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# Groundwater resources assessment of the Koyna River basin, India

Pradeep K. Naik · Arun K. Awasthi

**Abstract** The Western Ghats (hills) region of the Indian peninsula in western India receives heavy precipitation (4,000–6,000 mm/year), but the headwater basins that coalesce runoff from these hills retain very small quantities of water due to the steep topography. However, the narrow valleys in these hills support agriculture based on surface water irrigation, and several medium to large irrigation projects have already been constructed with well-defined canal networks. These developments have boosted agricultural productivity in the region, but at the same time they are causing an economic disparity between the command areas (irrigated by these canals) and non-command areas. Water-logging problems are also occurring in low-lying areas. While these problems are mainly due to poor groundwater management strategies in the region, the groundwater resources in these headwater basins should be properly assessed and suitable measures taken for uniform groundwater development. As a first step in this direction, groundwater resources have been assessed as a case study for the lower Koyna River basin, a head water basin on the east of the main ridge of the Western Ghats.

Regional specific yield (0.012) and groundwater recharge have been estimated on the basis of water table fluctuation method. Groundwater recharge amounting to 57 MCM (million m<sup>3</sup>) in a year takes place in the region through vertical percolation of rainwater (31 MCM), return flow of water applied for irrigation (23 MCM), and recharge due to surface water tanks (3 MCM). Recharge to deeper aquifers has been estimated at 1 MCM during

dry seasons (November–May). Safe yield has been estimated at 58 MCM annually which includes the present groundwater draft by wells for domestic, stock, and irrigational needs estimated at 16.50 MCM per year and the natural losses from the groundwater system which are mostly baseflow and spring discharges amounting to 38 MCM (35 MCM baseflow + 3 MCM spring flow) per year, out of which 7 MCM is already being directly pumped from the tributaries of the Koyna River for irrigational needs. Thus, there remains a balance of only 3.5 MCM of groundwater for further groundwater development. Assuming that at least 25% (7 MCM) of the unutilized baseflow (28 MCM) can be brought to fruitful use, about 10.5 MCM (7+3.5 MCM) of groundwater can be used in the existing hydrogeological environment through about 500 additional wells.

**Résumé** La région des Collines occidentales (Western Ghats) de la péninsule indienne en Inde occidentale reçoit de fortes précipitations (4.000–6.000 mm/an); mais les bassins situés en tête qui convergent dans ces collines retiennent très peu d'eaux souterraines du fait des mauvaises conditions de pente en surface. Les vallées étroites dans ces collines offrent de larges espaces pour la mise en valeur des eaux de surface, en sorte que plusieurs projets d'irrigation moyens ou importants ont déjà été réalisés dans ces régions avec un réseau bien défini de canaux. Cette mise en valeur a réellement poussé la productivité agricole de la région, mais en même temps elle produit aussi une disparité économique entre les régions desservies (zones irriguées par ces canaux) et non desservies. Des problèmes relatifs à l'eau se posent également dans les zones basses. Alors que ces problèmes sont surtout dus à de médiocres stratégies de gestion dans la région, il est recommandé que les ressources en eaux souterraines dans ces bassins en tête soient correctement évaluées et que des mesures adéquates soient prises en vue d'une mise en valeur uniforme des eaux souterraines. À titre de première étape dans cette direction, les ressources en eaux souterraines ont été évaluées lors d'une étude de cas du bassin de la rivière Koyna, un bassin de tête situé à l'est de la chaîne principale des Collines Occidentales. Tous les paramètres d'entrée et de sortie ont été estimés et un bilan a été réalisé entre ces deux composantes. Les ressources statiques et dynamiques en eaux souterraines ont été estimées et un

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rendement sûr a été déterminé pour le bassin de la rivière Koyna en aval du barrage de Koyna.

**Resumen** La región de las montañas de Western Ghats, al Oeste de la Península India, registra elevados valores de precipitación (de 4.000 a 6.000 mm/a), pero las condiciones topográficas de dichas montañas no permiten la existencia de acuíferos de entidad suficiente para albergar volúmenes grandes de aguas subterráneas. Los valles estrechos de las montañas sí permiten el desarrollo de las aguas superficiales, de manea que se ha realizado varios proyectos medianos y grandes de riego mediante redes de canales bien definidas. Estos desarrollos han propiciado un aumento de la producción agrícola en la región, pero, a la vez, se ha agudizado las diferencias económicas entre las zonas regadas y las no regadas. Además, las depresiones topográficas están padeciendo problemas de inundación. Como estos problemas son principalmente debidos a estrategias deficientes de gestión de las aguas subterráneas, se recomienda que los recursos subterráneos de las cuencas de cabecera sean adecuadamente determinados, y que se adopte medidas apropiadas para desarrollarlos uniformemente. El primer paso ha consistido en determinar los recursos subterráneos de la cabecera del río Koynam, situada al Este de la Sierra principal de los Western Ghats. Se ha estimado todos los parámetros de recarga y descarga, así como los recursos renovables, en la cuenca del río Koyna ubicada aguas debajo de la presa de Koyna.

**Keywords** Western Ghats · Groundwater resources assessment · Groundwater recharge · Groundwater discharge · Specific yield · Groundwater development · Safe yield

## Introduction

Groundwater resources development occupies a key place in the irrigation sector in India because of its role in stabilizing Indian agriculture. Starting with only 6.5 million ha in 1950–51 (Central Ground Water Board 1992), groundwater irrigation has increased to 46.5 million ha today (Sivanappan 2002), meeting about 50% of the irrigation water requirements of the country. With about 700 million people sustaining their livelihood through agriculture in India (Swaminathan 2002), dependence on groundwater has recently increased due to the introduction of high-yielding varieties of crops and adoption of multi-cropping patterns, both of which require a timely, assured water supply. This reliability on groundwater as the most dependable source for irrigation has led to its overexploitation in most parts of the country, in both hard rock terrains and alluvial areas. The Western Ghats (hills) region of the Indian peninsula falling in the Deccan Plateau of western India is no exception. Trending generally north–south, these hills extend for a distance of 1,600 km with an average elevation of 1,000–1,300 m above mean sea level (a.m.s.l.) (Krishnan 1982). They

