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Potential for Water Conservation and Harvesting against Drought in Rajasthan, India

P. Narain, M. A. Khan and G. Singh

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Contents

SUMMARY

Rajasthan is the largest state in India covering an area of 34.22 million hectares, i.e., 10.5 percent of the country's geographical area, but sharing only 1.15 percent of its water resources. The state is predominantly agrarian as the livelihood of 70 percent of its people depends on agriculture-based activities. Most of the state (60-75%) is arid or semiarid. In the last 50 years, a threefold increase in the human population and a doubling of the livestock populations have put tremendous pressure on the fragile water and land resources of Rajasthan. Recurring and prolonged droughts, particularly in the western arid part of the state, is a common phenomenon exacerbating water shortages. The estimated annual, per capita water availability in the state during 2001 was 840 m^3 and it is expected to be 439 m^3 by the year 2050, against the national average of 1,140 m^3 by 2050. Groundwater is overexploited in many districts of the state.

This study examines the potential for water harvesting and conservation against drought in the Indian state of Rajasthan. It indicates that despite water resources depletion, the state still has significant potential for harvesting and conserving water if an integrated water resources management approach is adopted, and proper policies and investment actions are implemented using recent technologies. The study suggests the following promising components of the water harvesting and conservation potential of the state.

- Rajasthan has about 50 million hectares of rocky/stony terrain. Over the existing storage, it offers the possibility of harvesting and conserving 90-145 million cubic meters (MCM) of runoff annually by developing suitable rainwater harvesting structures.

- Many additional sites have been identified for traditional water harvesting systems throughout the state and, when developed, they can satisfy the water requirements of large populations. A case study in Jodhpur district has shown that with the existing and proposed rainwater harvesting structures, over 68 MCM of water will be available even during severe drought, which may suffice to meet nearly 69 percent of the drinking water requirement of villages.

- Multiple existing tanks/reservoirs for storage and conservation of runoff need urgent rehabilitation. Rehabilitation could lead to additional storage that could be utilized in dry years.

- The state has 216 cities, which generate 522 MCM of utilizable roof runoff annually. Excluding losses, a potential of 265 MCM of runoff from roof surfaces is available from urban catchments for harvesting and conservation in underground cisterns or for recharging groundwater aquifer through bore wells, to mitigate drought. This could meet the domestic water requirements of nearly 9 million people.

- High flash floods, though occurring once in about 10 years, can bring as much as 22.6-54.8 billion cubic meters (BCM) of additional water in one year. This is comparable to 55.7 BCM of free underground storage, accumulated in the state during the last 20 years due to groundwater exploitation. Taming the excess flood water to rejuvenate the depleted aquifer is a major financial and technological challenge.

- Surplus water of the Indira Gandhi Canal may also be utilized to recharge the depleted aquifer.

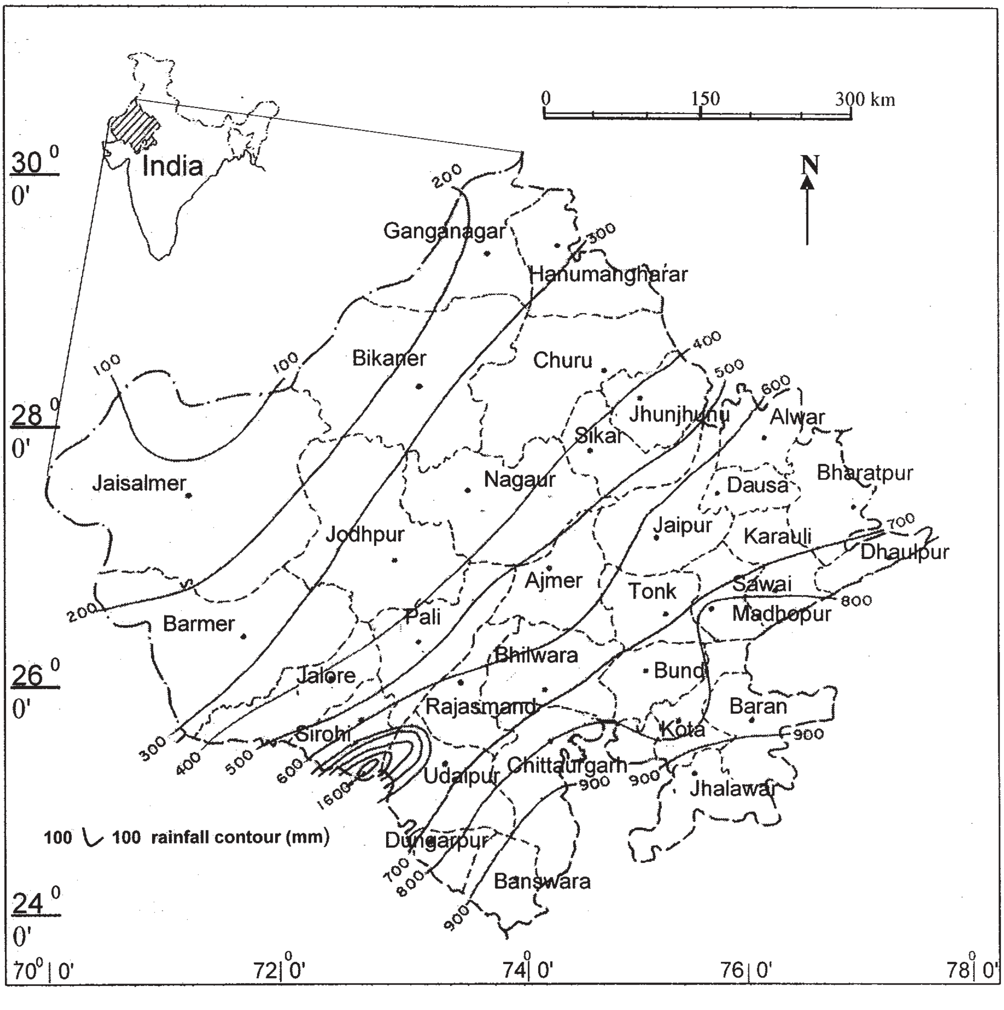
- In-situ water conservation on vast arable lands, recharging of the soil profile, runoff harvesting and its efficient and economic utilization through drip, sprinkler or conservation irrigation are vital for drought mitigation.

- It is estimated that one year’s drought-relief funds may be sufficient to develop rainwater harvesting structures to meet drinking water requirement in rural areas of western Rajasthan.

INTRODUCTION

Rajasthan (figure1) is the largest state in India covering an area of 342,226 km^2. The state is predominantly agrarian as the livelihood of 70 percent of its population depends on agriculture-based activities. Though it covers 10.5 percent of the country's geographical area, it shares only 1.15 percent of its water resources. Western Rajasthan is arid to semiarid with low and erratic rainfall, high summer temperatures, low humidity and high-velocity wind causing an average potential evapotranspiration of 2,000 mm, a negative water balance and acute water deficit. In the eastern part of the state, the climate is semi-arid to sub-humid with relatively better rainfall, low-velocity wind and higher humidity.

Figure 1. Location of the Indian state of Rajasthan and the isohyets of average annual rainfall.



The mean annual rainfall of the state is 490 mm with the local averages ranging from 100 mm in the northwestern part of Jaisalmer to over 1,000 mm in Jhalawar. Arid or semi-arid areas occupy 60-75 percent of the state. Droughts of varying intensity, particularly in the western part, are a recurring phenomenon. During 1901-2003, western Rajasthan experienced 20 moderate droughts (with 50% to 75% of the normal annual rainfall) and 10 severe droughts (rainfall below 50% of the normal) compared to 14 moderate and 5 severe droughts in eastern Rajasthan.

During the last 50 years, the human population has increased threefold and currently stands at 58.20 million. The cultivated area is 20,798,311 hectares with a cropping intensity of 124 percent, which leads to an increasing demand for water in the same or in a higher proportion. All this calls for an exploration of the potential for water harvesting, its conservation and efficient utilization to withstand growing demand, especially during droughts. The objective of this study was to assess the traditional and innovative water harvesting and conservation technologies in the context of their potential for drought mitigation throughout the state of Rajasthan.

