Land Use and Water Resources Research

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 consequent hardships faced by both urban and rural communities, India has invested heavily in rainwater harvesting. Unlike investment in large water resource systems, these efforts, by and large, lack hydrological planning and sound economic analysis: research on the impact of local water harvesting/groundwater recharge activities in India is very sparse. This paper identifies six critical issues in rainwater harvesting efforts in water-scarce regions of India. First: there is no emphasis on potential local supplies and the demand they have to cater for: local supply potential is low in most water scarce regions, a fact compounded by poor reliability, and demand far exceeds the supply potential. Second: there are complexities in the 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 maximising hydrological benefits and improving cost effectiveness. Fourth: many water-scarce basins are characterised by wide disparity in demand between upper catchments and lower catchments, so that there is a trade-off in maximising benefits of upstream water harvesting with optimising basin-wide benefits. Fifth: in many water-scarce basins, local water harvesting merely divides the hydrological benefits rather than augmenting them. Finally, poor integration between surface water and groundwater systems, and lack of inclusion of natural recharge, ultimately leads to reduction in potential for artificial recharge in hard rock areas.

Introduction

India has a long tradition of water harvesting. Many of the traditional water harvesting systems have either fallen into disuse due to a variety of physical, social, economic, cultural and political factors which have caused their deterioration, 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 fact that different periods in history are marked by the genesis, rise and fall of some new water harvesting tradition (Pandey *et al*., 2003), is also not appreciated.

In this paper, the term rainwater harvesting structures refer to all small structural interventions to impound excess runoff from agricultural fields and runoff from small natural catchments (0.01 – 100 km^2), either for direct use by humans and cattle or for aquifer recharging. They do not include roof water harvesting systems that capture water from artificial catchments, or large dams and diversion head-works that harness water from large catchments.

Water harversting in India has boomed during the past two decades in two markedly different ways from the traditional techniques. They can now use recent advances in soil, geosciences and hydro-sciences, plus modern-day techniques and technologies in survey and investigation, earth moving and construction. While the traditional techniques represented the best engineering feats of the times, in terms of water technology used for water harnessing and distribution (Agarwal and Narain, 1997) and the volume of water handled, modern water harvesting systems are at best miniature versions of the large water resource systems that use advances in civil engineering and hydrology.

The limited Indian research on rainwater harvesting (RWH)/artificial recharge so far has focused on the engineering performance of individual structures (Muralidharan and Athawale, 1998). While much anecdotal evidence 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 have raised questions of the possible unintended impacts of water harvesting (Bachelor *et al*., 2002), and its economics (Kumar, 2004). One of the reasons for the paucity of empirical research on the hydrological and economic aspects of water harvesting systems is the inability to generate accurate scientific data on hydraulic, hydrological and meteorological parameters that govern the performance and impact of water harvesting. Analysis of water harvesting systems also misses the influence of the 'scale factor'.

Here, we do not try to analyse the physical performance or hydrological impacts of water harvesting by taking a different approach. We begin with the basic premise that scale considerations are important in analysing the impact of water harvesting, i.e. one has to move from analysis at the local level to the river basin level and that basin level impacts are not always aggregates of local impacts. The paper therefore has the following objectives: (1) to discuss the critical issues in rainwater harvesting not only from a micro perspective but also a macro perspective; and (2) to present the issues for future research in water harvesting and recharging.

Critical issues in rainwater harvesting

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

Lack of emphasis on local water demand and potential pupplies

Rainwater harvesting 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. 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 recharge potential. Fourth is the aggregate demand for water from various sectors within the local area. Some basic hydrological phenomena, which make these 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, a threshold which varies according to the nature of soils and land cover. The estimated runoff based on the regression equation derived from observed flows in the Hathmati sub-basin of Sabarmati basin ($R=0.00193*X^{2.022}$) in western India (*source*: GOG, 1994) shows that for the runoff to exceed 100 mm, the minimum rainfall required is 682 mm, while in the Kabani sub-basin of Cauvery, runoff starts when the rainfall exceeds 366 mm[1]. However, actual runoff rates depend on the strength of the correlation between rainfall and runoff in a given basin, and this relationship weakens if year-to-year changes in rainfall intensity and pattern are major.

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

- Generally, a larger magnitude of annual rainfall means a greater number of rain days and a smaller magnitude of annual rainfall means less rainy days spread over the rainy season (Pisharoty, 1990); examples from Gujarat illustrate this further (see Kumar, 2002b; Kumar, 2004). Fewer rainy days also mean 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 rainfall can lead to high intensity runoff occurring in short durations, limiting the effective storage capacity of rainwater harvesting

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

systems to almost equal actual storage size.

- High evaporation during the rainy season means losses from surface storage structures. It also means a faster rate of soil moisture depletion through both evaporation from barren soils and evapotranspiration,decreasing the rate and quantity of soil infiltration. This reduces runoff generation potential. Among the seven locations in Gujarat for which ET_0 (reference evapotranspiration) data are available, ET_0 during monsoon (June to September) varies from a low of 543 mm in Vadodara to 714mm in Rajkot. As a percentage of annual ET_0, it varies from 33% in semi-humid Surat to 37.3% in Bhuj, Kachchh (*source*: authors' analysis based on data from IMD, Ahmedabad). In the case of Rajasthan, ET_0 during monsoon ranges from 433 mm in the hill station of Mt. Abu to 967.7 mm in Jaisalmer in the Thar Desert. In percentage terms, it varies from 32% of the total annual ET_0 in Sawaimadhupur to 49.3% in Anupgarh (GOR, 1992). Among the ten locations selected along the Narmada basin in Madhya Pradesh, the values range from 429 mm to 600 mm, as a percentage of total ET_0 ranging from 31.3% in Betul to 35% in Mandla (*source*: GOMP, 1972).

- Soil infiltration capacity can be a limiting factor for recharge. In sandy and sandy loam soils, the infiltration capacity of the recharge area can be sustained through continuous removal of soils. But clayey soils have inherent limitation. Results obtained from short-term infiltration tests carried out in dug wells in Andhra Pradesh in two different soil conditions show that the infiltration rate becomes negligible (< 0.60 mm hr^{-1}) within 10 minutes of starting the test in the case of silty clay, whereas infiltration stabilises at a rate of 129.1 mm hr^{-1} within the first 25 minutes in the case of sandy loam (NGRI, 2000). If the infiltration rate approaches to zero fast, it will negatively affect the recharge efficiency of percolation ponds. As thin soil cover has low infiltration potential (Muralidharan and Athawale, 1998), the extent of the problem would be larger in hard rock areas (ideal for percolation ponds) with thin soil cover. Based on several infiltration studies, Dickenson (1994) shows that the rate of infiltration declines to a minimum value within 4-5 days of ponding. This will also have adverse effects on the performance of structures built in areas experiencing 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 the dewatered zone.

