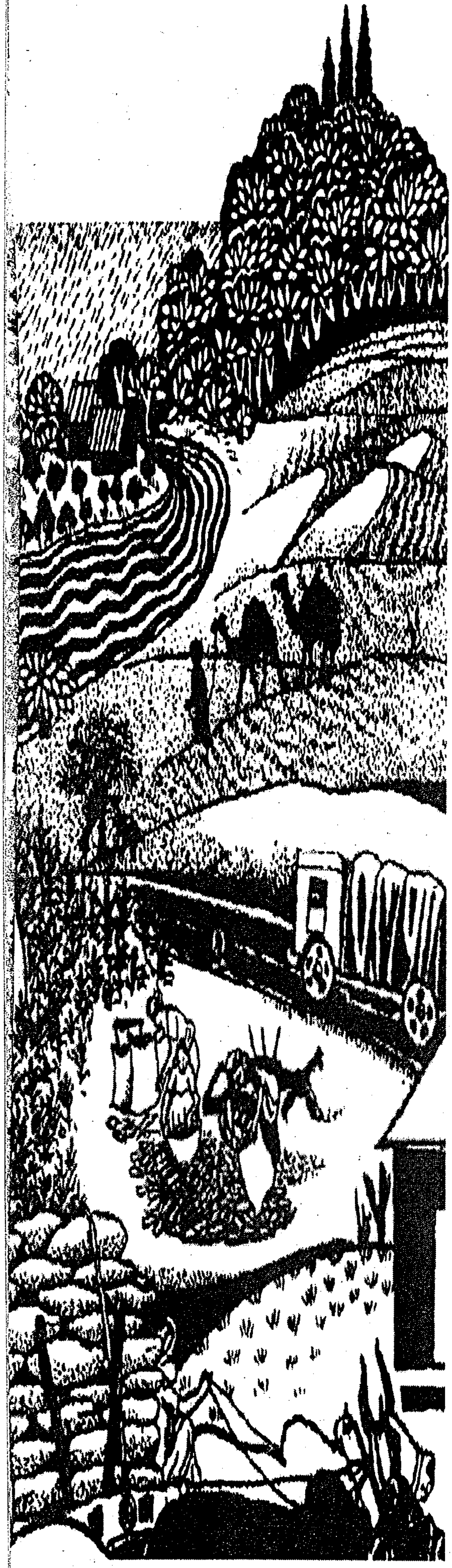

Rainwater Harvesting in India: Some Critical Issues for Basin Planning and Research

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RAINWATER HARVESTING IN INDIA: Some Critical Issues for Basin Planning and Research

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ABSTRACT

Often as a frantic response to problems of water scarcity and the consequent hardships faced by communities in urban areas as well as country-side, India had invested many millions in rainwater harvesting. Unlike investment in large water resource systems, these efforts had, by and large, lacked hydrological planning and sound economic analysis. The research on impact of local water harvesting/groundwater recharge activities in India is very scanty. Further, it is characterized by not so rigorous methodologies and analyses, and short periods of observations. More importantly, they fail to capture the scale effects of changing the unit of analysis from "local" to "large watersheds" and "river basins".

The paper identifies six critical issues in rainwater harvesting efforts in water scarce regions of India. First of all, it lacks emphasis on potential local supplies and the demand it has to cater to. While local supply potential is low in most water scarce regions, compounded by poor reliability, demand far exceeds the supply potential. Secondly, there are complexities involved in economic evaluation of RWH, due to lack of scientific data on inflows, runoff collection and storage efficiency, beneficiaries, value of the incremental benefits generated and scale considerations. With higher degrees of basin development, the marginal benefit from water harvesting at the basin level reduces, while marginal cost increases. Third: in many basins, there is a strong "trade off" between maximizing hydrological benefits and improving cost effectiveness. Fourth: many water-scarce basins are characterized by wide disparity in demand between upper catchments and lower catchments, due to which there is a trade off in maximizing benefits of upstream water harvesting with optimizing basin-wide benefits. Fifth: in many water-scarce basins, local water harvesting only divides the hydrological benefits rather than augmenting. Finally, lack of integration between surface water system and groundwater system reduces the potential of artificial recharging in hard rocks which also coincide with water-scarce regions.

Future research on water harvesting/groundwater recharging should focus on basin level marginal impacts and benefits to capture the scale effects, apart from covering different hydrological regimes, and typical rainfall years. This can help proper targeting of investments in water harvesting. Making water harvesting more effective calls for enhanced knowledge of catchment hydrology, basin-wide water accounting and water balance studies, improved efficiency of utilization of green and blue water for crop production, and "wet water" saving.

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1. INTRODUCTION

India has a long tradition of water harvesting. Many of the traditional water harvesting systems have either gone under disuse due to a variety of physical, social, economic, cultural and political factors which have caused their deterioration and decline of institutions which 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 the 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 resistance to appreciate the fact that different periods in history are marked by genesis, rise and fall of some new water harvesting tradition, is also very clear.

In India's water sector history, the past two decades are characterized by a boom in water harvesting. They are markedly different from the traditional ones in two ways; first-from the context; and second from the purpose. As regards the context, they 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 ones represented the best engineering feat of those times, in terms of 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 miniatures of the large water resource systems that use advances in civil engineering and hydrology. As regards the purpose, they are employed as resource management solution, 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 engineering performance of individual structures (see Muralidharan and Athawale, 1998). While a lot of anecdotal evidences on the social and economic gains exist, there is little understanding based on empirical work of: 1] the impacts of water harvesting activities on local hydrological regime in terms of net water gain; 2] basin level impacts on 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 the 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. Analysis of water harvesting systems also misses the influence of "scale factor".

2.0 OBJECTIVES OF THE PAPER AND APPROACH

The paper does not aim at analyzing the physical performance or hydrological impacts of water harvesting. Instead it takes a different approach. It begins with the basic premise that scale considerations are important in analyzing the impact of water harvesting; i.e., one has to move from local watershed level analysis to the river basin level analysis and that basin level impacts are not always aggregates of local impacts. The paper therefore has the following objectives: 1) discuss the critical issues in rainwater harvesting not only from a micro perspective from also macro perspective; and 2] the issues for research in water harvesting and recharging.

The paper would try and achieve the following: 1] provide an overview of traditional and modern rainwater harvesting systems in India and four different typologies of RWH in India; 2] discuss the physical--hydrological and meteorological--, socio-economic 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; 3] perform an extensive review of the literature on the performance/impact of rainwater harvesting to examine whether the more pertinent issues have been addressed in the research; and 4] the identify the issues for future research on rainwater harvesting that would help develop a comprehensive understanding of the performance and impact of rainwater harvesting/groundwater recharge systems.

3.0 RAINWATER HARVESTING IN INDIA: AN OVERVIEW

3.1 What is it all about?

The practice of "rainwater harvesting" dates back to ancient times. It is as old as human civilization. Some of the earliest known rainwater harvesting works was practiced in the Middle east, and Egyptian and other African deserts (Prinz, 2002) while recent studies correlating palaeoclimatological evidences and archeological and historical records show strong evidences of heightened human efforts for rainwater harvesting in response to climate change such as drought and aridity starting from as early as 4500 BC in ancient India (Table 1 in Pandey *et al.*, 2003: pp48). It refers to harvesting the raindrops where it falls. India has a long and rich tradition of rainwater-harvesting with different techniques practiced in different parts of ancient India over different time periods.

3.2 Different Techniques of Rainwater Harvesting

3.2.1 Modern Systems

The modern rainwater harvesting systems, which are widely practiced in India include: check dams built often in series across streams, percolation pond/tanks with and without injection wells, "well recharging" also known as aquifer storage and recovery (ASR) wells, sub-surface dykes, anicut, roof top rainwater harvesting systems and hydro-fracturing (Muralidharan and Athawale, 1998). Among these, the most common is check dam. In the past, check dams were constructed to check the speed of flow of water with the aim of mitigating the erosive effect of fast-flowing runoff. They were preferred in regions with steep slopes and high rainfall, and soils highly susceptible to erosion. The hydraulic design of check dams involved the following considerations: the high flood discharge from the catchment, and the high flood level. But, in the recent decades, it was widely promoted as a method of harvesting water in naturally water-deficit regions. Check dams of large size are now built to store water, while allowing overflow. Hence the technical consideration involves the total inflow as well.

Recharge tube wells are less popular in India. While recharge tube wells which work on pneumatic injection were successfully tried and practiced in western California, recharge tube wells which work on gravity injection were first tried in India. It makes use of the hydrostatic head between the low lying water table in depleted aquifers and water level in tanks/ponds

(Raju, 1995). The hydraulic process involved in gravity injection wells is just the reverse of the process involved in conventional tube wells used for sandy aquifers. Another innovative recharge system is sub-surface dyke or dam, used when the river or stream carrying water does not have good embankments that would enable the construction of a surface barrier. It is designed to allow heavy infiltration of water from river/stream bed; provide inter-mediate storage; block the onward movement of water with an impervious layer of plastic; and allow the water to move laterally in the sub-surface strata. This has been successfully tried on experimental basis in many parts of India (Athawale, 2003: pp90-92), and successfully in coastal villages of Kachchh (Raju, 1995).

Dug well recharging is a simple method of recharging the shallow aquifers using the runoff from small local streams, fields and drains. The runoff is collected in small sedimentation boxes, and then diverted to the dug well using a cement or plastic pipe (Kumar *et al.*, 1999; Shah, 2000). The open well used in ASR process is normally one which is also used for abstracting water from the aquifer. This method makes use of three important local advantages: 1] the large storage capacity available with open dug wells; 2] easiness in diverting water into the well; and 3] the presence of fracturing and weathering in the geological strata, which enables easy movement of water through the formation.