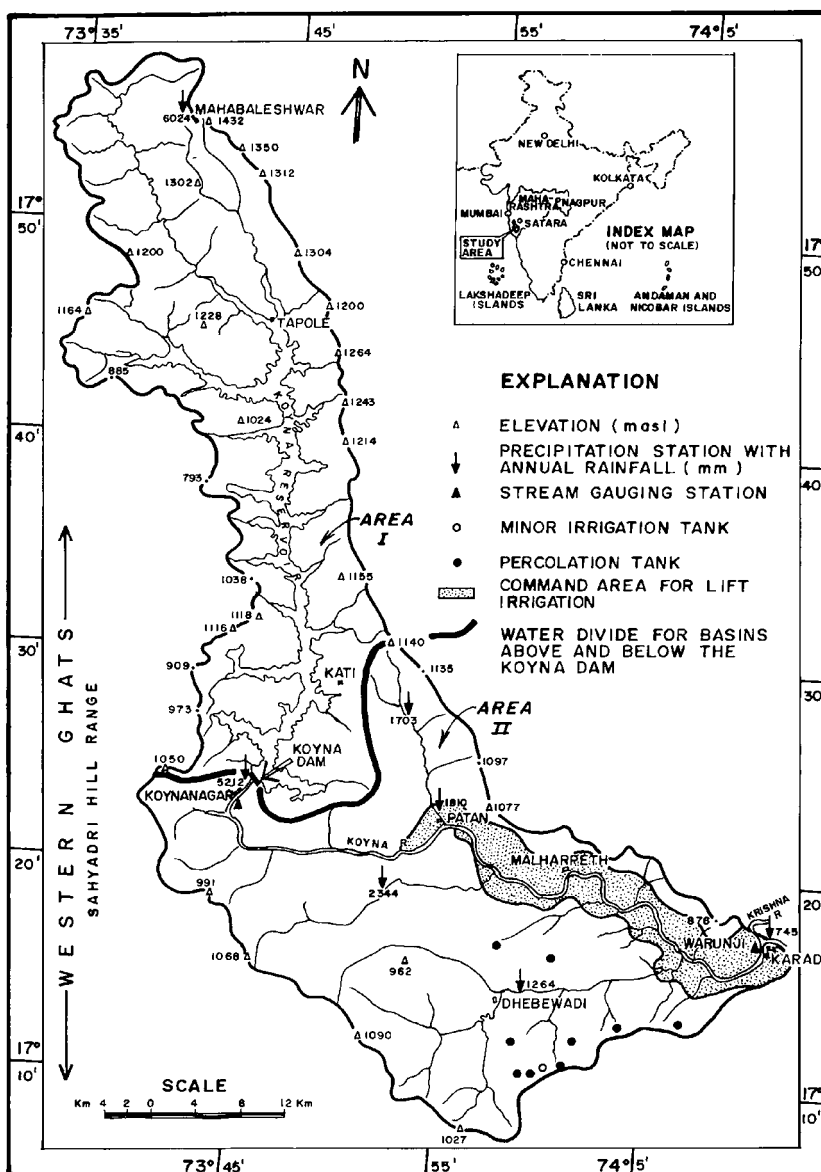
receive rainfall of about 4,000–6,000 mm annually. However, the headwater basins that coalesce runoff from these hills retain very small quantities of water due to the steep topography. Dugwells (large-diameter manually dug wells) and borewells constructed in these basins go dry long before the arrival of summer. However, the narrow winding valleys, especially in their upper reaches, offer ample opportunity for construction of small- to large-sized dams for retention of surface runoff. Several irrigation projects have already been constructed in these areas in recent years, and irrigation is practiced through canal systems in these projects. Agricultural productivity has dramatically increased. Areas that were once dry or could sustain only one seasonal crop are now full of lush greenery throughout the year. Cash crops such as sugarcane that need continuous watering for a prolonged period have become the favorable crops.

However, these developments have two side effects: (1) there is a growing economic disparity in the region; farmers in the canal command areas (areas irrigated by these canals) are prospering while their counterparts in the non-command areas are still very poor, and (2) because canal water is available at cheap rates, often subsidized by the government, farmers tend to rely more on surface water than on groundwater. As a result, many low-lying areas are being waterlogged due to overapplication of water. These issues call for better water resources management including augmentation of groundwater in the water-scarce areas through artificial recharge measures. However, these tasks are not very easy to practice and cannot be effective unless all recharge and discharge parameters are evaluated and a detailed assessment of the available groundwater resources is made. With these objectives, such an assessment of the groundwater resources of the Koyna River basin has been carried out as a case study. The Koyna River basin is a head-water basin on the east side of the main ridge of the Western Ghats, locally called the Sahyadri hill ranges, in the district of Satara, Maharashtra state, India. Locations of the basin and data collection sites are shown in Fig. 1.

The Koyna River basin with a geographical area of 2,036 km<sup>2</sup> represents a typical physiographic setting characteristic of the Deccan Plateau. The Koyna River flows from north to south for a distance of about 65 km, while other rivers originating from the Western Ghats flow from east to west or west to east. Before it takes an eastward turn to join the River Krishna, it is dammed by the Koyna Dam at Koynanagar which forms the Shivsagar reservoir, popularly known as the 'Koyna reservoir' (Fig. 1). The Koyna River basin is well drained, characterized by substantial surface runoff, a large gradient, a low rate of infiltration, and consequently limited groundwater recharge. Naik et al. (2001) give a detailed account of the basin.

Dugwells in the Koyna River basin are commonly used for drinking and irrigation purposes. Borewells are exclusively used for drinking purposes. At higher elevations, people rely mostly on natural springs. Water is released periodically (usually twice in a month) from the

**Fig. 1** Location of the Koyna River basin, India, and data collection sites



Koyna reservoir. This practice has made the Koyna mainstem a perennial river, whereas its tributaries are mostly ephemeral. Thus, various lift irrigation schemes have developed along the Koyna River defining a distinct zone of irrigation (command area) in the central valley (Fig. 1).

The Koyna dam divides the Koyna River basin into two parts—area I and area II—upstream and downstream of the dam respectively (Fig. 1). Area I, with an areal extent of 954 km<sup>2</sup>, covers the entire catchment area of the Koyna dam and is mostly hilly. People in this area depend exclusively on springs for drinking and irrigation purposes. The spring discharges in this area are estimated at 8 MCM (million m<sup>3</sup>) annually (Naik et al. 2001). Area II covers 1,082 km<sup>2</sup> and has a broad valley oriented in an east–west direction. This part can be divided into three distinct zones: (1) spring recharge areas (321 km<sup>2</sup>), (2) steeply sloping ground (185 km<sup>2</sup>), and (3) a plain area

including the dissected plateau in the foothill zones (576 km<sup>2</sup>). The third zone forms the central valley of the Koyna River basin. Groundwater development through dugwells and borewells is practiced in this zone only.