WATER RESOURCES OF RAJASTHAN

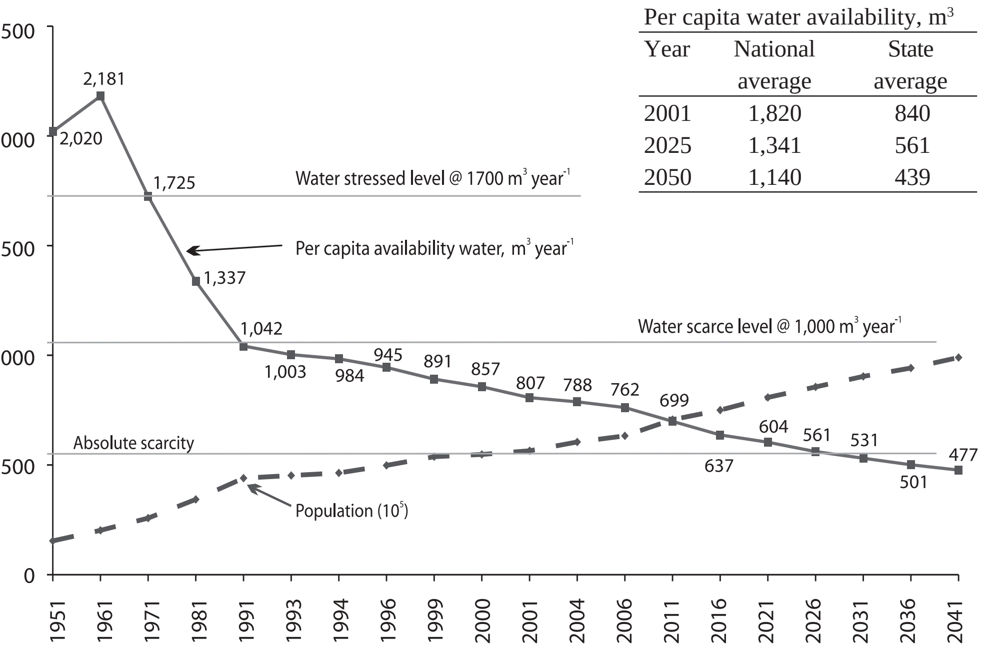
Projection of Water Use

Rajasthan is the driest state in India with scarce water resources. In the year 2001, annual per capita availability of water in the state was only 840 m^3. With increasing population, the scarcity will increase further and the per capita water availability in the state is expected to be as low as 439 m^3 by 2050, against the national average of 1,140 m^3 by the year 2050 (Vision 2004a; Vision 2004b; X-th Five-Year Plan 2004; figure 2). According to the State Water Plan, the projected nonagricultural demand for water is to increase from 3.29 BCM per year (the 1995 level) to 5.05 BCM per year in the year 2015, and it is estimated to reach 8.07 BCM per year in the year 2045. If all the 13.6 million hectares of cultivable land of Rajasthan are used for irrigation, the agricultural water requirement will be nearly 100 BCM per year, which obviously is not available. However, the State Water Plan has been prepared to create the irrigation potential for about 40 percent of the cultivable land of 5.125 million hectares (Vision 2004b).

Surface Water Resources in Major River Basins

There are eight major river basins in the state but Chambal and Mahi are the only perennial rivers that receive water from catchments located outside the state (figure 3). Water resources data simulated for each basin suggest that the internal surface water resources in the state during normal rainfall years amount to 48.01 BCM (table 1). However, only 16 BCM of surface water is utilizable (Vision 2004a). Besides, inter-basin water transfer from other states amounts to 17.9 BCM annually (Vision 2004b).

Figure 2. Population versus per capita water availability in Rajasthan.



Per capita water availability, m^3

Year	National average	State average
2001	1,820	840
2025	1,341	561
2050	1,140	439

Figure 3. River basins in Rajasthan.

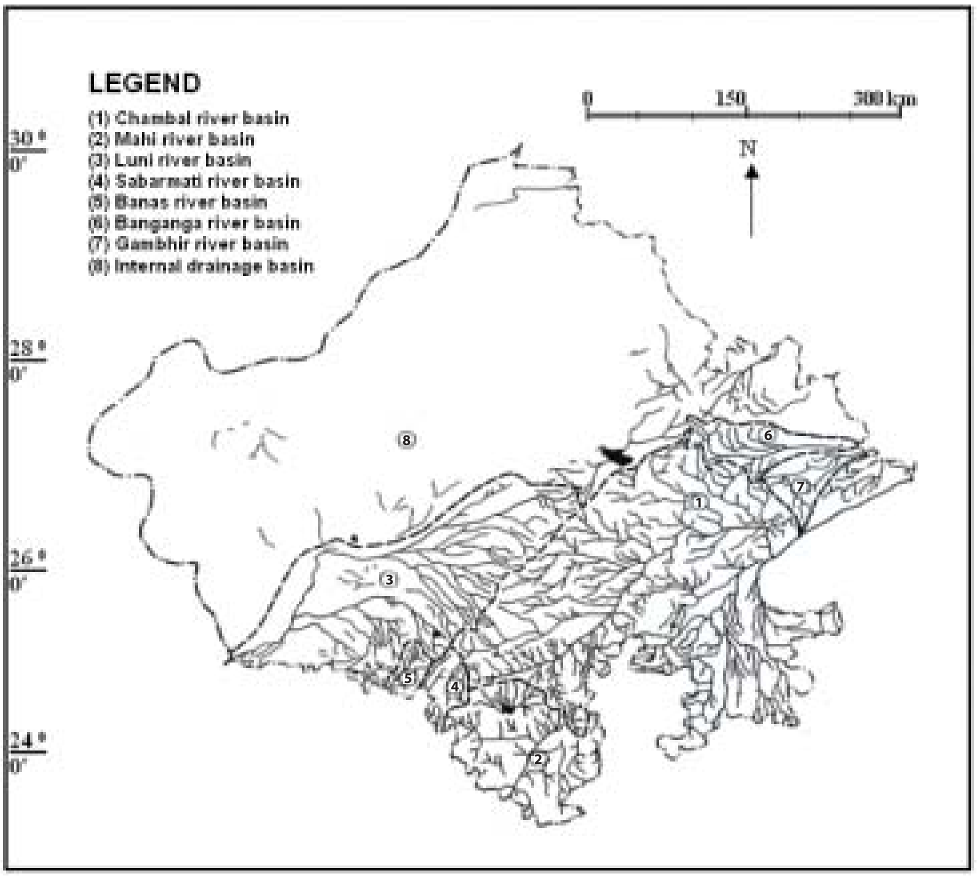


Table 1. Basinwise water resources potential (2004).

River basin	Area (km^2)	Population (million)	Available water resources (BCM)	Per capita water availability (m^3 per year)
Chambal	33,849	7.03	12.64	1,798
Mahi	16,985	4.15	4.65	1,120
Luni	38,310	5.99	3.14	524
Sabarmati	4,164	0.59	1.02	1,729
Banas	47,600	12.87	6.75	525
Banganga	12,763	5.12	0.97	190
Gambhir	4,173	5.17	2.23	431
Internal drainage (outside of the basin)	168,431	17.28	16.61	961
Total	342,239	58.20	48.01	825*

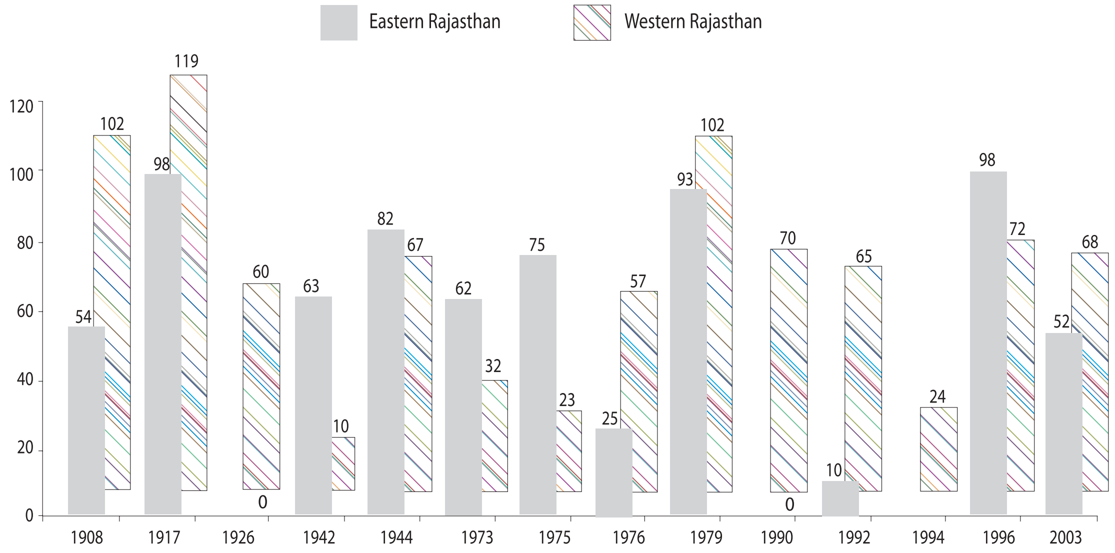
* Average per capita water availability.