Dug well recharging was first tried out by farmer leaders in Rajkot district of Saurashtra peninsula in Gujarat during the severe drought of 1985-87. No standard hydraulic design had been evolved for this method of recharging (Kumar *et al.*, 1999; Shah, 2000). However, this is one of the most popular recharge techniques gained acceptance in Orissa, Karnataka, Tamil Nadu and Madhya Pradesh (MP) because of the hard rock nature of geology and presence of open wells.

Percolation ponds and tanks are widely used in hard rock areas of peninsular and western India (Muralidharan and Athawale, 1998). It is provided with waste weir to allow surplus water to flow downstream. The technical consideration involved in its design is inflow volume estimated from the catchment characteristics and precipitation, high flood discharge for designing the waste weir. Sites with high density of geological structures such as lineaments and dykes are selected for construction of percolation tanks to enable vertical movement of water from the pond/tank. Most of the percolation tanks and ponds, which are being built today, are however, renovations of the age-old surface storage tanks that were either used for irrigation, and domestic purposes.

Bandharas (tidal regulators) are structures built to serve two major functions: 1] stop ingress of seawater into the rivers and streams during high tides; and 2] stop freshwater outflow into the sea during monsoon. It helps prevent seawater ingress; and build up freshwater in the coastal aquifers to prevent landward movement of freshwater/seawater interface. They are common in coastal Saurashtra, built under the programme of salinity ingress prevention. Roof rain water harvesting systems (RRWHS) were used in the part in desert region of Rajasthan and arid areas of Gujarat for centuries. During the past few years, they are popular among NGOs as an alternative source of drinking water in urban as well as rural areas facing water stress (Kumar, 2004).

3.2.2 Traditional Systems

Some of the traditional water harvesting systems, which are in vogue, are *Pal* found in north western Rajasthan, *haveli* system found in MP, *Johads* in Alwar district of Rajasthan (north west), *Anicuts* in South Rajasthan, Tanks in peninsular India, *Talav* (ponds) in Gujarat, *Khadins*, Nadi and Kund in the Thar desert in western Rajasthan, Lakes in South Rajasthan, *Ahar-pine* system in South Bihar, and *Tankas* found throughout the arid parts of Rajasthan and Gujarat. These apart, there are innumerous water harvesting systems found in other parts of the country, especially the north eastern tribal regions (see Agarwal and Narain (1997) for details).

From a functional view point, these systems can be classified as: those directly harnessing rainwater; those harnessing runoff; and those harnessing soil moisture. The *tankas* connected to roof top directly harvest rain water; some others, capture the runoff from artificial (lime treated) catchments); *talavs* and ponds are natural depressions that capture runoff (sometimes sheet runoff) from the nearest small catchments. The *pals* are long earthen bunds constructed on private land and capture runoff from several small streams originating from the nearby hill slopes. The stored water is used for watering the crops in the fields lying at higher elevations during the rainy season, where as the soil moisture in the submerged area is used for growing crops in winter.

Khadins are low height earthen barriers constructed across streams passing through fields. They store water in the stream bed, which subsequently form the crop-growing area (Kolarkar *et al.*, 1983). The *Ahar-pine* is a method of *in situ* water harvesting for paddy cultivation found in South Bihar; helps store water in soil profile at the end of a slope and u/s of a field bund. Both are runoff harvesting systems[3], where runoff water is stored in the soil of the crop growing area. *Anicuts* are check dams, constructed across narrow gorges in undulating terrain, without spillways, common in the hilly areas of Udaipur, Dungarpur of Banswara districts of South Rajasthan. *Johads* are low height earthen bunds that harness the runoff from several small streams originating from hill slopes in the Aravalli hills in Rajasthan. The water stored in these structures is used only for livestock drinking. The length of the bund can vary widely depending on the nature of the valley. They do not have spillways for safe passage of the overflow water.

3.3 Typologies of Water Harvesting

Rainwater harvesting as a major initiative started in two Indian States, viz., Gujarat and Rajasthan nearly two decades ago as a response to a growing water problems, some of which are: recurring droughts; widespread problems of groundwater over-draft; deterioration of groundwater quality caused by seawater intrusion; shortage of economically accessible water resources, all resulting in scarcity of water for irrigation and drinking.

The regions which are engaged in water harvesting can be put under four typologies. First typology of regions are those in which water demand for irrigation was exceptionally high but supplies from local sources were getting exhausted due to unsustainable levels of use to meet the excessive demands. These regions are also highly drought-prone. Examples are Saurashtra, Kachchh and north Gujarat in western India and parts of peninsular India covering many areas of Tamil Nadu, Karnataka and Andhra Pradesh. These regions also experience acute shortage of drinking water, during summer, even in years of good rainfall.

Second typology of regions are those in which the overall demand for water is low due to low level of dependence on irrigated farming as a source of livelihood. An example is north western Rajasthan where communities practice subsistence farming with rain-fed crops, and indigenous cattle herds. But, there is paucity of resources with the communities to access the

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[3] Systems where the runoff from barren catchments is either stored and used in or directly diverted to a nearly cropland. It requires a relatively large labour input and land requirement. The runoff area has sufficiently high runoff coefficient; the "run-on area", where the accumulated water is stored and or utilized, has high infiltration rate, and a high storage capacity.

local groundwater to meet various subsistence needs including livestock and human drinking[4] in this socio-economically backward region (Sharma, 2002). The water use priority in these regions is domestic and livestock drinking, which demand low volumes of water at the aggregate level. Example is Alwar district in Rajasthan. This region has seen a lot of efforts at rainwater harvesting using donor funds involving local communities.

There are a third category of regions, which are rain-rich, such as central India covering parts of Gujarat (eastern), Madhya Pradesh, Chattisgarh, Jharkhand and Maharashtra. These regions have highly undulating topography. The water endowment is poor due to excessive runoffs flowing out of the region, poor groundwater storage, and erosion of top soil resulting from poor vegetation and lack of soil and water conservation measures. Historically, there has been a gradual shift in livelihoods in this region from one which is forest-based to one which is based on farming, owing to erosion of forest resources. Need for water to stabilize agricultural production is high in this drought-prone region; though the level of use is poor due to backwardness. Access to cheap irrigation facilities can help farmers enhance kharif production and take winter crops (Phansalkar and Verma, 2004). Water harvesting and watershed management programmes have been undertaken in these regions with government and donor funds to augment surface water storage, increase groundwater recharge and conserve soil moisture, thereby improving agricultural production and drinking water security.

There is a fourth category of regions that are water-rich and agriculturally prosperous, and have high water demands for agriculture and other uses. It includes the exceptionally high rainfall region of Chirapunji and monsoon-rich Kerala. But, a large percentage of the water demand for agriculture is met through rainfall from South west and South east monsoon, with minimum dependence on irrigation. But the past few decades had changed the water use hydrology of Kerala. Farmers have shifted from paddy that heavily harness monsoon rains *in situ* and also recharge groundwater systems, to perennial crops such as banana, coconut and other plantation crops that use rainfall in small proportions, but largely depend on irrigation water (Down to Earth, 2004: pp 26-34). Even these regions face occasional droughts. These droughts play havoc in these densely populated regions as they abruptly boost water demand for crop production and domestic uses, thereby upsetting water-supply demand balance. It has become common phenomenon in Kerala for farmers to invest in small water harvesting structures for managing additional water to irrigate their high-valued plantation crops. Communities have also started harvesting rainwater using RRWHS for meeting their domestic needs, with major government sponsored water literacy programmes launched.

For a long time, rainwater harvesting programmes were mainly concentrated in semi-arid and arid parts of western India, with remarkable NGO initiatives (Shah, 2000a: pp 200-203). According to Shah, it became a movement in Saurashtra peninsula, catalyzed and spear-headed by religious and spiritual institutions (Shah, 2000a: pp 201). But, over the past one decade, it has spread to southern peninsula and central India with local water harvesting and groundwater recharge programmes being taken up by state governments in MP, Orissa, Tamil Nadu and Andhra Pradesh on inspiration from these western states, and with community and NGO support. Of late, the movement has also spread to the historically water-rich Kerala as an aftermath of the droughts in 2002. However, it is worth noting that the "spread of adoption" has not followed any general pattern, vis-à-vis the typologies we have explained here.

4. CRITICAL ISSUES IN RAINWATER HARVESTING

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[4] Though it is being argued by the agencies which work in this region that the scarcity of water is mainly caused by perennial rivers becoming ephemeral due to large-scale deforestation.

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] there is a huge amount of monsoon flow, which remain un-captured and eventually ends up in the natural sinks, especially seas and oceans, supported by the national level aggregates of macro hydrology; 2] local water needs are too small that exogenous water is not needed; 3] local water harvesting systems are always small, and therefore are cost effective; 4] since the economic, social and environmental values of water is 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.

4.1 Lack of Emphasis on Local Water Demand and Potential Supplies

Two important assumptions in RWH are: 1] there is significant monsoon flow which goes un-captured and joins the natural sinks; and 2] local water harvesting systems are sufficient to take care of local water needs. It ignores a few critical parameters that govern the potential of RWHS in meeting local water demand. First is the hydrological regime of the region/locality, comprising the rainfall--magnitude, pattern and intensity--and evaporation. Second is the reliability of the supplies, governed by the reliability of rainfall. Third is the constraint imposed by local geological and geo-hydrological settings on the recharge potential. Fourth is the aggregate demand for water from various sectors within the local area.