Area II is characterized by both abundance and scarcity of groundwater—abundance in the command areas and scarcity in the dissected plateaus in the foothill zones. The issues involved in the optimal groundwater development in the area are (1) water scarcity in the dissected plateau, a direct function of lack of saturation of the aquifers, owing to the rocks being well drained, and (2) abundance in the central valley because of its location in the discharge area of the basin and abundant irrigation which causes high groundwater levels. Countering these challenges is a very difficult task and needs systematic integrated water resources assessment and development.

The objective of this paper is to summarize a groundwater resources assessment for area II of the

Koyna River basin. Groundwater discharges and recharges from various sources for the water years 1988–89 and 1992–93 (May to May of the following year) have been estimated. A groundwater balance has been made considering all inputs (recharges) and outputs (discharges). Static and exploitable dynamic groundwater reserves have been estimated, and finally a “safe yield” has been determined for the Koyna River basin. All these assessments have been made only for the shallow unconfined aquifers. Naik et al. (2001) define the aquifers above a depth of 30 m as shallow aquifers in this river basin.

## Climate

The Koyna River basin has a subtropical monsoon type of climate. The Indian monsoon lasts from June to October and brings about 88% of the annual rainfall. The winter season is from November to February, and the summer extends from March to May. The winter brings about 8% of the annual rainfall and the summer about 4%. There is a systematic variation in the distribution of rainfall in the area due to orographic influence of the Western Ghats. The annual rainfall decreases steadily from the western to the eastern areas. Highest annual average rainfall is recorded at Mahabaleswar (6,024 mm) in the north whereas the lowest is received at Karad (745 mm) in the east (Fig. 1). January is the coldest month and daily mean monthly minimum temperature ranges from 10–14 °C. May is the hottest month; the daily mean monthly maximum temperature ranges from 31–37 °C.

## Hydrogeology

Aquifers in the Koyna River basin are classified as shallow and deep aquifers. Dugwells are mostly 2–14 m deep, and rarely go to 25 m deep. Diameters range from 2–10 m; 50% of them have a diameter of 2–4 m. The borewells, mostly 150 mm in diameter, are generally 30–90 m deep; most of them are 50–70 m deep. The dugwells thus tap shallow aquifers (<30 m), and the borewells the deeper aquifers (>30 m).

Geologically, the Koyna River basin consists of basaltic lava flows of late Cretaceous to lower Eocene age. Some of the basaltic flows are lateritized at their tops locally, and are potentially saturated. The laterites have a thickness of about 12–30 m in the eastern and northern parts and about 2–5 m in the southern parts. Alluvium of the Koyna River is localized in the valley sections. Eighty eight percent of dugwells tap shallow basaltic aquifers, and about 12% tap laterites, alluvium, and talus deposits. Thus, laterites, alluvium, and talus deposits are of secondary importance compared to the basaltic aquifers. Groundwater generally occurs under water table conditions in shallow aquifers.

Each basaltic flow consists of two main trap units: (1) a lower massive unit and (2) an upper vesicular unit. The

massive unit constitutes the main trap unit and forms 60–85% of the basaltic flows. It is mostly fine-grained, dense, compact, and greenish to dark gray in color. The massive unit possesses negligible primary porosity or permeability, and generally acts as an impermeable bed. However, the process of weathering and the occurrence of joints and fractures at places make it moderately permeable. It occasionally exhibits columnar and spheroidal structures and often shows well-developed joints. The vesicular unit forms the upper horizon of each basaltic flow and constitutes 15–40% of the flows. The vesicular unit is weathered in most parts and possesses primary porosity. Generally, the consecutive lava flows are separated by a weathered red layer called ‘redbole’, varying in thickness from 0.20–1.30 m. Redboles have low permeability.

Depths to water levels (DTW) were recorded at 42 representative wells in 1988 and 47 representative wells in 1992 during pre-monsoon and post-monsoon periods. DTW ranged between 0.38 and 9 m b.g.l. (meters below ground level) during the pre-monsoon period and 0.05 and 4.80 m b.g.l. during the post-monsoon period in 1988. In 1992, these ranges were 0.74–11.60 and 0.70–4.25 m b.g.l. respectively. The seasonal fluctuations ranged from 0.14–5.47 and 0.06–7.60 m during 1988 and 1992 respectively. Naik et al. (2001) give a detailed analysis of the groundwater levels in the area. On the basis of the long-term trends, it was concluded that the groundwater levels are rising in the command areas and declining in the non-command areas in both pre- and post-monsoon periods.

## Groundwater Discharge

The total amount of groundwater withdrawn artificially or naturally from aquifers is termed groundwater discharge (Central Ground Water Board 1984a). The artificial withdrawal of groundwater from shallow aquifers is by means of dugwells fitted with some water lifting devices, such as buckets and electric- or diesel-powered pumps. These withdrawals are mainly for domestic and agricultural purposes. The natural discharges of groundwater are by evapotranspirational losses and baseflow.

### Artificial Groundwater Discharge

#### *Domestic/stock needs*

Total human and stock populations that depend solely on groundwater are about 300,000 and 100,000 respectively. The Government of India recommends water consumption of about 40 l/day (or 14.6 m<sup>3</sup>/year) per person in the rural areas where house service connections are not contemplated and the water supply is through borewells/dugwells, and 50 l/day (or 18.25 m<sup>3</sup>/year) per animal (Central Ground Water Board 1984a). Based on these statistics, total yearly consumption of groundwater in the area is estimated as 4.38 MCM for human population and 1.82 MCM for stock population, or a total consumption of 6.20 MCM annually.

