# Classification and interpretation of piezometer well hydrographs in parts of southeastern peninsular India

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**Abstract** Well hydrographs from 275 piezometers between 1998 and 2001 in the southeastern parts of peninsular India were used in this study. The area has a monsoon-type climate. Hard rocks cover 85% of the area. The form (shape) of the hydrograph depends upon (1) climatic and hydrogeologic parameters and (2) the scale of the graph. Therefore, hydrographs are drawn to a defined and standardised scale, which allows comparison of hydrographs and helps in bringing out reasons for different forms of the hydrographs. Hydrographs can be divided into seasonal segments and the slope of each segment then used as the basic element of a classification scheme. Slopes are classed as *flat* (inclination <20°), *obtuse* (between 20 and 45°), *acute* (45 and 80°), *right angled* (80 and 90°) and *homoclinal* (segments of hydrographs are either rising or falling during one complete water year). Hydrographs are assigned names that are a combination of these classes and begin with the rising segment, such as *acute-obtuse*. Seventy-six percent of segments were *homoclinal*-falling in 1999, which had a poor monsoon. *Flat* segments constitute 27% of all segments in confined Mesozoic aquifer systems. Water table fluctuations suggest an approximate recharge of 120 to 180 mm per annum constituting 18% of the annual precipitation. Cumulative rainfall required to affect a rise in water table is between 45 to 200 mm and lag time varies from 30 minutes to 200 rainy days, which suggests that moisture in the vadose zone holds a part of the annual replenishment for these aquifers.

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## Introduction

Groundwater monitoring is carried out by the Governmental Organisations in India, although universities and other research organisations have carried out short-term monitoring from time to time. In Andhra Pradesh, in the southeastern peninsular of India, two organisations, one managed by the Central Government (The Central Ground Water Board – CGWB) and the other by the Local State Government (The Andhra Pradesh State Ground Water Department – APSGWD), began monitoring groundwater in the early 1970s by establishing a network of observation wells. These were small open dug wells with a diameter of 2 to 4 m and a depth of 8 to 12 m. Most of these observation wells were used for drinking water; the abstraction from the wells was manual and therefore small. Hence, it was presumed that the water level in such wells represented to a good degree the change in the water table of the area. However, this has some limitations, as there is hardly any control on the well parameters such as its dimensions particularly, the depth of the well and abstraction history. In the changed environment brought about by modern-day bore-wells (tube-wells) that lift water mechanically, many of the traditional wells are abandoned and not maintained; also some of them are dry due to the dramatic decline in water table during the last two decades.

This situation (generally described as undesirable, see for example Custodio 2002) has prompted the use of more modern and reliable methods for monitoring groundwater. These methods automate data collection by employing precision pressure transducers adhering to international standards, and downloading and processing data on personal computers. Andhra Pradesh State in India installed 366 precision pressure transducers between January 1998 and March 1999 (Fig. 1), which can record data in an interval from one second to seven days. Of these, 262 recorders obtain data at an interval of 6 h with a capability to record an event (i.e., anomalous rise or fall in water level) that may occur at any time outside the defined

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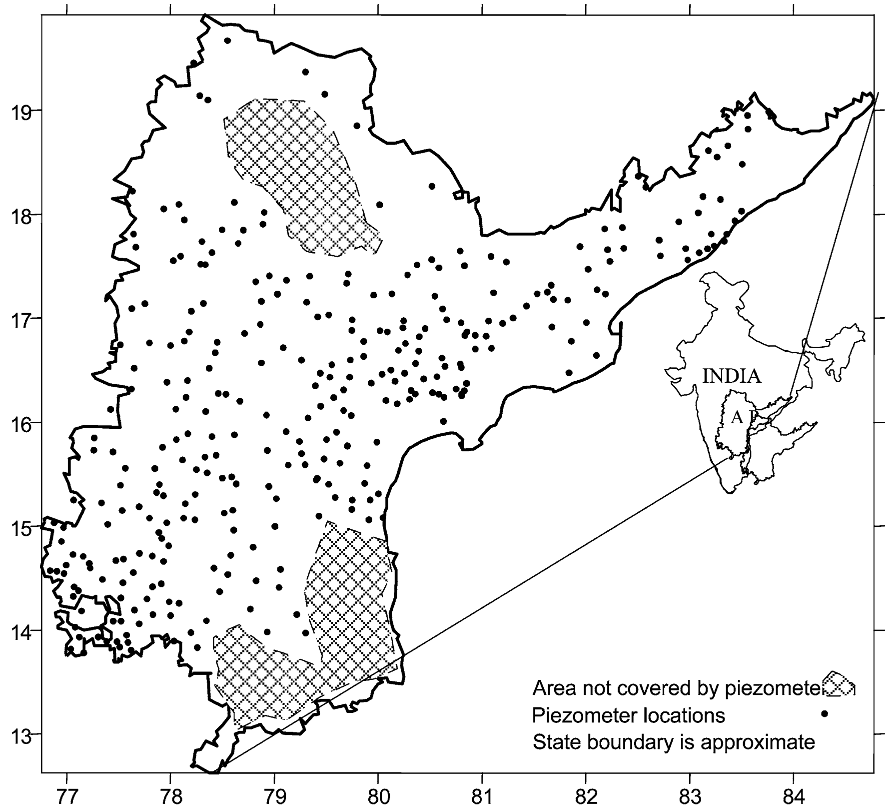