Basinwise analysis of population and total water availability (table 1) shows that the highest per capita water availability of 1,798 m^3 is in the Chambal basin, followed by the Sabarmati (1,729 m^3) and the Mahi (1,120 m^3), whereas the lowest (190 m^3) is in the Banganga basin. The higher per capita water availability in the Chambal basin is mainly due to the perennial nature of the river and inter-basin water input from outside the state. Lower water availability is mainly in ephemeral (monsoonal) river basins, such as Banganga, Gambhir, Luni, etc., receiving flow from high-intensity rainfall during the monsoon. As compared to ephemeral river basins, the per capita water availability in areas located outside of the basin is high due to their low population density. Overall per capita water availability in the state during 2004 was 825 m^3. The availability of water resources gets reduced by 40 to 60 percent during moderate and severe drought years causing serious water scarcity in the affected regions.

Floods and Their Potential

Although large parts of Rajasthan are drought-prone, flash floods (overtopping defined ephemeral rivers/streams and spreading in flood plains over a short duration) are not uncommon in the state. During 1979, large parts of the state witnessed flash floods due to a very heavy downpour of more than 500 mm in 3-5 days, which cut off the region from the rest of the country for several days. A small part of flood water recharges groundwater aquifers while most of it outflows and drains into the sea through Kutch. Similar floods occurred in some parts of western Rajasthan in 1973, 1975 and 1976. In some desert areas, 150 mm of rain, which is the normal rainfall for one year, was received in one wet spell in 1973. According to data on excess rainfall over the regional mean rainfall for the last 103 years (figure 4), the western region witnessed 9 moderate and 19 severe floods whereas 21 moderate and 4 severe floods had occurred in eastern Rajasthan. It is interesting to note that severe floods are occurring more frequently in drought-prone western Rajasthan, suggesting that an opportunity exists to convert a part of the flood water into groundwater recharge by constructing a large number of groundwater recharge structures, which are non-existent now. Floods are considered a natural calamity. But if excess flood water can be managed and utilized for rejuvenating the depleted aquifers in the state, the issue of water scarcity during droughts can be alleviated to a large extent. Due to terrain morphology, it is a difficult task to divert flood waters of the perennial Chambal and Mahi rivers; however, excess rain in the drought-vulnerable western region with sandy terrain can be diverted to groundwater aquifers and surface storage structures.

Figure 4. Rainfall above the long-term average (excess rainfall as percent of average rainfall) in eastern and western Rajasthan (1901-2003).



Present Status of Surface Water Resources Projects

At present, there are 203 major and medium tanks and reservoirs in the state, which store about 13.72 BCM of water at their full capacity and a reduced volume of 11.51 BCM during dry years (table 2). Besides, there are large numbers of minor rainwater harvesting structures with a storage capacity of 2.28 BCM, thus increasing the total storage at full-capacity level to 16 BCM. However, during droughts, the estimated total surface water availability is reduced to 12.88 BCM creating a shortfall of 3.12 BCM. During the last 50 years, the irrigated land area has increased many times and it is 2.81 million hectares at present. Thus, substantial development in the water resources sector has taken place considering the financial, geographical and hydrological constraints. Besides, the ongoing water resources projects when completed will create an additional 1.85 BCM water storage capacity. However, the existing water resources projects still cannot keep pace with population growth and increasing water requirements. Water scarcity is becoming a serious issue during droughts as most of the tanks and reservoirs receive low runoff from their catchments, remain only partially filled and dry out much earlier than their normal utility period.

Table 2 Present status of reservoirs and tanks with capacity exceeding 4.5 MCM.

No.	Capacity range (MCM)	No. of reservoirs and tanks	Total water storage (BMC)	Available water during dry period (BMC)
1	>150	7	10.17	9.17
2	100-150	3	0.36	0.22
3	50-99.9	20	1.05	0.84
4	25-49.99	20	0.69	0.41
5	10-24.99	49	0.77	0.46
6	5-9.99	80	0.56	0.34
7	<5	26	0.12	0.07
	Total	203	13.72	11.51

Note: MCM = million cubic meter; BCM = billion cubic meter.

Groundwater Resources

Hydrogeologically, the water-bearing formations with freshwater, designated as potential aquifers of Rajasthan, could be divided into consolidated (hard rock), semi-consolidated to consolidated, semi-consolidated and unconsolidated formations. The consolidated formations have negligible primary porosity and significant secondary porosity due to weathering and fracturing. The semi-consolidated to consolidated formation group occupies about 14.3 percent of Rajasthan and has significant primary porosity and secondary porosity by virtue of weathering and fracturing. Unconsolidated formations are valley fills, younger and older alluvium and blown sand aquifers. These aquifers occupy 22 percent of Rajasthan and are productive formations with significant groundwater resources.

Overall, the estimated groundwater resources in Rajasthan are limited due to deep aquifers and low recharge. Based on the ratio of annual pumping to annual recharge, the stages of groundwater development have been categorized as safe (<70 %), semi-critical (70-90 %), critical (90-100 %) or overexploited (>100) %) (CGWA 1999). The groundwater is overexploited in Ajmer, Alwar, Barmer, Bhilwara, Chittorgarh, Dausa, Dholpur, Jaipur, Jalore, Jhunjhunu, Jodhpur, Nagaur, Sikar and Udaipur districts, and, on average, over the entire state (table 3). In the last 10 years, out of the total 236 blocks (administrative zones) in the state, the number of safe blocks decreased from 155 to 49. The impact of droughts on groundwater depletion was very spectacular in the hard rock regions of Udaipur, Rajsamand, Dungarpur, Bhilwara, Chittorgarh, Ajmer, Sirohi and Pali districts, which have a limited aquifer thickness. In these districts, nearly 60 blocks have moved into the semi-critical, critical and overexploited stages.

Scope for Groundwater Recharge

An assessment has been made to quantify the possible quantum of groundwater that could be recharged to different potential aquifers of Rajasthan if additional water, say flood water, is made available. Out of the state geographical area of 342,226 km^2, the potential aquifer area for groundwater is 217,947 km^2 (63.7%). The maximum area of potential aquifers is under meta-sediments (16.8%) followed by older alluvium (16.1%), sandstone (11.6%), alluvium (5.9%), limestone (3.86%), tertiary formation (3.05%), Deccan Trap (2.52%), granite (2.03%), shale (1.28%), rhyolite (0.59%) and ultrabasic rock (0.02%). During 1984-2003, the average decline in groundwater level ranged from 0.18 m to 10.3 m in 29 out of 32 districts (table 4). Therefore, the void column created by depletion of groundwater could be refilled if additional water is available. Districtwise, the receptive space for groundwater recharge has been computed as the product of the area of the aquifer, average groundwater depletion (table 4) and specific yield of the aquifer. The latter varies from 1.5 to 8 percent, depending on the aquifer type. The total net space available in the groundwater aquifer for recharging is 55,748 MCM, and could be even higher if the period prior to 1984 is considered. There is good scope to rejuvenate, to a limited extent, the depleted aquifers during flood years when excess rainwater is available. Based on frequency of occurrence of floods, the estimated net storable flood water in 10 years in Rajasthan is 10,960 MCM with high variability within districts ranging from 17.78 MCM in Jaisalmer to 1477.22 MCM in Jodhpur (table 4).

Table 3. Groundwater resources potential of Rajasthan as on 01 January 2004.

District	Net annual groundwater availability (MCM)	Actual annual groundwater exploitation (MCM)	Present groundwater balance (MCM)	Stage of groundwater development (%)
Ajmer	314.42	348.82	-34.40	110.94
Alwar	912.30	1112.07	-199.77	121.9
Banswara	162.50	39.21	123.30	24.13
Baran	495.31	321.99	173.31	65.01
Barmer	249.80	255.91	-6.10	102.44
Bharatpur	514.26	479.66	34.60	93.27
Bhilwara	426.79	450.38	-23.59	105.53
Bikaner	197.61	144.52	53.09	73.13
Bundi	355.70	232.12	123.58	65.26
Chittorgarh	460.11	519.48	-59.37	112.9
Churu	197.69	117.35	80.34	59.36
Dausa	268.01	295.30	-26.29	109.77
Dholpur	237.21	245.80	-8.58	103.62
Dungarpur	92.78	76.53	16.26	82.48
Ganganagar	198.83	133.51	65.28	67.17
Hanumangarh	194.61	166.67	27.94	85.64
Jaipur	684.41	1015.99	-331.58	148.45
Jaisalmer	52.59	39.60	13.00	75.29
Jalor	423.61	827.48	-403.86	195.34
Jhalawar	397.70	381.24	16.46	95.86
Jhunjhunu	243.04	419.68	-176.64	172.68
Jodhpur	393.13	660.87	-267.74	168.1
Karauli	412.66	340.81	71.85	82.59
Kota	404.10	220.80	183.30	54.64
Nagaur	628.16	842.14	-213.98	134.07
Pali	413.39	330.34	83.05	79.91
Rajsamand	154.19	143.62	10.56	93.15
S. Madhopur	384.70	311.54	73.17	80.98
Sikar	324.52	344.70	-20.17	106.22
Sirohi	265.65	247.37	18.28	93.12
Tonk	414.53	270.67	143.86	65.3
Udaipur	283.63	298.58	-14.95	105.27
Total	11,158.97	11,634.78	-475.8	
Average				104.3

Table 4. Groundwater recharge potential of Rajasthan (base year 1984).