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

- For runoff harvesting, the rainfall has to exceed a threshold to generate runoff, though the threshold would vary according to the nature of soils and land cover. The estimated run off based on regression equation arrived at from observed flows in Hathmati sub-basin of Sabarmati basin ($R=0.00193*X^{2.022}$) in western India (source: GOG, 1994) shows that for the runoff to cross 100mm, the minimum rainfall required is 682 mm. Whereas in the case of Kabani sub-basin of Cauvery, runoff starts when the rainfall crosses 366 mm. The regression equation for Kabani estimated by 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).

- 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 larger magnitude of annual rainfall means more number of rainy days and smaller magnitude of annual rainfall means less number of rainy days spread over the rainy season (Pisharoty, 1990). The examples of Gujarat further illustrate this (see Kumar, 2002b; Kumar, 2004). Lesser rainy days also means longer dry spells and thus greater losses from evaporation for the same region.

- High intensity rainfalls are common in semi arid and arid regions of India (Garg, 1987 as cited in Figure 24; Athawale, 2003). Higher intensity of rainfall can lead to high intensity runoff occurring in short durations, limiting the effective storage capacity of rainwater harvesting systems to almost equal to its actual storage size.

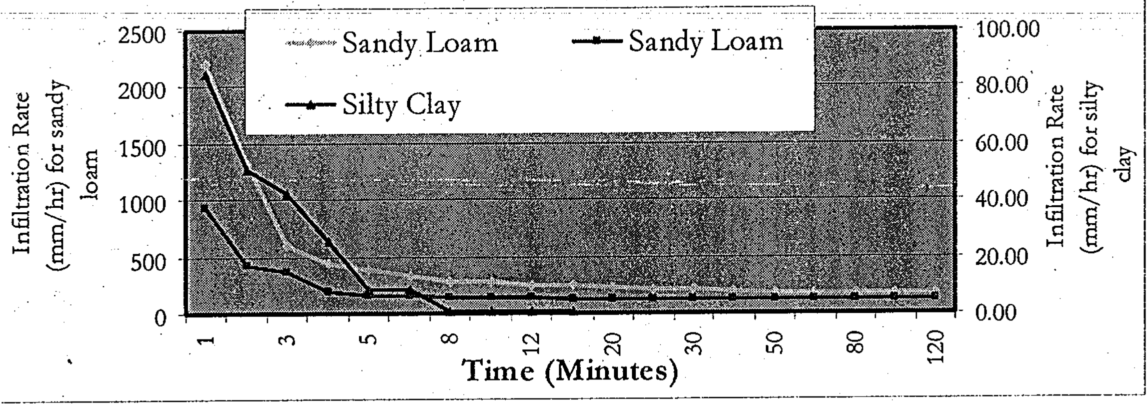
- High evaporation during rainy season means losses from surface storage structures. It also means faster rate of soil moisture depletion through both evaporation from barren soils and evapo-transpiration, increasing the rate and quantum of soil infiltration thereby reducing the runoff generation potential. Among the seven locations in Gujarat for which PET data are available, the PET during monsoon (June to September) varies from a lowest of 543mm in Vadodara to 714mm in Rajkot. As percentage of annual PET, it varies from a 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, the value of PET during monsoon ranges from 433mm 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 PET in Sawaimadhupur to a highest of 49.3% in Anupgarh (GOR, 1992). Among the 10 locations selected along Narmada basin in Madhya Pradesh, the values range from 429mm to 600mm, with it as a percentage of total PET ranging from 31.3% in Betul to 35% in Mandla (source: GOMP, 1972).

- Soil infiltration capacity can be a limiting factor to recharge. In sandy and sandy loam soils, the infiltration capacity of the recharge area can be improved through continuous removal of soils where as in clayey soils, there is an inherent limitation. The graph in Figure 1 shows the infiltration rates obtained from short term infiltration test carried out in dug wells in Andhra Pradesh in two different soil conditions. It shows 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 negative affect the recharge efficiency of percolation ponds. As thin soil cover reduces infiltration (Muralidharan and Athawale, 1998), the extent of the problem would be larger when we consider the fact that in hard rock areas (ideal for percolation ponds), soil cover is thin. Dickenson (1994) based on several infiltration studies shows that 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 flash floods and high evaporation rates, solutions for which would be wetting or drying of pond beds through 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 geological formation characteristics, and the likely depth of 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 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.

Figure 1: Infiltration Rate in Sandy Loam and Siltyclay Soil at the botton of dug well



The implications of some of these factors on the potential of rainwater harvesting systems are analyzed in the following two sections, i.e., 4.1.1 and 4.1.2.

4.1.1 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 deep-rooted belief that higher the size of water impounding structure, higher 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 of 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 high "runoff catchment area" to "run on" area ratio (Lalljee and Facknath, 1994), this is also ignored. Higher the aridity, 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 programmes 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, 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 (<300mm, 300-600mm, and 600-1000mm, 1000-1500mm, 1500-2500mm and >2500mm); and different PE regimes (< 1500mm, 1500-2500mm, 2500-3500mm and >3500mm). It is understood that regions with relatively low rainfall have higher potential evapo-transpiration due to relatively low humidity, higher 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). The analysis shows that Gujarat and Rajasthan have 11% and 42% area, respectively, fall under extremely low rainfalls (< 300mm); and 39% and 32%, respectively under low rainfall (300-600mm). The other states by and large fall in the medium rainfall (600mm-1000mm) and high rainfall (1000-1500mm) regimes. In the case of Maharashtra, MP, AP, Karnataka and Tamil Nadu, a lion's share (85% and above) falls in medium rainfall regime, and in case of Orissa and Chattisgarh, 45% and 40% respectively fall in high rainfall regime (see Map 1).

As regards PE, lion's share of Gujarat and Rajasthan fall under high evaporation (2500-3000mm); nearly 35-56% of the geographical area of other states (except Orissa and Chattisgarh) fall under high evaporation regimes; the area of these states falling in the medium evaporation regime (1500-2500mm) is in the range of 38-65%. The entire Orissa and Chattisgarh fall in medium evaporation regime. Overall, a large section of the area (of the 9 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).

Table 1: Rainfall and PE Regimes of States Having Water Harvesting Programmes

Name of State	% Area with Rainfall below						% Area with Evaporation (PE)			
	<300 mm (very low)	300-600 mm (low)	600-1000 mm (medium)	1000-1500 mm (High)	1500-2500 mm (Very high)	>2500 mm (Extremely High)	<1500 mm (low)	1500-2500 mm (medium)	2500-3500 mm (high)	>3500 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. Higher the magnitude of PET during monsoon, higher will be the negative impact on hydrological variables such as surface storage and recharge. While it reduces surface storage through evaporation, higher PET during 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 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 3 to 7 (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 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 per cent experience "low variability" in rainfall (see Map 3). They coincide with "medium rainfall-medium to high evaporation", "low rainfall-very high evaporation" and "high rainfall- medium evaporation" regimes, respectively.

It can be seen from Map 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 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). Higher the variability in rainfall, lower would be the reliability of local water harvesting/recharge systems. This is because chances of occurrence of low rainfalls and extremely low runoff would be higher under such circumstances, and at the same time, the demand for water would be high due to environmental stressed caused by poor soil moisture storage, low runoff and high temperature.

Table 2: Rainfall Variability Regimes of States Having Water Harvesting Programmes

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

In the third step, we analyze the average number of rainy days and its variability across regions. We attempt to find out the percentage of geographical area of each region, falling under different rainy day (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 regions which experience monsoon rains in a fewer days. To elaborate: nearly 21% of Gujarat and 45% of Rajasthan state 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 1/3rd of both the states receive 30-40 days of rain. As regards the states 3-7, 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 the states receive 50-75 days of rain in a year. To sum up, the regions which receive fewer days of rain (erratic rains) coincide with those experiencing low rainfall and high evaporation and high variability in rainfall. The regions which experience many wet days coincide with those which experience high and reliable rainfall and medium evaporation (see Map 1, 2, 3 and 4).

Table 3: Distribution of Rainy Days in States Having Water Harvesting Programmes

Name of State	% 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

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: the inter-annual variability in rainfall increases with reducing rainfall; the number of wet spells reduces with lowering magnitude of rainfall; the PE increases with lowering magnitude of rainfall. The implications of this trend on the potential of water harvesting in a region needs to be understood. Lower the rainfall, coupled with higher potential evaporation and inter-annual variability in rainfall and fewer rainy days, lower would be the potential of water harvesting. This is due to the following processes. First: the runoff potential by and large would be low in low rainfall regions with 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.

4.1.2 Limitations Imposed by Socioeconomic System

Water harvesting arguments totally misses on the water demand-availability perspective at micro level. Ideally, the RWHS would work if the area which has uncommitted flows to harness has "un-met demand" or vise versa. This is unlike large water resource systems where provisions exist for 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 which were heavily into irrigated agriculture in the past, supported by good water endowments, institutional support and favourable policies, might continue demand 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. In fact many of the water-scarce regions that are practicing water-harvesting had adopted highly water-intensive socio-economic production systems.

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 corps is 25.42 MCM. The entire water requirements in the village were 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). Now Kachchh has a surface water potential of 0.014 MCM/sq. km (IRMA/UNICEF, 2001). Going by this figure, the amount of runoff water that would be available for replenishment through natural process and artificial systems from within the village is only 0.40 MCM, as substantial amount of water is used up in evaporation from barren soils and evapo-transpiration from the rain-fed crops. 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.

