
Groundwater demand management at local scale in rural areas of India: a strategy to ensure water well sustainability based on aquifer diffusivity and community participation

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Abstract Watershed development programmes provide an opportunity for sustainable management strategies, although currently, they remain largely 'supply-side' mechanisms of water resources development. Hydrogeological conditions, community participation and status of groundwater usage are important in evolving strategies on 'demand-side' groundwater management.

Neemkheda aquifer is a typical low-storage, low-hydraulic conductivity aquifer from a watershed in the dryland regions of Madhya Pradesh State of central India. A shallow unconfined aquifer, it consists of an upper coarse, calcareous sandstone unit underlain by a fine-grained sandstone unit. A 'well commune' of seven wells is poised to test the concept of joint groundwater management, wherein wells are mechanisms of tapping a common water source, the Neemkheda aquifer.

The strategy for systematic groundwater management in the Neemkheda well commune is based upon the

relationship between Transmissivity (T) and Storage coefficient (S), i.e. aquifer diffusivity, and its variation within the aquifer. Wells within a high diffusivity domain tend to dewater more quickly than wells within a low diffusivity domain. A well-use schedule during the dry season, based upon aquifer diffusivity forms the basis of the groundwater management concept. The distribution of local aquifer diffusivities governs the relationship between local and regional aquifer depletion times and forms the basis of the groundwater management exercise being proposed for the Neemkheda aquifer.

Resumen Los programas de desarrollo de una cuenca hídrica son una oportunidad para el uso de estrategias de gestión sostenible, aunque hoy en día estas siguen siendo principalmente mecanismos para el desarrollo de recursos hídricos con énfasis en la "oferta". Las condiciones hidrogeológicas, la participación comunitaria y la condición de utilización del agua subterránea, son importantes en el desarrollo de estrategias para la gestión del agua subterránea, desde el punto de vista de la "demanda".

El acuífero de Neemkheda es un acuífero típico de almacenamiento bajo y conductividad hidráulica baja, perteneciente a una cuenca hídrica ubicada en las regiones secas del Estado de Madhya Pradesh, en la parte central de India. Un acuífero de tipo libre, somero, formado por una unidad superior de arenisca calcárea de grano grueso, subyacente por una unidad de arenisca de grano fino.

Un campo de pozos comunitario compuesto por siete pozos, pone a prueba el concepto de gestión conjunta del agua subterránea, dentro del cual los pozos son mecanismos para usar una fuente de agua común: El acuífero de Neemkheda.

La estrategia usada para la gestión sistemática del agua subterránea, en el campo de pozos comunitario de Neemkheda, se basa en la relación existente entre Transmisividad (T) y Coeficiente de Almacenamiento (S), es decir en la Difusividad del Acuífero y en su variación observada dentro del mismo acuífero. Los pozos cuya difusividad esta dentro de un rango alto, tienden a experimentar un descenso en su nivel mas rápidamente que aquellos pozos con una difusividad baja. El concepto de gestión de agua subterránea se basa en un programa especial de operación para cada pozo durante la estación seca, el cual a su vez se basa en la difusividad del acuífero. La distribución de

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diffusividades locales del acuífero rige las relaciones entre las épocas de descensos de nivel en el acuífero a escala regional y local, y además constituyen la base del ejercicio de la gestión del agua subterránea que se está proponiendo para el acuífero de Neemkheda.

Résumé Les programmes de développement des bassins versants offrent une occasion de développer des stratégies pour une gestion durable, bien qu' à présent elles restent en grande mesure 'le terme source' dans le mécanisme de développement de la ressource en eau. Les conditions hydrogéologiques, la participation de la communauté et l'usage des eaux souterraines sont importants pour le 'terme demande' dans les stratégies de gestion des eaux souterraines.

L'aquifère de Neemkheda presents des caractéristiques typiques pour un bassin versant dans les régions arides de l'état Madhya Pradesh de l'Inde centrale en ce qui concerne les faibles valeurs de la conductivité hydraulique et du coefficient d'emmagasinement. Il s'agit d'un aquifère phréatique dont la partie supérieure est constituée par des grès calcaire qui restent sur des grès plus fins. Afin d'essayer le concept de gestion intégrée, on a réalisé dans l'aquifère de Neemkheda un captage ayant sept forages qui forment la ressource en eau communale.

La stratégie de la gestion systématique du captage est basée sur la relation entre la transmissivité (T), le coefficient d'emmagasinement (S), donc la diffusivité hydraulique ainsi que sa variation spatiale. Les puits forés dans les zones à grande diffusivité tendent à s'assécher plus vite que ceux creusés dans des zones à faible diffusivité. Le concept de la gestion des eaux souterraines est donc basé sur la distribution spatiale des diffusivités. À partir de ce concept on a développé un programme d'exploitation des forages pendant les saisons sèches. La relation entre les temps d'épuisement locaux et régionaux est déterminé par la distribution spatiale de la diffusivité et forme la base de l'exercice sur la gestion des eaux proposée pour l'aquifère de Neemkheda.

Keywords Transmissivity · Storage coefficient · Diffusivity · Groundwater management · Aquifer depletion time

Introduction

Groundwater forms an important source of water supply in rural India. It is often the only source of water supply, particularly in remote villages, where surface water supplies cannot be relied upon for more than a couple of months. With increasingly growing demands on the stock of replenishable groundwater supplies, many areas of rural India have started facing acute water crises, including the drying up of wells in many villages. It is a common practice to tank water to such villages during dry periods for meeting basic drinking water needs.

The overall increase in the demand for groundwater has resulted in its "overexploitation" (Macdonald et al. 1995;

Balukraya 2000). It is quite obvious that traditional approaches of watershed development that stress enhancing recharge to groundwater do not pay adequate attention to the challenge of sustainably utilizing the recharged water (Shah et al. 1998). Sustainable and equitable groundwater use would put the concept of watershed development one step ahead of its current status of simply enhancing groundwater recharge to increase soil moisture bases and/or promote more wells, without studying the impact of such changes in future scenarios. Using groundwater to supply human needs has great advantages, but there are also negative effects, as with the development of any other natural resource, effects that depend upon specific characteristics of the resource (Custodio 2002).

Current discussions around groundwater management in India can be classified into three main areas:

1. Groundwater legislation
2. Groundwater markets
3. Community based groundwater management

Although the scope of discussing each of these issues in detail is beyond this paper, it must be mentioned that each of the above has its share of limitations, particularly while implementing groundwater management initiatives. Groundwater legislation has been formulated comprehensively in the state of Maharashtra, the first state to do so in India (Government of Maharashtra 1993, 2000). However, implementation of groundwater laws is difficult. In a typical low rainfall, Deccan basalt area, long-term field monitoring and modelling indicates that setting up of broad-based protection zones as mentioned in the Maharashtra Groundwater Act of 1993 (Government of Maharashtra 1993) around public supply wells may not always be effective (Macdonald et al. 1995). Moreover, inherent problems with licensing have encountered difficulties such as siting and licensing norms essentially denying the right to establish water extraction mechanisms (wells, pumps etc.), favouring early exploiters at the expense of penalizing late ones (Shah 1992).