District	Geographical area (km^2)	Potential zone area (km^2)	Average groundwater depletion in 1984-2003 (m)	Net space available for recharge (MCM)	Net storable flood water in 10 years (MCM)
Ajmer	8,481.00	7,466.76	-3.04	406.18	79.85
Alwar	8,720.46	6,825.81	-4.34	2,027.81	398.66
Banswara	5,037.00	4,288.92	-4.14	329.24	64.73
Baran	6,955.31	6,892.21	-5.12	1,429.23	280.98
Barmer	28,387.00	12,734.65	-3.18	2,147.50	422.19
Bharatpur	5,044.10	3,412.52	-4.27	846.42	166.40
Bhilwara	10,455.00	9,354.85	-6.38	981.06	192.87
Bundi	5,500.00	4,240.18	-10.34	1,695.42	333.32
Chittaurgarh	10,856.00	8,277.87	-6.87	1,247.18	245.19
Churu	16,830.00	7,895.62	-0.98	466.81	91.77
Dausa	3,420.17	3,085.62	-8.65	1,538.98	302.56
Dholpur	3,009.05	2,049.90	-4.90	527.34	103.67
Dungarpur	3,770.00	2,634.13	-4.00	160.11	31.48
Jaipur	11,061.00	9,994.67	-10.55	5654.07	1,111.57
Jaisalmer	38,401.00	9,868.30	-0.18	90.45	17.78
Jalore	10,640.00	8,228.10	-10.17	5,050.02	992.82
Jhalawar	6,219.00	6,106.16	-4.49	632.11	124.27
Jhunjhunu	5,928.00	5,273.69	-9.14	2,436.63	479.04
Jodhpur	22,250.00	18,867.92	-9.08	7,513.80	1,477.22
Karauli	5,038.60	3,902.42	-8.09	1,619.25	318.34
Kota	5,203.94	5,123.17	-6.39	1,801.45	354.16
Nagaur	17,718.25	16,378.50	-8.68	6,805.78	1,338.00
Pali	12,357.00	7,362.54	-10.11	2,315.53	455.23
Rajsamand	4,635.46	3,540.09	-7.09	376.49	74.02
S. Madhopur	5,020.65	4,325.63	-6.79	1,326.38	260.76
Sikar	7,880.85	7,273.46	-8.39	3,273.66	643.59
Sirohi	5,136.00	4,075.70	-8.66	1,216.38	239.14
Tonk	7,200.00	6,525.72	-8.77	1,374.56	270.24
Udaipur	12,643.54	8,229.48	-3.64	458.54	90.15
Total				55,748.38	10,960.00

Although Bilara limestone, Lathi and Jodhpur sandstone and alluvium aquifers are suitable from a recharge standpoint, rejuvenation of depleted aquifers of such a magnitude is not possible through natural recharge processes. Therefore, induced recharge utilizing excess water during flood years is the option. However, huge investments and efforts will be required to ensure enhanced artificial recharge. An integrated approach to artificial groundwater recharge is possible through percolation tanks, ponds, subsurface barriers, minor check dams, injection wells, harvesting of roof water, etc.

WATER HARVESTING AND ITS POTENTIAL FOR DROUGHT MITIGATION

Water harvesting and conservation at basin, area, field or micro level can bring sustainability to the water sector and, consequently, increase water availability in drought years. Water harvesting is the process of concentrating rainfall as runoff from a catchment to be used in a target area.

In Rajasthan, and particularly in the low-rainfall western zone, there are several kinds of rainwater harvesting systems such as *bawari, jhalara*, *talab, nadi*, *tanka*, *khadin, kund* and harvesting of roof water. Out of these, *bawari* and *jhalara* depend on groundwater, while *talab*, *nadi*, *tanka*, *kund* and *khadin* are based on harnessing surface runoff (Khan 1995; Khan and Narain 2000). With the implementation of government schemes for domestic water supply in many areas, some of these systems were neglected. However, with increasing human population, shortfall in groundwater and recurring droughts, these rainwater harvesting systems are attracting growing attention. Modern technologies of rainwater harvesting and groundwater recharge such as anicut, percolation tank, subsurface barrier and pond with infiltration wells have recently been developed to rejuvenate the depleted freshwater aquifers (Khan 1996a; Khan 1996b; Narain and Khan 2000; Narain and Khan 2002).

Bawari and Jhalara

Bawari and *jhalara* are local names given to step wells. These ancient water harvesting systems were mainly set up in cities and big towns to provide a water supply to the community. They were constructed at exorbitant cost and were often monumental, beautiful mansions with fine embroidery stone works covering large areas and were associated with religion and culture (figure 5).

Historically, many of these step wells were named after some renowned social or royal personality or a holy site. Groundwater aquifers like bawari and jhalara are essentially sweet water aquifers getting a regular, heavy recharge. At present, 88 jhalaras and bawaris are found in Rajasthan. With the introduction of pipe-borne water supply schemes and the dumping of waste material in these structures, these water sources got relegated and abandoned. However, in recent years, some of these systems have been renovated and the quantity and quality of the drinking water are maintained through the use of low-head electric pumps. Upkeep, renovation and minor repair of damaged structures, desiltation and detoxification of polluted water and rehabilitation of catchments of the existing structures would provide 4.40 MCM of water for the benefit of a (largely urban) population of about 336,000 during drought periods. The economic life of a bawari is 20 years whereas that of a jhalara it is 30 years. The cost-benefit ratios of bawaris and jhalaras are 1:3.2 and 1:1.8, respectively.

Figure 5. A drawing of a jhalara.

Nadi

A *nadi* or dug-out village pond is the oldest and still prevalent storage structure for rainwater harvesting. The water stored in a nadi is generally used for drinking by livestock and human beings. A nadi also acts as a source of groundwater recharge through seepage and deep percolation. It is estimated that the recharge from a nadi covering 2.25 ha and having a storage capacity of 15,000 m^3 in an alluvial area may induce a groundwater recharge of 10,000 m^3 in one rainy season.

A poorly maintained nadi suffers high water losses through evaporation, seepage and biotic interference resulting in rapid siltation and pollution. The Central Arid Zone Research Institute (CAZRI) in Rajasthan has designed nadis of different capacities for varying morpho-climatological conditions (Khan 1989). These improved nadis have low-density polyethylene (LDPE) lining on the sides and the bottom to prevent seepage, a surface to volume ratio optimized from 0.25 to 0.28 to minimize evaporation, a silt trap at the inlet to control biotic interference and a hand pump for water withdrawal, all of which have enhanced their efficiency. Trees that take water from the deeper soil profile strata are recommended for planting around the structure in order to reduce evaporation and improve the microclimate. Such an environmentally friendly nadi constructed at a location in the Barmer district was sufficient to serve 500 people throughout the year and was replicated at ten different locations in the region.

A district-wise water resources survey, undertaken as part of this study, shows that the capacity of a nadi ranges from 1,200 m^3 to 15,000 m^3 under different topographical and climatological situations. The estimated number of nadis in varying formations and situations in Rajasthan are about 83,000 with a maximum storage capacity of 1,227 MCM. Potential sites have been identified for 14,500 new nadis to create an additional water storage capacity of 216.2 MCM for rainwater harvesting, making a total storage capacity of 1,443 MCM for the benefit of a rural population of 880,000 throughout the year. The existing nadis and the ones to be built may contribute 360-680 MCM of groundwater replenishment annually. It has also been estimated that construction of 422 nadis using the CAZRI design in the hyper-arid district of Jaisalmer can satisfy the drinking water demand of 211,000 people. Besides, increased recharge would make more groundwater available during dry years. The economic life of a nadi is 25 years with a cost benefit ratio of 1:2.8. However, some of the functional nadi are more than 50 years old in western Rajasthan. This suggests that with due care in repair, maintenance and desilting, a nadi may function for a much longer duration than the designed life.

Tanka

The *tanka* (underground cistern) is another major source of drinking water in western Rajasthan. It is constructed in a circular or rectangular shape, normally on bare ground where surface runoff can be diverted to the tanka by creating a clean catchment around it. A traditional tanka constructed with lime plaster and thatched with bushes has a life span of 3-4 years. With the decomposition of brush wood, falling of leachate and entry of foreign material with runoff through the open inlet, the quality of stored water in the tanka deteriorates over time making it unhygienic for drinking.

