Chasing a Mirage: Water Harvesting and Artificial Recharge in Naturally Water-Scarce Regions

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The analysis presented in this paper shows that in water-scarce regions of India, run-off harvesting does not offer any potential for groundwater recharge or improving water supplies at the basin scale. The issues are many: (1) Water harvesting in the "closed" basins have downstream negative hydrological impacts. (2) Due to high inter-annual variability in rainfall and therefore run-off, during drought years the water harvesting structures have become highly unreliable, whereas an attempt to capture run-off during wet years would remarkably increase the unit cost of harvesting water. (3) In closed basins, intensive water harvesting would lead to negative welfare outcomes due to high negative externalities at higher degrees of basin development. (4) Even at the local level, physical efficiency of water harvesting is likely to be poor, mainly due to groundwater-surface water interactions and the poor storage capacity of hard rock aquifers underlying most of the water-scarce regions. The artificial recharge systems in natural water-scarce areas in India are economically unviable. Also, the much talked about virtues such as promoting equity in access to water, social justice, water security for the poor, and realisation of greater economic value from the use of water, can be hardly achieved through water harvesting programmes in water-scarce regions, as practised today.

India has a long tradition of water harvesting [Agarwal and Narain 1997]. But, the past two decades have been characterised by a boom in water harvesting. This development is markedly different from the traditional in two ways. First the context of this boom is different and second 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 modelling [Kumar et al 2006]. 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 [Kumar et al 2006].

The limited Indian research on run-off rainwater harvesting (RWH)/artificial recharge so far had focused on engineering performance of individual structures [Muralidharan and Athawale 1998; Patel 2002]. While a lot of anecdotal evidences on the social and economic gains exist, there is little understanding based on empirical work of: (i) the impacts of water harvesting activities on local hydrological regime in terms of net water gain; (ii) basin level impacts on overall basin water balance; and (iii) economic imperatives from a long-term perspective [Kumar et al 2006]. Analysis of performance of run-off harvesting systems also misses the influence of "scale factor", with the exception of the work by Ray and Bijarnia (2006). Of late, researchers had raised questions about the reliability of water supplies from these systems in water-scarce regions, its possible unintended impacts [Batchelor et al 2002; Kumar et al 2006; Ray and Bijarnia 2006], its economics [Kumar 2004; Kumar et al 2006], and its role in improving the overall basin water economy [Kumar et al 2006]. But, such arguments are being challenged by the proponents on the ground that what is being achieved through decentralised water harvesting and recharge is greater equity in access to water, and social justice.

1 Purpose and Scope

The purpose of this paper is to: (i) assess the effectiveness of run-off harvesting in water-scarce regions of India from the point of view of improving both local hydrological regimes, and basin water balance; (ii) discuss the various considerations involved in analysing economics of run-off harvesting, and their imperatives

This paper draws partly on the ideas and data presented in a paper published by the authors in 2006, in addition to fresh analyses and insights.

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for determining the optimum level of water harvesting in water-scarce basins; and (iii) finally, examine whether the much-talked about virtues such as social justice, equity in access to water, water security for the poor and higher economic value realised from its use really achieved through rainwater harvesting. In order to do this, we analyse and synthesise macro level hydrological and geo-hydrological data for the country, including data on annual rainfalls, rainfall variability, number of rainy days, soil infiltration, potential evaporation (PE); data on rainfall, run-off and reference evapo-transpiration (ET_o) for selected basins, viz, Narmada, Cauvery, Pennar, Krishna and Sabarmati; and data on effects of water harvesting on stream flows and groundwater levels for Ghelo river basin in Saurashtra, Gujarat.

2 Run-off Harvesting: Peter Taking Paul's Water?

In order to understand the issue of negative downstream impacts of intensive water harvesting, we define "natural water-scarce regions", and "closed and open basins".

Naturally Water-Scarce Regions: From an anthropogenic perspective, water-scarce regions are those where the demand for water for various human uses far exceeds the total water available from the natural system, or the technology to access it is economically unviable. This includes the surface water, water stored in the aquifers, and that held in the soil profile. Water scarcity can also be felt when the resources are available in plenty in the natural system in a particular region, but adequate financial resources to access it are not available with the populations living in there. The former is called physical scarcity, and the latter economic scarcity. North Gujarat in India and Israel are ideal examples of physical scarcity, whereas Ethiopia in eastern Africa and Bihar in eastern India are ideal examples of economic scarcity of water. In this article we are concerned with regions facing physical scarcity of water.

Physical scarcity of water occurs in regions which experience low to medium rainfalls and high evaporation rates. Most parts of western, north-western central and peninsular India fall under this category. They have low to medium rainfalls[1] and high potential evaporation rates. The mean annual rainfall ranges from less than 300 mm to 1,000 mm, whereas the PE ranges from less than 1,500 in some pockets in the north-east to more than 3,500 in some pockets in Gujarat and Maharashtra.

We would explain the process which determines the supplies and demand for water, which in turn induces water scarcity in those regions, in the subsequent section. As regards natural water supplies, the run-off available from rainfall precipitation and groundwater recharge from a unit land area in such regions is generally low. This is because run-off is the amount in excess of the soil moisture storage and infiltration. Since evaporation rates are high, soil moisture generated from precipitation gets depleted during the rainfall itself, increasing infiltration of water which fulfils the soil moisture deficit. This leaves much less chance for water to run-off [see Kumar et al 2006 for detailed discussion].

As regards the demand for water, crop evapo-transpiration mainly determines the requirement of water for agriculture, as agriculture is the largest source of water demand for human uses in all major river basins in India.