Formal groundwater markets can enable efficient reallocation of scarce supplies to high-value uses while compensating existing users for effective implementation, such markets must function within a clearly defined framework of rights and institutions (World Bank 1999). Often, at the ground level, there is a possibility of misquoting excellent works on water markets and encouraging water markets without researching them. In the absence of controls over groundwater extraction, informal markets can lead to overdraft (World Bank 1999) and it would require large-scale research inputs to really look at the feasibility of water market mechanisms as part of a large-scale groundwater management initiative (ACWADAM 2001a).

The limitations in legislation and water markets leave the third option of community based efforts in managing groundwater resources. Community based groundwater management can be defined as a set of conscious efforts by a community (village, township or a city) to take up

actions pertaining to systematic management of groundwater resources. Such management may include community efforts at augmenting recharge as well as managing the use of groundwater resources. Community based groundwater management holds the immediate answers to many groundwater related problems in India. There are examples of community based, 'informal laws' pertaining to co-operative groundwater utilisation through examples like "Pani Panchayat" at Naigaon (Salunkhe and Rasal 1996) and community management of water resources at Hivre Bazar (Popatrao Pawar 2001, personal communication). However, these efforts are more of social movements than systematic, scientifically based attempts. Community based groundwater management is only just emerging as a major initiative to tackle large-scale groundwater problems, especially in rural India.

Neemkheda is a typical village from the low-rainfall area of the Malwa region of central-west India where watershed development work has been completed. This work has included soil conservation measures like bunds and trenches along contours, percolation tanks and check dams along drainage lines and dugout farm ponds in the low-lying valley areas. Neemkheda village falls under the Bagli tehsil in Dewas district of Madhya Pradesh State (Fig. 1). This paper is only the beginning of an endeavour to pilot groundwater management initiatives based on the hydrogeological understanding of the area. It is envisaged that a systematic strategy for sustainable groundwater utilization, which is in agreement with local hydrogeological factors will evolve subsequently, based on the small beginning made in Neemkheda. A small experiment is being developed in Neemkheda, on the basis of hydrogeological studies so far. The scientific logic behind this experiment is the main subject of this paper. It may be mentioned here that the farmers involved in the experiment have actually begun some sharing along the lines mentioned here but it is still in a rudimentary state. It is anticipated that with sustained inputs the experiment will become more refined and the strategy will evolve with concurrent scientific and community inputs.

At the onset of this study, it was felt necessary to hydrogeologically characterize the Neemkheda watershed (admeasuring about 600 ha, i.e. 6 km²). The first phase of this study included a hydrogeological study that formed the basis of such a characterization, most significantly, the hydrogeological mapping, some hydrological parameter monitoring and pumping tests to ascertain aquifer characteristics (ACWADAM 2001b). Based on this hydrogeological study, a small experiment on community groundwater management has been set up in Neemkheda. The background of this experiment and the strategy evolved are explained in this paper.

Figure 2 illustrates the need to differentiate between groundwater resources development (A) and groundwater resources management (B). The latter is seldom achieved, within or outside watershed development programmes. A fine line divides groundwater resources development and groundwater resources over-development; quite often conservation and recharge within a watershed is likely

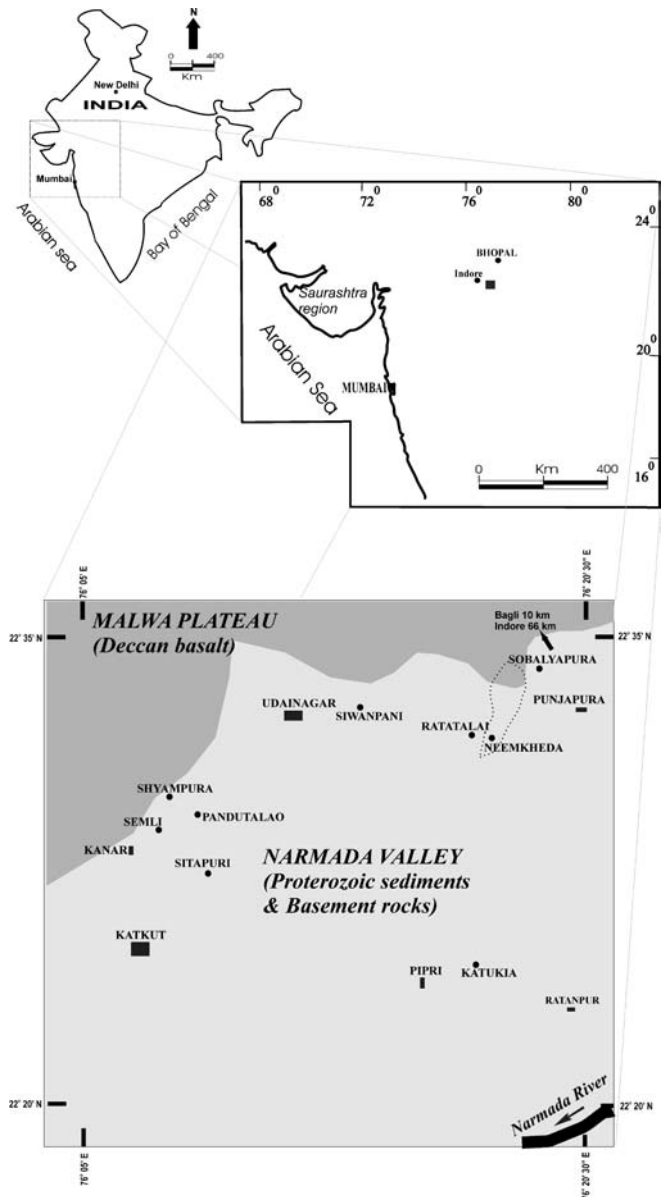


Fig. 1 Location map of area

to lead to the latter (ACWADAM 2001b). Hence, there is need to treat the aquifer as a total resource with the wells being only mechanisms of tapping this resource. This is the basis of the proposed strategy in Neemkheda watershed.