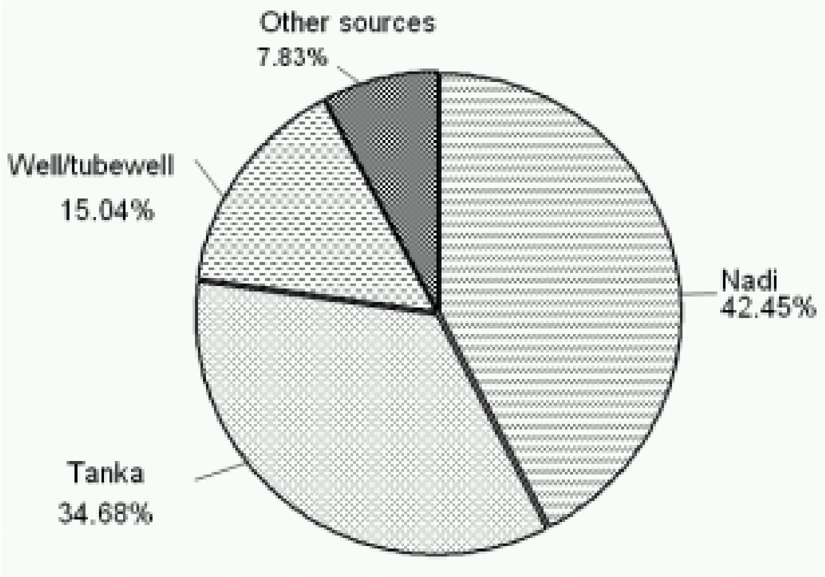
CAZRI has developed a tanka of improved design with a capacity ranging from 10,000 to 600,000 liters and provision for three inlets with a wire mesh and a silt trap, to ensure pollutant and silt free inflow (Khan 1996a; Khan 1996b), and an outlet for overflow. The water is generally withdrawn manually from its roof top or sometimes through a pump. A life span of such a structure is more than 20 years. The improved tanka developed by CAZRI has become popular and widely adopted in Rajasthan. About 12,000 tankas of CAZRI design have been constructed in western Rajasthan to store 475,000 m^3 of rainwater per year, which is sufficient for domestic use for 32,000 people throughout the year.

The tanka system of water harvesting is highly economical (US$1.1/$m^3$ water) and comfortable as compared to the hauling of water by women folk from long distances (US$16.7/$m^3$ water). As they have confidence in this technology, people are willing to share 50 percent of the cost of a tanka. The construction of 200,000 improved tankas at a cost of about US$100 million (which is equal to a year's drought relief) will eradicate at least the problem of drinking water permanently in 12 districts of western Rajasthan.

Dependency on Drinking Water Sources

The dependency of the population on sources of drinking water in western Rajasthan is shown in figure 6; 42.4 percent of the population depends on nadis, 34.7 percent on tankas, 15.0 percent on open wells and tube wells and 7.8 percent on other sources. From July to September, people generally use nadi water, which is open to evaporation losses, and they save the water in other sources like tankas for the period of scarcity. For the sake of convenience, a tanka is refilled by transporting water from other sources. In May and June, after the stored water in nadis and tankas is exhausted, dependency on open wells, tube wells and other sources increases.

Figure 6. Dependency on drinking water resources in western Rajasthan.



Roof Water Harvesting

Harvesting of roof water is an age-old practice to obtain safe drinking water, which is being revived and emphasized now. In ancient times, houses in western Rajasthan were constructed with stone and lime and roof water was diverted to tankas. Harvesting of roof water is being neglected because of pipe-borne water supplies even in rural areas, which is essentially based on groundwater withdrawal locally or in the vicinity. Roof water harvesting is now becoming the order of the day in towns as well as in rural areas due to the alarming rate of groundwater depletion. If harvesting of roof water is revived on a large scale, it will alleviate the scarcity of drinking water and also reduce the rapid depletion of groundwater. The estimated water yield from a 1,500 m^2 roof top with an effective rainfall of 250 mm and a 0.8 runoff coefficient is 300 m^3, which is enough for a drinking water consumption of 30,000 person days at 10 liters per capita per day (lpcd).

Roof water harvesting for the recharging of groundwater can also be recommended for areas having suitable aquifers. This approach requires harvesting and channelizing roof water to either existing wells, tube wells, bore wells or specially designed wells. It is most suitable for urban housing complexes or institutional buildings located in drought-prone arid and semi-arid regions. Based on CAZRI recommendations, the Government of Rajasthan has made harvesting of roof water mandatory in all new buildings with a covered area of more than 1,500 m^2.

The runoff efficiency of roofs made up of different material has been evaluated (Khan 1995). Runoff efficiency is highest (85%) for corrugated iron sheet roofs followed by stone slab roofs (80%), paved surface (68%) and clay tile roofs (56%). The lowest (39%) is for thatched straw roofs. Based on an 80 percent runoff efficiency of cement concrete roofs, the water yield for varying sizes of roof in different rainfall zones has been estimated (table 5).

Table 5. Water yield from rooftops in different rainfall zones.

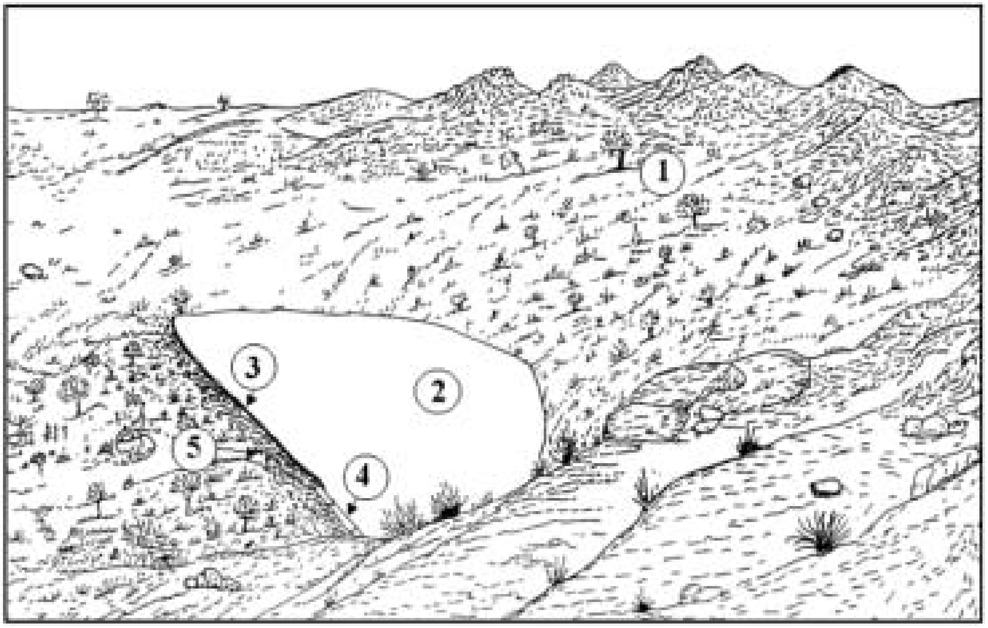
Rooftop	Rainfall (mm)										
area (m^2)	100	200	300	400	500	600	700	800	900	1,000	1,200
	Water yield (m^3)										
100	8	16	24	32	40	48	56	64	72	80	96
200	16	32	48	64	80	96	112	128	144	160	192
300	24	48	72	96	120	144	168	192	216	240	288
400	32	64	96	128	160	192	224	256	288	320	384
500	40	80	120	160	200	240	280	320	360	400	480
600	48	96	144	192	240	288	336	384	432	480	576
700	56	112	168	224	280	336	392	448	504	560	672
800	64	128	192	256	320	384	448	512	576	640	768
900	72	144	216	288	360	432	504	576	648	720	864
1,000	80	160	240	320	400	480	560	640	720	800	960
1,500	120	240	360	480	600	720	840	960	1,080	1,200	1,440
2,000	160	320	480	640	800	960	1,120	1,280	1,440	1,600	1,920
2,500	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000	2,400
3,000	240	480	720	960	1,200	1,440	1,680	1,920	2,160	2,400	2,880
3,500	280	560	840	1,120	1,400	1,680	1,960	2,240	2,520	2,800	3,360
4,000	320	640	960	1,280	1,600	1,920	2,240	2,560	2,880	3,200	3,840

The state of Rajasthan has 216 cities and big towns generating nearly 522 MCM of roof runoff annually, of which nearly 12 percent is stored in surface water bodies and groundwater aquifers. Excluding losses, a potential 265 MCM of roof runoff is available to meet domestic water requirements on a sustainable basis and to mitigate drought for an urban population of 8.8 million.