The Imbalance

Table 1 gives the reference evapo-transpiration against the effective renewable water resources from surface run-off and replenishable groundwater.[2] It shows that for all the five basins, annual reference evapo-transpiration is many times more than effective renewable water resources. But, what is available for crop production includes the soil moisture storage as well. But since the soil moisture storage is a small fraction of the rainfall even in very high rainfall regimes, the potential evapo-transpiration (PET) for the entire year would be much higher than the sum of soil moisture storage – which is a fraction of rainfall – and effective renewable water resources.

Table 1: Average Reference Evapo-transpiration against Mean Annual Rainfall in Selected River Basins in Water-Scarce Regions (mm)

Sr No	Name of the Basin	Mean Annual Rainfall		Average Annual Water Resources[1]	Effective Annual Water Resources[2]	Reference Evapo-transpiration[3]	
		Upper	Lower			Upper	Lower
1	Narmada basin	1352.00	792.00	444.70	937.60	1,639.00	2,127.00
2	Sabarmati basin	643.00	821.00	222.84	309.61	1,263.00	1,788.80
3	Cauvery basin	3,283.00	1,337.00	316.15	682.80	1,586.90	1,852.90
4	Pennar basin	900.00	567.00	193.90	467.80	1,783.00	1,888.00
5	Krishna basin	2,100.00	1,029.00	249.16	489.15	1,637.00	1,785.90

Sources: (1) The average annual water resources was estimated by taking the sum of annual utilisable run-off [GoI 1999: Table 3.6] and the dynamic groundwater resources from natural recharge in these basins [GoI 1999: Table 3.9] and dividing by the geographical area of the basin.

(2) The effective renewable water resources were estimated by dividing the average renewable water resources for the basin by the fraction of total cultivated land to the total basin drainage area. The basin-wise total cultivated land considered was for the year 1993-94 [GoI 1999: Annexure 3.2, p 422].

(3) Reference evapo-transpiration values were estimated using meteorological data from FAO CROPWAT model, except for Pennar basin and upper Krishna. For Pennar and upper Krishna, the data were obtained from IWMI climate atlas.

In that case, the imbalance between effective water availability and water demand for agricultural uses is very high for all the five basins. In addition to the agricultural water, there are demands for water from other sectors such as domestic and industrial uses. But, for the time being, we can ignore this. This gap between demand and renewable supplies can be reduced if we have very little arable land, and very large amount of land serving as natural catchments for supplying run-off water. But, unfortunately, the amount of virgin catchment left out in water-scarce regions of India is very small. It varies from 58.6 per cent in case of Pennar basin to 28 per cent in case of Sabarmati basin.

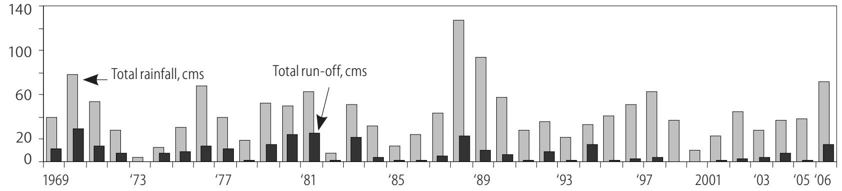
The increasing intensity of crop production in the rich upper catchments of river basins and watersheds has two major negative impacts on available renewable water resources. First, it captures a share of the run-off generated from the area, and therefore reduces the available surface water supplies. Second, increase in cultivated land increases the water requirement for irrigation. This way, large regions in India are facing shortage of water to meet the existing demands. The recent report on groundwater resource assessment and irrigation potential in India clearly shows that the regions facing problems of groundwater over-exploitation are mostly in Gujarat, Rajasthan, Maharashtra, Madhya Pradesh, Andhra Pradesh, Tamil Nadu and parts of

Karnataka, and coincide with the naturally water-scarce regions [GOI 2005].

'Closed' vs 'Open Basins': "Closed" basins are those where no extra renewable water resources are available for diversions to meet consumptive water demands, or "closed" basins are those where new diversions would reduce the availability of water for uses at some other points within the basin. This means in such basins, it is not possible to increase the beneficial evapo-transpiration, as wastage of water through non-beneficial evaporation or flows into the natural sink such as saline aquifers or seawater do not take place. "Open basins" are those where wastage of water through non-beneficial evaporation or flow into natural sinks take place, and where it is possible to increase utilisable water resources and increase beneficial evapo-transpiration. In the subsequent section, we show which basins in India are considered "closed".

Downstream Impacts of Upstream Water Harvesting: The states, viz, Gujarat, Rajasthan, Madhya Pradesh and Maharashtra took up intensive water harvesting during the past 20 years. The first decentralised modern water harvesting intervention in India was dug well recharging, and was started in Saurashtra region after the three-year consecutive droughts during 1995-87. This involved diverting field run-off and run-off in the local streams and 'nallas' into open wells, which are characteristic of hard rock regions [Kumar 2000]. Grassroot level non-governmental organisations (NGOs), spiritual and religious institutions, private agencies and social activists participated in this programme, which later on came to be known as Saurashtra dug-well recharge movement (ibid).