- In hilly catchments, 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, yet the surface water potential for harnessing is generally low due to the lower rainfall, and low runoff coefficients owing to gentle slopes, high PET and deeper soil profiles.

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. There is a deep-rooted belief that the greater the size of the water impounding structure, the higher will be the hydrological benefit in terms of water storage and recharge. Part of the reason for this misunderstanding is the lack of data on streamflows 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, 1999), this is also ignored. The higher the aridity, the larger would be the required catchment area to the cropped area 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, Rajasthan, Maharashtra, Tamil Nadu, Karnataka, Andhra Pradesh (AP), Madhya Pradesh (MP), Orissa and Chhattisgarh. 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 1000 m^3 of renewable water per annum (Gupta, 2000: pp 116). Now let us look at the hydrological regime existing in these states.

The percentage area of each state falling under different rainfall regimes (<300 mm, 300–600 mm, 600–1000 mm, 1000–1500 mm, 1500–2500 mm and >2500 mm); and different PE regimes (<1500 mm, 1500–2500 mm, 2500–3500 mm and >3500 mm) has been analysed (data from Pisharoty, 1990). It is assumed that regions with relatively low rainfall will have higher potential evapotranspiration due to relatively low humidity and a 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, falling under extremely low rainfall (< 300 mm); and 39% and 32%, respectively under low rainfall (300–600 mm). In the case of Maharashtra, MP, AP, Karnataka and Tamil Nadu, a lion's share (85% and above) falls in the medium rainfall regime (see Figure 1). As regards PE, most of Gujarat and Rajasthan have high evaporation (2500–3000 mm), as does nearly 35–56% of the geographical area of the other states (except Orissa and Chhattisgarh) with 38–65% falling in the medium evaporation regime (1500–2500 mm). Orissa and Chhattisgarh fall entirely in the medium evaporation regime. Overall, a large section of the area (of the nine states considered) has medium rainfall, and medium to high evaporation (see Figure 2).

We then analysed the proportion of the geographical area from each of these states falling under different rainfall variability classes such as >25%, 25–30%, 30–40%, 40–50% and >50%, and the different percentage of PE occurring during monsoon. Analyses showed that more than 50% of

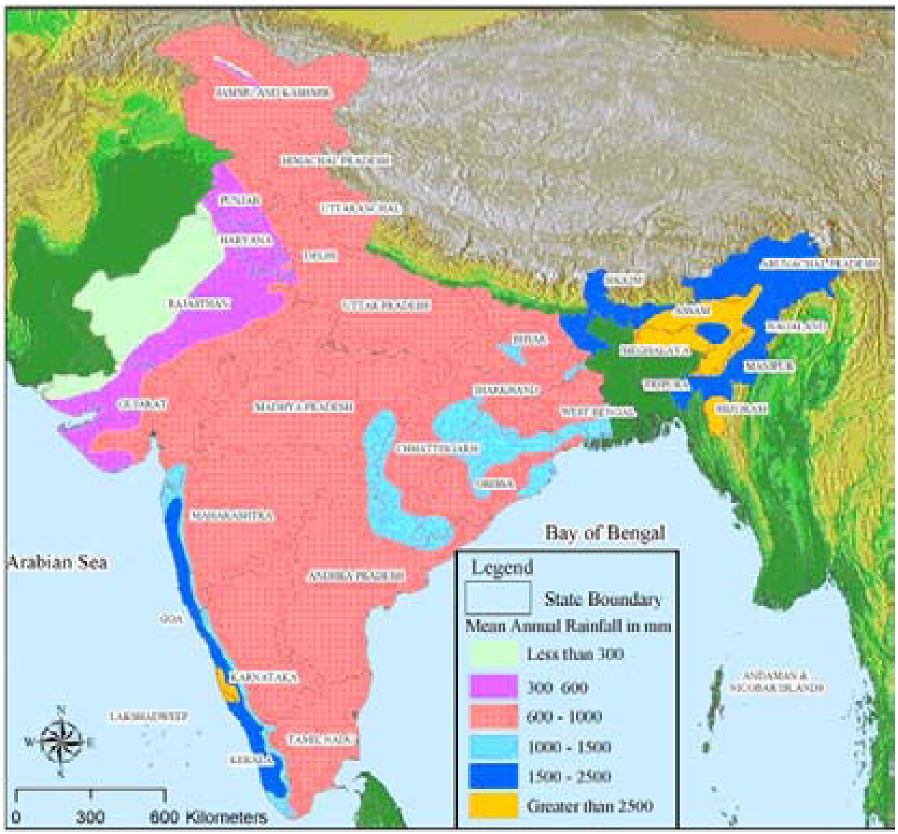

Figure 1. Average mean annual rainfall: prepared on GIS platform based on data from Pisharoty (1990)

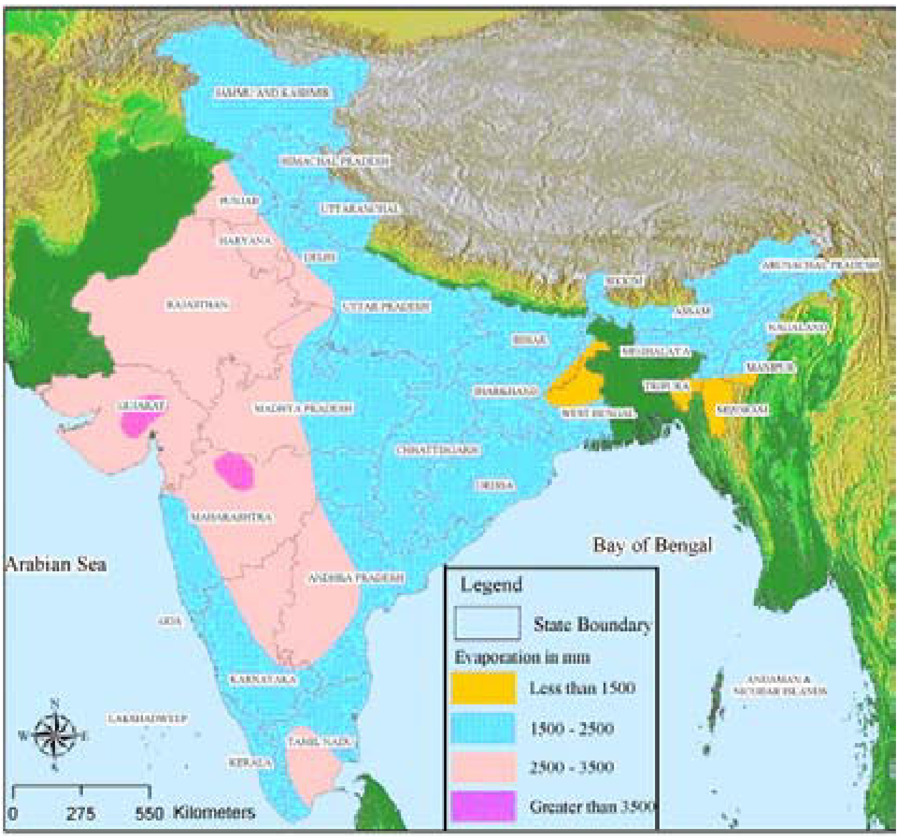

Figure 2. Average annual evaporation: prepared on GIS platform based on data from Pisharoty (1990)