Khadin

The *khadin* (figure 7), a runoff farming and groundwater recharging system, is popular in the hyper-arid part of Rajasthan. Here, runoff from upland and rocky surfaces is collected in the adjoining valley against an earthen embankment having a masonry waste weir for outflow of runoff excess. Sometimes a sluice gate is provided in an earthen embankment for draining out standing water for crop cultivation. A khadin farm is developed on the basis of rainfall probability, available catchment area and its runoff generation potential. Apart from the submerged area, khadin beds are cultivated from top to bottom on receding moisture. Ponding of water in a khadin induces continuous groundwater recharge. The perched subsurface water is extracted through bore wells developed in the khadin or in the immediate vicinity downstream. Khadin designs developed by CAZRI have proved their merit in water conservation for crop production and increasing groundwater availability even during drought years (Singh and Khan 1999). During the severe drought of 2002 in western Rajasthan, khadin farmers were able to meet domestic water needs and also grow sorghum for fodder, earning US$630/ha. The average rise in the water level in shallow wells was 0.8 m in sand stone and 2.2 m in deep alluvium (Khan 1996b). A water balance study of a 10 ha khadin with a 120 ha rocky catchment in the Baorli-Bambore watershed showed that with 250 mm effective rainfall received in 3 spells the water yield from the catchment was 180,000 m^3,

Figure 7. A khadin system.



1. Catchment
2. Khadin bed
3. Earthen bund
4. Spillway
5. Pipe sluice

which was harvested and stored in the khadin. In addition, 25,000 m^3 of rain directly falling on the khadin increased the total available water to 205,000 m^3. Nearly 62 percent of this water contributed to groundwater through recharge, which resulted in a 1.2 m rise in the static water level in wells in a zone of influence of the khadin of about 10 ha (Khan and Narain 2003).

In recent years, nearly 550 khadin farms have been developed in western Rajasthan for an average water harvest of 54,000 m^3 per khadin benefiting 6,400 farm families. Potential sites for developing 490 new khadin farms of different sizes in western Rajasthan have been identified and delineated on 1:50,000 scale topographical sheets. When these are developed, the total of 1,040 khadin farms would have a runoff harvesting potential of about 42 MCM water for increasing sustainability of crop production, meeting the drinking water requirement of 12,000 farm families, enhancing groundwater availability through recharging and providing a sound drought mitigation strategy.

Water Harvesting Dams

In ravines or heavily gullied lands, small earthen check dams with drop inlet spillways are recommended. These check dams have a small pondage, which helps retention of the silt load, supplements irrigation, contributes groundwater recharge and enhances the overall biomass production of the system. Water harvesting dams have been constructed across ephemeral streams at several locations in western Rajasthan and other arid and semi-arid states under watershed management programs to impound 40,000 to 800,000 m^3 of water behind each structure.

Anicuts

An anicut in Rajasthan is a small water harvesting masonry dam constructed across a stream to hold sufficient water and submerge the upstream area during the rainy season. The stored water is used for lift irrigation and for recharging groundwater in adjacent wells used for drinking. If the submerged area is large, bed cultivation is practiced using the stored soil profile moisture like in a khadin. A study conducted by CAZRI on artificial recharge of groundwater, during 1989-1994 in the Ujalian watershed of the Jodhpur district of Rajasthan, revealed an annual increase in water level of 1.8-2.2 m in the zone of influence of anicuts as against a 0.5 m rise in outside wells (Khan 1996a; Khan 1996b). At another location in the Pali district, the increase in recharge in the zone of influence of anicuts was 68.5 percent higher than that outside the zone of influence.

Based on satellite imagery, topographical maps and field surveys, more than 2,100 potential anicut sites, under varying land forms in different districts, have been identified (table 6). By constructing anicuts at all these identified locations it is possible to harvest and conserve nearly 25.8 MCM of additional water, from which a population of nearly 470,000 people can benefit by using it both for drinking and limited supplemental irrigation.

Percolation Tanks

Percolation tanks are recharge structures constructed on small streams with adequate catchment for impounding surface runoff. These tanks are used solely for quick recharging of groundwater. Percolation tanks are more efficient than ponds for recharging and conserving water due to low evaporation losses. Selection of suitable sites for the construction of percolation tanks and subsequent maintenance are crucial for their effective functioning.

Under favorable hydrogeological conditions, percolation rates may be increased by constructing recharge (intake) wells within percolation tanks. At the beginning of the first seasonal runoff intake, the rate of percolation is as high as 178 to 166 mm/day, which remains at that level for a day or two, and thereafter the rate of percolation declines drastically due to the deposition of a fine soil matrix on the tank surface.

Studies conducted on artificial recharge through percolation tanks constructed in hard rock and alluvium formations in the Pali district of Rajasthan showed a percolation rate of 14 to 52 mm/day (table 7). Percolation accounted for 65-89 percent losses whereas the evaporation loss was only 11-35 percent of the stored water. The results also indicate that the tanks in a hard rock area contain water for 3-4 months after the receding of the monsoon.

Percolation tanks have been of great benefit in recharging groundwater in the neighboring Gujarat state. There is a huge scope and potential to adopt this technology in western Rajasthan as well, where groundwater depletion is very high. Fifty-four (54) potential sites have been identified for the construction of percolation tanks to add about 2.0 MCM of water to the depleted groundwater aquifer through recharge, and provide sufficient water to meet the domestic water requirement (40 lpcd) of a population of 136,986. Thus percolation tanks hold a great promise for drought mitigation in regions having impermeable strata beneath a sandy profile of limited water holding capacity but high percolation rate.

Table 6. Suitable sites for the construction of anicuts in Rajasthan.

No.	District	Number of suitable sites
1.	Ajmer	49
2.	Alwar	78
3.	Banswara	225
4.	Baran	25
5.	Barmer	22
6.	Bharatpur	15
7.	Bhilwara	100
8.	Bikaner	NA
9.	Bundi	72
10.	Chittorgarh	148
11.	Churu	NA
12.	Dausa	10
13.	Dholpur	15
14.	Dungarpur	176
15.	Ganganagar	NA
16.	Hanumangarh	NA
17.	Jaipur	37
18.	Jaisalmer	NA
19.	Jalor	28
20.	Jhalawar	179
21.	Jhunjhunu	41
22.	Jodhpur	32
23.	Karauli	60
24.	Kota	9
25.	Nagaur	52
26.	Pali	57
27.	Rajsamand	65
28.	Sawai Madhopur	26
29.	Sikar	33
30.	Sirohi	141
31.	Tonk	NA
32.	Udaipur	370
	Total	2,099

Source: CGWA 1999.

Table 7. Percolation and evaporation losses from percolation tanks.

Location of tank	Basin	Formation	Tank capacity (m^3)	Average rate of percolation (mm per day)	Percolation rate (%)	Evaporation (%)
Sablipura	Guriya	Hard rock	35,400	18	77	23
Dhaneri	Lilri	Hard rock	25,700	14	65	35
Sojat	Sukri	Alluvium	3,80,000	52	88	12
Sheopura	Sukri	Alluvium	64,300	38	83	17
Dhabar	Phunpheriya	Alluvium	29,500	33	89	21
Mev	Guhiya	Hard rock	67,000	27	81	29

Subsurface Barriers

Subsurface barrier is the most suitable artificial recharge structure in a sandy bed of an ephemeral desert stream. Since it is constructed below the riverbed on impervious subsurface strata, the structure is secure from floods, does not need elaborate overflow arrangements or periodic desilting and has limited evaporation. The construction needs a concrete or brick masonry wall, 30-60 cm wide, extending down to the impermeable/compact basement. A subsurface barrier may also be constructed with angular rock pieces arranged in the form of a 100 cm wide dry masonry wall or with a 250-micron polyethylene sheeting, properly embedded in the soil. Subsurface barriers within 300 m from the water supply well are enough to store drinking water required for a village with a population of 500 people. As the domestic wells are located in the village, there is a need for constructing these structures close to the villages. One of the structures should be upstream and the other downstream of the village. During the dry season, when the pumping water level in the well is low, the hydraulic gradient is reversed and the water is drawn from the groundwater mound downstream to supply safe drinking water. These structures have been found very promising at Chauri-kalan and Kalawas test sites in the Jodhpur district showing an average annual groundwater rise of 1.2 m and a 40 percent increase in the daily water yield in wells in a 1.5 km^2 area.

In the present study, 128 potential sites for the construction of subsurface barriers were identified using satellite images of February 2003, topographical maps and field surveys. These sites have the potential to contribute 3.68 MCM of water to the groundwater aquifer for drought mitigation. The estimated cost of developing subsurface barriers at all the potential sites will be around US$4.8 million.

Harvesting and Conservation of Flash Floods

Flash floods are extreme hydrological events that occur in response to very high rainfall or a cloudburst of short duration. Their characteristic feature is the overtopping of defined courses of rivers/streams and spreading into flood plains causing colossal damage. Meteorological records show that heavy rainfall once in 4 to 5 years is a common phenomenon in Rajasthan causing localized floods and waterlogging.