Less rigorous analyses are available for 15 villages from semi-arid Saurashtra and arid Kachchh, which are facing groundwater over-draft problems (Table 4). All these villages depend fully on groundwater for all uses. Table 4 shows the total annual water use is far higher than the total groundwater recharge in 14 out of the 15 villages. In six villages, it is close to or even more than the rainfall. It is understood that the only a fraction of the total rainfall is available in the form of groundwater and surface runoff for various consumptive uses after leaving aside water for evapo-transpiration from the rain-fed crops and evaporation losses from the barren land. The surface runoff potential estimated on the basis of the average runoff potential for these two regions (source: IRMA/UNICEF, 2001) shows that it would be a small fraction of the total consumptive use in all the villages. Therefore, local runoff will not be adequate for harvesting.

In a village named Manund, in Patan district in the alluvial plains of north Gujarat, which has seen widespread water harvesting activities through de-silting of ponds, the total groundwater abstraction for agriculture alone was estimated to be 3.78 MCM (or 275mm column of water over the entire village), with 35 deep tube wells pumping water at a rate of nearly 15000 gallons per hour for nearly 1500 hours a year (Kumar, 2000b). The village represents general groundwater socio-ecology of north Gujarat region. Against this, the total amount of rainfall over the village is only 7.56 MCM, with a mean annual rainfall of 550mm over an area of 1374 ha. The runoff which this amount of rainfall can generate is 63.8mm as per the rainfall runoff relationship (for Hathmati sub-basin of Sabarmati), 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 chunk of the runoff generated from the crop land, which falls in catchment, *in situ* for crop production, unlike large basins with good part under virgin catchments. Kumar (2000) estimated the groundwater over-draft in the village as nearly 247.5mm 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 per cent of the over-draft.

Table 4: Estimated Village Water Balance for 15 Villages from Saurashtra and Kachchh

Name of Village	Total Water Use (MCM)	Total Groundwater Recharge	Extent of Over-draft	Total Rainfall (MCM)	Total Runoff
Lusadi	1.875	0.549	341.3	2.210	0.347
Rampara	0.201	0.277	72.70	1.114	0.175
Moti Pipala	1.165	0.319	364.8	1.285	0.202
Nana Pipala	0.496	0.176	281.0	0.710	0.112
Samdhiyala	5.850	0.676	864.0	2.722	0.428
Moti Kherali	4.296	1.035	414.9	4.165	0.655
Nani Kherali	1.412	0.484	291.8	1.947	0.306
Khari	1.066	0.356	299.0	1.434	0.225
Bharaptana	3.640	0.849	428.6	3.416	0.537
Vadjar	0.305	0.232	131.5	5.811	0.232
Tappar	1.067	0.334	318.6	8.374	0.335
Kanajra	1.206	0.131	916.3	3.291	0.132
Talwana	2.973	0.236	1259.0	5.905	0.236
Pipri	1.147	0.064	1796.3	1.596	0.064

Gundiyali	25.096	0.406	6266.3	10.144	0.406

Sources: authors' own estimates based on Kumar (1997) and IRMA/UNICEF (2001)

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 in this category. The region has enormous amount of groundwater stock, with deep alluvial aquifers, apart from having high rainfall and cold humid climate that generate sufficient surface flows. Cheaper access to water might increase the demand for irrigation water slightly, but there are significant limits to it imposed by the cold and humid climate and very low per capita arable land and therefore would continue to be below what the water endowment can provide (Shah 2000b; Kumar, 2003). Already, the irrigation intensities (gross irrigated area/gross cropped area) are high in Uttar Pradesh and Haryana (Table 5). Though irrigation intensity in Bihar is just below that of Tamil Nadu, the state lies in semi-humid and cold climate, reducing the irrigation requirement significantly, whereas Tamil Nadu has semi arid climate. In most part of this region, the issue is not of the physical availability of water, but the ability of communities to access it for irrigation, which is the major user (Kumar, 2003; Shah, 2000b). Water harvesting anyway does not offer any economic solution here for the poorer communities to access water.

Table 5: Percentage Irrigated Area in 18 Indian States

Name of State	Percentage Area irrigated	Name of State	Percentage Area irrigated	Name of State	Irrigation Intensity
Madhya Pradesh	22.27	Gujarat	28.93	Assam	14.99
Maharashtra	15.27	Bihar	43.21	Haryana	83.38
Uttar Pradesh	64.06	Orissa	25.75	Kerala	13.58
Rajasthan	29.06	Tamil Nadu	49.51	Jammu Kashmir	41.11
Andhra Pradesh	39.82	West Bengal	28.70	Himachal Pradesh	17.54
Karnataka	23.90	Punjab	94.95	Tripura	13.04

Source: based on data provided in Table 3.20 in GOG 1999: pp 56

4.2 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 lack of emphasis on "cost" (per cubic metre of water harvested) 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, its pattern, 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 the vital data at the micro level on hydrological parameters such as daily rainfall, soil infiltration rates, catchment slopes, land cover and PET which determine the potential inflows; and evaporation rates that determine the potential outflows. Further for small water harvesting project, implemented by local agencies and NGOs with small scale investments, the cost of hydrological investigations and planning is hard to justify.

That said, the amount of runoff which 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 depends on the pattern of its occurrence. 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 flood. Many parts of Kachchh, which records one of the lowest mean annual rainfalls (350 mm) and runoffs (0.014 MCM/sq. km as per IRMA/UNICEF (2001)), had experienced flash floods during 1992 and 2003 with many structures overflowing. Flash flood occurs even in some of the water scarce basins such as Sabarmati and Banas, which experience semi-arid climate (Kumar, 2002b). If the entire runoff occurs in a major rainfall event, the runoff collection efficiency[5] would reduce with reducing capacity of the structures built. If large structures are built to capture high intensity runoff thereby increasing the runoff collection efficiency, that would mean inflating cost per unit volume of water captured. In fact, authors such as Oweis (1999) and Hachum and Kijne (1999) have argued that runoff harvesting should be encouraged in arid area 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 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 the effective storage, unit costs are worked out on the basis of the design storage capacity of the structures and standard norms 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 thumb rule to evaluate the cost effectiveness of 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 of water harvesting in different regions of India, does not deal with economics 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 the level of watershed and river basins. 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 proportional increase in the hydrological benefits (Kumar, 2000a), as interventions in the upper catchments reduce the potential hydrological benefits from the lower systems. What is important is the net increase in 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 cost angle when compared against the additional benefit it brings in.

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 higher (see Figure 2). The reason being: 1] higher the degree of basin development, 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 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

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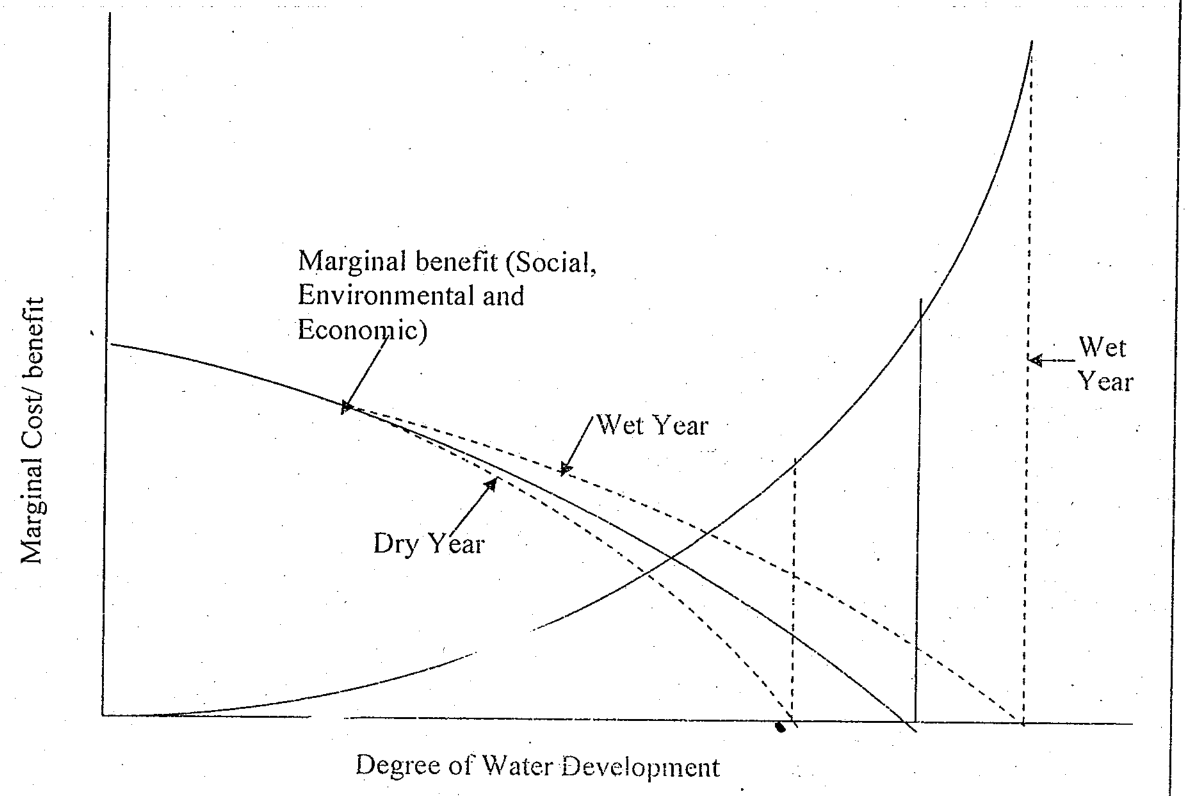
[5] Defined as the ratio of the runoff captured and the total runoff generated in the up stream catchment.

wet year or 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 starts accruing, reducing the overall benefits. Here, O is the optimum level of basin development.