Figure 1: Ghelo-Somnath Rainfall and Reservoir Inflows



The argument was that the seven lakh open wells in the region could be recharged using monsoon run-off, which was all flowing waste into the sea. The people, who were behind this movement, did not consider the fact that approximately 110 medium and a few large reservoirs, which were located downstream, and were not getting sufficient flows even in normal rainfall years to supply for irrigation and drinking. The dependable run-off of the entire Saurashtra peninsula, generated from 91 small river basins, is 3,613 million cubic metre (MCM), whereas all the major and medium reservoirs in the region have sufficient storage capacity to capture up to 5,458 MCM water annually. This clearly shows that dug well recharging if carried out in the upper catchments of these basins, would only help reduce the inflows into these reservoirs (ibid).

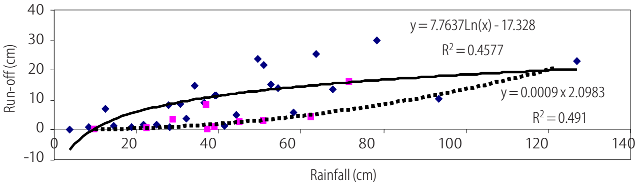
The Sardar Patel Participatory Water Conservation programme was launched by the government of Gujarat in Saurashtra and north Gujarat in 1999, and involved building of check dams in local streams, and nallas. As per the official claims, nearly 54,000 check dams were built in Saurashtra and north Gujarat with the involvement of local communities [GOI 2007]. As Saul Arlosoroff, an Israeli water expert, opined, this indiscriminate water harvesting activity has the potential to spell doom for the ecology of Saurashtra region.

But, the general belief is that because these structures are too small they are benign [Batchelor et al 2002] though present in large numbers in most cases. The primary reason for such an outlook 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 a coordinated fashion at the level of the basin. Building of small water harvesting systems such as tanks and check dams is often the responsibility of minor irrigation circles of irrigation departments 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 reservoir schemes downstream [Kumar et al 2000]. As regards the quality of implementation of the programme, it came under severe attack from the Public Accounts Committee, which found poor quality of construction, and misappropriation of funds. While the work was expected to be carried out by panchayats, the entire construction work was awarded to a few big contractors.

Adverse Impacts

Data collected from Ghelo river basin shows that the inflows into Ghelo-Somnath reservoir had significantly reduced after intensive water harvesting work was undertaken in the upper catchment. The total number of structures in the upper catchment area of 59.57 sq km is around 100. Figure 1 shows the catchment rainfall and run-off in Ghelo-Somnath. After 1995, the year which saw intensive water harvesting work, the reservoir overflowed only in 2005 when the rainfall recorded was 789 mm. Regressions of rainfall and run-off, carried out for two time periods, i e, 1969-95 and 1995-2005, clearly show that the relationship between rainfall and run-off had changed after water harvesting interventions (see Figure 2). The amount of rainfall required for filling the reservoir had now increased from 320 mm to 800 mm. Though the curves intersect at higher rainfall magnitudes, this is not a problem as such high rainfall does not occur in the basin.

Figure 2: Impact of Water Harvesting on Inflows in Reservoir: Ghelo-Somnath



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. Some of them are Pennar, Cauvery and Vaigai in the south [based on GOI 1999: 472-77], 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, one basin which is still "open" is Godavari in the east [based on GOI 1999: 466-69].

In nutshell, water harvesting interventions in the "closed basins" located in the naturally water-scarce regions would have adverse impacts on stream-flow availability for downstream uses. One could always argue that in wet years, the run-off would be much higher than the normal rainfall. While harvesting this water would mean huge investments for the structures, the aquifers in hard rock areas lack the storage capacity to absorb the run-off diverted into the system. This is dealt with separately in Section 3.2. On the other hand, in low rainfall years, the downstream impact of intensive water harvesting systems in the upper catchments would be severe. This is also evident from Figure 2 where the difference in run-offs between pre- and post-water harvesting scenarios is quite high for low rainfall regimes.

3 Recharging of Groundwater

The effectiveness of groundwater recharging in any area depends on three factors: (i) technical efficiency of recharging; (ii) storage potential of aquifers, which are being recharged; and (iii) dynamics of interaction between groundwater and surface water. Finally, we also discuss about hydrological variability and its implications for reliability of supplies and cost of water harvesting.

3.1 Poor Technical Efficiency in Artificial Recharge

From a technical perspective, there are three major problems facing artificial recharge efforts in water-scarce regions of India. Let us discuss them. First, most water-scarce regions are underlain by hard rock formations [Kumar et al 2006]. These hard rock formations consist of Deccan basalt, crystalline rocks and sedimentary sandstone and limestone aquifers.

Most of south Indian peninsula has crystalline rocks and basalts, whereas central India has basalt formations, crystalline rocks and sedimentary aquifers. The soils in the hard rock regions, mostly loamy clay, have very poor infiltration capacity [Muralidharan and Athawale 1998]. After the first few minutes, the rate of infiltration comes down to zero. The performance of water harvesting structures such as tanks, ponds and check dams, which depend on infiltration, therefore suffers. Second, in water-scarce regions, the evaporation rates are very high. Tanks and ponds are the common water harvesting systems found in south Indian peninsula. These structures have very high surface area in relation to the total amount of water they impound. Therefore, evaporation losses from these structures are bound to be very high. Third, hard rock geology induces significant constraints in recharge efforts through percolation tanks. The high depth to water table below and around the recharge structure due to occurrence of recharge mount and shallow bed rocks prevent percolation of water [Muralidharan 1990 as cited in Muralidharan and Athawale 1998]; and low infiltration capacity of the thin soils overlaying the hard rock formations.