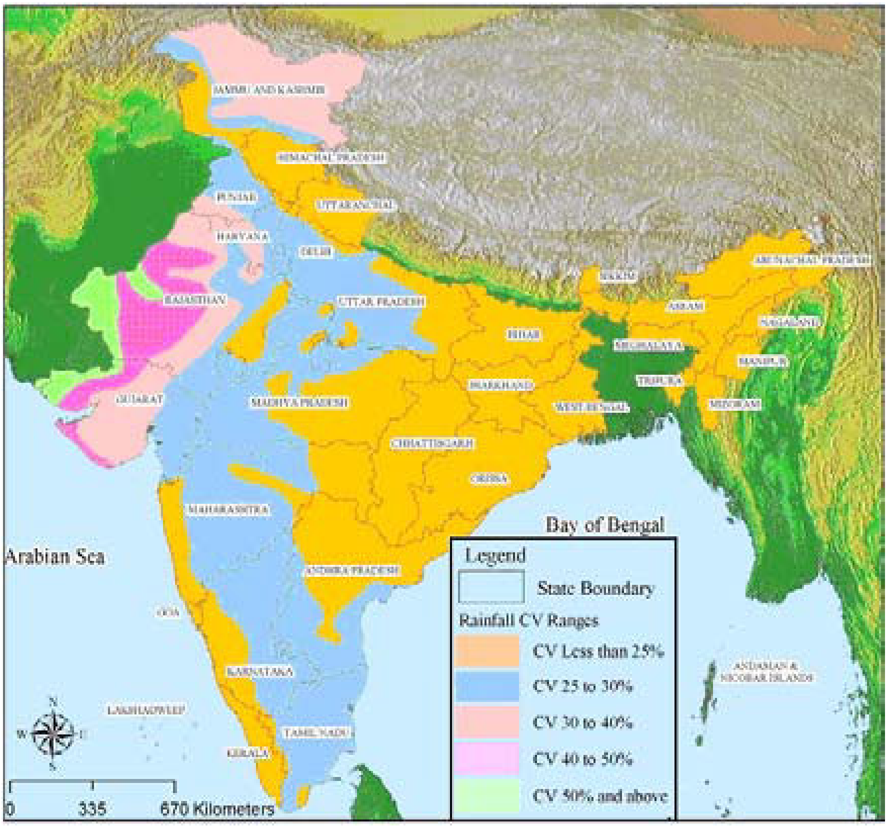

Figure 3. Average coefficient of varaition of rainfall: prepared on GIS platform based on data from Pisharoty (1990)

the total geographical area of all the states put together experience medium variability, nearly 25% experience 'high to very high variability' and nearly 20% experience 'low variability' in rainfall (see Figure 3). They coincide with 'medium rainfall–medium to high evaporation', 'low rainfall–very high evaporation' and 'high rainfall– medium evaporation' regimes, respectively.

Synthesising readings from Figures 1, 2 and 3, regions with high rainfall variability coincide with those with low magnitudes of rainfall and high PE, which also have a high dryness ratio. In such areas, a slight variation in precipitation or PE can substantially change the water stress on biological systems as compared with humid regions (Hurd *et al*., 1999). The higher the variability in rainfall, the lower would be the dependability of local water harvesting/ recharge systems. This is because the chances of occurrence of low rainfall and extremely low runoff would be higher under such circumstances, while the demand for water would be high due to environmental stress caused by poor soil moisture storage, low runoff and high temperature.

In the third step, we analysed the average number of rain days and its variability across regions. We attempted to find the percentage of geographical area of each region falling under different rain day regimes (say <20, 20–30, 30–40, 40–50, 50–75 and >75 days). We also analysed the implications for the magnitude of rainfall in each rainfall event and the maximum and minimum daily rainfall under different rainfall regimes.

The analysis shows that nearly 21% of Gujarat and 45% of Rajasthan state receive less than 20 days, nearly 51% of Gujarat and 70% of Rajasthan fall in areas which experience less than 30 days and nearly one-third of both states receive 30–40 days of rain a year. As regards the other five states, the area which receives 30–40 rain days 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). Both Orissa and Chattisgarh receive 50–75 days of rain in a year.

Synthesising the results of the spatial analysis of rainfall, PE, rainfall variability and number of rain days that are provided in Figures 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 for water harvesting in low rainfall regions would be: (1) the runoff potential by and large would be low due to a high dryness ratio; (2) evaporation from surface storage would be high due to high PE; and (3) the probability of occurrence would be low.

Limitations imposed by high water demands

Water harvesting arguments totally miss out on the water demand–availability perspective at the micro level. Ideally, RWHS would work if an area which has uncommitted flows to harness has an 'un-met demand' or vice versa. This is unlike large water resource systems where provisions exist for transfer of water from areas of surplus 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 technologies available for accessing them and