**Fig. 1**
Location map of the piezometers in the study area

interval. The remainder of the transducers are set to record data at an interval of an hour. By comparison with manual measurements, automatic recorders produce hydrographs with high data density and eliminate human bias or errors from the data recording. A large amount of data was generated in less than two years; these data need proper organisation and rapid analytical methods to make them comprehensible.

## Purpose and scope

Todd (1980), Karanth (1987), Fetter (1994), etc, dealt with water level fluctuations in time frames as short as a few minutes to very long periods involving a few decades or even more. They also dealt with the causes of fluctuations, use of fluctuations in estimation of evaporation losses and recharge to groundwater, etc. Bredenkamp (1999), Healy and Cook (2002) made use of well hydrographs for estimation of recharge to groundwater. Taylor and Alley (2001) dealt with relative merits of frequency of water level monitoring, drought indexing using hydrographs, canal stages and water levels, saline water intrusion, etc. Todd (1980) and Karanth (1987) presented physical effects like land subsidence due to long-term decline in water levels, i.e., de-saturation of aquifers. However, there is a dearth in literature that concerns well hydrographs and no attempt was made to classify them. Classification helps in the interpretation of data and makes the data more meaningful. In this case the classification made it possible to group together a number of aquifers and help find the reasons for a particular form of a hydrograph. This paper analyses and classifies the piezometer hydrographs in the study area using records from 275 locations (that were available to the author for analysis) and suggests a few broad categories into which different hydrographs can be placed. The classification proposed, which is the main purpose of this paper allows comparison of hydrographs from different aquifers and for different periods of time. Reasons for different forms of the hydrographs can be easily found in terms of influence of the climate or the deviations from normal climatic conditions, lithology, aquifer parameters, etc. A particular class of hydrograph may tend to be associated with a particular climate or lithology. This exercise will encourage the workers in the field to try and place their hydrographs in this scheme and develop it further.

However, much of the discussion that follows in this study is with respect to a category of rocks described as the hard rocks, which cover 85% of the study area.

Some of the hydrographs in hard rock (taken from locations where daily rainfall data was also available) are also analysed to obtain cumulative quantum of rainfall required to affect a rise in water levels, and probable order of rainfall recharge to the aquifers, which is an improvement on the earlier approach of the author (Raj 2001).

## Physical setting

The study area enjoys a monsoon-type climate, which imposes a strong signature on hydrographs caused by episodic recharge during monsoon. Southwest monsoon winds blow between mid-June and mid-October and bring 400 to 700 mm of rainfall that decreases away from the coast. Similarly, northeast monsoon winds blow between November and January and bring about another 50 to 225 mm of rainfall, mostly in the southern coastal regions of the study area. Other months are more or less dry. Hence, in this region June to May is defined as the water year (Groundwater Estimation Committee 1997).