Over the past couple of decades, "dug well recharging" had attracted a lot of attention from government agencies in other states facing water shortages. This is also known as the Aquifer Storage and Recovery (ASR) method of recharging. This was considered as a simple method for conservation of rain water, involving a meager expense of Rs 150 ($ 4 approximately). According to the proponents, 3,00,000 wells were recharged in Saurashtra alone using this method. As regards the hydrological impact, the proponents argued that a single well could recharge as much as 4,000 m^3 of water, based on the assumption that each well will have a storage capacity of 800 m^3 on an average, and could receive five fillings.

Planning New Artificial Recharge Schemes

These success stories from Saurashtra motivated the government planning new artificial recharge schemes in hard rock district of south India. But, planning such a project did not consider the availability of uncommitted flows in the particular river basins/regions, for which such schemes are proposed. The government of India report on groundwater management and ownership [GOI 2007] cite a figure of 214 billion cubic metre (BCM) as the uncommitted run-off in India for recharging, and 35 BCM as the total annual recharge technically feasible. But, the calculation does not consider the availability of uncommitted flows in the regions where groundwater is over-exploited. Instead, it looks at the aggregate figures at the country level, and instead only considers the storage space in the aquifers. Further, from the point of view of technical efficiency, no thought has gone into working out the amount of catchment needed to harvest run-off as high as 4,000 m^3 per well, nor the storage efficiency of the dug wells in hard rock areas.

As regards the first point, the catchment area required in four different basins in south India, estimated on the basis of the average run-off in these basins, are given in Table 2. But, as we know, in all these basins, the hilly, forested upper catchments are much rich in terms of run-off generation potential. The run-off generation potential of much of the moderately plain agricultural land in the basin would be much lower due to the lower rainfall, higher aridity (as Table 1 indicates), milder slopes, and the presence of field bunds and standing crops. Hence, the actual catchment required would be much higher than this. Again, this ignores the flows that are committed for downstream tanks, ponds and reservoirs.

Table 2: Catchment Area Required to Harness Field Run-off for Well Recharging

Sr No	Name of Basin	Average Utilisable Annual Run-off (m)*	Catchment Area (acre) Required for a Run-off of 5,000 m3
1	Cauvery river basin	0.216	5.76
2	Pennar river basin	0.120	10.24
3	Krishna river basin	0.220	5.58
4	East flowing rivers in the south**	0.168	7.45

Sources: * Estimated on the basis of the utilisable run-off in the basin and the total drainage area provided in GOI (1999).
** Between Pennar and Cauvery, and east flowing rivers south of Cauvery.

Even if we assume that such a large volume of water can be recharged effectively into the aquifers through dug wells at the farmer level, the availability of sufficient amount of private land to be used as catchments is open to question. In the most optimistic situation, some of the large farmers would be able to manage such a large amount of field run-off.

As regards the storage efficiency, for each well has to harness 4,000-5,000 m^3 of water, the number of fillings a well has to receive would be 15-20 during the monsoon. But, the hydraulic diffusivity is very poor in hard rock areas. Hence, the recharge mount created from a filling is unlikely to disappear before the wells starts getting the next inflow. An empirical study carried out in 1997 in Saurashtra region of Gujarat showed very limited impact of this method of recharging groundwater with a total recharge to the tune of 320 m^3.

3.2 Poor Aquifer Storage in Hard Rock Areas

With two-thirds of the country's geographical area underlain by hard rock formations, storage capacity of aquifers poses a major challenge for artificial recharge from local run-off. Most parts of water-scarce states, viz, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, Orissa, Chhattisgarh and Tamil Nadu are underlain by hard rocks ranging from basalt, crystalline granite, hill aquifers and sandstone. Small areas in Gujarat Narmada valley and Cambay basin have extensive alluvium. The hard rock aquifers have no primary porosity and have only secondary porosity. Due to low specific yield (0.01-0.03), 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.

Significant recharge efforts were made in Saurashtra. 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 2000].

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

This leads to the point that in hard rock areas, the aquifers get fully replenished during good rainfall years even without water harvesting systems. Therefore, the only way to store the run-off would be through surface storage. This would have serious negative implications for the cost of the system. This issue is dealt with in detail in Section 3.4.

3.3 Hydro-schizophrenia

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 [Sahuquillo 1985; Llamas 2000]. In many river basins, which do not get snow melt but have perennial flows, part of the monsoon recharge in the upper catchment areas outflows into the surface streams as base flow. This is the water which is available as non-monsoon flows in these river basins. Examples are basins in central India such as Narmada, Mahi and Tapi, and those in peninsular India such as Krishna, Pennar and Cauvery. Such outflows occur due to negative hydraulic gradients existing between groundwater levels and water levels in the streams. A recent analysis showed significant impact increased groundwater withdrawals in the upper catchments in reducing stream-flows in the Narmada basin [Kumar et al 2006].

In that case, water harvesting interventions 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 run-off 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 2002].

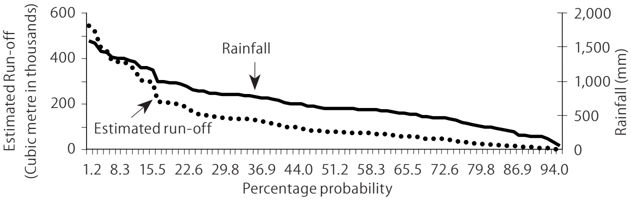
3.4 High Inter-Annual Variability in Rainfall

Regions with semi-arid and arid climate experience extreme hydrological events [Hurd et al 1999]. Regions with high variability in rainfall in India coincide with those with low magnitudes of rainfall and high PE, which also have high dryness ratio [Kumar et al 2006]. In such areas, a slight variation in precipitation or PE can substantially magnify the water stress on biological systems as compared to humid regions (ibid). Rainfall variability induces higher degree of variability in run-off. We take the example of the catchments of the Banas basin in north Gujarat of western India to illustrate this.