**Table 1** Estimation of baseflow (in MCM) for area II (1988–89)

Date	Stream flow (Koynanagar) (A)	Stream flow (Warunji) (C)	Water applied for irrigation (B)	Baseflow
November 1988	80.20	85.54	61.08 (Nov–May)	$C-(A-B)=585.5-(609.67-61.08)=585.49-548.59=37$ , less 30%=26 MCM <sup>a</sup>
December 1988	62.18	61.20		
January 1989	61.38	57.02		
February 1989	102.59	98.16		
March 1989	119.21	111.77		
April 1989	84.29	72.89		
May 1989	99.82	98.91		
Total	609.67	585.49	61.08	

<sup>a</sup> See Eq. 1 in text

**Table 2** Estimation of baseflow (in MCM) for area II (1992–93)

Date	Stream flow (Koynanagar) (A)	Stream flow (Warunji) (C)	Water applied for irrigation (B)	Baseflow
November 1991	85.80	59.62	61.08 (Nov–May)	$C-(A-B)=863.50-(881.07-61.08)=863.50-819.99=43$ , less 30%=30 MCM <sup>a</sup>
December 1991	129.31	111.66		
January 1992	163.32	169.67		
February 1992	172.39	171.64		
March 1992	172.42	184.06		
April 1992	94.56	91.29		
May 1992	63.27	75.56		
Total	881.07	863.50	61.08	

<sup>a</sup> See Eq. 1 in text

#### *Groundwater draft through wells*

Groundwater is abstracted for irrigation purposes during dry seasons from dugwells using a variety of pumping devices. Diesel-driven centrifugal pumps of 5 hp (horse power) are used in remote areas, whereas in the areas having good infrastructure for electricity 3- to 5-hp electric-driven centrifugal pumps are used. On the basis of a number of field tests, the average yield per well has been taken as 30 m<sup>3</sup>/h. For an average pumping duration of 8 h/day in the Koyna command areas by about 300 dugwells and 5 h/day in the non-command areas by about 450 dugwells, and 60 typical pumping days in the winter (November to February), the groundwater draft is estimated at 4.32 and 4.05 MCM respectively for the command and non-command areas. In the summer, groundwater extraction is negligible in the non-command areas while in the command areas the extraction is on an average of 5 h/day. For 45 typical summer pumping days, the groundwater extraction is estimated at 2.03 MCM in these areas. Thus, in total, an estimated 10.40 MCM of groundwater is withdrawn annually through wells in the Koyna River basin.

#### *Use of baseflow for irrigation from the Koyna River tributaries*

The Koyna River tributaries are ephemeral and dry up by the middle of March. Hence, baseflow from these

tributaries sustain only winter crops (rabi crops). As per the well census data collected from local authorities, streamflow is withdrawn by about 500 mobile pump sets from the Koyna tributaries. These pumps run for about 8 h/day at an average rate of 30 m<sup>3</sup>/h for about 60 days/year. Thus, the total yearly consumption of baseflow from these tributaries is estimated as 7.20 MCM. Direct withdrawal of water from the Koyna mainstem by individual farmers is legally prohibited, and is done only on a co-operative basis through several lift-irrigation schemes.

#### *Natural groundwater discharge*

The major sources of natural groundwater discharges are: (1) baseflow, (2) evapotranspirational losses, (3) spring discharges, (4) sub-surface outflow, and (5) leakage from shallow aquifers to deeper aquifers. The sub-surface outflow from the Koyna River basin to the adjoining basins is considered negligible at shallower level. Leakage to deeper aquifers is discussed in the following section on groundwater balance.

#### *Estimation of baseflow*

There are two river gauging stations along the Koyna River—one situated below the Koyna dam at Koynanagar and another at Warunji before the Koyna meets the river

**Table 3** Water requirements of crops in command area of the Koyna lift-irrigation schemes. [After Water and Land Management Institute (1987)]

Season (no. of days: months)	Name of crop	Area irrigated (ha)	Interval of irrigation (days)	No. of waterings	Depth of watering (cm)	Volume of water required	
						(ha cm)	(MCM)
Kharif (90 days: July to September)	Sugarcane	1,091	12	4	7.5	32,730	3.27
	Jowar (sorghum) (1 July–31 Oct)	6,181	30	2	7.5	92,715	9.27
Rabi (150 days: October to February)	Sugarcane	1,091	12	12	9.0	117,828	11.78
	Wheat (hybrid variety) (16 Nov–15 March)	1,854	12	10	7.5	139,050	13.90
	Hybrid jowar (sorghum) (1 Oct–28 Feb)	4,327	15	10	7.5	324,525	32.45
Hot weather (120 days: March to June)	Sugarcane	1,091	10	12	12.0	157,104	15.71
Total							86.38

Krishna (Fig. 1). While the station at Koynanagar measures the released water from the Koyna dam, the one at Warunji measures the runoff from area II including the released water from the dam.

Baseflow is usually estimated with the help of streamflow hydrographs. However, the streamflow hydrograph at Warunji does not represent the true flow of the Koyna River. Moreover, huge quantities of water are abstracted from the Koyna River by lift-irrigation schemes, further compounding the problem. Therefore, a different technique has been adopted for baseflow estimation in the Koyna River in area II.

The Koyna catchment has some runoff up to the month of October. From November onwards until May the streamflow in the Koyna River is due to baseflow. Here, if the monthly river discharge at Warunji is deducted from that of the Koynanagar, it gives an estimate of the baseflow found in the Koyna River and its tributaries in area II. However, there are months, as shown in Tables 1 and 2, when the river discharge at Warunji is less than that of the Koynanagar. This gives an impression that the Koyna River is a losing stream. This can happen due to: (1) the streamflow contributing to the groundwater table or seeping through its banks, (2) the streamflow leaking to deeper aquifers, or (3) artificial withdrawal of streamflow. The first case is unlikely since the groundwater table is shallower than the Koyna River bed (Naik et al. 2001). The second case may be true since the Koyna flows over several lineaments (Naik et al. 2001), although no major faults have been detected. Even if such type of seepage occurs, it may be minimal (discussed in the section on groundwater balance) and may be neglected. The third case is true since there are numerous lift irrigation schemes withdrawing water from the Koyna River for irrigation purposes. These withdrawals have been estimated on a seasonal basis (Table 3) on the basis of the water requirements of crops. Based on this table, estimates of the monthly water requirements of crops have been estimated and are given in Table 4. It is found that a quantity of 61 MCM of water in total is extracted from the Koyna River after the month of October until May. Thus, from the monthly Koynanagar discharge (A), if the monthly abstraction of water (B) is deducted, since A is always greater than B, and the monthly value obtained is deducted again from the monthly Warunji discharge (C), the baseflow ( $RO_{bf}$ ) found in the river is obtained for every month (Table 4). This relationship can be expressed in the form of an equation:

$$RO_{bf} = C - (A - B) \quad (1)$$

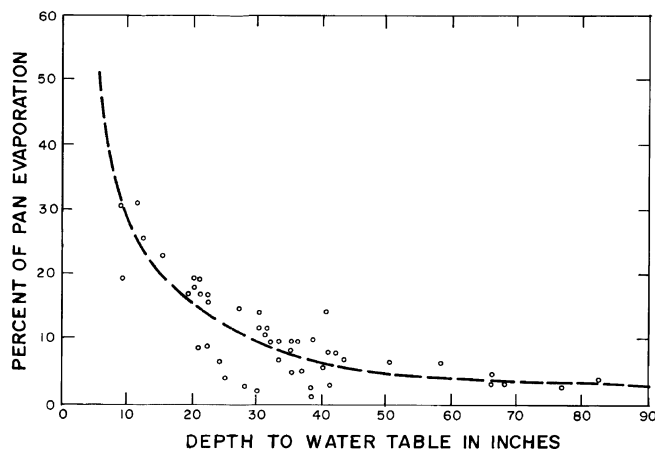
However, after doing all the monthly calculations, it is still found that in some months the baseflow has a negative value. For example, in the water year 1988–89 (Table 1), the baseflow for the month of March is  $-1.77$ , i.e.,  $[111.77 - (119.21 - 5.67) \text{ MCM} = -1.77 \text{ MCM}]$ . This shows that in some months the volume of streamflow extracted from the river is greater than the baseflow component. Such cases in some months may also be

**Table 4** Monthly water requirements of crops (in MCM) during rabi (winter) and hot weather seasons. Total water requirement from November to May is estimated as 61.08 or 61 MCM

Crop	Oct	Nov	Dec	Jan	Feb	March	April	May	June	Total
Sugarcane (perennial)	2.36	2.36	2.36	2.36	2.36	3.93	3.93	3.93	3.93	27.52
Wheat (hybrid variety) (mid-Nov to mid-March)	–	1.74	3.47	3.47	3.47	1.74	–	–	–	13.89
Hybrid jowar (sorghum) (Oct–Feb)	6.49	6.49	6.49	6.49	6.49	–	–	–	–	32.45
Total	8.85	10.59	12.32	12.32	12.32	5.67	3.93	3.93	3.93	

happening because while estimating monthly water usages, the total water requirement in a season has been distributed equally among the concerned months depending on the crops and their growing periods. In some months the interval of watering may be two and in some months three, thus bringing some error in the estimation of water requirement in a particular month. For example, wheat needs 10 waterings at an interval of 12 days from the middle of November until the middle of March (Table 3). If the first watering is done on 16 November on the sowing day, it needs two waterings in November (16 and 28 November), two waterings in December (9 and 21 December), three waterings in January (2, 14, and 26 January), two waterings in February (7 and 19 February), and only one watering in March (3 March) before it is ideally harvested on 15 March. Also, surface water availability is not very regular in the command area. Due to all these considerations, taking a certain number of waterings in a calendar month will be illogical. Therefore, to simplify the procedure and avoid erroneous results, the total of the monthly discharges at Koynanager (A) from the month of November to May has been deducted from the total water abstracted from the Koyna River (B) for these months, and the resulting figure has again been deducted from the total of monthly discharges at Warunji (C) for these months (Tables 1 and 2). Using this procedure, the provisional baseflows for the water years 1988–89 and 1992–93 are estimated as 37 and 43 MCM respectively. However, communication with the officials of the Command Area Development Agency at Karad reveals that at least 30% of the water lifted from the Koyna River flows back to the river as excess water through a number of small surface channels. This happens because of the flooding method of irrigation adopted by the farmers. Sometimes farmers have to wait for a long period for their turn to come for irrigation, and whenever their turn comes they apply as much water as their fields permit. In some cases, water is lifted at night and during this time there is no control over irrigation. Therefore, about 70% of the baseflow estimated by the water requirement method has been taken as the actual baseflow contributed by the groundwater system. Thus, the estimated baseflow comes to about 26 MCM for the water year 1988–89 and 30 MCM for the water year 1992–93, and 28 MCM in average. This is the amount of baseflow actually unutilized and flowing in the Koyna River.

It has been estimated in the previous section that 7.20 MCM of baseflow is lifted for irrigation purposes

**Fig. 2** Percent of pan evaporation with respect to depth to water table. [After White (1932)]

from the tributaries of the Koyna River. Thus, the total amount of baseflow in the Koyna River is estimated as 33.20 MCM (26+7.20 MCM) for the water year 1988–89 and 37.20 MCM (30+7.20 MCM) for the water year 1992–93. The average baseflow has, therefore, been taken as 35 MCM annually for the Koyna River downstream of the Koyna dam in area II. Such a high amount of baseflow from an area of 1,082 km<sup>2</sup> may be attributed to the large quantity of surface water (61 MCM) lifted and applied for irrigation that actually returns to the Koyna River in the form of baseflow.

#### *Estimation of evapotranspiration from groundwater*

Aquifers with a water table near ground surface frequently exhibit diurnal fluctuations, which can be ascribed to evaporation and/or transpiration. Both processes cause discharge of groundwater into the atmosphere and have nearly the same diurnal variations as both are related to temperature variations. White (1932) measured groundwater evaporation in tanks filled with soils ranging from clays to loams. Based on his results, evaporation is comparatively high, as shown in Fig. 2, for water tables less than 0.3 m b.g.l., it is low for water tables up to about 1 m b.g.l., and it further decreases and becomes almost negligible for water tables below 3.5 m b.g.l.

It is observed from the water level data of the selected hydrograph stations in the Koyna River basin that the average water level during the period from November to

June is usually below 3.5 m b.g.l., and as such during this period evapotranspiration from groundwater is considered negligible. However, during the monsoon months (July to October) when the groundwater table is high (1.30–1.80 m bgl), evapotranspiration does take place. Based on the average water level during a particular month and the values of pan evaporation for that month (recorded at Koynanagar by the Central Water Commission, Government of India), the actual evapotranspiration from groundwater was estimated on a monthly basis, and is shown in Table 5. The evapotranspiration was estimated as 2.54 MCM for the year 1988, 4.49 MCM for 1991, and 4.05 MCM for 1992, and 3.70 MCM as an average in a year.

*Estimation of annual discharges by natural springs*

Spring discharges have been estimated as 6 MCM annually (3 MCM during the rainy season, 2 MCM during the winter season, and 1 MCM during the summer) in area II (Naik 1994). These discharges do not include the combined spring discharges of a chain of springs which eventually form a stream and contribute to the streamflow. If the combined discharges of such clusters of springs are measured, they form third to fourth magnitude springs (Naik et al. 2002) as per Meinzer’s scale (1923).