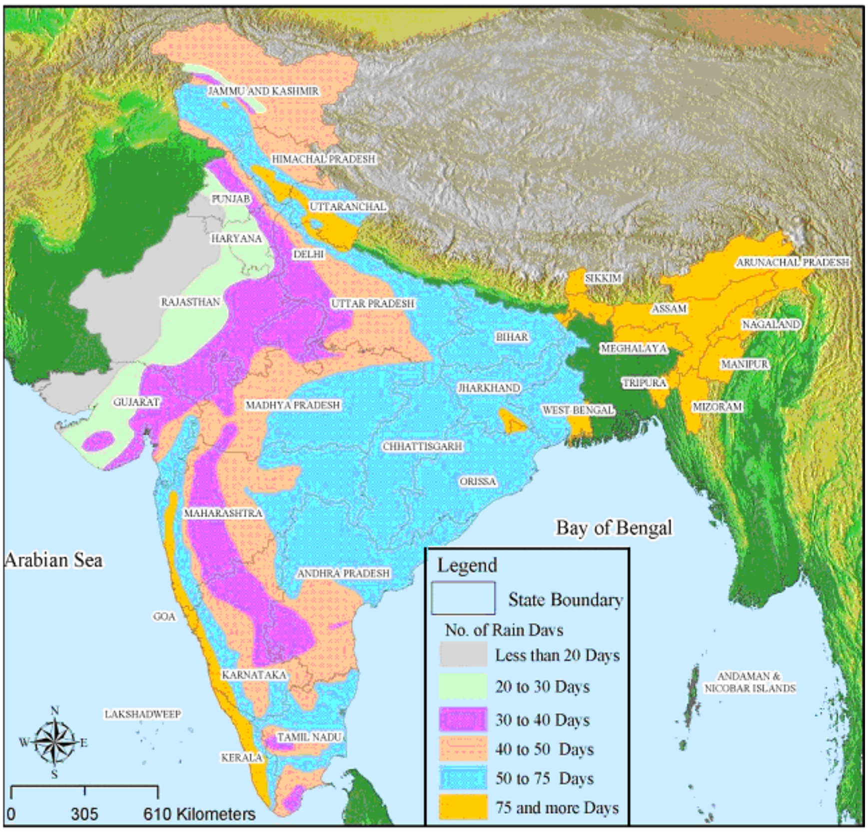

Figure 4. Average rain days

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 to demand large quantities of water for irrigation even when they run out of water. This is because communities take some time to devise coping and adaptive strategies to manage conditions of water deficits.

Studies in a village in Mandvi taluka of Kachchh, which is one of the most arid districts in India, showed that the annual water withdrawal from aquifers for irrigating crops is 25.42 MCM. The entire water requirements in the village were being met by groundwater, which was experiencing severe over-draft conditions (Kumar, 1997). Total rainwater falling over the village is nearly 10.14 MCM (*source*: based on data provided in Kumar, 1997, on geographical area and the mean annual rainfall of Kachchh). With a surface water potential of 0.014 MCM km^2 (IRMA/UNICEF, 2001), the volume of runoff that would be available for replenishment through natural and artificial recharge from within the village is only 0.40 MCM. The runoff is, therefore, a small fraction of the total consumptive use. This means that the village has to depend on exogenous sources of water to keep water use sustainable. This is representative of almost the entire region of peninsular India, excluding Kerala, central India and western India.

In the village of Manund, in the Patan district of north Gujarat, which has seen widespread pond de-silting, the total groundwater abstraction for agriculture alone was estimated to be 3.78 MCM (or 275 mm), with 35 deep tube wells pumping water at a rate of nearly 15 000 gallons per hour for nearly 1500 hours a year (Kumar, 2000b). The groundwater condition of the village is typical of the north Gujarat region. Against this, the total amount of rainfall over the village is only 7.56 MCM, with a mean annual rainfall of 550 mm over an area of 1374 ha. The runoff which this amount of rainfall can generate is 63.8 mm as per the rainfall–runoff relationship, with total runoff being 0.877 MCM. But, in practice, it is unlikely to achieve this as farmers harness for crop production a significant chunk of the runoff generated *in situ* within the catchment, unlike large basins where a good part is under virgin catchments. Kumar (2000b) estimated the groundwater over-draft in the village as being nearly 247.5 mm by considering the recharge as 5% of the annual rainfall. Hence, even if the entire runoff generated is harnessed for recharge, it would amount to only 25.7% of the over-draft.

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, such as the entire Ganga-Brahmaputra basin. This region has an enormous amount of static groundwater, estimated to be 8787.6 BCM, apart from having high rainfall and a cold, sub-humid climate that generates sufficient surface flows. Cheaper access to water might increase the demand for irrigation water slightly but the cold and humid climate and very low *per capita* arable land impose limits (Shah 2001; Kumar, 2003). Irrigation intensities are already high in Uttar Pradesh and Haryana. Though irrigation intensity in Bihar is low, the sub-humid and cold climate reduces the irrigation requirement significantly. In most of this region, the issue is not one of the physical availability of water, but the ability of communities to access it for irrigation (Kumar, 2003; Shah, 2001); water harvesting does not offer any economic solution here for the poorer communities to access water.

Issues in evaluating costs and economics

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

Part of the reason for lack of emphasis on 'cost' is the lack of scientific understanding of the hydrological aspects of small scale interventions, such as the volume of streamflow 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 analysing catchment hydrology, there are great difficulties in generating the vital data at the micro level on daily rainfall, soil infiltration rates, catchment slopes, land cover and PET which determine the potential inflows; and evaporation rates that determine the potential outflows. Further, for small water harvesting projects, implemented by local agencies and NGOs with small budgets, the cost of hydrological investigations and planning is hard to justify. Often, provision for such items is not made in small water harvesting projects.

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

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

In lieu of these difficulties in assessing the effective storage, unit costs are worked out on the basis of the design storage capacity of the structures and rule of thumb 'guestimates' on the number of fillings. The Shri Vivekananda Research and Training Institute, Mandvi, Kachchh, which has done pioneering work on artificial groundwater recharge in India, often resorts to this strategy to evaluate the cost effectiveness of recharge structures built in Kachchh (e.g. Raju , 1995). The recent book by Dr. R.N. Athawale on rainwater harvesting in India, although it covers a range of technical aspects of water harvesting in different regions of India, does not deal with economic issues (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 incremental hydrological benefits due to the new structure. A system in itself may be cost-effective and economically viable if evaluated independently but, if evaluated as a part of a large-scale water-harvesting intervention at the level of river basins, the system may not be justifiable on costs alone when compared with 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 is higher (see Figure 5). The reasons for this are: (1) the higher the degree of basin development, the lower the chances of getting socially and economically viable sites for building water impounding structures, and (2) with a higher degree of development, the social and environmental costs of harvesting every unit of water increases (Frederick, 1993), reducing the net economic value of benefits. Therefore, the cost and economic evaluation should move from watershed to basin level. As Figure 5 indicates, the level at which basin development can be carried out depends on whether we consider the flows in a wet year, a dry year or a normal year. Nevertheless, there is a stage of development (marked by O in the chart) beyond which the negative social, economic and environmental benefits start accruing, reducing the overall benefits. Here, O is the optimum level of water resource development.

However, it is important to keep in mind that the negative social and environmental effects of over-

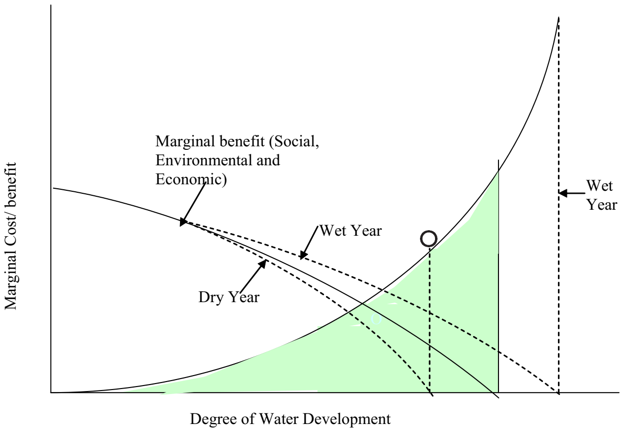

Figure 5. Marginal costs and benefits of water harvesting with different degrees of basin development

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

appropriation of a basin's water resources may be borne by a community living in one part of the basin while the benefits are accrued to a community living in another part. Ideally, water development projects in a basin should meet the needs and interests of different stakeholders living in different parts. Therefore, the optimum level of water development should not aim at maximising the net basin level benefits, but rather at optimising the net hydrological and socio-economic benefits for different stakeholders and communities across the basin. That said, in certain situations, the local economic benefits from RWH against the economic costs themselves may be questionable. But such interventions could be justified if there are potential social benefits in changing patterns of water availability and use, in terms of increasing water availability to poorer farmers with low capability land holdings: such decisions should be based on evaluation of alternative strategies to meet the local water needs of the poor.