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 56 mm in 1987 to 1,584 mm in 1907. The run-off 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 run-off can vary from a lowest of 0.6 mm to 541 mm (Figure 3, p 66). Thus the lowest run-off is close to 1/1,000th of the highest run-off. This means, in drought years, when the actual water demand for irrigation increases, the amount of run-off that can be captured becomes almost negligible. Hence, the systems become unreliable. Though what can occur at the sub-basin level may not be representative of that in small upper catchments, the difference cannot be drastic.

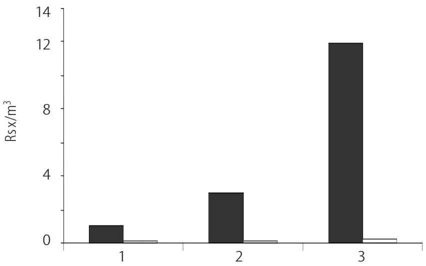
When there is a high inter-annual variability in the run-off a catchment generates, a major planning question which arises is "for what capacity the water harvesting system should be designed". When scarcity is acute, highest consideration is given to capturing all the water that is available. If all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

Figure 3: Probability of Occurrence of Rainfall and Run-off in Banas Basin



In order to illustrate this point, we use the data generated from Ghelo river basin in Saurashtra. The basin has a total catchment area of 59. 20 sq km. It had a medium irrigation reservoir with a storage capacity of 5.68 MCM and has been functional since 1966. On the basis of inflow data of the reservoir for the period 1969-95 showed that the total run-off generated in the basin varied from zero in the year corresponding to a rainfall of 39 mm to a maximum of 17.78 MCM in the year corresponding to a rainfall of 1,270 mm. Today, the total capacity of water harvesting systems built in the upstream of Ghelo reservoir is 0.15 MCM. During the period from 1969 to 2005, the reservoir showed overflow for 13 years with a total quantum of 60.936 MCM. If one MCM of run-off had to be captured in addition to the 5.89 MCM that would be captured by the medium irrigation reservoir, it would cost around 0.09 x/m^3 of water, while capturing 3 MCM would cost 0.11 x/m^3 of water. If the maximum run-off observed in the basin, i e, 17.785 MCM has to be captured, the total volume of water captured would be only 60.91 MCM, in which case the unit cost of water harvesting would be around 0.21 x/m^3 of water (Figure 4). Here, "x" is the cost of storage structures for creating an effective storage space of one MCM. Here, again, we are not considering the incremental financial cost of .the special structures for capturing high magnitudes of run-off, which cause flash flood.

Figure 4: Cost of Rainwater Harvesting with Increasing Collection Efficiency



4 Economics of Water Harvesting

In planning 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).

4.1 Economics for Groundwater Recharge

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 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 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 project, implemented by local agencies and NGOs with small budgets, 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 run-off which a water harvesting structure could capture, depends on not only the total quantum of run-off, but also how it occurs. A total annual run-off 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. The low rainfall, semi-arid and arid regions of India, which experience extreme hydrological events, have annual rains occurring in a fewer number of days as compared to sub-humid and humid regions with high rainfall regions [Kumar et al 2006]. As a result, as Garg (1987: 110-81) points out, in these regions, high intensity rainfalls of short duration are quite common [Garg 1987 as cited in Athawale 2003: Figure 24]. These run-offs generate flash flood.[3] If the entire run-off occurs in a major rainfall event, the run-off collection efficiency would reduce with reducing capacity of the structures built. If large structures are built to capture high intensity run-off thereby increasing the run-off collection efficiency, that would mean inflating cost per unit volume of water captured. In fact, authors such as Oweis, Hachum and Kijne (1999) have argued that run-off harvesting should be encouraged in arid area only if the harvested water is directly diverted to the crops for use.

Ex Benefits

Given the data on inflows and run-off collection efficiencies, predicting the impacts on local hydrological regime is also extremely complex, requiring accurate data on geological and geohydrological 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 thumb rules about number of fillings [Raju 1995]. The recent book by 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 [Athawale 2003]. In order to get projects through, proponents show them as low cost technology, underestimating the costs and inflating the recharge benefits. The best example is the government of India report on groundwater management and ownership [GOI 2007], and recently-sanctioned government of India scheme for recharging aquifers in hard rock districts of south India, with an investment of Rs 1,800 crore.

The government of India report (ibid) bases its arguments for rainwater harvesting on the pilot experiments conducted by the Central Ground Water Board (CGWB) in different parts of India using five different types of structures [GOI 2007: 13-15 for details]. While the estimated costs per cubic metre of water were one-time costs (Table 3), the report assumes that the structures would have a uniform life of 25 years. Two things in these figures are very striking. First, the costs widely vary from location to location and from system to system, and the range is wide, which the report duly acknowledges. Second, even for a life of 25 years, the upper values would be extremely high, touching Rs 7.7/m³ of water for percolation tank and Rs 18.2/m³ for sub-surface dyke. But, such a long life for recharge system is highly unrealistic.[4] Considering an active life of 10 years for a percolation tank, five years for check dam and sub-surface dyke, and three years for recharge shaft, we have worked out the unit cost of recharging using these systems.