Three distinct lithologies are observed from the point of view of groundwater in the study area: (1) hard rocks, (2) soft rocks and (3) unconsolidated or weakly consolidated rocks. The hard rocks comprise (a) various granitoids, granulites, gneisses and schists of Archaean age; (b) quartzites, dolomites, dolomitic limestones, slates, phyllites and shales of Proterozoic age; and (c) basaltic lava flows of Eocene age. Typical settings of this type of hard-rock terrain are described by Raj and others (1996). Reddy and Raj (1997) and by Taylor and Howard (2000). They occupy about 85% of the area of the state. The rest of the state is covered by the soft rocks comprising the Mesozoic coal-bearing sequence of sandstones, shales and coal beds, and the unconsolidated or very weakly consolidated Tertiary formations (largely fragile sandstones and shales) and recent alluvium along coastal plains and riverbeds (Krishnan 1960; Ramam 1999). Many of these rock types form good aquifers and in many areas they are the only sources of water for a large part of the year. Transmissivity and specific yield values for these formations are listed in Table 1 (modified after Karanth 1987). However, the values of transmissivity (and also the well yields, not in this table) are heavily skewed towards the lower end as shown by the mean. The low value of mean transmissivity for the alluvial aquifers is due to the fact that most of the data were drawn from the areas where the alluvium occurs as thin and narrow strips along the river beds in the upland parts of the state (above 200 m msl). On the other hand, low-yielding wells in hard-rock terrain are rarely tested; hence, the mean of the data (in case of the hard rocks) is higher than what it would be if all the drilled wells were tested.

## Methods and material

### Well hydrographs, their forms and classification

Each hydrograph has a form or a shape, which depends upon the water-bearing and yielding properties of the rock, namely, porosity, hydraulic conductivity and specific yield. It also depends on the amount, duration and frequency of recharge to the aquifer and the location of the discharge zone. The scale of observation also imposes a control on the form of the hydrograph (Fig. 2). Obviously, if all these parameters were similar, the hydrographs would also look similar. As the scale of the hydrograph also influences the form of hydrograph, an arbitrary uniform scale—one metre on the vertical axis and one month on the horizontal axis, both equal to a unit distance, is chosen for this study. Hydrographs plotted to this standardised scale are divided into seasonal segments and the slope of each segment is then used as a basic element for classification of hydrographs. Slopes are classified as *flat* (segment's inclination <20°), *obtuse* (segment's inclination between 20 and 45°), *acute* (segment's inclination between 45 and 80°), *right angled* (segment's inclination between 80 and 90°) and *homoclinal* (when the hydrograph cannot be divided into rising and falling segments and are either rises or falls during one complete water year). *Homoclinal* segments showing a rise are suffixed as *rising*, while *homoclinal* segments that show a fall are referred to as *homoclinal.* Figure 2 justifies the necessity to use a standardised scale for the hydrographs and Fig. 3 shows the elements of this classification.

### Assigning a category to hydrographs

Hydrographs are assigned names or signatures, which are combinations of the classes of slope as mentioned in this text. But, the names always begin with the start of the water year in a monsoon type of climate as in India, which would correspond; to the rising segment, e.g. *acute-obtuse* (segments are separated by a hyphen; Fig. 4). However, if the rising and recession slopes are of the same category then that hydrograph is assigned the name of the slope such as "*obtuse*" or "*acute*" hydrograph (Fig. 5). Some hydrographs show different slopes if the observations extended over more than one hydrologic cycle. For example, such hydrographs could be *acute-obtuse, obtuse-acute, acute (98–01)* as in Fig. 6. The time period is suffixed in the parentheses and a comma separates each cycle. If a hydrograph shows the same form year after year then the corresponding period is suffixed in parentheses without the name being repeated, as in *acute-obtuse (98–01)*, Fig. 4.

The hydrograph in Fig. 7 is without a rising segment in 1999–2000; it is a *right angled-obtuse, homoclinal, acute-obtuse (98–01)* hydrograph**.** In this case six segments are counted for statistical analysis of the data with two counts

**Table 1**
Summary of aquifer parameters of the main rock units in the study area

| Geologic unit | Transmissivity ($m^2$/d) |  | Depth (m) | Specific yield (%) |  |
|---|---|---|---|---|---|
|  | Range | Mean |  | Range | Mean |
| Recent Alluvium | 60 to 2,700 | 90 | 40 | – | 12 |
| Eocene Lava flows basalt | 0.02 to 140 | 22 | 121 | – | 2.7 |
| Soft rocks Sandstones | 29 to 4,180 | 1808 | 200 | – | 16 |
| Proterozoic Limestone and shale | 1.3 to 1,910 | 173 | 69 | 0.8 to 5.5 | 3.0 |
| Archean Granites and gneisses | 0.05 to 904 | 79 | 40 | 0.5 to 4 | 2.2 |