Harvesting and conservation of floodwater to rejuvenate depleted high-capacity aquifers by adopting integrated artificial recharge techniques, such as dams, tanks, anicuts, percolation tanks, etc., could improve water availability and create a water buffer to sustain 8-10 droughts in Rajasthan.

Analyses of long-term rainfall data and water balance studies have shown that during a high-magnitude flash flood, 22.6 to 54.8 BCM of excess water is available in the state. Assuming this excess water is harvested and conserved by adopting integrated water management technologies, not only will it minimize the colossal damage to life and property but also work as an underground water bank for drought mitigation for a long time. As discussed above under “Groundwater Resources,” the empty space to store water in potential aquifers in Rajasthan during 1984-2003 was on the order of 55.7 BCM. Thus, if the maximum available flood water, 54.8 BCM, can be managed to recharge groundwater, using all possible recharge technologies listed above, the potential aquifers will be fully saturated. Practically, it is not possible to direct 100 percent of the flash flood water to groundwater. But even the utilization of 10-20 percent of flood water will result in an equal proportion of aquifer replenishment. Similarly, Rajasthan has a high runoff potential in 50 million hectares of rocky/stony terrain, where most of the existing rainwater harvesting structures are located. It has been estimated that at 70 percent rainfall probability there is further scope to harvest and conserve 90-145 MCM runoff annually over the existing storage in the state.

In-situ Water Harvesting and Moisture Conservation

In-situ water harvesting and moisture conservation are field based, low-cost, location-specific soil and water conservation technologies that are highly useful in drought mitigation and in enhancing land productivity.

Contour furrowing is practiced on mild slopes. It is made quite effective by the creation of large numbers of mini-storages across the slope and it alleviates drought.

Contour bunding is recommended for soil and water conservation for rain-fed farming throughout the semiarid region of the country. Their specifications vary depending upon rainfall and soil but were found suitable for sandy soil bunds of 0.3 to 0.6 m height. These bunds are placed in a series from the ridge to the bottom of a valley, one below another, to form terraced slopes with drainage. It was observed that 25 mm of rainwater could be stored in 130-150 mm of soil depth for growing crops. On average, contour bunds had 27 percent higher soil moisture and 14 to 181 percent higher fodder yield than flat surfaces on grasslands of western Rajasthan (Wasi-Ullah et al. 1972).

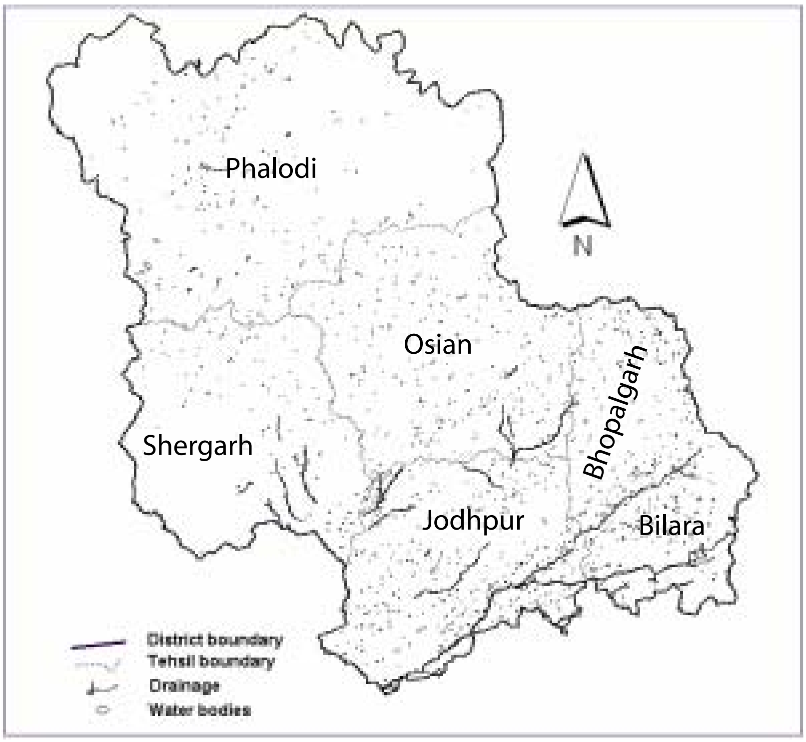
Contour vegetative barriers (CVB) of suitable grass and shrub species are cheap and environmental friendly measures for in-situ soil and water conservation, and to improve land productivity. Locally adapted, native, fast-growing perennial grasses with extensive root systems, such as *Cymbopogon jwarancusa, Cenchrus ciliaris, Cenchrus setigerus* and *Cenchrus munja*, are planted 0.30 m apart on contours at 0.6-1.0 m vertical intervals to form a dense hedge against the slope and convert the area into micro planes to control erosion and conserve soil moisture by checking sheet flow. In a study at CAZRI, it has been observed that with CVB the runoff volume was reduced by 28 to 97 percent and that the soil stored about 2.5 times more moisture than in control sites.

A CASE STUDY: THE JODHPUR DISTRICT

Although the present study was carried out for the entire state of Rajasthan, a more detailed small-scale assessment of water harvesting potential was done for the Jodhpur district. The district (figure 8) is 22,850 km^2 in area and receives an annual rainfall of 350 mm, mainly from June to September. There are 1,060 villages and 4 towns with a total population of 2,880,777 of which 66 percent live in villages (Basic statistics 2003).

The district is covered by hills, rocky pediments, older alluvial plains, interdunal sandy plains and sand dunes. Sand dunes and interdunal plains are located in the northwestern and western parts of the district. The Luni river and its tributary Jojri form a drainage network in the eastern and southeastern parts of the district. These rivers are ephemeral and contribute water to existing reservoirs, tanks, anicuts, etc. during the rainy season. In the rest of the area, only internal drainage exists, emanating from the isolated hills and disappearing in sandy beds.

Figure 8. Water features of the Jodhpur district.



Note: A tehsil is an administrative division comprising several villages.

Among the potential aquifers, the largest area is covered by sandstone (52.52%) followed by older limestone (18.62%), granite (6.28%), older alluvium (4.19%), rhyolite (1.79%), schist and phyllite (1.77%) and younger alluvium (1.63%).

The Jodhpur district is water-scarce and largely dependent on rainfall, with the exception of the city of Jodhpur, which receives water for drinking from the Indira Gandhi lift canal. There are no perennial water sources in rural areas and, therefore, the population has to rely largely on harvested and conserved rainwater. Irrigated agriculture is practiced in fresh groundwater zones.

In the present study, the groundwater status was estimated and the existing rainwater harvesting structures and potential sites for future development were delineated and mapped using 48 topographical maps (1:50,000), IRS satellite data of February 2003 and field verifications. These maps were digitized and processed using Arc GIS 9 software.

Present State of Groundwater

Groundwater is overexploited in the Jodhpur district. Against the annual recharge of 393.13 MCM, the groundwater use is 660.9 MCM, making a negative balance of some 267 MCM of groundwater in the district. Out of the 9 blocks in the district, five have already become an overexploited zone with an annual stage of exploitation of 147 to 286 percent (table 8).

Table 8. Groundwater resources in the Jodhpur district.

Tehsil	Block	Net annual groundwater recharge (MCM)	Annual draft (MCM)	Net groundwater balance (MCM)	Stage of exploitation (%)
Pholodi	Bap	65.71	9.86	55.85	15.00
	Phalodi	51.49	36.42	15.07	70.7
Osian	Osian	69.28	198.30	-129.02	286.2
Shergarh	Shergarh	33.22	26.83	6.39	80.8
	Balasar	19.14	28.30	-9.16	147.9
Bhopalgarh	Bhopalgarh	56.12	149.06	-92.94	265.6
Bilara	Bilara	48.53	138.03	-89.50	284.5
Jodhpur	Luni	22.08	15.02	7.06	68.0
	Mandore	27.57	59.04	-31.47	214.1
Total		393.13	660.87	(-)267.77	168.1

Water Balance

An understanding of the water balance of a region is essential to account for the different components of water input and output and for reliable water resources planning. Based on available information on rainfall, surface water resources, groundwater extraction and recharge, and water use by crops and trees, it is possible to work out the approximate water balance of a basin or a region. Several procedures of water accounting are available in the literature, but we have followed Molden's water accounting procedures (Molden and Sakthivadivel 1999) for a normal rainfall year for the Jodhpur district (table 9).