Table 3: Estimated Unit Cost of Artificial Recharge Structures Built under Pilot Scheme of CGWB

Sr No	Type of Recharge Structure (Life in Years)	Expected Active Life of the System	Estimated Recharge Benefit (Thousand Cubic Metres)	Capital Cost of the Structure (Rs Lakh)	Cost of the Structure Per m^3 of Water (Rs/m^3)	Annualised Cost* (Rs/m^3)
1	Percolation tank	10	2-225	1.55-71	20-193	2-19.30
2	Check dam	5	1-2100	1.50-1050	73-290	14.60-58
3	Recharge trench/shaft	3	1-1550	1-15	2.50-80	0.83-26.33
4	Sub-surface dyke	5	2-11.5	7.30-17.70	158-455	31.60-91

Source: GoI, 2007, Table 7: pp 14.
*Estimated by dividing the capital cost by the life of the system.

The results are provided in Table 3. They show that the costs are prohibitively high for sub-surface dyke and check dam, and very high for percolation tanks. Added to the cost of recharging, would be the cost of pumping out the water from wells. The size of returns from crop production should justify such high investments. A recent study in nine agro-climatic locations in the Narmada river basin showed that the gross return ranged from Rs 2.94/m³ to Rs 13.49/m³ for various crops in Hoshangabad; Rs 1.9/m³ to Rs 10.93/m³ for various crops in Jabalpur; Rs 2.59/m³ to Rs 12.58/m³ for crops in Narsingpur; Rs 1.33/m³ to Rs 17/m³ for crops in Dhar; and Rs. 3.01/m³ to Rs. 17.91/m³ for crops in Raisen [Kumar and Singh 2006]. The lower values of gross return per cubic metre of water were found for cereals, and high values were for low water consuming pulses, and cotton. This means that the net returns would be negative if recharge water is used for irrigating such crops. Contrary to this, the report argues that the costs are comparable with that of surface irrigation schemes [GOI 2007: 13]. Such an inference has essentially come from overestimation of productive life of the structures.

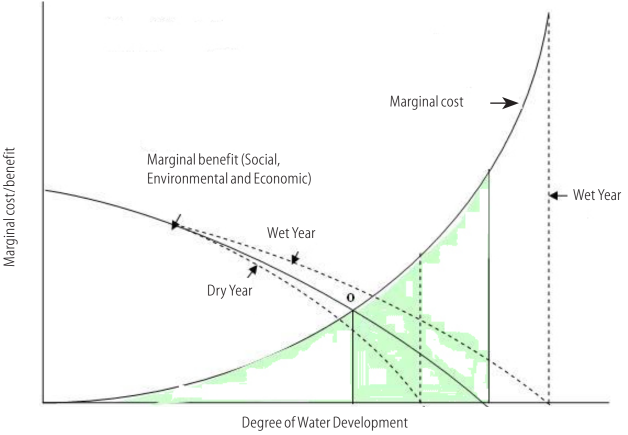
Potential Impacts

As regards dug well recharging, a close look reveals that this method of in situ water conservation suffers from many problems. First, the open wells used for irrigation are always located at the highest elevation in the farms, which makes it easy for farmers to take the pumped water to the fields by gravity. This means that farmers have to cut deep channels to convey the runoff water from the farthest points in the field to the wells for recharging, which may run into hundreds of metres. This can be cost significant amounts of money. The filter box alone could cost around Rs 5,000 per farmer. We have already seen in Section 3.1 that against these investments, the benefits that are likely to accrue are quite low.

Now, 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 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 [Kumar 2000], as interventions in the upper catchments reduce the potential hydrological benefits from the lower systems [Kumar et al 2006; Ray and Bijarnia 2006]. In the case of Arwari basin it was found that while the irrigated area in the upper catchment villages increased (where structures were built), that in the lower catchment village significantly reduced [Ray and Bijarnia 2006]. What is therefore important is the incremental hydrological benefit due to the new structure.

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 (Figure 5). The reason being: (i) 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 (ii) 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 5 indicates, the level at which basin development can be carried out depends

Figure 5: Marginal Cost and Benefit of Water Harvesting with Different Degrees of Basin Development



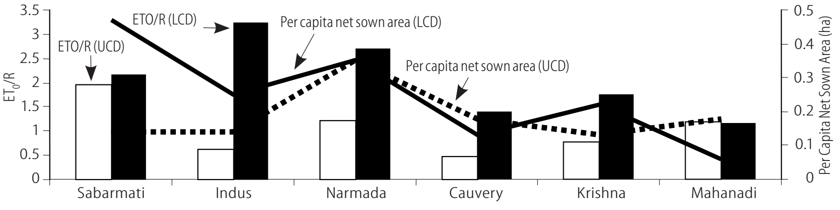
on whether we consider the flows in a wet year or dry year or a normal year. Nevertheless, there is a stage of development (marked by O in the chart) beyond which the negative social, economic and environmental benefits starts accruing, reducing the overall benefits. Here, O is the optimum level of water resource development.

But, it is important to keep in mind that the negative social and environmental effects of over-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 all the stakeholders. Therefore, optimum level of water development should not aim at maximising the net basin level benefits, but rather optimising the net hydrological and socio-economic benefits for different stakeholders and communities across the basin.