The ability to derive economic benefit from 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 of recharge structures extend up to a few kilometres downstream or upstream, depending on the pattern of occurrence of geological structures such as lineaments, fractures and dykes (*source*: based on Muralidharan and Athawale, 1998). Tracing the recharge water in such situations would require sophisticated studies involving isotopes. This is a common problem in the hard rock areas of Saurashtra, Kachchh, north Karnataka and Tamil Nadu where large-scale water harvesting/groundwater recharge interventions are taken up through check dams, ponds and percolation tanks. Often the communities, for whom investments in the recharge system are made, do not get the benefit (Moench and Kumar, 1993). In certain other situations, the recharge water could end up in saline aquifers.

The economics of RWH will also be a function of the incremental value of benefits accrued from the use of newly-added water. Apart from the recharge volume, the value of the use to which the additional water is put is extremely important in determining the incremental benefits, an issue often ignored in the project planning. Often, the benefits of RWHS are not clearly identified or understood. While the cost of water harvesting is significant, it is critical to divert the new water to high-valued uses. Phadtare (1988) pointed out that recharge projects would be economically viable in alluvial north Gujarat if the water is diverted for irrigation, as structures are expensive. Yield losses due to moisture stress are extremely high in arid and semi-arid regions and that providing a few protective irrigations could enhance yield and water productivity of rain-fed crops remarkably, especially during drought years (Rockström, 2002). The available extra water harvested from monsoon rains should therefore be diverted to supplementary irrigation in drought years.

There are regions where potable water for people and livestock becomes a high priority demand. North-western Rajasthan, which is arid and dominated by pastoral communities, named *Gujjars*, is one such example. The social and economic value realised from the use of water for human drinking and livestock use, respectively, would be much more than the economic value realised 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 realise maximum value from the added water is largely missing in water harvesting efforts.

Lack of integrated approach

In many river basins, surface water and groundwater systems are often inter-connected. Any alterations made in either one could change the availability of water in the other (Sohiquilo, 1985; Llamas, 2000). In many hilly areas, especially in the Western Ghats, the water levels rise steeply after monsoon, and groundwater contributes significantly to the streamflows downstream during lean seasons due to the steep groundwater flow gradients. In that case, any water harvesting intervention to store water underground may not make much sense as it would get rejected and appear as surface flows (Mayya, 2005). On the other hand, in regions with deep water table conditions like in north Gujarat, the runoff moves directly 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).

With two-thirds of the country's geographical area underlain by hard rock formations, the storage capacity of aquifers poses a major challenge for artificial recharge. Most parts of the water-scarce states, namely Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, Orissa, Chhattisgarh and Tamil Nadu, are underlain by hard rocks ranging through basalt, crystalline granite hill aquifers and sandstone. A small area in Gujarat has extensive alluvium, i.e. the Narmada valley and (Cambay basin) (see Figure 6). The hard rock aquifers have no primary porosity and only secondary porosity. 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 the occurrence of the recharge plume and shallow bed rocks, which prevent percolation of water (Muralidharan, 1990 as cited in Muralidharan and Athawale, 1998) and the low infiltration capacity of the thin soils overlying the hard rock formations. Due to low specific yield (0.01–0.03), a sharp rise in water levels is observed in aquifers during monsoon, leaving little space for infiltration from structures. While harnessing water for recharge is extremely important during normal and wet years, the natural recharge in hard rock formation is high during such years as it is a function of seasonal rainfall (based on regression equations shown in Figure 7 in Athawale, 2003), further reducing the scope for artificial recharge.

In Saurashtra, in spite of the poor potential offered by low rainfalls, high variability and high evaporation rates (see Figures 1–3), significant recharge efforts were made. Nevertheless, 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 become 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 a small fraction of the surplus runoff. In such situations, proper water use programming is required to use the surplus water effectively, whereby water from aquifers is pumped out and used during the rainy season itself thus creating storage space for the incoming flows (Muralidharan and Athawale, 1990; Shah, 2002).

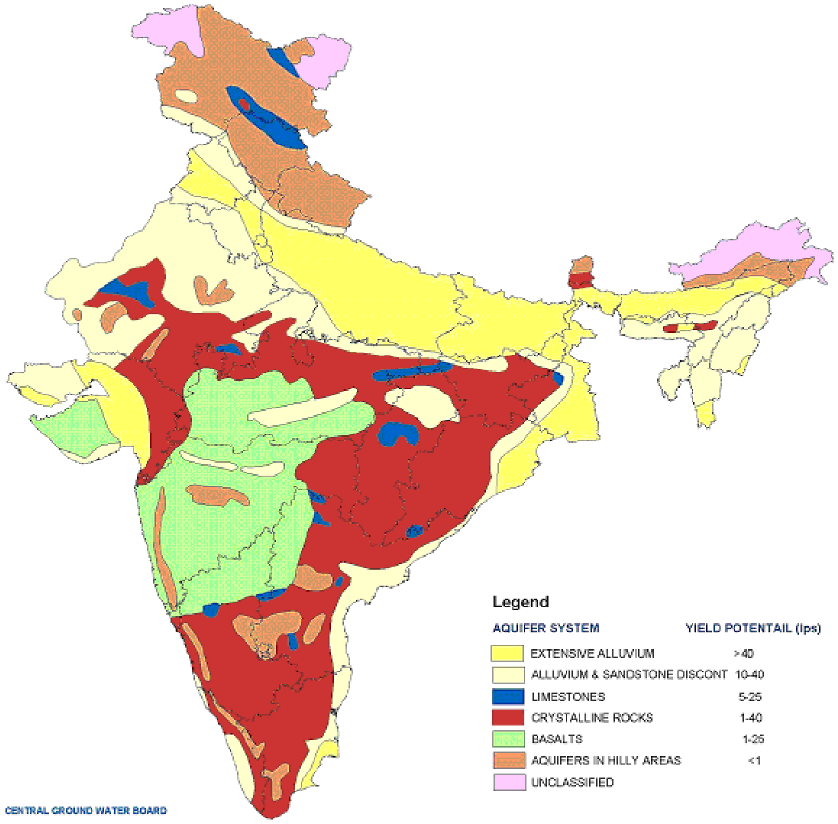

Figure 6. Aquifer system in India

Trade-off between local vs. basin impacts in closed basins

Lack of integration between plans for local water harvesting and basin water resource development, means that 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 subsequent plans for WH do not take into account the 'committed flows' for downstream reservoir/water diversion systems.