Figure 2: Marginal Cost and Benefits of Water-harvesting with different degrees of Basin Development



Now the ability to derive economic benefit of recharge depends on where the recharged water ends up. In regions underlain by hard rock geology, the groundwater flow patterns are quite complex. Often, the benefits are 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 which invest in the recharge system do not get the benefit (Moench and Kumar, 1993). In certain other situations, the recharge water could end up in natural sinks such as saline aquifers, and seawater, more particularly in the case of coastal areas. This is an issue which reduces the ability of NGOs and communities in making water harvesting and groundwater recharge projects bankable.

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 volumetric recharge benefits, the value of the use to which the additional water is put is extremely important in determining the incremental value of economic benefits, an issue often totally ignored in the planning of water harvesting projects. 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, 2002). The available extra water harvested from monsoon rains should therefore be diverted to supplementary irrigation in drought years.

There are regions where human and cattle drinking become high priority demands, especially during the peak of summer. 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 its use 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 maximum value from the added water is largely missing in water harvesting efforts.

4.3 Lack of Integrated Approach

In many river basins, the surface water systems and groundwater systems are often interconnected. Any alterations made in one of them could change the availability of water in the other (Sohiquilo, 1985; Llamas, 2000). In many hilly areas, especially in western Ghat and north eastern hilly regions, the groundwater contributes significantly to the stream flows downstream during lean seasons due to the steep groundwater flow gradients. 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 cumulative percolation (Kumar, 2002b). It was found during the recent years that the rivers in this region do not carry any runoff till the lower reaches even in years of normal rainfall. In the first case, any water harvesting intervention to store water underground may not make much sense as it would get rejected and appear as surface flows. In the second case, any interventions to storage water on the surface would be ineffective.

In certain cases, the storage capacity of groundwater system itself poses a major constraint to water harvesting/recharge. This issue is critical for India, as 2/3rd of the country's geographical area is underlain by hard rock formations comprising crystalline rocks and lava flows of basalt formations. Most parts of water-scarce states, viz., Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, Orissa, Chattisgarh and Tamil Nadu are underlain by hard rocks ranging from basalt, crystalline granitic rocks, hill aquifers and sandstone. A small areas in Gujarat has extensive alluvium, Narmada valley and (Cambay basin) (see Map 5). The hard rock aquifers have no primary porosity and have only secondary porosity due to the fractures, weathered zones, fissures and dykes. The constraints imposed by hard rock geology in recharge efforts through percolation tanks are: high depth to water table below and around the recharge structure due to occurrence of recharge mount and shallow bed rocks, which prevent percolation of water (Muralidharan, 1990 as cited in Muralidharan and Athawale, 1998). Given the low specific yield values (0.01-0.03), during monsoon, sharp rise in water levels is observed in the underground formation, leaving little space for incoming flows from recharge structures. While harnessing water for recharge is extremely important during normal and wet years so as to create buffer for drought 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: pp30), 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 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 small fraction of the surplus runoff. In such situations, proper water use programming is required to achieve effective utilization of the available surplus water, where in water from aquifers is pumped out and used during the rainy season itself thereby creating storage space for the incoming flows (Shah, 2002). Similar opinion was made by Muralidharan and Athawale (1990), which argues that utilization of the recharge water from the vicinity of the structure is critical to sustaining the percolation rates.

4.5 Trade off between Local Vs Basin Impacts in Closed Basins

Due to 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 planning of conventional water development projects is based on dependable yields from the catchments, the plans for WH which happen subsequently 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 which are concerned with small water harvesting (in the upper catchment) and those which are concerned with major head- works are different and they do not act in coordinated fashion at the level of the basin. Building of small water harvesting systems such as tanks, check dams is often the responsibility of minor irrigation circles of 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).

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. Some of them are Pennar, Cauvery and Vaigai in the South (based on GOI 1999: pp 472-477), and Sabarmati, Banas in the west, which are closed. In addition to these, all the west-flowing rivers in Saurashtra and Kachchh in Gujarat are also closed (Kumar, 2002). While Krishna basin is on the verge of closure, some of the basins which are still "open" are Godhavari and Mahanadi in the east (based on GOI 1999: pp 466-469).

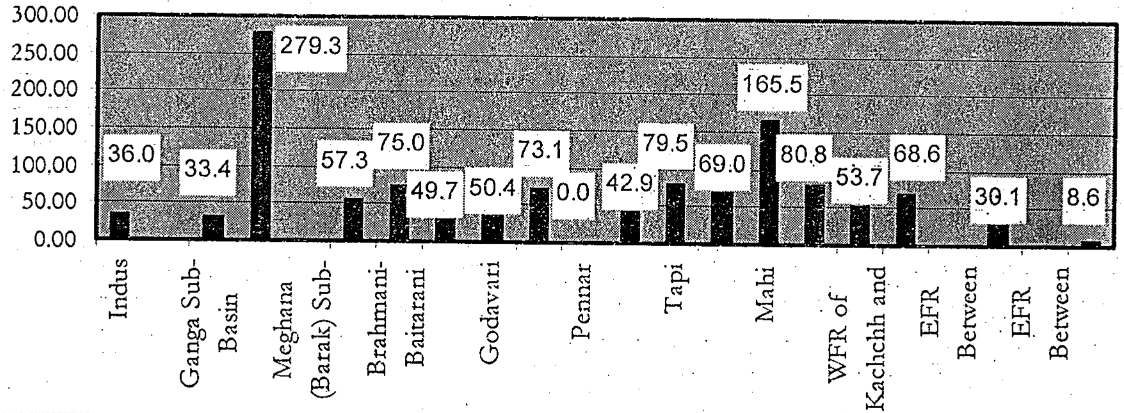
Sabarmati basin, for instance, having a drainage area of 21,678 sq. km, has a utilizable surface flow of 1513.4 MCM allocated to Gujarat (Kumar and Singh, 2001), where as the total live storage capacity of irrigation schemes built in the basin, estimated to be 1470 MCM (GOI, 1999) is still slightly below 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 1560 MCM as per Kumar and Singh (2001)) leaving no spill over. At the aggregate level, the basin is over-appropriated. At the sub-basin level, the scenario is different. Two of the sub-basins, viz., Dharoi and Hathmati are heavily over-appropriated (Kumar *et al.*, 2000). Still, one of the sub-basins, 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 monsoon season, making the effective water utilization more than the live storage capacity. Figure 3 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 per cent, leaving the impression that there is much more uncommitted flows in the basin for future harnessing. But this is not correct. Take for instance Narmada basin. The total live storage volume of all terminal dam built in Narmada, i.e., Sardar Sarovar, is 5800 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 Sardar Sarovar reservoir. Again the estimates of stage of development do not take into account the reservoirs having live storage capacity of less than 10 MCM.

4.6 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 in section 4.1.1, high inter-annual variability in rainfall is a common phenomenon in most parts of these water-scarce regions. Rainfall variability induces higher degree of variability in runoff. Such high variability is found even in the high rainfall regions as well as low rainfall regions. We take the example of the upper catchment area of Cauvery basin and one of the catchments of Sabarmati River basin in North Gujarat of western India.

Figure 3: Stage of Storage Creation in Some Major River Basins in India



In 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 55.8mm in 1987 to 1583.7mm in 1907. The runoff estimated on the basis of regression equation developed for a sub-basin, named, Hathmati of Sabarmati basin in north Gujarat, which is physiographically quite similar to Palanpur area of Banaskantha, shows that the runoff can vary from a lowest of

0.6mm to 541mm. Thus the lowest runoff is close to 1/1000th of the highest runoff. Though what can occurs at the sub-basin level may not be representative of that in small upper catchments, the difference cannot be drastic. Even for a humid, high rainfall region of Wayanad district in Kerala, the runoff estimated for a small catchment of Karappuzha on the basis of the rainfall-runoff relationship developed for Kabani sub-basin (catchment area of 7040 sq. km) of Cauvery river basin, to which the region falls, and the observed rainfall of the area shows a variation in runoff from 528mm in the lowest rainfall year (2002) to 1458mm 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, highest consideration is given to capturing all the water that is available. If all the runoff which occurs in a high rainfall year is to be captured, then the cost of building the storage system would go up by many hundred times from that required to capture the one which occurs during the lowest rainfall. But, the system would receive water to fill only a small fraction of its storage capacity in the rest of the years. This could make the system cost-ineffective. While the issue of variability is applicable to the design of large head works as well, in the case of large systems, the water in excess of the storage capacity could be diverted for irrigation and other uses in areas which face water shortages during the monsoon season, without providing for storage, thereby increasing the effective storage.

4.7 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 the climatic conditions--such as steep slopes, high rainfall in the mountains, and high humidity--, which provide favourable environment for runoff generation. The upper catchments also provide good source of base flows due to forest cover which causes favourable conditions for water storage and infiltration. On the demand side, these regions generally are less endowed in terms of 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, increasing the aggregate demand for irrigation.

There are numerous examples for this. A few to cite are: the upper catchment of Cauvery basin in the south, Narmada basins in central India, Sabarmati basin in western India, tributaries of Indus in the north western India, Krishna basin in Central India and Mahanadi basin in eastern India. Some parts of Kabani sub-basin of Cauvery river basin have cold and semi humid climate, and parts of this sub-basin receives the second highest rainfall in India after Chirapunji with the mean annual rainfalls crossing 4000 mm. Irrigation demands in these regions are low owing to high precipitation and low reference evapo-transpiration, and low per capita availability of arable land. On the other hand, the lower parts of Cauvery in Tamil Nadu are hit by scarcity of water for irrigation owing to lower rainfalls and high evapo-transpiration.