Two organizations, the Advanced Center for Water Resources Development and Management (ACWADAM) and the Samaj Pragati Sahayog (SPS), have evolved a strategy for groundwater resources management in a shallow aquifer from the drylands of central India while conducting hydrogeological research in this region. SPS is a voluntary organisation engaged in infusing science into development activities in the tribal drylands of central India. SPS started its work in Neemkheda with a comprehensive watershed development programme. ACWADAM studied the hydrogeological implications

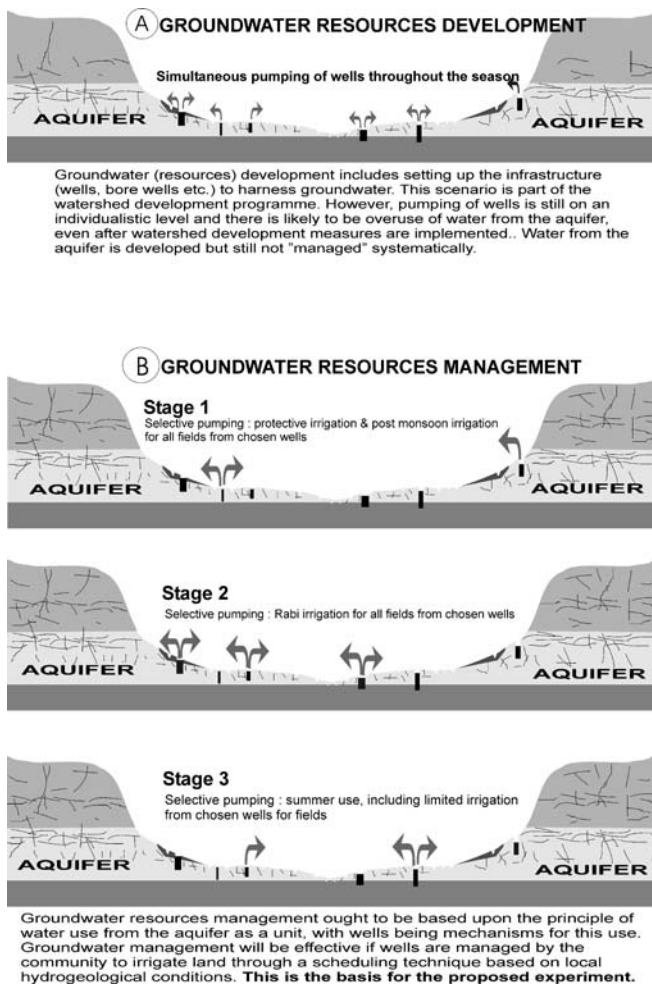


Fig. 2 Diagrammatic illustrations explaining groundwater resources development (A) and management (B). The former is frequently an integral aspect in watershed development programmes but the latter is still not a part of any watershed development programme

of the Neemkheda model of watershed development and realised the necessity of evolving a community-based effort to ensure sustainability of the watershed development programme that SPS had implemented. Ensuring groundwater management forms the basic objective of future efforts to be pursued in Neemkheda and the surrounding region where SPS is working. The concept and the strategy being developed for a cluster of wells from a typical village (Neemkheda) in the region are presented here. The experiment here is planned for six wells in Neemkheda village. It is also an effort in groundwater management and at its current state is still far from aquifer management. However, it is envisaged that such small-scaled, appropriate approaches in groundwater management are likely to evolve into aquifer management in the rural regimes of India. In addition to having conducted hydrogeological mapping and measurements of stream flows and water levels in Neemkheda watershed, pumping tests to gain some insight into the

storage and transmission properties of the groundwater system formed a significant component of the study.

Geology, Geomorphology and Drainage of the Neemkheda Watershed

Several workers have attempted to define the regional geological succession around the study area (Samaj Pragati Sahayog 1996; Kale 1989). The explanations provided by earlier workers are significant in defining the regional geological regimen. However, while working on a microwatershed level, the scale of mapping is much greater than that of a regional base map. The primary objective of mapping a microwatershed such as the Neemkheda watershed is the variability in lithological and structural elements of the geological domain because the geology defines the physical framework of the watershed. Considering that the Neemkheda catchment is situated at the boundary of two regionally different geological domains—the Deccan basalts that define the Malwa plateau and the older Vindhyan rocks that define the valley plains—a thorough mapping of the surface and subsurface was undertaken. A detailed study of surface outcrops, stream cuttings, road cuttings, excavations for irrigation/percolation ponds and most significantly, nearly 40 odd well sections helped develop a geological map of the watershed (Fig. 3).

Table 1 depicts the generalized geology and lithological succession in the Neemkheda watershed based on observations made by Kale (1989). The geology of the Neemkheda watershed consists of four distinct lithological types. It would have been appropriate to assign local names to the sandstones and dolomite within the succession. However, since these are an integral part of an established stratigraphy, the names assigned by Kale (1989) have been retained even on a microwatershed level.

Development of a Sustainable Groundwater Management System

Geophysical surveys, detailed hydrogeological mapping and sustained monitoring of wells helped describe the groundwater resources in Neemkheda watershed. The principal aquifer consists of a shallow unconfined aquifer formed by three distinct stratigraphic units, namely, the upper Deccan basalt, the middle Katkut sandstone and the lower Kanar sandstone. The Neemkheda aquifer is a well-defined unit in the sense that the Deccan basalts forming the ridgeline to a large portion of the watershed represent a topographic boundary, roughly coincident with a groundwater divide. Water table contours across adjacent catchments separated by the Deccan basalts indicate a groundwater divide. Moreover the Deccan basalts in and around Neemkheda watershed are represented by a stack of low-permeability lavas that would preclude flow from or to adjacent watersheds.

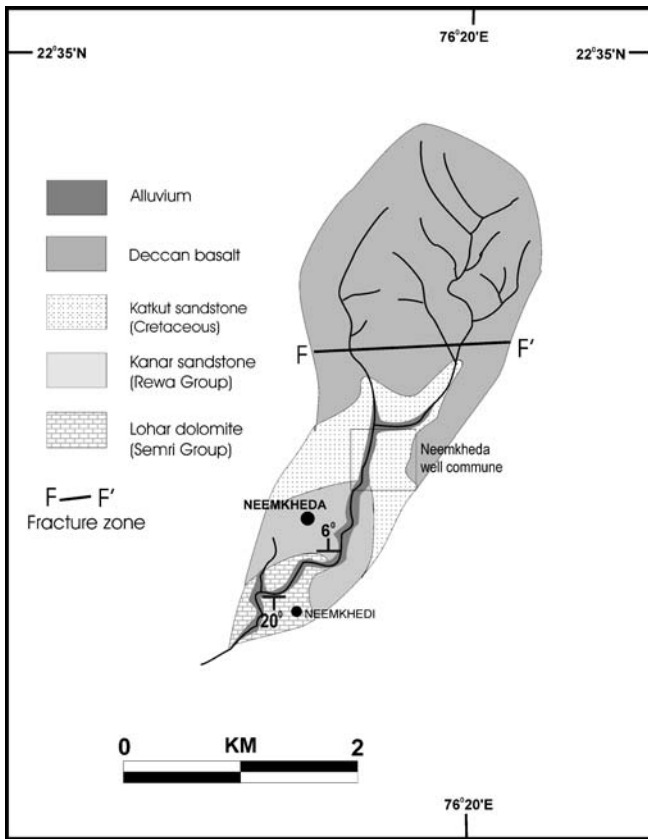


Fig. 3 Geological map of Neemkheda watershed (inset frame indicates area for groundwater management approach)