In this case, precipitation (7,997.5 MCM) constitutes the major component of gross inflow, while the committed annual canal inflow to Jodhpur is 82.9 MCM and the basin inflow is 2.7 MCM, making a net inflow of 8,349 MCM. Annual groundwater extraction is 660.87 MCM against a recharge of 393.13 MCM, making a negative balance of 267.77 MCM, which has been added to the gross inflow. As suggested by Molden, the depleted water has been classified into the categories, processes, beneficial non-processes, and non-beneficial non-processes. Process beneficial water accounts for 4,171.9 MCM of which water use by crops and trees is 4,052.96 MCM, whereas domestic and industrial uses are 118.9 MCM. Water use by plants has been worked out by taking the average evapotranspiration (ET) of crops and trees. The non-beneficial water through evaporation losses from catchment and soil storage accounts for half of the total depletion. This may be associated with sandy morphology, short crop duration and a prolonged dry period. Outflow from the district boundary is nil except for a meager (1.8 MCM) non-utilizable flow. However, during some years there is no basin inflow or outflow.

The different components of water balancing suggest that strategic efforts should be aimed at reducing the withdrawal of groundwater on the input end—economizing on the non-beneficial use of water, which forms a major component in arid region—and the output end—maintaining equilibrium and enhancing economic productivity of the precious water resources.

Table 9. Water accounting components of the Jodhpur district (MCM).

Description	Total	Part
Gross inflow	8,083.10	
Surface diversion (Indira Gandhi Canal water from Punjab)		82.9
Precipitation		7,997.5
River inflow		2.7
Subsurface inflow		0
Storage change	-267.77	
Surface storage		0
Subsurface storage (groundwater)		-267.77
Net inflow	8,350.87	
Depletion Process	4,171.86	
Irrigation – Crop and tree ET		4,052.96
Domestic and industrial use		118.90
Non-process, non beneficial		
Irrigation flows to sink		0
Non-process, beneficial		
Home gardens		0
Beneficial	4,171.86	
Non-beneficial (Evaporation from catchment storage plus soil storage)	4,179.01	
Outflow		
Committed outflow for downstream water right		0
Committed outflow for environment		0
Uncommitted outflow: Utilizable		0
Nonutilizable		1.80
Available water at district level (net, committed, non-utilizable)	8,349.07	

Note: ET = evapotranspiration.

Water Resources Potential

The water demand of the Jodhpur district for irrigation and domestic use during normal rainfall, moderate drought and severe drought years (table 10), based on the long-term analysis of data, reveals that—with the existing rainwater harvesting structures and excluding seepage and evaporation losses—the net availability of water resources is 111.17 MCM, 68.35 MCM and 53.47 MCM during a normal rainfall year, a moderate drought year and a severe drought year, respectively. However, with further development of the proposed structures at potential sites (some of them are shown in figure 8 and given in table 10) the net availability will increase to 146.46 MCM, 92.25 MCM and 68.05 MCM, respectively. It has been observed that during moderate drought and severe drought years there is an average reduction in water availability of 60 percent and 40 percent, respectively. Our findings suggest that during moderate droughts over 90 percent of the demand for drinking water can be met with the available water in the structures, whereas during severe droughts nearly 68 percent of the demand could be met. Additional requirements for drinking water have to be supplemented through groundwater resources or outsourcing from adjoining regions.

Table 10. Water potential of the Jodhpur district.

Water resources	Net available water (MCM)		
	Normal rainfall year	Moderate drought year	Severe drought year
Rainwater harvesting structures			
Existing			
Tanks and reservoirs (4)	64.40	42.64	37.88
Nadis (2,120)	31.80	19.08	12.72
Tankas (107,870)	1.62	1.62	0.90
Khadins (131 nos. 1,452 ha)	11.80	4.08	1.50
Anicuts (62)	1.55	0.93	0.47
Subtotal	111.17	68.35	53.47
Proposed			
Nadis (332)	19.08	11.45	7.63
Tankas (12,250)	0.25	0.25	0.25
Khadins (160)	14.20	10.70	5.80
Anicuts (32)	0.96	0.80	0.38
Subsurface barriers (20)	0.80	0.70	0.52
Subtotal	35.29	23.90	14.58
Total	146.46	92.25	68.05
Groundwater resources (annual recharge)	393.13	235.88	157.25
Present water exploitation			
a) Irrigation	555.80	555.80	555.80
b) Domestic and other uses	105.07	105.07	105.07
Total	660.87	660.87	660.87

It is further estimated that the total utilization of groundwater in Jodhpur is around 661 MCM annually, against a recharge of 393 MCM in a normal rainfall year, 236 MCM in a moderate drought year and 157 MCM in a severe drought year. Overall, an estimated 7,514 MCM of net storage has been created since 1984, which may be filled by adopting groundwater recharge technologies, such as percolation tanks, subsurface barriers, ponds with infiltration and injection wells, augmentation in normal years and arresting floods.

CONCLUSIONS AND RECOMMENDATIONS

Issues related to water management in Rajasthan are highly complex and need to be resolved through the involvement of government departments, research institutions, NGOs and other stakeholders. The present study is an effort to assess the available water resources, current demand and future projection and technological options for water management to improve water availability and management efficiency for various uses and mitigate droughts. Conclusions and points for future action are summarized below.

- The estimated internal surface water resources in Rajasthan are around 48 BCM. However, the assured availability is only 14-22 BCM, which is drastically reduced during drought years. In addition, 17.9 BCM of water is available through inter-basin water transfer of the Indira Gandhi Canal Project (IGNP), partially serving six districts.

- Increasing demand for water and shortfalls in surface water resources have put tremendous pressure on groundwater. At present, with intensive well irrigation and domestic water needs, the annual groundwater exploitation is 11.63 BCM, which is much more than the recharge. It is estimated that in the last 20 years, nearly 55.7 BCM of the nonrenewable water reserve has been exploited. If the present trend continues, it will be difficult to meet the water requirements of the future generations, especially during drought years.

- The current rate of annual exploitation of groundwater is 476 MCM. On average, there are severe or moderate floods once in 5 years, and even if 10 percent of flood water is diverted to groundwater, it will make up for the aquifer exploitation of 5 years at the current rate. This may be achieved by adopting large-scale groundwater recharge programs with a predefined time frame.

- The traditional systems of water harvesting, like the bawari, jhalara, nadi, tanka, khadin, etc., prevalent in the region over centuries, are still viable and cost-effective. If these systems are improved and utilized on a large scale, they can meet the requirements of drinking water of the rural population and mitigate the drought impact at least partially. In addition, modern rainwater technologies, such as anicuts, percolation tanks, injection wells and subsurface barriers, are highly effective in rejuvenating depleted groundwater aquifers. With the existing and proposed rainwater harvesting structures in the Jodhpur district, over 68 MCM of water will be available even during severe droughts, which may suffice to meet nearly 69 percent of the requirements of drinking water in villages.

- Water and soil conservation through agronomic and engineering measures need to be integrated. Other measures of water conservation like contour cultivation, different kinds of bunding, bench terracing in conjunction with cover cropping and appropriate land-use practices enhance water conservation and productivity and also recharge the aquifer over a long period. They have to receive more focus in an integrated fashion.

- The water sector is administered by several government departments and organizations and, therefore, there is a need for an appropriate water policy and institutional arrangements for coordination in the management of water resources for both livelihood security and drought mitigation. The role and responsibilities of these organizations should be clearly defined to avoid overlap and to ensure active management of water resources at all levels. Active participation of stakeholders and local elected bodies in water management should be ensured for its successful implementation.

- Inter-basin water transfer, though expensive, is a permanent solution to the desertification of water-scarce regions, at least in India. Policies need to be developed and executed to interlink rivers for water transfer to the drought-prone regions of western Rajasthan. At present only a small parts of the state is served through inter-basin water transfer.

- Drought is a phenomenon having many facets although water is the most crucial factor in its mitigation. Huge funds are made available as drought relief to make provisions of water, food and fodder, for income generation, etc. Policies should be enacted to develop water resource structures on a permanent basis. As estimated, all the drought-relief funds for a drought year may be enough to develop rainwater harvesting structures that could provide at least drinking water to all in drought-vulnerable western Rajasthan.

- Land-use systems should match water availability. Therefore, there is a need for the continuous education of farmers in order to adopt water efficient practices, low water requiring crops, conservation irrigation and deficit irrigation, to economize and save more water.

- More detailed research needs to be conducted to quantify natural groundwater recharge processes in different parts of the state and to define safe limits for groundwater use.

- The issue of water management and drought proofing should be tackled by adopting suitable policies with the involvement of government organization, NGOs and the public, with people participating voluntarily. A consortium approach should be adopted for the management of water and drought. A sound drought mitigation policy for vulnerable regions needs to be designed and implemented.

- In Rajasthan, particularly in the western region, data on hydrological processes at field, basin, region and state level are sparse and, in many areas, doubtful. Therefore, there is a need for extensive data collection through hydrological instrumentation. Efforts should be made to develop suitable hydrological and water resource models for the prediction and utilization of water resources.

- There is long-felt need to develop a strong network to share the limited database for better planning and management of water resources in drought-prone regions. Efforts of the International Water Management Institute (IWMI) in this direction are a welcome step.

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