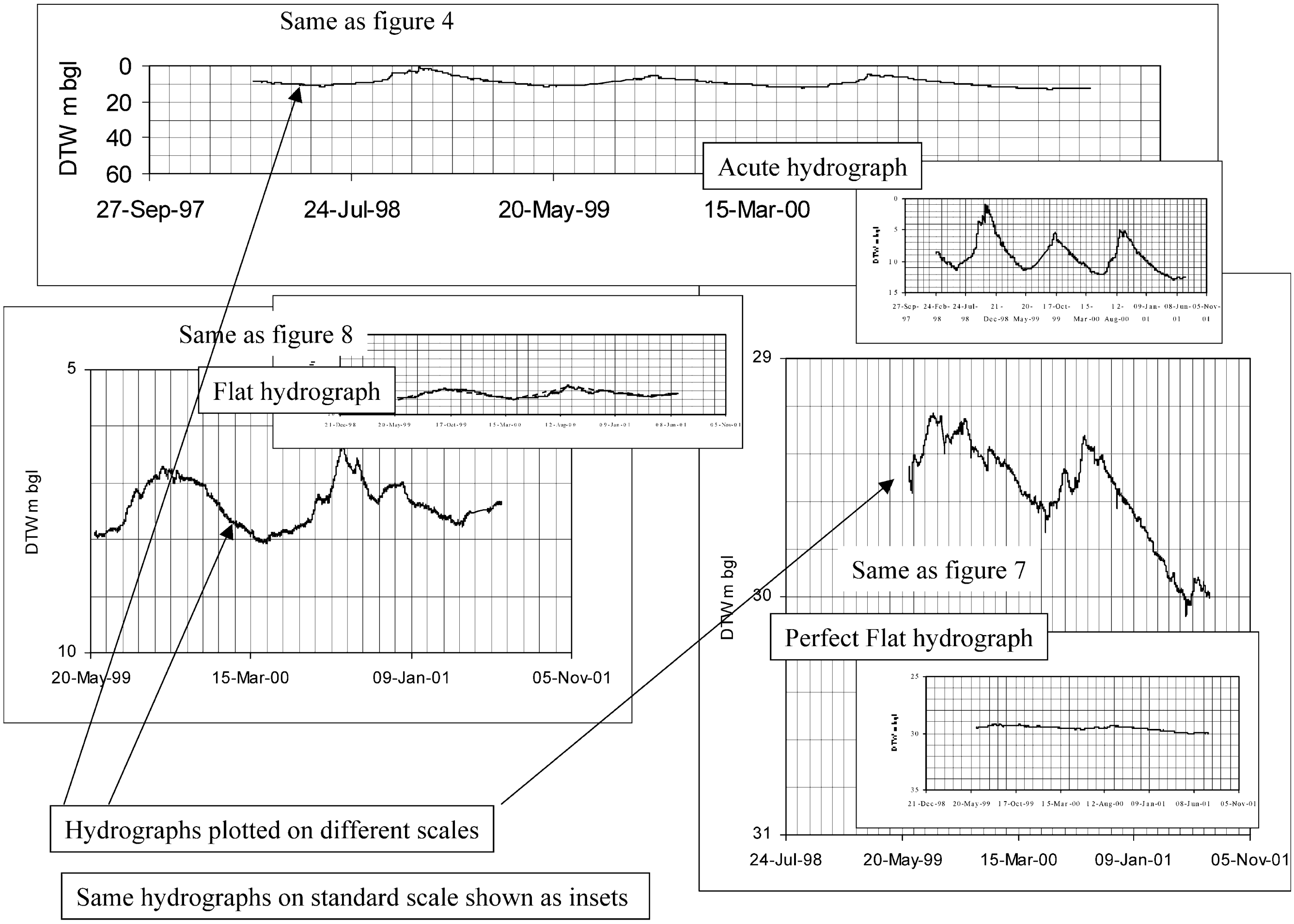

**Fig. 2**
Some of the hydrographs plotted on different scales and used to justify the need for plotting the hydrographs on a standardised scale

for the *homoclinal* segment (which is falling). Similarly, four segments are counted for *flat* (*99–01*) hydrographs (Figs. 8 and 9) spreading over 2 years and also four segments are counted for *homoclinal* rising hydrograph for the same 2-year period (Fig. 10).