Also, there is an increasing tendency to believe that because these structures are so small they are benign (Batchelor *et al*., 2002), even though they are present in large numbers in most cases. The primary reason for this is that the agencies concerned with small water harvesting in the upper catchment and those concerned with major head-works are different and they do not coordinate their actions at the basin level. Building of tanks and check dams is often the responsibility of minor parts of an irrigation department or district arms of the rural development departments. 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 utilisable through conventional engineering interventions. Examples of these 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 km^2, has a utilisable surface flow of 1513.4 MCM allocated to Gujarat (Kumar and Singh, 2001), whereas the total live storage capacity of irrigation schemes built in the basin, estimated to be 1470 MCM (GOI, 1999) is still slightly below this. But the basin has many water diversion structures, including weirs and a barrage. Indeed, the dependable runoff upstream of the reservoirs/diversion structures in the basin is far below the planned water utilisation (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, Dharoi and Hathmati, are heavily over-appropriated (Kumar *et al*., 2000) while one of the sub-basins, Watrak, has uncommitted flows (Kumar and Singh, 2001), which eventually end up in the Gulf of Cambay.

It is hard to judge whether a basin is closed or open on the basis of the storage capacity of reservoirs and the dependable flows, as many reservoirs also divert a lot of water during the monsoon season, making the effective water utilisation more than the live storage capacity. Take, for instance, the Narmada basin. The total live storage volume of the terminal dam, Sardar Sarovar, is 5800 MCM, whereas the total water utilisation 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 and outside the basin, particularly from the Sardar Sarovar reservoir. Again, the estimates do not take into account the reservoirs having live storage capacity of less than 10 MCM.

Trade-off between economics and hydrological opportunity

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

In the Palanpur area of Banaskantha district in north Gujarat, which has semi-arid to arid climatic conditions, the rainfall records vary from a low of 56 mm in 1987 to 1584 mm recorded in 1907. The runoff estimated on the basis of a regression equation developed for Hathmati, a sub-basin of the Sabarmati in north Gujarat, physiographically quite similar to the Palanpur area of Banaskantha, shows that the runoff can vary from 0.6 mm to 541 mm. But actual runoff could be different from this, depending on how other variables that are not considered in the regression, such as the intensity and pattern (over space and time) of rainfall, influence the runoff intensity. Thus the lowest runoff is close to 1/1000th of the highest runoff. Even though what can occur 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 such as the Wayanad district in Kerala, the runoff estimated for the small catchment of Karappuzha, on the basis of the rainfall–runoff relationship developed for the Kabani sub-basin (catchment area of 7040 km^2) within the Cauvery river basin, and the observed rainfall of the area, ranges from 528 mm in the lowest rainfall year (2002) to 1458 mm in the highest rainfall year (1994) in a 31-year period from 1973–2003.

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 a favourable environment for runoff generation. The upper catchments also provide a 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 well endowed in terms of availability of arable land and consequently the demand rates for irrigation are generally low. On the other hand, the lower catchments are generally characterised by lower rainfalls and higher levels of aridity (rainfall deficit to meet ET demands) and the better access to arable land increases 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, the Narmada basins in central India, the Sabarmati basin in western India, tributaries of the Indus in the north-western India, the Krishna basin in central India and the Mahanadi basin in eastern India. Some parts of the Kabani sub-basin of the Cauvery river basin have a cold and semi-humid climate, and parts of this sub-basin receive the second highest rainfall in India after Chirapunji, with mean annual rainfall over 4000 mm.

We have defined the agricultural water demand as a function of *per capita* net sown area and the ratio of ET_0 and rainfall; and water availability as a function of rainfall. It is assumed that the higher the ET_0/R ratio, the higher would be the irrigation requirement for a unit of land; the higher the *per capita* (rural population) net sown area, the higher would be the aggregate demand for irrigation per capita. Table 1 shows the estimated values of two agricultural water demand variables, ET_0/R and *per capita* arable land; and one water availability variable, i.e. rainfall.

Major water resource/irrigation projects undertaken in the past tap streamflows generated from the upper catchments, but cater to either the lower parts of these

Table 1. Comparison of agricultural water demand variables in upper and lower catchment districts of selected Indian river basins

Name of Basin	*Name of UCD*	*Name of LCD*	*Mean annual rainfall (mm)*		*Mean annual PET (mm)*		*ET_0/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	NA	1029.0	NA	1785.9	NA	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 evapotranspiration (ET_0)

basins or other less water endowed regions outside these basins (Verghese, 2001 and 2002). Bakhra reservoir and Nangal diversion projects located in the high rainfall Shivalik hills of Himachal Pradesh essentially cater to the ravenous low rainfall and drought prone regions of Punjab and sparse 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 characterised by low and erratic rainfall (Verghese, 2001). 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.

Moreover, as irrigation water use efficiency and water productivity are likely to be high in areas with variability in rainfall and high drought-proneness (Rockström, 2002), with transfer of water from the well-endowed regions to the poorly-endowed regions, the economic value of water in agriculture increases. The recent research carried out by IWMI in water-scarce and land-rich western Punjab and water-rich and land-scarce eastern Uttar Pradesh showed that the value of water realised from irrigation is much higher in Punjab (Rs. 14.85/$m^{3)}$ than in eastern UP (Rs. 11/m^3). Because of water scarcity, the farmers in Punjab make better use of water by choosing cropping systems that are economically more efficient and using agronomic practices to obtain higher yields, higher physical productivity and greater economic efficiency (Kumar, Malla and Tripathy, 2006).

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

As is 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 reduces the downstream uses should be done with due consideration of the net change in 'gross value product' of water in the basin. 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 optimised to derive maximum regional social equity, environmental value and overall output from the economic uses of water. In basins where the available water resources are already committed (closed basins), the challenge is greater since maximising the gross value product might mean reallocating some water from one low valued use to a high valued use.

Critical issues for research on RWH in India

Issues emerging from past research

There have been several research studies which attempted to analyse the local and regional impacts of local water harvesting/recharge schemes. The research papers dealt with the following key questions:

- the physical performance of recharge structures;
- how much do the recharge structures actually contribute to groundwater availability in a region?
- what is the socio-economic impact of increased water availability?
- does water harvesting help alter the water balance from a river basin perspective?
- what are the second generation issues in water harvesting?
- is water harvesting an elixir for farmers, or are they engaged in a process of ecological destruction?
- what are the unintended impacts of rainwater harvesting, particularly on the water use hydrology of small catchments?