We have defined the agricultural water demand as a function of per capita net sown area and the ratio of PET and rainfall; and water availability as a function of rainfall. It is assumed that: higher the PET/R ratio, higher would be the irrigation requirement for a unit of land; higher the per capita (rural population) net sown area, higher would be the aggregate demand for irrigation per capita. Table 6 shows the estimated values of two selected agricultural water demand variables, viz., PET/R and per capita arable land; and one water availability variable, i.e., rainfall. Table 5 shows that the irrigation demand is much higher in the lower catchment areas, and availability higher in upper catchments in all these six important basins.

Major water resource/irrigation projects undertaken in the past have been in the upper reaches of these basins which tap the 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). Bakra 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 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: pp 80). Similarly, the large reservoir projects in Cauvery 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.

Table 6: 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	1263.0	1788.8	1.96	2.18	0.14	0.47
Indus	Shimla	Ludhiana	1597.0	525.0	986.60	1698.6	0.62	3.24	0.14	0.25
Narmada	Shahdol	Jhabua	1352.0	792.04	1639.0	2127.0	1.21	2.69	0.35	0.35
Cauvery	Wayanad	Nagapattianan	3283.0	1337.0	1586.9	1852.5	0.48	1.39	0.18	0.13
Krishna	Raigarh	Guntur		1029.0		1785.9		1.74	0.13	0.22
Mahanadi	Raipur	Puri	1388.0	1440.0	1667.0	1667.0	1.20	1.16	0.18	0.06

UCD: Upper catchment district; LCD: Lower Catchment District

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

More over, 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 comparing the economic value of water in agriculture between water-scarce and land-rich western Punjab and water-rich and land-scarce eastern Uttar Pradesh showed that the value of water realized from irrigation is much higher in Punjab (net value product from every unit of water used for irrigation) than in eastern UP. The economic value of water was Rs. 14.85/m^3 of water in western Punjab, where as it was Rs. 11/m^3 in eastern UP. Due to scarcity of water, the farmers in Punjab use better economic use of water by choosing cropping systems that are economically more efficient and doing agronomic practices to obtain higher yields, higher physical productivity and economic efficiency (Kumar, Malla and Tripathy, 2005).

But, often water harvesting initiatives, especially those by NGOs, are driven by considerations other than economic efficiency, most important of which are social equity and environmental justice. Impounding water in the upper catchments might serve 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 which reduce the downstream uses should be done with due consideration to the net change in "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 the basin's water resources meet. The amount of water to be captured upstream through RWH interventions should also be optimized to derive maximum 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 one low valued use to a high valued use.

5.0 CRITICAL ISSUES FOR RESEARCH ON RWH IN INDIA

5.1 Issues Emerging from Past Research

In the past, there have been several research studies which attempted to analyze the local and regional impacts of local water harvesting/recharge schemes. The research papers dealt with the following key questions: [1] the physical performance of recharge structures; 2] how much the recharge structures actually contribute to groundwater availability in a region?; [3] what is the socioeconomic impact of increased water availability?; [4] does water harvesting help alter the water balance from a river basin perspective?; [5] what are the second generation issues in water harvesting?; [6] is water harvesting an elixir for farmers, or are they engaged in a process of creative destruction?; and [7] what are the unintended impacts of rainwater harvesting, particularly on the water use hydrology of small catchments.

The Central Ground Water Board (CGWB) and the National Geophysical Research Institute (NGRI) had carried out several studies to analyze the performance of different types of recharge structures in different locations in India. CGWB carried out artificial recharge experiments in Mehsana district in alluvial area of north Gujarat using injection and surface spreading method, in coastal Saurashtra using injection and spreading basin methods (in 1983); Ghaghar basin of Haryana. NGRI carried out recharge experiments using siphon principle in Anantapur district of AP, artificial recharge and retrieval studies in Nagpur area; recharge experiments conducted on percolation tank beds in Anantapur; artificial recharge experiments using wastewater carried out by Physical Research Laboratory in Sabarmati river bed are the most significant of them (see Muralidharan and Athawale, 1998 for details). In the Mehsana experiment, a high rate of intake of 156.25 litres per minute was achieved in injection method and 180.56 litres per minute (17 cm/day) in spreading method.

The injection recharge experiment in Haryana showed a rate of intake of 40 litre per second of water into the aquifer and established favourable conditions for recharge. The NGRI's experiment in 1986 conducted with siphon method of recharging involved a single bore well. It showed a recharge rate of 30-40 litres per minute. Experiments with in tank recharge bore hole carried out failed to quantify the volume of recharge. Recharge measurements in percolation tank bed with sandy loam soils and granitic bed showed no recharge in five out of 8 tanks and very low rates in the rest three, in spite of existence of fractures (source: Muralidharan and Athawale, 1998). The study attributed this phenomenon to the shallowness of the basement, existence of shallow water table both in the tank bed and immediate area (source: Muralidharan, 1990 as cited in Muralidharan and Athawale, 1998).

Palanisamy and others evaluated the economic impact of 10 percolation tanks from Coimbatore and Avinashi districts of Tamil Nadu. It found that only 14% of the wells in the vicinity were benefited by the tanks, with a total area of 14.4 ha and average additional income at tank catchment ranging from Rs.1323/ha to Rs.2736/ha. The analysis did not involve the cost of the tank structures and was based on one-year data. The study attributed the poor economic performance of the tanks to inadequate rainfall in the particular year and improper tank location (Palanisamy and Kandaswamy (1990) as cited in Muralidharan and Athawale, 1998).

A 1997 study on dug well recharging in Saurashtra showed that a recharged dug well can increase the well yield equivalent to an additional area of 0.80 acres of onion (Kumar *et al.*, 1999; Kumar 2000a). Further, the study contended on the basis of regional hydrological data that increase in number of recharge structures would not lead to proportional increase in physical benefits. The paper argued that the surplus water available within a region, in a particular year, being constant, and so long as we do not alter the hydrological balance, the total amount of water that could be captured, is fixed. This means, increase in number of recharge structures beyond a certain number will lead to re-distribution of physical gains.

Badiger *et al.* (2002) made a quick evaluation of the variety of physical and socioeconomic impacts of the *pal* systems built by PRADAN in northeastern Rajasthan on the basis of studies carried out in four micro watersheds. These watersheds fell in the large watershed of Mewan in Mewat region of Alwar district. The *pal* project of PRADAN used a combination of field bunds, field leveling, and *pals* in a comprehensive manner to rejuvenate groundwater in the area.

The study found significant reductions in depth to water level in wells from season to season after the water harvesting interventions. For instance, the study showed that the number of wells, which recorded such reduction ranged from 5 to 10 in different watersheds. The study argued that the recharge caused by the *pal* systems continues even after the rains; the post monsoon recharge component is larger than the recharge during the monsoon. Further, water levels in the wells continued to rise till mid November in the artificial recharge conditions, while under the normal conditions, water levels start receding by the end of September. The study quantified the additional recharge from the *pal* system as 3-8 per cent of the rainfall based on estimates of total abstraction, total storage change in the aquifer, and natural recharge from rainfall. The study found that after the water harvesting interventions, the value of irrigated land rose by Rs.50, 000 to Rs. 75,000 per hectare.

Patel (2002) evaluated the various hydrological and hydro-chemical aspects of recharge systems such as percolation tanks, check dams and dug well recharging in three different geological settings, namely, miliolite limestone, gaj limestone, and weathered basalt rock. The different hydrological aspects of artificial recharge system studies were development and decay of recharge mount, recharge rates, and radius of influence of recharge structures. The hydro-chemical aspects are changes in total dissolved solids and fluoride content of groundwater. The study involved actual measurements of some parameters governing the physical impacts of recharge structures.

The study found that the rate of development and decay of recharge mount vary according to variations in geological settings. It also established that the recharge rates are far higher in the case of percolation tanks and check dams, which are periodically de-silted than those not de-silted. The recharge rate estimated for a normal percolation tank was 7.87 mm/day while that for a de-silted percolation tank was 20.4 mm/day. Accordingly, the recharge-evaporation ratio was found to be much higher for the de-silted percolation tank (4.2) against 1.83 for the normal percolation tank. Further, the radius of influence of percolation tank was found to be varying across geological formations. The study established recharge equations for these structures for both de-silted and normal conditions using time as a dependent variable.

Sharma (2002) examined the drought proofing impact of water harvesting structures, namely, *johads*. The study area was located in a macro watershed having a drainage area of 503 sq. km., and focused on a village, Hamirpura. The study found that with the construction of *johads*, the water levels in 9 out of the 34 wells in the village have shown remarkable changes as compared to that in rest of wells during all three seasons. Based on some empirical data of irrigation water rates for wheat, the paper argued that increased water availability led to increased pumping, therefore leaving no water for drought years. He further argued that the isolated examples of income impact of recharge structures were probably because of over-appropriation through a large number of structures. A first cut analysis of the basin level impact of water harvesting structures on water balance of Arvari watershed provided an optimistic figure of 18 MCM and a pessimistic figure of 9 MCM of water as potential recharge, respectively, with potential income impact of Rs.135 per capita per annum in the most optimistic case and Rs. 67/capita per annum in the pessimistic case.

Shah (2002) examined the socio-economic and livelihood impacts of water harvesting structures in Saurashtra. The study found a higher rise in static water levels during the monsoon (1-2 metres) of year 2001 as compared to the long-term average rise. It estimated the additional recharge because of water harvesting structures in the entire Saurashtra region as 1.00-1.50 km^3 per annum. The paper argued that with improved water availability in the wells, farmers hired more labour. After the water harvesting interventions, the number of farmers using hired labour for 0-3 person months a year decreased from 85 to 45, while those using 13-16 person months increased from 18 to 38.