**Evaluation of Regional Specific Yield**

Specific yield is defined as the volume of water (expressed as either per cent or fraction of the total volume of the aquifer) that an aquifer (unconfined) releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface (Todd 1980). This can be determined either from pumping tests on shallow wells tapping the unconfined aquifer or from soil moisture measurements or from groundwater budgeting or water level fluctuations (Healy and Cook 2002). The pumping test methods give unreliable estimates of the specific yield (Naik et al. 2001). Detailed soil moisture measurements could not be carried out in the present studies. Groundwater budgeting is the purpose of this study and estimates of the major parameters are not yet known. Therefore, the water-table fluctuation method was adopted for estimation of the regional specific yield with the help of the following formula:

$$S_y = \frac{(D_w + RO_{bf} + S_d) - (RF_w + I_{I_g})}{WL_d \times A_e} \tag{2}$$

where  $S_y$  is regional specific yield,  $D_w$  is groundwater draft by wells and direct pumping from the Koyna tributaries,  $RO_{bf}$  is baseflow (unutilized),  $S_d$  is spring discharges,  $RF_w$  is winter rainfall,  $I_{I_g}$  is recharge due to return flow of water applied for irrigation,  $WL_d$  is average water level decline, and  $A_e$  is effective area for groundwater recharge.

**Table 5** Monthly actual evapotranspiration values from groundwater. N Negligible

Month	Pan evaporation (mm)	Average water level during the month (m b.g.l.)				Groundwater evapotranspiration as % of pan evaporation (%)				Groundwater evapotranspiration (MCM)						
		1988	1991	1992	1988	1991	1992	1988	1991	1992	1988	1991	1992			
Jan	61.32	4.60	3.81	2.83	N	N	N	N	N	N	N	N	N			
Feb	69.86	4.92	4.61	3.38	N	N	N	N	N	N	N	N	N			
March	102.41	5.35	5.00	4.01	N	N	N	N	N	N	N	N	N			
April	111.58	5.24	5.12	4.68	N	N	N	N	N	N	N	N	N			
May	110.11	6.83	5.46	4.99	N	N	N	N	N	N	N	N	N			
June	50.16	4.14	2.46	3.32	N	3.0	0.50	N	3.0	0.50	N	0.86	0.14			
July	23.03	1.64	1.29	2.14	4.0	5.50	3.50	4.0	5.50	3.50	0.52	0.75	0.46			
Aug	13.16	2.23	1.64	1.55	3.50	4.0	4.0	4.0	4.0	4.0	0.29	0.29	0.29			
Sept	35.28	1.81	1.77	1.57	4.0	4.0	4.0	4.0	4.0	4.0	0.86	0.86	0.86			
Oct	47.18	2.71	2.10	1.85	2.50	3.50	4.0	4.0	3.50	4.0	0.98	1.15	1.15			
Nov	45.08	3.64	3.05	2.35	N	1.50	3.0	N	1.50	3.0	N	0.58	0.86			
Dec	50.96	3.19	3.55	3.18	1.0	N	1.0	1.0	N	1.0	0.29	N	0.29			
Total														2.94	4.49	4.05



The recession period from November to May was chosen for estimation of the regional specific yield, because of (1) better control over the measurement of baseflow during this period, (2) insignificant recharge due to rainfall during this dry span, and (3) negligible discharge from evapotranspiration due to deeper water table. The parameters thus obtained (from November to May) are (1)  $D_w=21.22$  MCM (3.62 MCM for domestic/stock needs + 10.40 MCM for irrigation from wells + 7.20 MCM for irrigation through baseflow), (2)  $RO_{bi}=26$  MCM (1988–89) and 30 MCM (1992–93), (3)  $S_d=3$  MCM, (4)  $RF_w=\text{negligible}$ , (5)  $I_g=20.46$  MCM (taken as 30% of the applied irrigation from surface water; discussed in the section on groundwater recharge), (6)  $WL_d=2.82$  m (1988–89) and 3.18 m (1992–93), and (7)  $A_e=897.2$  km<sup>2</sup> or  $897.2 \times 10^6$  m<sup>2</sup> (measured by planimeter).

Using these parameters, the specific yield for the water years 1988–89 and 1991–92 is estimated as 0.012 or 1.20%. This value compares well with the regional specific yield determined by various workers elsewhere in the basaltic terrains [0.01 (Central Ground Water Board 1984a); 0.015 (Angadi 1986); 0.0132 (Sahoo 1989)].

## Groundwater Recharge

Groundwater recharge is defined in the general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (De Vries and Simmers 2002). A number of methods have been formulated for estimating groundwater recharge, such as through direct measurement, Darcian approaches, tracer techniques, isotope dating, chloride mass-balance equations, analysis of baseflow hydrographs and spring discharges, water-table fluctuations, numerical modeling, water budgeting, etc. Information about these methods is given in Gee and Hillel (1988), Simmers (1988, 1997), Sharma (1989), Lerner et al. (1990), Allison et al. (1994), Stephens (1994, 1996), Bredenkamp et al. (1995), Lerner (1997), De Vries and Simmers (2002), and Scanlon et al. (2002). Examples of relatively low-cost investigations at regional scales are provided by Adar et al. (1988), Gieske and De Vries (1990), Athavale et al. (1992), Edmunds and Gaye (1994), Kennett-Smith et al. (1994), Leaney and Herczeg (1995), Sukhija et al. (1996), Birkley et al. (1998), and Rangarajan and Athavale (2000). Choosing an appropriate technique for a particular site is not straightforward (Scanlon et al. 2002), and depends on several factors, including field constraints and availability of field data. However, techniques based on groundwater levels (water-table fluctuations) are among the most widely applied methods for estimating recharge rates (Healy and Cook 2002). These methods are based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Scanlon et al. 2002). In the present study, the groundwater fluctuation method has been adopted for estimating groundwater recharge because of its simplicity and straightforwardness.

Groundwater recharge in the Koyna River basin mainly occurs as vertical percolation of rainwater and return flow of water applied for irrigation. Some recharge also takes place through percolation from surface water tanks. Recharge due to sub-surface inflow from the adjoining sub-basins to the area has been considered negligible.

## Recharge Due to Rainfall

Rainfall occurs in the area mainly during the monsoon months. Recharge due to winter or summer rainfall is quite negligible and has not been considered. The annual groundwater recharge due to monsoon rainfall has been estimated with the help of the following equation:

$$G_r = (A_e \times WL_r \times S_y) \quad (3)$$

where  $G_r$  is the total groundwater recharge due to monsoon rainfall,  $WL_r$  is average water level rise during the period of recharge;  $A_e$  and  $S_y$  were defined earlier.