The potential impacts of the artificial recharge projects of the government have to be seen from this perspective. Even if recharging of millions of wells and tanks and ponds in the region becomes successful in creating an additional recharge in the order of magnitude, it is unlikely to create equivalent additional economic benefits from agriculture production. As per official estimates, the total storage capacity created in the river basins of south and central India, viz, Cauvery, Pennar, Krishna, Narmada, east flowing rivers between Pennar and Cauvery, and east flowing rivers south of Cauvery is 57.11 BCM, against utilisable water resources of 100.32 BCM [GOI 1999: 37, Tables 3.5 and 3.6]. Now, the actual volume of water being effectively diverted by the reservoirs/diversion systems in these basins would be much higher due to diversion during the monsoon, and additional water stored in the dead storage. This apart, the traditional minor irrigation schemes such as tanks are also likely to receive inflows during monsoon. It is estimated that south India peninsula had nearly 1,35,000 tanks, which cater to various human needs of water, including irrigation. Thus, the existing storage and diversion capacities in the region would be close to the utilisable flows. Hence, the livelihoods of farmers, who do not have access to groundwater, will be at stake at least in normal rainfall years and drought year.

To improve the economics of RWH, 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 rainfed crops remarkably, especially during drought years [Rockström et al 2003]. 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. 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.

Figure 6: Upstream vs Downstream Water Demands in Six Basins



5 The Myth and the Reality

The proponents of rainwater harvesting argue that what is being achieved through decentralised water harvesting and recharge is greater equity in access to water, and social justice. According to them, these are overriding concerns over economic efficiency. Needless to say, these are some of the principles of sound water management, especially for countries like India where a large percentage of the population in rural areas still live in poverty, due to inadequate access to water for livelihood. Whereas some even argue that economic efficiency in the use of water is more when locally harvested water is directly diverted for irrigation. Now, let us look at each one of these points to see the merits of these arguments.

As regards social justice, the major concern among the crusaders of water harvesting is intra-regional and intra-basin equity. The age-old argument is that in many river valley projects, the people living in the hills or the upper catchment areas are excluded from sharing the benefits of development interventions such as irrigation, drinking water supplies and hydropower. While demand for water should be the guiding principle for intra-regional water allocation within the basin, an analysis of six river basins in India shows that the demand for water in irrigation are much higher in the lower plains as compared to the upper catchments (Figure 6). As the figure shows that the value of two key factors, viz, the ratio of ET_0 and rainfall and net per capita arable land which determine the irrigation water demand, are higher for lower basin areas, as compared to upper basin areas.

Equity is a goal which is far from being achieved in both the case of run-off harvesting. In the case of Ghelo basin, indiscriminate building of water harvesting structures had already led to drying up of reservoirs downstream affecting the prior uses. In the case of Aji river basin, large number of check dams built in the upper catchment village of Rajsamdhiyala for groundwater recharge while replenishing the village wells [Kumar 2001], had reduced the inflow into Aji reservoir near Rajkot city, affecting irrigators in its command area and water users in the urban area. This had precipitated in conflicts where the irrigators in the Aji command area took to rioting. In case of Alwari river basin, well irrigated area in the downstream villages declined owing to reduced recharge in those areas [Ray and Bijarnia 2006: 2377-80]. As Mehta (1998) notes: "the social boundaries determining the patterns of uses of water are not always in conformation with village administrative boundaries and can change significantly within villages", and therefore such variations can affect the prospects of bringing about equitable benefits across villages and also within them.

As regards the value generated water use, the argument is that when the water from local WHS is diverted for supplementary irrigation, the yield and water use efficiency improves so much so that it offsets the losses in crop production due to reduction in water availability in other parts of the basin. As regards the validity of this argument, there has been limited analysis on the potential impact of water harvesting on water productivity in some east African countries [for instance Oweis et al 1999; Rockström et al 2002], Mexico [Scott and Silva-Ochoa 2001] and in India. But, they do not show the incremental return from water harvesting against the additional costs associated with WHS and the devices for supplementary irrigation.

But, the cost of water harvesting systems would be enormous, and reliability of supplies from it very poor in arid and semi-arid regions of India, which are characterised by low mean annual rainfalls, very few rainy days, high inter-annual variability in rainfall and rainy days, and high potential evaporation leading to a much higher variability in run-off between good rainfall years and poor rainfall years [Kumar et al 2006]. With high capital cost of systems needed for supplemental irrigation, the small and marginal farmers would have less incentive to go for it. As of today, there are no cases in India in which the farmers on their own had invested in WHS like tanks, ponds and check dams using their own funds. Wherever it has happened it is either under government schemes or with NGO initiatives supported by donor funds.

That said, even if the benefits due to supplementary irrigation from water harvesting exceed the costs, it will not result in higher water productivity in economic terms in closed basins, unless the incremental returns are disproportionately higher than the increase in ET. This is because, in a closed basin, increase in beneficial ET at the place of water harvesting will eventually reduce the beneficial ET downstream. Therefore, incremental net benefit considerations alone can drive water harvesting at the basin scale only if there is no opportunity cost of water harvesting.

6 Summary and Conclusions

In most instances, the regions facing problems of water shortage in India have them so due to natural water scarcity. In these regions, demands for water far exceed the utilisable water resources. This is one reason why these regions are facing overdraft of groundwater. These regions are characterised by low and erratic annual rainfalls, high inter-annual variability in rainfall, high aridity due to excessively high evaporation rates including that during monsoon, low and highly variable run-offs. These regions are mostly underlain by hard rock formations, which have poor water holding capacity. These regions have also experienced high degree of water resources development in the past many decades. The basins here are either "closed" or on the verge of "closure". Modern water harvesting initiatives are concentrated in these regions.

Analysis of data available from pilot projects of the CGWB shows that artificial recharging using methods such as percolation tank, check dam, sub-surface dyke and recharge shaft is prohibitively expensive. Also, the cost of using a cubic metre of recharge water for irrigation is much higher than the expected gross returns per cubic metre of the water, making irrigated crop production with it unviable.