It may also be possible to abbreviate long names by considering only the first two letters of the alphabet from the category name or even using numerals for each category with a higher number suggesting greater slope and the highest two numbers suggesting *homoclinal* hydrograph, as indicated in Table 2. The hydrograph for one cycle (or one groundwater year starting in most cases with a rising segment) can be named with just four letters or two numerals (or six letters of the alphabet in case of plateau forms) with the time period shown in parenthesis as the suffix. Thus, the hydrograph in Fig. 4 can be termed *AcOb (98–01)* hydrograph or *32 (98–01)* and "32" may be pronounced as "three two". The hydrograph in Fig. 7 would be *42,55,32 (98–01)*; the homoclinal segment represents two seasons; hence, the number 5 is repeated. Finally, when data for large-time periods become available the hydrograph can be identified using a dominant signature as 42 or 32 hydrograph. Comparing signatures 55 or 42 or 32 or 11 would immediately indicate that the water table is declining in the area around 55, recharge is relatively quicker in the case of 42 compared with 32; a 43 or 44, on the other hand, would suggest quicker discharge, also possibly indicating a poor aquifer. Two-digit signatures will not suggest deviations. Hence, if significant deviations are noted, the signature can be expanded to include the deviation; such as deviation of 32 (*a cute-obtuse*) to 55 (*homoclinal*) in 6 years out of a record for 20 years; and its signature can be 42_55 (6/ 1998–2018).

### Symmetric and asymmetric hydrographs

Most hydrographs are *asymmetric*. The rising segment is sharper indicating a recharge surge or an event, which is followed by a recession segment, which has gentle slope. This indicates that recharge is faster and discharge is slower (See for example Fetter 1994). Hence, hydrographs are rarely *symmetric* (Fig. 5).

### Other categories of hydrographs

Some descriptive forms that do not readily fit into this scheme, for example, *smooth*, *jagged*, *plateau*, etc, can also be recognised. *Plateau*-shaped hydrographs (Figs. 11 and 12) show a rising segment, a recession segment and a *flat* part, when the water level in a piezometer stands at a distinctly higher elevation. A hydrograph of any category can be qualified as relatively *smooth* or *jagged*. However, *acute* forms are usually *jagged* as well.