The chert breccia horizon at the interface of the Kanar sandstone and the Lohar dolomite (Table 1) represents the base of this principal, shallow aquifer. In the lower parts of the Neemkheda watershed and beyond its physical limits, the Lohar dolomite constitutes a fairly thick but highly heterogeneous aquifer. However, most of the wells within the Neemkheda watershed tap the aquifer above the chert breccia that marks the top of the Lohar dolomite. The chert breccia is a relatively thin (less than 3 m), hard and impermeable horizon that forms a ubiquitous base to the Kanar sandstone in and around Neemkheda village. Most wells tap the Katkut sandstone and the Kanar sandstone as aquifer, and are located within the area close to Neemkheda village, where most of the agricultural land is situated. However, a few wells upstream, tap the Deccan basalt as aquifer and irrigate lands at the base of the basalt ridge-line. Hence, the surface topographic boundaries can be assumed to represent the lateral boundaries of the aquifer whereas the chert breccia horizon represents the base of the shallow unconfined aquifer.

Simple hydrological monitoring including measurement of rainfall, runoff (base flows included) groundwater levels and abstraction from wells has helped estimate some basic water balance parameters. Groundwater storage in the Neemkheda aquifer is limited to about 50 to 60 mm of water. Therefore, the maximum recharge that

Table 1 Lithostratigraphic succession within the Neemkheda watershed

| Geological name (after Kale 1989) | Lithology | Hydrogeologically significant features | Estimated range of thickness (m) | Correlation to regional setup of Kale (1989) | Age (after Kale 1989) |
|-----------------------------------|-----------------------|---|--|--|-----------------------|
| Deccan basalt | Basalt | Predominantly compact basalts with alternate thin layers of vesicular-amygdaloidal basalt. Jointing is vertical/sub-vertical. The lowermost unit bears columnar joints | ca. 200 | Deccan Trap | Cretaceous-Eocene |
| Katkut sandstone | White sandstone | Coarse-grained, friable, calcareous sandstone. Nodular at a few places. Cavities and openings developed within sections of this sandstone | 10-18 | Katkut sandstone | Cretaceous |
| Kanar sandstone | Pink/purple sandstone | Vividly coloured, fine grained, indurated sandstone. Dips gently northwards. Weak horizontal partings apparent, parallel to the bedding planes | 18-20 | Kanar Sandstone | Neoproterozoic |
| Lohar dolomite | Chertbreccia | Thin band capping the dolomites below. Not mappable, therefore included within the dolomites below. Coarsely textured and hard. This band stands out as a small ridge at a few places within the low-lying flat plains | <5 | Mehdikhera Chertbreccia | Mesoproterozoic |
| | Dolomite | Grey coloured, finely laminated dolomites. Some cherty laminations occur within predominantly pure dolomitic mass. Very few joints. At places there is evidence of exsolution structures. Karstic effects on a local scale are apparent. Steep dips towards south | Actual thickness is expected to be greater than 25 m but only the top 5-7 m are exposed within the watershed | Lohar dolomite | Mesoproterozoic |

the aquifer is capable of receiving is not even 10% of the average annual rainfall of about 700 mm. Most of the water from the aquifer is extracted during the winter period (called Rabi) after the monsoon season, with very little water left in the aquifer at the end of the following summer.

There are some 40 large diameter dug wells in the Neemkheda watershed. The unconfined aquifer is tapped by these 40 odd wells as per the individual requirements of each farmer. In short, wells are considered to be individual “sources” of water and are used as such. In reality, wells are only mechanisms of tapping the limited stock of groundwater in the Neemkheda aquifer and in Neemkheda, as in any other aquifer, pumping of one well is likely to affect adjacent wells which tap the same aquifer.

The extent of this “interference” between wells depends upon various factors including the rate of pumping, transmissivity of the aquifer and the distance between wells. However, in the lower, agricultural tracts of Neemkheda watershed, where the well density is more than 20 wells/km², there is one well within an area of less than 0.05 km². This indicates that the average well spacing in this area is just over 100 m. Naturally, one would expect the wells to interfere during pumping, especially during the Rabi season (winter cropping), when practically all wells are pumping. However, in the absence of a controlled environment for testing, the exact nature of this interference is still unclear. Pumping during the Rabi has three distinct characteristics (observations based on nearly 30 odd pumping tests conducted on key irrigation wells in the watershed):

1. Most wells have a residual drawdown.
2. Most wells start pumping at some residual drawdown.
3. Recovery in each well (due to pumping in neighbouring wells) is slower than its normal recovery (when neighbouring wells are not being pumped).

The above characteristics imply that:

- Nearly all wells are pumped at less than normal efficiency because the level in the well never fully recovers.
- The aquifer is never in a state of natural equilibrium, since it is either providing water to pumps (through pumping wells) or it is providing water to the well recovery (wells that are recovering after pumping).
- In the absence of regular power supply and under individual control on well pumping, there are periods of large scale over-pumping (more than the crop requirement and more than the aquifer can sustain), especially during night-pumping schedules.

Systematic pumping from the aquifer (as a source) alone will ensure efficient use of water and prevent undue loss of water from the aquifer through over-pumping of wells. Notwithstanding theories on regulation and control through groundwater legislation, community groundwater

management seems the only viable alternative, especially in small villages (like Neemkheda) in order to cope with groundwater use within a common property framework (ACWADAM 2001a).

It is only through aquifer management that some semblance of sustainability can be achieved in terms of groundwater resources use. Described below is a groundwater management effort in a part of the Neemkheda watershed, an experiment that promises to have both scientific and practical potentials in dryland areas of India.

Basis of Aquifer Management Strategy in Neemkheda Watershed

The Neemkheda experiment is based upon simple criteria and practical observations made in the case of the shallow unconfined aquifer, the physical framework for which is described above. Any aquifer management ought to be based upon two primary criteria:

1. Hydrogeological properties of the aquifer – namely the storage coefficient and the transmissivity.
2. Community participation for sharing of water, based on the above.