The above equation does not include baseflow, spring discharges, evapotranspiration, groundwater draft due to domestic and stock needs, and leakage to deeper aquifers during the monsoon months. These parameters should actually be added to the above equation to obtain the total groundwater recharge due to monsoon rainfall. However, baseflow as part of the total runoff, spring discharges which subsequently join the streamflow, and evapotranspiration during the monsoon period, when no water is required for irrigation, are lost during the same period and are not of much importance from the utilization point of view. Groundwater draft due to domestic and stock needs forms a small percentage of the total monsoon discharge, and has been neglected. It is also difficult to estimate the exact amount of leakage to deeper aquifers. As such, these factors have not been taken into account while estimating the groundwater recharge due to rainfall.

The average rise in water levels in the representative wells in non-command areas (water levels in command areas are not considered since they are influenced by surface water irrigation) between May and November due to rainfall is found to be 2.72 m for the year 1988 and 2.96 m for 1992. Thus, the annual groundwater recharge due to monsoon for the year 1988 is 29.28 MCM while for the year 1992 it is 31.87 MCM. On average, the total minimum replenishable groundwater recharge due to monsoon rainfall is estimated as 31 MCM annually for the area downstream of the Koyna dam (area II) (Fig. 1).

## Recharge Due to Surface Water Tanks

The Koyna River basin has nine percolation tanks, one minor-irrigation tank, and many other smaller tanks. These structures have a cumulative annual gross storage of 6.26 MCM. Studies indicate that about 70–90% of the gross storage from these structures may contribute towards the groundwater recharge (Sharma et al. 2000). However, the existing tanks are very old and have been

silted up. Many of them lie on hard massive basalt, inhibiting the downward movement of water (Naik et al. 2001). Therefore, it is assumed that about 50% of the gross storage from such structures may be contributing towards groundwater recharge in these areas. This assumption is further corroborated by the recommendations given by the Groundwater Estimation Committee (Central Ground Water Board 1984b) for the amount of groundwater recharge due to surface water tanks. The recharge due to these structures is thus estimated as 3.13 MCM annually.

### Recharge Due to Return Flow of Water Applied for Irrigation

The water applied for irrigation has already been estimated as 61 MCM annually from the Koyna River, 7.20 MCM from other tributaries and 10.40 MCM from dugwells. As per the norms prescribed by the Central Ground Water Board (1998), 30% of the return seepage from the surface water irrigation and 25% from groundwater irrigation in a basaltic terrain goes towards groundwater recharge. Thus, groundwater recharge due to the return seepage from water applied for irrigation is estimated at 23.06 MCM annually, 20.46 MCM from surface water irrigation, and 2.60 MCM from groundwater irrigation.

From the estimates made above, the total annual recharge received by area II in the Koyna River basin is found to be about 57 MCM (31 MCM from rainfall, 3 MCM from surface water tanks, and 23 MCM from the return flow of water applied for irrigation). Out of this 57 MCM, 40% is due to recharge from the applied irrigation water.

### Groundwater Balance

The basic hydrological principle states that a balance must exist between the quantity of water supplied to the basin (inputs) and the amount leaving the basin (outputs) and the change in groundwater storage (Karanth 1999). Normally in the study area, rain starts in the middle of June and the recession period after monsoon (October) extends till the middle of next June. Therefore, the hydrological year has been taken from the end of May to the end of May of the next year for working out the groundwater balance of the area.

The groundwater balance of the top shallow zone (<30 m deep) only has been attempted and discussed in this section. The basic equation for the groundwater balance during a hydrological year may be stated as:

$$\begin{aligned} &\text{Groundwater Inflow (Inputs)} \\ &= \text{Groundwater Outflow (Outputs)} \\ &\pm \text{Change in Groundwater Storage } (\Delta S_G) \end{aligned} \quad (4)$$

**Table 6** Groundwater balance (all figures in MCM)

1988-89		1992-93	
Inputs	Outputs	Inputs	Outputs
$I_p=29.28$	$D_w=21.22$	$I_p=31.87$	$D_w=21.22$
$GW_1=0$	$RO_{bf}=26.0$	$GW_1=0$	$RO_{bf}=30.0$
$I_{CT}=3.13$	$ET_g=0.29$	$I_{CT}=3.13$	$ET_g=1.15$
$I_{ig}=23.06$	$S_d=3.0$	$I_{ig}=23.06$	$S_d=3.0$
	$GW_o=0$		$GW_o=0$
	$S_G=2.26$		$\Delta S_G=2.37$
	$R_{DP,Aq}=2.70$		$R_{DP,Aq}=0.32$
Total: 55.47	55.47	58.06	58.06

The groundwater inflow consists of recharge due to (1) infiltration of precipitation ( $I_p$ ), (2) sub-surface inflow ( $GW_1$ ), (3) seepage from canals and surface water reservoirs/tanks ( $I_{CT}$ ), and (4) return flow of water applied for irrigation ( $I_{ig}$ ). The outflow consists of (1) groundwater draft by wells and direct pumping from tributaries during dry months after the monsoon ( $D_w$ ), (2) baseflow (unutilized) ( $RO_{bf}$ ), (3) spring discharges ( $S_d$ ), (4) groundwater evapotranspiration ( $ET_g$ ), (5) sub-surface outflow ( $GW_o$ ), and (6) recharge to deeper aquifers below the shallow zone ( $R_{DP,Aq}$ ). The equation thus can be expressed as:

$$\begin{aligned} I_p + GW_1 + I_{CT} + I_{ig} = D_w + RO_{bf} + S_d + ET_g + GW_o \\ + R_{DP,Aq} \pm \Delta S_G \end{aligned} \quad (5)$$

Table 6 gives an account of the groundwater balance for the water years 1988–89 and 1992–93. As the water level rises during the monsoon, simultaneous loss takes place from the groundwater reservoir in the form of baseflow, spring discharges, evapotranspiration, and withdrawal due to domestic and stock needs. These parameters have to be added to the recharge factor to calculate the total amount of infiltration from precipitation. However, these parameters also have to be accounted for under outputs. Therefore, instead of double accounting in both inputs and outputs, these parameters have been eliminated altogether for the monsoon months. Sub-surface groundwater inflow or outflow from the basin does not take place at shallower levels, and therefore these parameters have been taken as nil.