The study found substantial increase in outputs from three major irrigated crops viz., cotton, wheat, and groundnut--resulting from increased use of inputs such as fertilizers, labour and irrigation water. The major contribution of the study was with regard to the attitudinal changes in farmers who are engaged in recharging their own wells. It found that wherever groundwater recharge activities had produced results, there was a shift in the mindset of farmers. Farmers are increasingly realizing the fact that water needs to be "generated", planned and husbanded. Further, water harvesting ensures security of kharif crops, leading to overall welfare of the region.

The findings of the empirical studies can be summarized as follows: 1) percolation tanks in hard rock areas have poor recharge rates, 2) siphon method shows good recharge effects; and 3) artificial recharging using injection method is effective in deep alluvium. There is differential impact of water harvesting structures built in the same physical setting and that the nature of impact of water harvesting structures depends on the method of treatment and types of recharge structures. Such differences could be attributed to the differential nature of treatments adopted. The other findings are as follows. Geology plays an important role in deciding the rate of development and decay of recharge mount and the radius of influence of recharge structures. The positive physical impact of water harvesting structures also leads to rise in land value. Last, wherever groundwater recharging has produced positive results, there is increasing realization among the farmers of the fact that water needs to be "generated", planned, and husbanded.

Finally, the technical studies on performance and impact of water harvesting/recharge are based on individual systems in local areas, and do not take into account the scale effects of large-scale work in a hydrological system context, which is mainly on the overall availability of water for recharging. The reason is simple. A major drive obtained for artificial recharge programmes in India was the experiment done in a semi arid area (see Athawale (2003)), which showed higher observed runoff rates for smaller catchments, and reducing runoff rates with increasing catchment size (Boughton and Stone, 1985). Extension of the findings of this experiment beyond its geographical boundaries assumes that the reduction in runoff rate is only due to loss of water into the natural sink or evaporation, and incremental structures at micro catchment level gives proportional increase in hydrological benefits by preventing this loss. Such an outlook can lead to serious over-estimation of net hydrological benefits, as actually a significant portion of runoff vertically moves down to join the aquifers. This seems to have influenced the engineering research on water harvesting and recharge. Such engineering research carried out in micro catchments also ignores the presence of large water-impounding structures in downstream catchments, thereby overestimating the potential of water harvesting systems.

As regards the impact studies, analyses of rainfall data for a large number of stations in Gujarat and Narmada basin in MP show that the coefficient of variation in rainfall increases as mean annual rainfall reduces (Kumar 2002b; Kumar, 2004). There are enough empirical evidences now available to show that the hydrological impact of water harvesting interventions in areas, which experience higher variability in the rainfall, would be highly non-uniform over a time horizon, resulting in poor social impacts. Therefore, in future, it is important to study situations under different rainfall regimes--high, medium and low, and in typical rainfall years-wet, dry and normal--, to generate comprehensive and useful insights on impact of water harvesting and draw policy inferences.

Batchelor and others (2002) carried out a study in a tank catchment in Karnataka to analyze how various physical and socioeconomic processes in catchments affects the water use hydrology of catchments. This is the first study of its kind in India looking at the unintended impacts of water harvesting/watershed development. Their water balance estimates for the tank catchment showed that evapo transpiration (including non-beneficial evaporation) in the catchment increased six fold during 11 years, which has been possible by construction of wells and water harvesting structures. It also showed reduction in inflows into the irrigation tanks downstream to an extent of nearly 40%, where as the tank irrigators resorted to well irrigation. They argued that increased groundwater pumping for irrigated cropping and increased water impoundment through building of water harvesting structures such as check dams and nulla bunds in the agricultural watershed upstream.

A limitation of the study is that it could not estimate the relative contribution of the two above mentioned factors to inflow reduction. It also did not analyze the groundwater-surface water interaction to establish the effect of increased groundwater pumping on surface flows. Further, it was not clear whether the study took into account the historical changes in infiltration rates due to changes in cropped land, where as it is known that increased cultivation would also increase the *in situ* water harvested.

5.2 Issues for Future Research

The question often asked amongst water resource scientists and practitioners is "are there limits to local/decentralized water harvesting?" The potential impact of local water harvesting on large water systems is central in the ongoing debate on decentralized water harvesting. This is because many of the water harvesting projects are underway in the upper stream of large storage systems. Kumar (2000a) argued on the basis of regional data on the hydrological balance that increase in number of water harvesting structures in Saurashtra would not result in incremental benefits. Similarly, Sharma (2002) argued, on the basis of water balance assessment for the watershed, named, Arvari in Alwar district of Rajasthan that widespread construction of water harvesting structures across a watershed/basin would result in "thinning" of hydrological and economic benefits. However, some water resource scientists argue that the small structures complemented the large water storage systems by preventing siltation. But, this will be true if one is concerned about the life of large water systems being threatened by siltation.

The fact remains that the potential downstream hydrological impacts of new water harvesting structures in a basin would depend on the degree to which the runoff in a basin is harnessed. In a "closed basin", the construction of new structures would lead to dividing the hydrological/economic benefits (Frederick, 1993). Again, the same basin can be open in a high rainfall year, while closed in a low rainfall year owing to variations in the runoff. The type of impacts, which the new water harvesting structures makes on a large water system in a basin, depends, therefore, on the rainfall in a particular year. Today, village is the basic unit for planning local water-harvesting interventions, and the scale of interventions is decided by the drainage density and the presence of favourable topography. This should be replaced by a "basin-wise" planning, based on robust water accounting exercises to estimate the surplus runoff in typical years, considering typical rainfall years.

"Cost and economics of water harvesting" also pose serious concerns. Many researchers have recently argued that in regions of high inter-annual variability in rainfall and rainy days, water harvesting could produce very limited impact on a time scale (Kumar 2002a; personal communication with Shaktivadivel, Senior Fellow, IWMI). Moench and Kumar (1992) have also argued that harvesting runoffs of low reliability and flash floods, which are characteristics of arid and semi-arid regions, would be prohibitively expensive, resulting in higher cost per cubic metre of water. Several of the recent scientific debates on water harvesting have centered on the constraints imposed by hydrological uncertainty and their implications for technical feasibility, reliability, and economic viability of local water harvesting systems (Kumar, 2004). The recent report of Gujarat Ecology Commission on hydrological regime of Gujarat (see Kumar, 2002b) analyzed how hydrological uncertainty becomes a constraint to supply-side interventions in water management. Analysis of economics of water harvesting should be marginal returns at the basin level rather than local returns to capture the scale effects.

Finally, in an era of greater environmental consciousness and increasing public pressure against building of large dams, decentralized water harvesting is increasingly being advocated as the sustainable alternative from the ecological point of view. The underlying assumption is that large water resource systems such as major and medium reservoirs cause negative ecological and environmental impacts in the up stream as well as the downstream areas (Rangachari *et al.*, 2000). But, there has been little empirical research to understand the ecological consequences of local water harvesting, as they could further reduce the environmental flows, if carried out extensively, in basins that have very little uncommitted flows. A study of tank systems in Sri Lanka's Anuradhapura district by IWMI showed that for tank systems to be feasible for irrigation, the tank surface area should be less than 1/8th of its catchment area (Sakthivadivel, 1997). But there could be instances, where water harvesting upstream results in groundwater replenishment. Outflows from aquifers upstream into the streams could result in increased lean season flows downstream making positive environmental effects, particularly in mountainous regions.

6.0 MAJOR FINDINGS

Following are the major findings emerging 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 offers extremely limited potential in terms of its ability to reduce the demand-supply imbalances and provide reliable supplies in water scarce regions. The reason being: a] significant part of these regions (states 1 and 2) are characterized by low mean annual rainfalls, high inter-annual variability in rainfall, with high potential evaporation and larger share of evaporation occurring during rainy season, reducing the 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 such as sandstones. The percolation tanks, the most preferred recharge structures, are likely to have low efficiency in these hard rock areas and also 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 lack of integration of groundwater and surface water use. In these regions, planning of recharge schemes should consider surface water impoundment of all the available excess flows, than direct recharge. This should be followed by water use programming to create underground storage for incoming surface flows. However, this is not followed.

- Many water-scarce regions have water demands which far exceed the supplies, with vulnerability to hydrological stresses, that 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.

- 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. Further, higher in degree of basin development, higher will be the marginal cost and lower would be the marginal benefit.

- The basins which experience high inter-annual variability in the stream flows are many and cover significant areas in India. In such basins, the trade off between hydrological impacts of water harvesting and economic benefits is likely to be large. With increasing storage capacity of RWH systems, the economic viability becomes poorer as the average cost of water harvesting per unit volume of water increases.

- In "closed basins", there is apparent trade off between local benefits and downstream benefits. U/S diversions reduce the prospects of storage and diversions systems d/s. 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 immediate future would join this category of river basins.

- In many important basins, there is an apparent trade off between maximizing overall benefits for basin communities in terms of enhancing the gross value 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 northwestern India, Cauvery and Krishna in the southern Peninsula, Narmada in central India and Sabarmati basin in western India.

- Extensive review of existing literature on RWH shows that the past studies did not involve "scale considerations" in analyzing the physical and economic impacts of water harvesting. The scale considerations should include both space and time. "Space considerations" are important as water harvesting only follows large water development projects in many river basins in India. "Temporal considerations" are important almost everywhere due to high inter-annual and inter-seasonal variability in rainfall and erratic nature of monsoons.

- The major issues for future research in water harvesting include: 1] potential impacts of water harvesting on large water resource systems in basins that have undergone high degree of water resource appropriation; 2] optimal level of water harvesting/degree of water development in different river basins that averts unintended downstream impacts; and 3] ecological and environmental impacts of water harvesting in terms of reduction in environmental flows, or increase in lean season flows in different hydro-ecologies.