As a first step, the concept of “aquifers as a source and wells as mechanisms of water supply” was explained to some farmers of Neemkheda village. As an order of progression, a small experiment is being attempted in ‘community oriented aquifer management’ based on local hydrogeological conditions and participation by a small group of seven farmers to begin with (Fig. 4). The 40 dug wells in the Neemkheda aquifer can be broadly classified into four or five groups or well fields, with streams and/or topographic highs bounding each of these fields. Although it is difficult to say how much of the aquifer storage is used up by each well field, pumping schedules imply that the group of seven wells discussed here, being located in the downstream portion of the watershed and within the ‘yielding zone’ of the aquifer, is likely to influence other wells fields rather than being significantly influenced itself.

There are certain practical difficulties in conducting and analyzing pumping test data on large diameter dug wells in rural settings in India. The significant ones are listed below:

1. Irregular power supply makes it impossible to conduct uninterrupted pumping tests of long duration. All farmers use high-rated pumping systems (3 or 5 horsepower) to pump wells.
2. It is nearly impossible to avoid interference effects from neighbouring wells while conducting pumping tests. Hence, the drawdown and the recovery of water levels in a well do not necessarily imply the effects from the pumped well alone. Aquifer parameters derived from the test could be wrongly estimated.

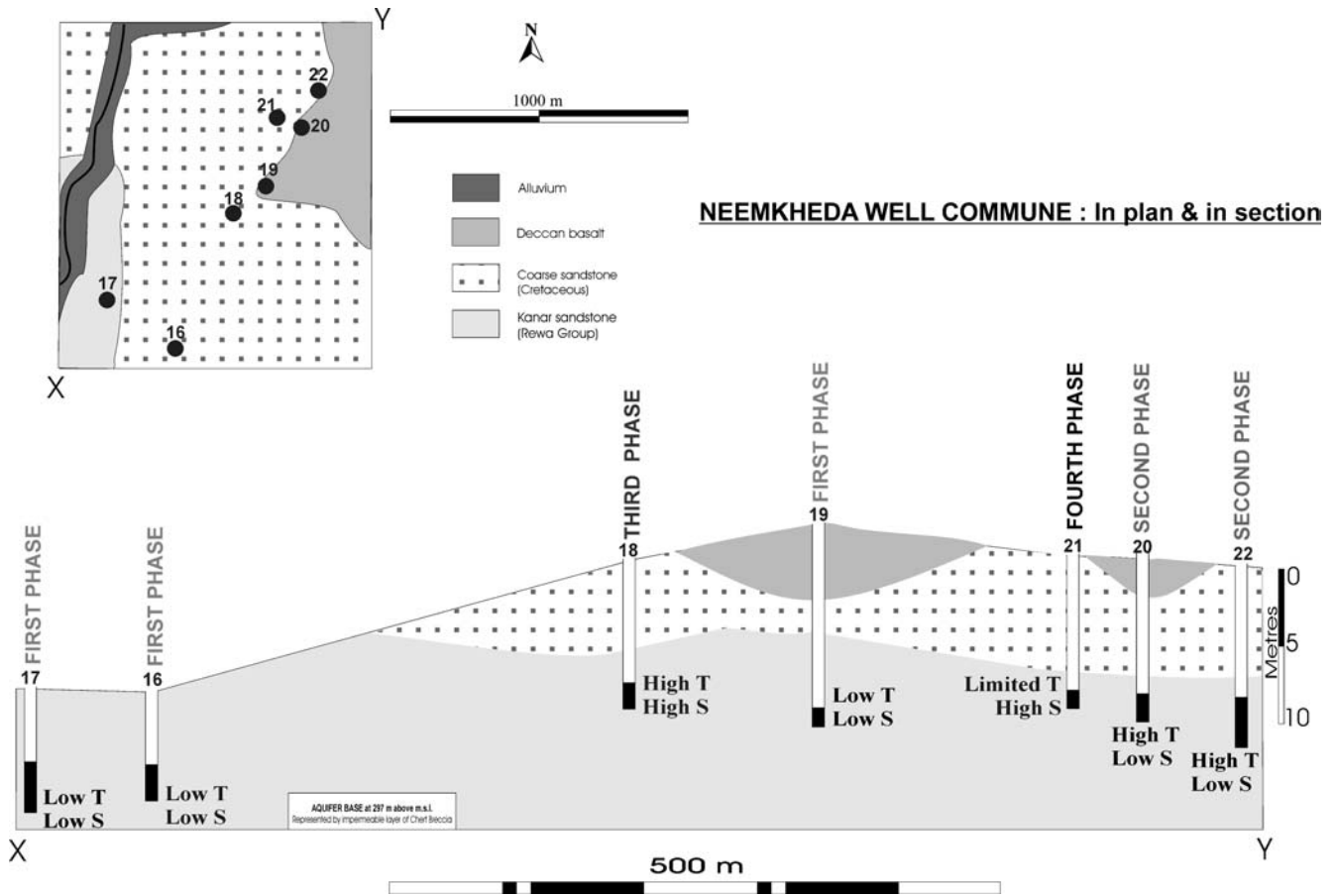


Fig. 4 Neemkheda 'well commune' in plan and in section

3. Analysis of large diameter pumping test data is more difficult than data from slimline bore holes due to the well storage and the unusual well dimensions in many large diameter dug wells.
4. Usually, consolidated sedimentary formations, as in Neemkheda village, are heterogeneous and fail to meet homogeneity and isotropy assumptions normally used in the analysis of pumping test data. Moreover, many shallow aquifers are finite and thin.
5. During pumping tests, water is often discharged in fields adjoining the pumping well, inducing return flow to the well. Such return flows affect aquifer parameter estimation, particularly for late-time data.

Acknowledging these difficulties, pumping tests were conducted on the seven wells to obtain values of Transmissivity (T) and Storage coefficient (S). In order to ensure some degree of systematics to the pumping test data, some basic principles were followed. These included:

- Pumping test data for at least 3 h uninterrupted duration was considered for analysis.
- Care was taken to ensure that the pumping well and the wells in its immediate vicinity were not pumped for a

few days prior to the pumping test so as to minimize effects of residual drawdown. Adjacent wells were kept idle during the test to minimize interference effects. This was possible only through community participation and this difficulty was largely overcome since the concerned well-field was the focus of the experiment to follow.

- Pumped water was discharged at a sufficient distance from the pumped well to reduce the effect of return flow.
- Pumping test conditions in all seven wells were kept as uniform as possible so that whatever errors remained in the protocol were uniformly distributed over the entire set of data from the seven wells.