The change in groundwater storage ( $\Delta S_G$ ) has been estimated by taking the difference in the average water level recorded at the beginning and the end of the hydrological year, i.e. end of May to the end of May of the next year, and multiplying this value by the average regional specific yield and the effective area for groundwater recharge (897.20 km<sup>2</sup>). There is a decline of 0.21 m of the water table between May 1988 and May 1989. Similarly, there is a decline of 0.22 m of the water table between May 1992 and May 1993. Thus, the change in groundwater storage ( $S_G$ ) is found to be 2.26 MCM for 1988–89 and 2.37 MCM for 1992–93. Recharge to deeper aquifers ( $R_{DP,Aq}$ ) below a depth of 30 m has been taken as the amount to balance both sides of the equation as all

other items of the equation, except this parameter, have been estimated. This comes out as 2.70 MCM during 1988–89 and 0.32 MCM during 1991–92, and 1 MCM on average. However, this estimate is only for the period from November to May, and during monsoon months a higher quantity of recharge to deeper aquifers may be expected.

### Estimation of Static Groundwater Reserve

Groundwater available below the zone of natural (dynamic) water level fluctuation is called static groundwater reserve. It has been estimated using the formula:

$$G_{rs} = B \times A_e \times S_y \quad (6)$$

where  $G_{rs}$  is the static groundwater reserve and  $B$  is the saturated thickness of the aquifer below the deepest level of water in the pre-monsoon period;  $A_e$  and  $S_y$  were defined earlier.

The total thickness of the weathered and fractured zone below the land surface in shallow aquifers has been estimated with the help of a well inventory, borewell data, and other hydrogeological investigations. In the non-command areas, the dugwells are fully penetrating, and the summer water level almost reaches the bottom of the wells. In the Koyna command areas, on the other hand, there lies a thick weathered and fractured zone below the summer water levels. The well inventory of 240 dugwells reveals that the thickness of the shallow water-bearing horizons below the zone of dynamic water level fluctuation varies between 0.10 and 18.20 m and is 7.17 m on average. Thus, using the above formula, the static groundwater reserve is estimated at 77 MCM. This is the amount of groundwater contained within the permanently saturated zone of the groundwater reservoir, and represents the total groundwater reserve minus the dynamic reserve.

### Estimation of Exploitable Dynamic Groundwater Reserve

The dynamic groundwater reserve actually represents the long-term average annual recharge under conditions of maximum groundwater use (Karanth 1999). Generally, up to the end of October soil is saturated with moisture and no additional groundwater for irrigation is required. Groundwater irrigation actually starts from the beginning of November until May of the next year. The exploitable dynamic groundwater reserve has been estimated using the equation:

$$G_{re} = WL_d \times A_e \times S_y \quad (7)$$

where  $G_{re}$  is exploitable/utilizable groundwater reserve and  $WL_d$  is average water level decline between November and May next year;  $A_e$  and  $S_y$  were defined earlier.

The average water level fluctuation between November and May of next year is found to be 2.82 and 3.18 m

respectively for the hydrological years 1988–89 and 1991–92. Thus, the exploitable/utilizable groundwater reserves for these two water years are estimated as 30.36 and 34.24 MCM respectively. On average, it is estimated at 32.30 MCM annually for the whole catchment downstream of the Koyna dam (area II).

### Estimation of Safe Yield

Safe yield of the groundwater system is that amount of groundwater that can be exploited continuously without detrimental effects on the groundwater reservoir (Central Ground Water Board 1984a). It includes all exploitable groundwater originating within the catchment and consists of (1) utilizable or exploitable dynamic groundwater, (2) amount of water used for domestic and stock needs in monsoon months, and (3) return flow of water applied for irrigation. These three parameters have already been estimated as 32.30, 2.58, and 23.06 MCM respectively in the earlier sections. Thus, the safe-yield or total exploitable groundwater reserve for the Koyna River basin has been estimated at 58 MCM annually.

### Summary and Conclusions

Groundwater resources have been estimated for the Koyna River basin for the catchment downstream of the Koyna dam (area 1,082 km<sup>2</sup>). Artificial and natural groundwater discharges have been estimated that amount to 23.80 and 34.70 MCM respectively. Artificial groundwater discharges include domestic/stock needs (6.20 MCM), groundwater draft through wells (10.40 MCM), and use of baseflow from the Koyna River tributaries (7.20 MCM). Natural groundwater discharges include unutilized baseflow (28 MCM), evapotranspiration (3.70 MCM), and spring discharges (3 MCM). Regional specific yield (0.012 or 1.20%) and groundwater recharge have been estimated on the basis of the water-table fluctuation method. Groundwater recharge amounting to 57 MCM takes place in the region through vertical percolation of rainwater (31 MCM), return flow of water applied for irrigation (23 MCM), and recharge due to surface water tanks (3 MCM). On the basis of the water balance study, recharge to deeper aquifers has been estimated at 1 MCM excluding the rainy season (June to October). The static and dynamic groundwater reserves have been estimated as 77 and 32 MCM respectively.

Safe yield has been estimated as 58 MCM annually. This includes the present groundwater draft by wells for domestic, stock, and irrigational needs estimated at 16.50 MCM per year and the natural losses from the groundwater system which are mostly baseflow and spring discharges amounting to 38 MCM (35 MCM baseflow + 3 MCM spring flow) per year, out of which 7 MCM is already being directly pumped from the tributaries of the Koyna River for irrigational needs. Thus, there remains a balance of only 3.5 MCM of groundwater

for further groundwater development without modification of the present hydrogeological environment. It will be difficult to intercept baseflow during the initial months after the monsoon rainfall. Also, there will be little demand for water at that time. However, during the dry span of the year, the unutilized baseflow can be tapped by constructing additional dugwells, dug-cum-borewells, or horizontal trenches, or by deepening the existing wells. It is thus assumed that at least 25% of the unutilized baseflow can be brought to fruitful use. This amounts to about 7 MCM annually. Thus, about 10.5 MCM (7+3.5 MCM) of groundwater can be used in the existing hydrogeological environment through wells only. The unit draft per well per year is calculated to be 0.021 MCM in the command areas and 0.01 MCM in the non-command areas. Taking into consideration the declining trends of groundwater levels in the non-command areas (Naik et al. 2001), it is recommended that the 10.5 MCM of available groundwater be utilized in the command areas only so as to minimize the rising trend of groundwater levels in these areas. Thus, about 500 additional dugwells can be constructed in the command areas alone to make the best utilization of the available groundwater resources.

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