Patel (2002) evaluated the various hydrological and hydro-chemical aspects of recharge systems such as percolation tanks, check dams and dug well recharge 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 the recharge plume, recharge rates and radius of influence of recharge structures. The hydrochemical aspects were 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 varied according to variations in geological settings. It also established that the recharge rates were far higher in the case of percolation tanks and check dams which were periodically de-silted than those not de-silted. The recharge rate estimated for a normal percolation tank was 7.87 mm day^{-1} while that for a de-silted percolation tank was 20.4 mm day^{-1}. 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 vary across geological formations. Though the study is about the local hydrological impacts of recharge schemes, it supports the argument made in this paper that it may not be appropriate to use thumb rules to assess the size of benefits from recharge structures.

Palanisamy and others evaluated the economic impact of ten percolation tanks from Coimbatore and Avinashi districts of Tamil Nadu. It was 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^{-1} to Rs.2736 ha^{-1}. The analysis did not involve the cost of the tank structures and was based on one year of data. The study attributed the poor economic performance of the tanks to inadequate rainfall in that particular year and improper tank location (Palanisamy and Kandaswamy (1990) as cited in Muralidharan and Athawale, 1998). These findings corroborate to a great extent the arguments made earlier in this paper, with regard to limited physical impact of RWH structures and uncertain benefits.

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 catchments. These catchments fell within the large basin of Mewan in Mewat region of Alwar district. The *pal* project of PRADAN used a combination of field bunds, field levelling 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 number of wells which recorded such reduction ranged from five to ten in different catchments. 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 normal conditions water levels start receding by the end of September. The study quantified the additional recharge from the *pal* system as 3–8% 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. Such aspects can therefore be considered as the local economic benefits from water harvesting interventions.

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 onions (Kumar 2000a). Further, the study contended that, on the basis of regional hydrological data, any increase in number of recharge structures would not lead to a proportional increase in physical benefits. This is because the surplus water available within Saurashtra region is limited and, as long as the hydrological balance is not altered, the total amount of water that could be captured is fixed. Therefore, any increase in recharge structures beyond a certain number would not lead to incremental gains but only to its re-distribution.

Sharma (2002) examined the drought-proofing impact of water harvesting structures, namely *johads*. The study area was located in a catchment having a drainage area of 503 km^2. The study found that with the construction of *johads*, the water levels in nine out of the 34 wells in the village have shown remarkable changes as compared with the rest of the wells during all three seasons. Based on some empirical data on irrigation water rates for wheat, the paper argued that increased water availability led to increased pumping, therefore leaving no water for drought years. The paper 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 impact of water harvesting structures on the water balance of the Arvari basin provided an optimistic figure of 18 MCM and a pessimistic figure of 9 MCM of water, respectively, as potential recharge. The figures provide empirical support for our argument about limited physical impacts of RWHS even at the local level in low rainfall areas. The potential income impact was Rs.135 *per capita* per annum in the most optimistic case and Rs. 67 *per 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) in 2001 as compared to the long-term average rise. It estimated the additional recharge due to 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, cotton, wheat and groundnuts, due to 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, farmers were increasingly realising the fact that water needs to be ‘generated’, planned and husbanded. Further, the study showed that water harvesting ensured the security of kharif crops, leading to overall welfare. However, it did not examine the impact of the interventions on the inflows into the more than 110 medium reservoirs in the region that cater for irrigation and drinking water needs of the region. Most of these were located downstream of the catchments which experienced intensive water harvesting work and therefore scale effects of RWH are extremely important.

The findings of the empirical studies can be summarised as follows: (1) percolation tanks in hard rock areas have poor recharge rates, (2) siphon method shows good recharge effects, both supporting the arguments made in the paper; and (3) there is differential impact of water harvesting structures built in the same physical setting and that the nature of the impact of such water harvesting structures depends on the method of treatment and types of structure. The other findings are as follows. Geology plays an important role in deciding the rate of development and decay of recharge plume and the radius of influence of recharge structures. The positive physical impact of water harvesting structures also leads to a rise in land value, increased use of labour and other inputs in farming, generating more social welfare in the local areas.

Finally, there were several technical studies on performance and impacts of water harvesting/recharge based on individual systems in local areas by National Geophysical Research Institute and Central Ground Water Board in the past (see Muralidharan and Athawale, 1998), which did not integrate the fact that water harvesting impacts are ‘scale-dependent’ in their study designs. One reason could be that a major driver 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 reducing runoff rate is only due to loss of water into the natural sink or evaporation, and incremental structures at micro catchment level give incremental benefits by preventing this loss. Such an outlook can lead to serious over-estimation of net hydrological benefits, since a significant portion of runoff actually moves down vertically to join the aquifers. This seems to have influenced the engineering research on water harvesting and recharge.

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 is enough empirical evidence now to show that the hydrological impact of water harvesting interventions in areas which experience higher rainfall variability would be highly non-uniform over time , 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 the impact of water harvesting and to draw policy inferences.

Batchelor and others (2002) carried out a study in a tank catchment in Karnataka to analyse how various physical and socio-economic processes in catchments affect the water use hydrology of catchments. This is the first study of its kind in India looking at the unintended impacts of water harvesting/catchment 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 of nearly 40%, whereas the tank irrigators resorted to well irrigation. They argued for 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.

However, the study did not estimate the relative contribution of the above two factors to inflow reduction. It also did not analyse 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, as increased cultivation would also increase the *in situ* water harvested.

Issues for future research

The question often asked amongst water resource scientists and practitioners is: “are there limits to local/decentralised water harvesting?” The potential impact of local water harvesting on large water systems is central in the ongoing debate on decentralised water harvesting. This is because many of the water harvesting projects are underway in the upper stream of large storage systems. The two main counter-arguments are: increasing the number of water harvesting structures would not result in incremental benefits (Kumar, 2000a) and widespread construction of water harvesting structures across a watershed/basin would result in ‘diluting’ hydrological and economic benefits. However, some water resource scientists argue that the small structures complement large water storage systems by preventing siltation (but this will be true only 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 is harnessed. In a ‘closed basin’, the construction of new structures would merely divide the hydrological/economic benefits (Zhu *et al*., 2004; Molle *et al*., 2004). Further, the same basin can be ‘open’ in a high rainfall year, while ‘closed’ in a low rainfall year because of variations in runoff. The type of impacts which the new water harvesting structures make on a large water system in a basin depends, therefore, on the rainfall in a particular year. Hence, impact research should cover typical rainfall years. Today, the 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 ‘basin-wise’ planning, based on robust water accounting exercises to estimate the surplus runoff in 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 rain days, water harvesting may produce very limited impact over any time scale (Kumar 2002a). Moench and Kumar (1992) have also argued that harvesting runoffs of low reliability and flash floods would be prohibitively expensive, resulting in higher cost per cubic metre of water. 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). Economic analysis of water harvesting should be based on incremental returns at the basin level rather than from individual structures to capture the scale effects.