Pumping test data were analyzed using the BGSPT package developed by The British Geological Survey (Barker 1989) for analyzing large-diameter well test data. Values of T and S computed using BGSPT are given in Table 2. The table also includes well yield characters and trends observed in the seven wells over the dry season from October to the subsequent summer, i.e. the month of May in the following year. Storage coefficient is given as specific yield S because the aquifer in Neemkheda is a shallow unconfined aquifer. A combination of Transmis-

Table 2 Well and aquifer characteristics for Neemkheda water management commune wells

| Well no (Owner's name) | Well base elevation (m above msl) | Well yield characters and trend over the dry season ^a | T | | S | | T/S (m ² /day) | Index (Based on priority to protect as "sustainable over the season") |
|---------------------------|--------------------------------------|--|---|-------------------------------|---|-------------------------------|------------------------------|---|
| | | | Transmissivity (m ² /day) | Specific yield as fraction | Transmissivity (m ² /day) | Specific yield as fraction | | |
| 16 (Bilman) | 299 | Moderate but seasonal (drastically drops in summer) | 10 | 0.00001 | 1,000,000 | | 4 (low T and S) | |
| 17 (Kamal) | 297.5 | Moderate but seasonal (drastically drops in summer) | 10 | 0.00001 | 1,000,000 | | 4 (low T and S) | |
| 18 (Rukhdia) | 304.5 | Sustained high yield even during summer | 100 | 0.01 | 10,000 | | 2 (high T and high S) | |
| 19 (Gendatal) | 303 | Moderate but seasonal (drastically drops in summer) | 10 | 0.00001 | 1,000,000 | | 4 (low T and S) | |
| 20 (Jam Singh) | 303.5 | High yield during the early part of the season but reduces drastically in summer | 200 | 0.00001 | 200,000 | | 3 (high T and low S) | |
| 21 (Gopal) | 304.5 | Moderate but sustained yield throughout season | 50 | 0.005 | 10,000 | | 1 (limited T and high S) | |
| 22 (Sukhlal) | 302 | High yield that reduces in summer | 50 | 0.0001 | 500,000 | | 3 (moderate T and low S) | |

^a Dry season is October to May

sivity and Storage coefficient was used to arrive at an index (Table 2) that mainly considers the priority to protect aquifer portions that provide various degrees of sustainability to the system. The Neemkheda aquifer is a low T, low S aquifer. The terms "high" and "low" used in this paper are used only in a relative sense, to indicate 'relative' properties of various portions of the aquifer.

Well behaviour and a combination of T and S imply four types of situations within the group of seven wells. Figure 4 illustrates the plan and section of the "well commune" described above. These four situations are described below in brief, as a reverse order of priority to protect the resource running into the dry season. The four situations were based on a correlation between how wells behave over the dry season period of about eight months and their estimated characteristics. Wells behaviour can be described broadly as:

1. Low yields and only at the beginning of the dry season.
2. High but very short (seasonal) yields.
3. High, sustained yields over almost the entire dry season.
4. Moderate to low yields that are sustained throughout the dry season.

Using this qualitative well-behaviour, a well index, ascribed to each category of wells, denotes the priority of use over the non-monsoon season, usually beginning in October and extending into early June of the following year.

1. Index 4: Three wells (wells 16,17 and 19) yield water only at the beginning of the dry season. These wells show low T and low S values, implying limited storage within the aquifer surrounding these wells that gets rapidly depleted due to a low S. Wells 16 and 17 are situated in a low lying area close to Neemkheda village where only the fine grained Kanar sandstone is exposed. This sandstone has limited storage of groundwater and poor hydraulic conductivity. Well 19, on the other hand, taps only a thin portion of the Katkut sandstone sandwiched between the Deccan basalt above and the fine grained Kanar sandstone below. Hence, it possesses limited potential for storage and transmission of groundwater.
2. Index 3: Two wells show high yield during the early part of the season. The yield gradually reduces as the dry season progresses so much so that their peak summer yield is negligible. These wells show high T and low S values. Wells 20 and 22 tap the Katkut sandstone as the aquifer, but the geometry of the sandstone (it is finer grained, relatively less weathered and only slightly friable in these wells) permits only limited storage, but the relatively higher hydraulic conductivity helps dewater the aquifer quickly over the irrigation season.
3. Index 2: Only one well has a sustained high yield throughout the dry season. Well 18 yields high T and S values implying a good storage and hydraulic conduc-

tivity around the well, attributed to the relatively thick and permeable, coarse, weathered Katkut sandstone. This well shows no significant decrease in its yield even during peak summer pumping.

4. Index 1: Well 21 is quite unique because it shows a moderate yield that is maintained throughout the entire dry season. The Katkut sandstone is perhaps the thickest in this well and is quite uniform in its coarse grain-size. It is also uniformly weathered but not as weathered as in the case above. It shows a relatively limited T and a high S, implying significant groundwater storage in the aquifer surrounding the wells. The limited T exercises a natural control on the depletion of available storage within the aquifer surrounding the well.

Modeling of a shallow, heterogeneous Deccan basalt aquifer indicates that the drawdown in irrigation wells relative to the regional decline of water level depends upon the aquifer diffusivity, the ratio of T and S (Macdonald et al. 1995). The most significant findings of this study indicate that the regional decline of water levels depends upon the specific yield of the aquifer. In other words, for two cases with a common diffusivity, drawdowns in the aquifer will be significantly higher for the case with a lower specific yield.

The Neemkheda experiment is based upon using the local aquifer diffusivity to schedule use of wells within the well commune over the dry season. Figure 5 illustrates the approach of how a combination of Transmissivity and Storage coefficient (Specific yield) for the shallow Neemkheda aquifer can be used to schedule well use, beginning after the rainy season (October–November) and proceeding through the dry season until the following summer (May).

The Neemkheda aquifer shows a noticeable degree of variability in its aquifer properties. The variation in aquifer diffusivity implies four situations (Table 3). These four situations can be reviewed in light of the ‘aquifer depletion time’ that is defined here as the time it takes for the aquifer storage to be depleted. In practice, this is equivalent to the time over which wells yield significant amounts of water.

The regional aquifer depletion time (t_R) represents the total time it takes for the aquifer storage to deplete over the dry season. For the Neemkheda aquifer, it is about six to seven months. The local aquifer depletion time (t_L) indicates the time it takes for the aquifer to deplete locally, depending upon the local diffusivity situations in the aquifer. Four situations (A, B, C and D) of relative local and regional aquifer depletion times emerge, corresponding to the four diffusivity scenarios (Fig. 5).