In these regions, as evidences suggest, it is impossible to carry out local water harvesting and groundwater recharge activities in an economically efficient way and without causing negative downstream impacts. The reasons are many: high variability in run-off means high unit cost of capturing water; low infiltration rates for soils overlaying hard rock areas reduce technical efficiency of recharging through percolation tanks and check dams; hard rock aquifers offer very little storage space to absorb the high run-off in rainfall good years; due to high aridity, evaporation from surface storage is very high during monsoon; and the degree of water development is already very high in most water-scarce basins with small traditional water harvesting systems and large reservoirs/diversion systems. This is leading to colossal waste of scarce resources, apart from causing several negative social and environmental consequences. In the light of all these, the recent plans by the government of India to undertake artificial recharge of groundwater in overexploited areas of the country raises certain fundamental questions about the method used for analysing the hydrological and economic impacts of the interventions.

The much talked about virtues such as promoting equity in access to water, ensuring social justice, drinking water security for the poor, and realisation of greater economic value from the use of water, can hardly be achieved through WH programmes in water-scarce regions, as it is practised today. Further intensive run-off harvesting in basins with high degrees of water development can lead to several negative externalities on the ecosystem, health and the socio-economic production functions, leading to an overall negative welfare impact, and therefore has to be discouraged even if it happens at private costs.

In sum, there are no "quick fix solutions" to the complex water problems facing India. There has to be a better application of natural and social sciences, the socio-economic and institutional and policy context while designing water management programmes and policies. In this particular case, it is important to generate better understanding of the catchment and basin hydrology, the groundwater storage potential, the stage of water development in the basin, and climatic and socio-economic factors that determine water demands. The experiences from different parts of India show that piecemeal solutions, which do not take cognisance of these, would do more harm than mitigating the problems.

Afterword

The foregoing analysis does not suggest that water harvesting and groundwater recharge systems do not generate benefits. The analysis presented in this paper on the effectiveness and impacts of WHS are for those structures and systems which have been built during the past two to two and a half decades. India had a long history of building water harvesting systems, and it goes without saying that they benefited the local people by providing protective irrigation to their crops and domestic water supplies in the socio-economic and cultural milieu of those times.

With the building of the large modern day water resource systems including large reservoirs/diversion systems, particularly in the semi-arid and arid regions, the potential for building new water harvesting systems had declined considerably. The question therefore is not whether small WHS are good or bad against large water resource systems, but "what is the optimum level of water harvesting possible in a river basin from the point of view of generating optimum hydrological and economic benefits, when a basin had already undergone certain degree of water development".

To make water harvesting effective at the local level, scientific inputs need to go into planning of these interventions. On the natural science front, such inputs include: the rainfall intensity and pattern; reliable estimates of run-off from the catchments; analysis of engineering properties of the soils; topography; and, geo-hydrological data including geo-hydrological parameters of the formations, mapping of geological structures and groundwater-surface water interactions. If such data are available, site selection and working out optimum designs of structures would be easy. It would help prevent construction of structures which are structurally inefficient and expensive.

Further, there should be a realistic assessment of the different water needs of the local communities, against what the small water harvesting solutions could provide. This requires a proper understanding of the socio-economic features of the area and the social and cultural background of the communities. The absence of this would lead to bad investments and a lack of interest among the local communities in case the newly created water is too little against the existing local demands.

So far as the constraints in artificial recharge go, though not all hard rock areas suffer from poor infiltration capacity of soils and lack of storage potential in the aquifers, the regions in India which generate considerable amount of run-off mostly have crystalline rock and basalt. The specific yield of crystalline rocks and basalt is in the range of 0.01 and 0.03. There is very little area under hard rocks in India which have good rainfall conditions, and which have favourable geo-hydrology for artificial recharge.

Hence, as Kumar (2007) argues, the solutions to manage groundwater in arid and semi-arid regions with "closed basins" should focus more on water demand management in agriculture, which still takes the lion's share of the pumped groundwater. The primary areas of focus should be improving the productivity of existing crops through technological interventions such as efficient irrigation devices and agronomic practices; introduction of water-efficient crops at least in areas that are facing severe water stress – for instance replacement of sugar cane in semi-arid areas of Maharashtra by low water-intensive crops such as jowar and wheat; and import of surplus run-off from water-rich regions for irrigation, which reduces the stress on groundwater, while contributing to recharge through return flows. Metering and pro rata pricing of electricity in agriculture is the first step towards creating the economic incentive among farmers for doing this. But, it is also likely that with adoption of efficient irrigation devices, the farmers expand the area under irrigation. Such instances can be avoided only if we establish well-defined property right regimes in groundwater [Kumar 2007].

NOTES

1 Based on Pisharoty (1990) as provided in Kumar et al (2006).

2 For a basin, if only a small fraction of the drainage area is under cultivation, then effective renewable water availability per unit of cultivated land would be more, and vice versa.

3 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 flood occurs even in some of the semi-arid and water scarce basins such as Sabarmati and Banas [Kumar 2002].

4 The life of the system depends on the type, and also a variety of complex hydrological and hydraulic parameters. In regions receiving flash floods, and where the silt load in flood water is high, the technical efficiency of recharge structures drastically reduces after every major rainfall event. Percolation tanks would require desilting continuously year after year, cost of which is quite significant when compared to the capital cost of the system. Filters attached to recharge shaft become dysfunctional very fast, after one or two years of rains. So is the case with the recharge tube wells fitted with sub-surface dykes.

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