Finally, the value underlying the promotion of decentralised water harvesting is that large water resource systems cause negative ecological and environmental impacts in upstream as well as downstream areas (Rangachari *et al*., 2000). But there has been little empirical research to understand the ecological consequences of local water harvesting as, if carried out extensively, they could further reduce the environmental flows 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 one-eighth of its catchment area (Sakthivadivel, 1997). Furthermore, 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 creating positive environmental effects, particularly in mountainous regions. Hence, comprehensive research is needed to assess these impacts.

Major findings

The following are the major findings emerging from the study:

- Rainwater harvesting has extremely limited potential to reduce the demand–supply imbalances and provide reliable supplies in water scarce regions. The reason is that a significant part of these regions is characterised by low mean annual rainfalls, high inter-annual variability in rainfall and with high PE, a larger share of which occurs during the rainy season, reducing the runoff potential and increasing the occurrence of hydrological stresses.

- A large part of the water-scarce regions of India 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. Percolation tanks are likely to have low efficiency in these hard rock areas and this is also the case in areas having silty clay and clayey soils. In regions with high rainfall and medium evaporation such as parts of Orissa and western

Ghat, the overall potential of 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, rather than direct recharge. This should be followed by water use programming to create underground storage for incoming surface flows to meet the basic human needs. However, this scenario is not followed.

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

- The higher the degree of basin development, the higher would be the marginal cost and lower the marginal benefit from water harvesting. The economics of water harvesting, therefore, cannot be performed for structures based on their individual benefits and costs when the basin has limited surplus water; rather it should be on the basis of incremental benefits. Scale considerations are extremely important in evaluating the cost and economics of water harvesting, which should also include social and environmental costs and benefits. Sometimes, potential social benefits of improved regional equity may influence political decisions to intensify upstream water harvesting, even if it may reduce the net benefits at the basin level. Such decisions should be based on proper evaluation of alternative ways of meeting those upstream needs.

- The basins which experience high inter-annual variability in the streamflows 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. Upstream diversions reduce the prospects of storage and diversion systems downstream. Examples of closed basins are river basins in north Gujarat, Saurashtra, Kachchh, western Rajasthan and basins in peninsular India, such as Cauvery, Pennar and Vaigai. Narmada is another basin which in the immediate future would join this category of river basins.

- In many basins, there is an apparent trade-off between maximising overall benefits for basin communities in terms of enhancing the gross value product of water, and maximising the local benefits of water harvesting in upper catchments. This is because 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.

- Past studies did not involve ‘scale considerations’ when analysing 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. ‘Time’ considerations are important almost everywhere due to high inter-annual and inter-seasonal variability in rainfall and the erratic nature of monsoons.

- Issues for future research include: (1) potential impacts of water harvesting on large water resource systems in basins that have undergone high degree of development; (2) optimal level of water harvesting 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 hydroecologies.

Practical suggestions for efficient water harvesting

Enhancing knowledge of catchment hydrology

In water harvesting, what is least understood is the catchment hydrology. Most small rivers in India are not gauged for streamflows and siltation. An example is the Narmada river basin. It has a total of 56 gauging sites of which 25 collect data on siltation load. Data on siltation rates are often available for large reservoirs from siltation studies done by the Central Board of Irrigation and Power (CBIP) but applying this to small catchments can lead to either underestimation of siltation rates as siltation rates are generally high for hilly upper catchments. On the other hand, applying rainfall–runoff relationships of large basins for small upper catchments would result in under-estimation of runoff, as small upper catchments would normally have steeper slopes. The scale problems in hydrology are well documented (see Sivapalan and Kalma, 1995; Wood *et al*., 1990).

Although runoff data can be generated through runoff modelling for streams which otherwise are not gauged, scientific data on hydrological parameters such as soil infiltration characteristics, weather patterns, land-use characteristics and catchment slopes are essential to arrive at reliable results (Evans and Jakeman, undated; Jakeman *et al*., 1994). Managing hydrological data for small catchments is still a major challenge in India.

Research to focus on green as well as blue water

Green water refers to the water in the soil profile which is used directly by natural vegetation and crops in the form of beneficial transpiration and non-beneficial evaporation[3], whereas blue water refers to the water diverted from natural systems (both surface and underground) for various human

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[3] The concept of green water was first introduced by Prof. Malin Falkenmark in 1995.

uses. 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 also an important component of the hydrological system and there has been no focus on improving efficiency of utilisation of the water harvested in tanks, *Khadin*, percolation ponds and *Johad*. For any basin, it is crucial to know how much of the total precipitation falling on the basin is available as green water, how much is used in crop production and how much is lost in non-beneficial evaporation from the soil.

In high rainfall regions like Kerala, the utilisable 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 the area under paddy — would help improve green as well as blue water use, and alter the hydrology positively.

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, natural sinks or if a significant amount of water 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 without causing negative effects on the downstream uses. However, both water accounting and water balance studies should be carried out for typical rainfall years so as to capture the hydrological variability.

Wet water saving

In river basins which experience high aridity during the summer months, water stored in tanks, ponds and other small reservoirs can lead to heavy losses through evaporation. If this is prevented, it can lead to wet (or real) water saving, through increase in output per unit of depleted water. Directly diverting the harvested water from the RWH system to the crop land is critical for maximising the net hydrological gain, especially in areas with poor groundwater storage or areas experiencing high inter-annual variability in runoff (Oweis *et al*., 2002). Allocation of blue water harnessed to rain-fed crops to avoid moisture stress during critical stages of crop growth would increase the yield of crops remarkably (Seckler, 1996; Rockström *et al.*, 2002), thereby increasing the productivity of green as well as blue water. In the case of sub-saharan Africa, Rockström *et al*. (2002) showed that yield could be doubled in certain cases through hydro-climatic alterations.

Conclusions

In the most water-scarce regions of India, RWH offers limited potential. In many other regions, which have medium rainfalls but experience 'medium to high' evaporation, the poor groundwater potential of hard rock which underlies these regions poses a constraint for recharge. Economic evaluation of water harvesting systems poses several complexities due to the problems in quantifying the hydrological impacts and the various benefits. The economics of water harvesting cannot be worked out for structures on the basis of individual benefits but rather on the basis of incremental benefit. In many water-scarce basins, there is a strong trade-off between maximising 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 to help optimise the gross value product of water *vis-à-vis* economic, social and environmental outputs basin-wide. While there are some areas for research, 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 balance; (3) focusing on wet water saving; and (4) enhancing the productivity of green water in the basin.

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