In situations A and B, the local aquifer depletion time is very short because of the poor aquifer storage. The T, in this case, plays an insignificant role because the limited aquifer storage implies rapid aquifer depletion, meaning these wells have very short periods of yields, at the beginning of the dry season. In situation C, the local aquifer depletion time is nearly equal to the regional

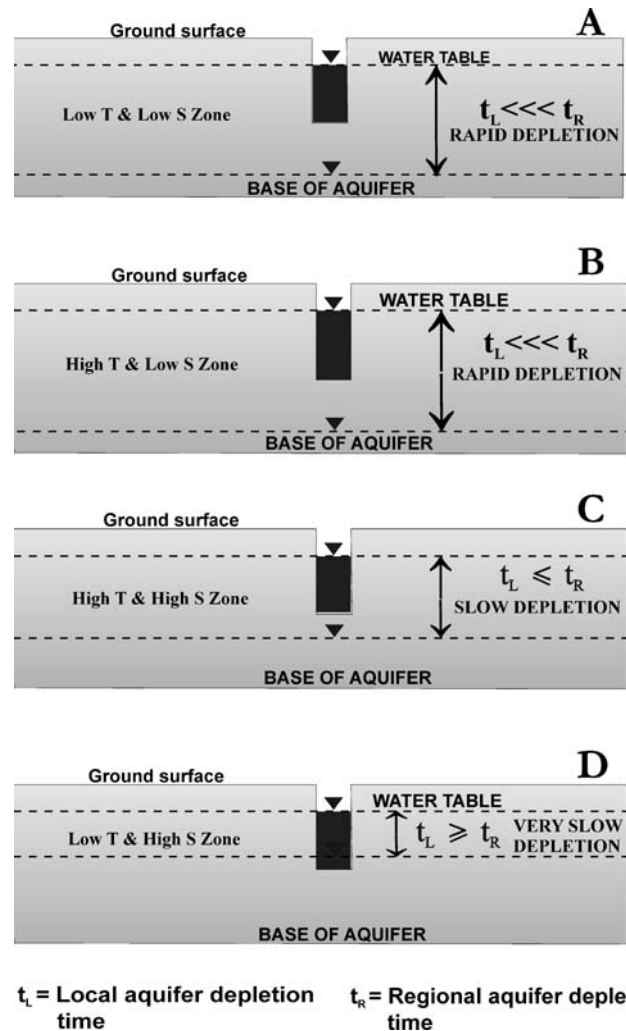


Fig. 5 Conceptual model of community based groundwater management strategy. A, B, C and D are the four typical scenarios of aquifer diffusivity represented by the Neemkheda aquifer and used as a basis for the Neemkheda model

aquifer depletion time, implying that wells dewater the aquifer gradually and that the aquifer can sustain high well-yields throughout the season. In situation D, locally, the low T induces a natural protection on the relatively high S, with wells being able to sustain prolonged pumping. Local aquifer depletion time is equal to or slightly longer than the regional aquifer depletion time. For practical purposes, the regional aquifer depletion time is 7 to 8 months following a normal rainfall year, when the water levels within the shallow aquifer at Neemkheda are nearly at the base of the aquifer.

Methodology of the Pumping Schedule

Although this paper does not deal with the detailed methodology for a comprehensive experiment based upon the strategy proposed here, the broad strategy must include the following components:

Table 3 Well-use schedule using “well index” derived through table above

| Index (wells) | Characteristics | Phase of use |
|----------------|---|---|
| 4 (16, 17, 19) | Low yields (partial penetration in some wells) clearly indicate low transmissivity. Further reduction in well yields over the season implies a dewatering of a major portion of limited aquifer storage | Phase 1: First use after the monsoon and during the initial Rabi irrigation period. Pumping of these wells means dewatering the well-storage predominantly (since the aquifer response is slow on account of low T and S) |
| 3 (20, 22) | Higher yields (initially) that drastically dwindle, progressing into summer. The high transmissivity within the aquifer leads to a quicker dewatering of aquifer storage | Phase 2: Initial rabi irrigation, perhaps beginning with a support to Phase 1 wells and gradually taking over from Phase 1 wells for rabi irrigation. Higher transmissivity in the upper sections (Katkut sandstone) of both these wells would allow pumping until the water table remains within the Katkut sandstone unit |
| 2 (18) | Aquifer transmissivity and storage are both high and therefore the well has a sustained high yield even in summer | Phase 3: This well could almost entirely irrigate a large portion of the land alone during the rabi season. However, Phase 2 should grade into Phase 3 in such a manner that the first irrigation(s) would involve all three wells (Phase 2+Phase 3), the middle irrigation(s) would involve only well 18 and the end irrigation(s) would involve well no. 18 and well no. 21 |
| 1 (21) | The relatively moderate transmissivity is neither prohibitive for well use nor does it allow dewatering as in case of wells with index 3 above. Well yield is moderate but is consistent even during summer | Phase 4: Mainly limited summer cropping with the cycle for rabi being repeated. However, in this case the Phase 3 and Phase 4 wells would need to be more frequently pumped. Well 21 would be reserved primarily for summer use |

1. A scientific base (including understanding of the system through the concepts presented above) that keeps improving with refinement in testing procedures.
2. A scheduling of wells based on observed well behaviour and hydrogeological aspects.
3. Active participation from the community.
4. Other practical considerations to make the strategy effective, such as changes in layout of piping for delivery of water to respective locations at any point of time.

Wells numbered 17, 18, 19, 20, 21 and 22 from the Neemkheda watershed are being considered for the experiment. Since each well has its own unique set of lithological and structural characters, these characters are being quantified. Each well has been identified by a set of key parameters. These are:

- Well-depth indicating the degree of penetration of the aquifer.
- Well yield and trend of reduction of well yield over the dry season.
- Transmissivity (T).
- Storage coefficient (Specific yield in case of the Neemkheda aquifer) (S).

Each well has been indexed on the basis of these characters and a “Well Use Schedule” has been drawn for the non-monsoon season beginning September–October and ending May–June (Table 3). The schedule primarily depends upon a strategy based upon the key parameters given above. At any given time, the irrigation for the cropped land belonging to the participant farmers will be from one or two wells from the ‘commune’ of wells given above. The scheduling will be broadly along the following lines:

- Phase I (first use): Wells that only partially penetrate the aquifer, have a seasonal yield and indicate the lowest T and S values within the aquifer. Most significantly, however, these wells show high diffusivity values. These wells will be used during the initial part of Rabi (winter cropping) season.
- Phase II (second use): Wells that penetrate the aquifer fully, have a high yield that reduces towards summer; wells that indicate high T and low S in the surrounding aquifer, again with a high diffusivity but a significantly higher S than the Phase I wells. These wells will be used over most part of Rabi and into early summer.
- Phase III (third use, but could begin concurrent to the end of phase II wells): Wells that show good yields throughout the dry season and show high T and high S in the surrounding aquifer. These show moderate to low diffusivity. These wells will be used over a part of the Rabi (generally, late Rabi) and through the entire summer.
- Phase IV (Last use): Wells that penetrate the aquifer fully, show a moderate yield during pumping but are sustainable enough to run into summer; wells that

indicate a limited T but a high S within the surrounding aquifer, clearly denoting a low diffusivity domain. These wells will constitute a safeguard for late Rabi and summer, or only for summer use. In fact, such wells can be reserved for priority use of drinking water supplies in summer.