7.0 PRACTICAL SUGGESTIONS FOR EFFICIET WATER HARVESTING

7.1 Enhancing Knowledge of Catchment Hydrology

In water harvesting, what is most understood and widely known are the technologies for water harvesting and mechanism of working. But what is least understood is the catchment hydrology. Very little is known about the rates of runoff from small catchments, and how it varies over the years. Most small rivers in India are not gauged for assessing stream flows and siltation. Example is Narmada river basin. It has a total of 56 gauging sites of which 25 collect data on siltation load. Silt load is an important variable which influence the performance and life of water harvesting systems. Data on siltation rates are often available for large reservoirs from siltation studies done by Central Board of Irrigation and Power (CBIP). But applying this to small catchments can lead to either under-estimation of siltation rates as siltation rates are generally high for hilly upper catchments. On the other hand, applying runoff coefficients and rainfall-runoff relationships of large basins for small upper catchments would most likely result in under-estimation of runoff, as small upper catchments would normally have steeper slopes.

Though runoff data can be generated for streams which otherwise are not gauged, through runoff modeling, scientific data on hydrological parameters such as soil infiltration rates, land use characteristics, catchment slopes are essential to arrive at reliable results. This is still a major challenge in India.

7.2 Research to Focus on Green as well as Blue Water

The central focus of any rainwater harvesting project in India is about capturing the excess water which flows out of the domain of interest, storing and subsequently diverting it for beneficial uses. But, green water is an important component of the hydrological system and the harvested water in many RWH systems such as tanks, *Khadin*, percolation pond and *Johad*. The focus has never been on improving the efficiency of utilization of this green water, though in watershed development projects, efforts are made to produce biomass in wastelands that tap some of the soil moisture which otherwise is lost in non beneficial ET. By efficiency of utilization, we refer to the fraction of the total green water that is converted into beneficial ET; and its physical and economic productivity. For any basin, it is crucial to know how much of the total precipitation falling on the basin is available as green water and how much of it gets used up in crop production; how much of it is lost in non-beneficial evaporation from the soil. Technological interventions such as mulching and zero tillage can be introduced.

In high rainfall regions like Kerala, the utilizable surface water resources are much less in comparison to the runoff generated. Here, effective strategies to capture runoff in situ for crop production through proper land use planning--including increasing area under paddy--, would help improve green as well as blue water use, and alter the hydrology positively.

7.3 Basin Water accounting and Water Balance

For any water scarce river basin in India, water accounting is the first and the most important step to begin with before planning any water harvesting and recharge project. It is important to know whether the basin has any surplus flows, which goes into the natural sink--oceans, saline aquifers--, or significant amount of water that is lost in evaporation from natural depressions. This can be followed by water balance studies to examine what percentage of the water could be captured by conventional water harvesting interventions without causing negative effects on the downstream uses including downstream storage/diversions. Needless to say, such studies both water accounting and water balance should be carried out for typical rainfall years so as to capture the variability in runoff. This is because the amount of water that can be captured upstream would be normally high in a high rainfall year. Such water balance studies that cover time horizons can provide critical inputs to basin-wide water resource planning for optimal water harvesting to ensure sound economic viability.

7.4 Wet Water Saving

In river basin which experience high aridity during the summer months, such as those in western Rajasthan, north and western parts of Gujarat, eastern Orissa, most parts of Andhra Pradesh, North Karnataka and most of Tamil Nadu, the water stored in surface impoundments such as tanks, pond and other small reservoirs can lead to heavy losses through evaporation. If this is prevented, it can lead to wet water saving, through increase in output per unit of evaporated water. Directly diverting the harvested water from the RWH system to the crop land is critical in maximizing the net hydrological gain, especially in areas with poor groundwater storage or areas experiencing high inter-annual variability in runoff (Oweis, Huchum and Kijne, 2002). Allocation of blue water harnessed to rain-fed crops to avoid moisture stress during critical stages of crop growth would increase the yield crops remarkably (Seckler, 1996), thereby increasing the productivity of green as well as blue water.

8.0 CONCLUSIONS

In India, in some of the most water-scarce regions, rainwater harvesting and groundwater recharge offer limited potential in regions where it is required, owing to very low surplus runoff potential, poor reliability of occurrence of runoff, high evaporation and excessively high water demand for agriculture. In many other regions, which have medium rainfalls, but experience "medium to high evaporation", the poor groundwater potential of hard rock which underlie these regions pose a constraint for recharging. Economic evaluation of water harvesting systems poses several complexities due to the problems in quantifying the hydrological benefits, and the economic value of various benefits. Economics of water harvesting cannot be worked out for structures on the basis of individual benefits, but on the basis of incremental benefit, when there is limited surplus water in a basin. 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 distribution of hydrological benefits, rather than augmentation. There is an optimum level of water harvesting which a basin can undergo which can help maximize the gross value product of water vis-à-vis economic, social and environmental outputs. Large-scale local water harvesting in the upper catchments of many Indian basins would lead to sub-optimal economic benefits.

Some areas for future research are: 1] potential impacts of water harvesting on large water resource systems in basins with various degrees of water resource development; 2] optimal level of water harvesting/degree of water development in different river basins that averts unintended downstream impacts, but maximize the gross value product of water; and.3] ecological and environmental impacts of water harvesting in terms of reduction in environmental flows, or increase in lean season flows in different hydro-ecologies. From the point of view of action, the following steps seem to be important to make water harvesting more efficacious: 1] developing a better understanding of catchment hydrology; 2] developing basin water accounting and water balance; 3] focusing on wet water saving; and 4] enhancing the productivity of green water in the basin.

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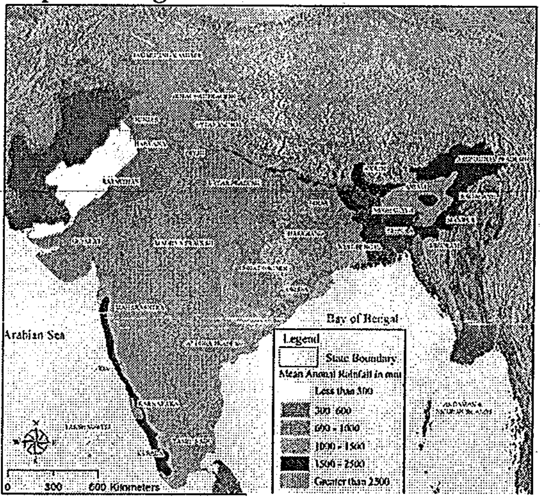
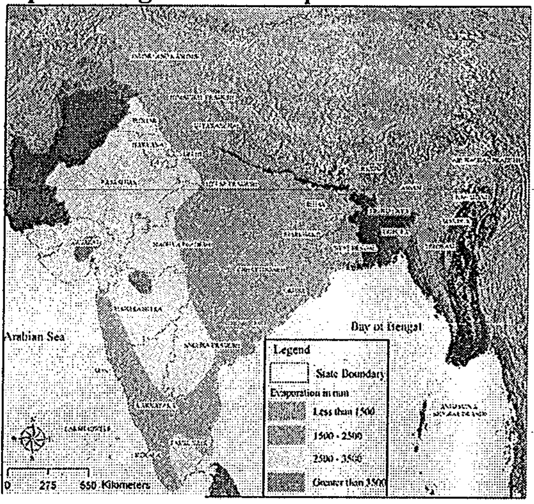
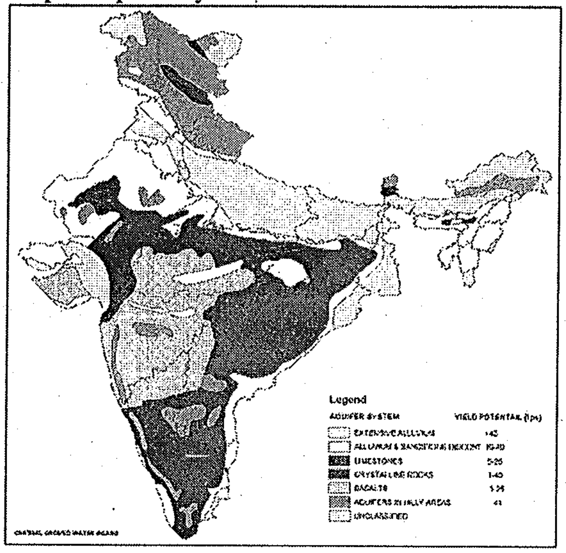
Map 1: Average Mean Annual Rainfall



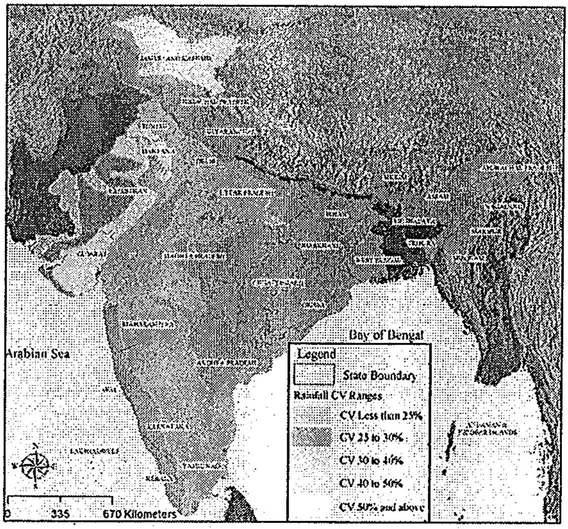
Map 2: Average Annual Evaporation



Map 5: Aquifer System in India



Map 3: Average Coefficient of Variation of Rainfall



Map 4: Average Rainy Days