Community Participation

The Neemkheda watershed development programme that SPS implemented some eight years ago was based primarily on peoples' participation. The idea of sharing wells was first proposed by the villagers themselves, some of whom actually practice this method, albeit in a limited manner. The community – institution (SPS) bond in Neemkheda is very strong, with many villagers involved in SPS's various other programmes (in other project villages). Many of these 'barefoot' scientists have through repeated interactions with the scientific community, acquired sufficient understanding of natural resources systems and related problems, including groundwater resources and issues surrounding them. These barefoot scientists handle the hydrological and hydrogeological monitoring in Neemkheda and the surrounding regions. Most of the communities in the area are aware of the limited nature of groundwater resources and the need to manage these resources.

Having realised the benefits of the watershed development programme, most of Neemkheda's residents wish to take a step further into dealing with restricting the demand of water from a limited resource, i.e. the Neemkheda aquifer, and doing it on a community basis. In other words, the community and SPS, both perceive that there has to be an effort at managing water resources after the completion of watershed development projects. This approach has helped immensely in getting things off the ground as far as the well commune experiment is concerned. Although not complete, the outcome of the experiment will largely depend upon how the community takes it forward, especially into other well-fields.

Discussion

India's dryland regions almost exclusively depend upon groundwater as a perennial source of water supply (Shah et al. 1998). Further, many of India's drylands are underlain by formations that can store and transmit only limited quantities of groundwater, constraining the natural availability of this basic source. Recharge to such sources is almost exclusively from the limited annual rainfall, which in most areas occurs over a period of 3–4 months. Very often, rainfall fails drastically, reducing the normal recharge to groundwater and inducing drastic water shortages in many areas.

Notwithstanding the general theory that groundwater supplies are advantaged through the buffering effect of aquifers in relation to climatic variability and water

demands (Calow et al. 1997), aquifers with a limited storage and transmission capacity often desaturate enough to create a "groundwater drought". A groundwater drought is manifested primarily through the drying up of water wells that constitute sources for both domestic and agricultural supplies. In order to provide a supportive role to 'drought proofing programmes' during rainfall deficit periods and also ensure sustainable use of groundwater from low-storage, heterogeneous aquifers, 'demand-based' groundwater resources management becomes necessary. Such management becomes necessary for provision of drinking water, in drought-prone, dryland areas.

Demand-based groundwater resources management is not evolving on a scale it should, even within participatory programmes like watershed development. It is necessary to distinguish between various aspects integrated into a typical watershed development programme, such as conservation, artificial recharge, groundwater resources development and groundwater management. The last of these is seldom attempted in any watershed development project. Aquifer management becomes imperative if watershed management programmes ought to achieve the success that they so nobly envisage. Development of effective approaches of groundwater management will require a long-term process through which national, regional and local systems can evolve (Burke and Moench 2000). The Neemkheda concept is only a beginning to such a process.

Rural communities in India have traditionally used shallow, unconfined aquifers as reliable sources of water supply. Lately, a conflict between deeper aquifers, tapped by bore wells and tube wells and these shallow aquifers tapped by large diameter, open dug wells is emerging in hard-rock areas and in dryland areas such as the central-west Indian region. In order to develop groundwater management strategies in such regions, an understanding of the geometry and characteristics of the aquifer, especially how these aquifers perform on a local (village-level) scale becomes important.

This study attempts to explain the concept of managing a part of a typical shallow aquifer through a systematic well-schedule that is based upon the characteristics of the aquifer and their variability in space through community participation. The concept is taken ahead into a strategy of well-use wherein aquifer diffusivity values are used to schedule a set of wells through the dry season (October to the following May).

The strategy of well scheduling involves using partially penetrating wells within high diffusivity domains (but low aquifer storage) first, and then going on to wells that fully penetrate the aquifer portions having lesser diffusivity. Protecting of very low diffusivity domains by staggering the use of wells within such domains to the end of the dry season will ensure that some water will be available to all the members of the well commune even during the end of the summer period.

The strategy proposed here is being tried out in Neemkheda village from the tribal drylands of Bagli

tehsil in Dewas district of Madhya Pradesh State. The experiment is being monitored and some indicators for testing the success of the strategy are given below. The applicability of the concept has far reaching consequences since low-storage, heterogeneous aquifers are found in many regions of peninsular India. Detailed researches and a conducive social environment will make efforts such as the one being conducted in Neemkheda, distinctly possible.

The authors are aware that there are certain constraints that might have to be overcome, particularly in upscaling the strategy to a watershed or a region. Values of T and S are likely to be different if calculated using other methods. Also, values estimated from short-duration tests may be biased as compared to using long-duration pumping test data obtained in controlled settings. However, relative values are required within a well-commune and hence any single method coming closest to the field conditions can be used to calculate these values. On a regional scale, aquifer configuration is bound to be complex and it would become necessary to understand the aquifer geometry on an appropriate scale before attempting large-scale 'pilots' based on the concept proposed here. It must be admitted that potential conflicts with other well fields in the watershed are not examined here. Even in regional aquifer systems key groundwater management issues are actually addressed on the local level (Burke and Moench 2000). Hence, actual groundwater management initiatives need to evolve through local-level interventions such as the one suggested for the Neemkheda aquifer. The refinement of the Neemkheda initiative will be based on answering several questions that this experiment has raised. These questions include the amount of water available to the well field in relation to the aquifer storage, recommended abstraction rates for different wells, whether there will be any changes in the recharge process within the aquifer after scheduling well pumping and will over-pumping in other well fields affect the well commune. Addressing these questions will not only refine the strategy proposed here, but will also help during upscaling groundwater management projects to larger aquifer management programmes.

The importance of community management of groundwater cannot be overemphasized as all other attempts to regulate its use (through market incentives or disincentives such as electricity pricing, subsidies etc., and state legislation such as creation of new regulating agencies like the Groundwater Regulatory Authority) have limitations in checking overextraction of groundwater. Community management seems a viable option for experimentation as a 'stand alone' solution or a part of a larger solution that includes regulation of use through formal legislation.

Indicators and Indications of the Time Period when These Indicators can be Tested

Indicators of a successful groundwater management experiment will depend as much upon the location of the area as on the post-management status of the aquifer. However, some simple and broad-based indicators can be thought of in order to evaluate such an experiment. These indicators are:

1. Water levels in wells at the end of the summer (as compared to summer water levels in the pre-experiment scenario).
2. Increase in sustainability of the source, i.e. increased period over which irrigation is possible.
3. Increase in cultivated area, i.e. cultivated area over the entire annual cycle.
4. Decrease in variability of cropped area between the Kharif (rainfed crop), Rabi and summer seasons.

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