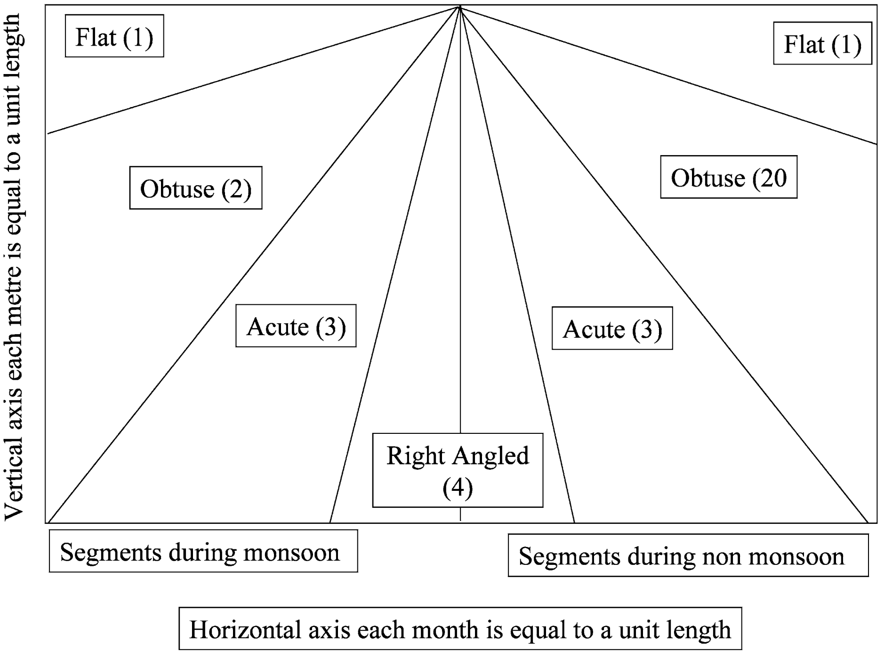

**Fig. 3**
Classification scheme of the hydrographs

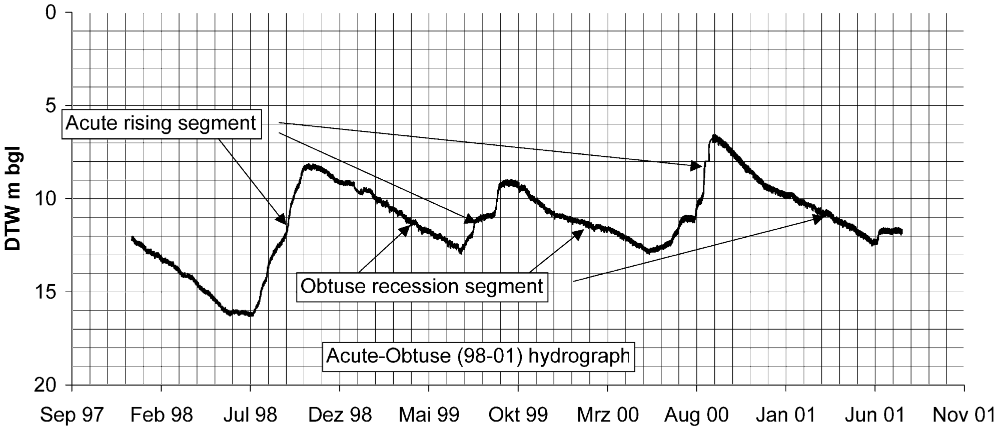

**Fig. 4**
Acute-obtuse hydrograph, which is the dominant type of hydrograph in the study area

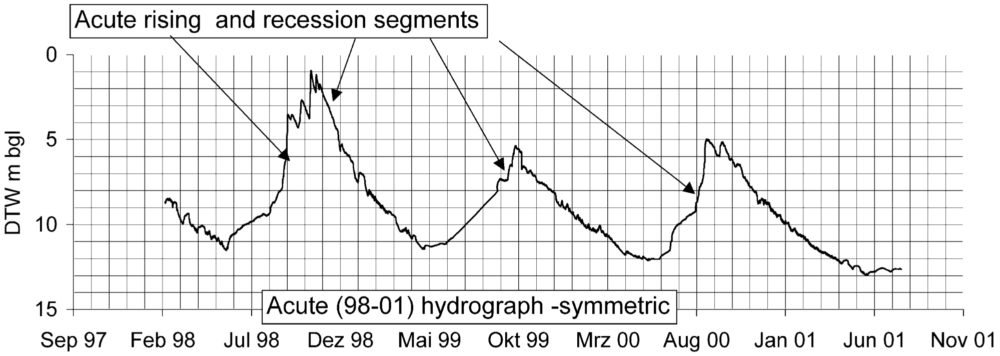

**Fig. 5**
Acute hydrograph, common in Archaean granulites and upper Proterozoic meta-sediments (shaly-phyllitic types)

# Inferences

### Hydrographs and aquifers

Comparison of hydrographs provides an insight into the nature of the aquifer. The most common form of hydrograph is *acute-obtuse*. *Acute* varieties are fairly common and are dominant in hard rocks, such as Proterozoic phyllites and shales and the Archaean granulites, gneisses and schists in the eastern parts of the study area. *Homoclinal* and *obtuse-acute* hydrographs were observed in 1999, which had a poor monsoon.

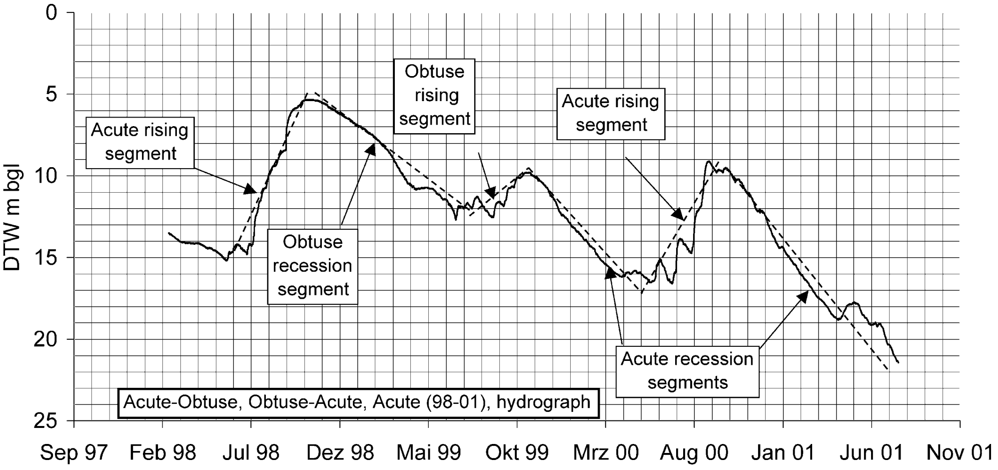

**Fig. 6**
Acute-obtuse, obtuse-acute, acute (98–01) hydrograph, which shows change in both the rising segments and recession segments over a period of three years. Note the recession segment above 9 m is *obtuse* and water level was above it in only 1998. This type of change in recession segments is not common (see next hydrograph)

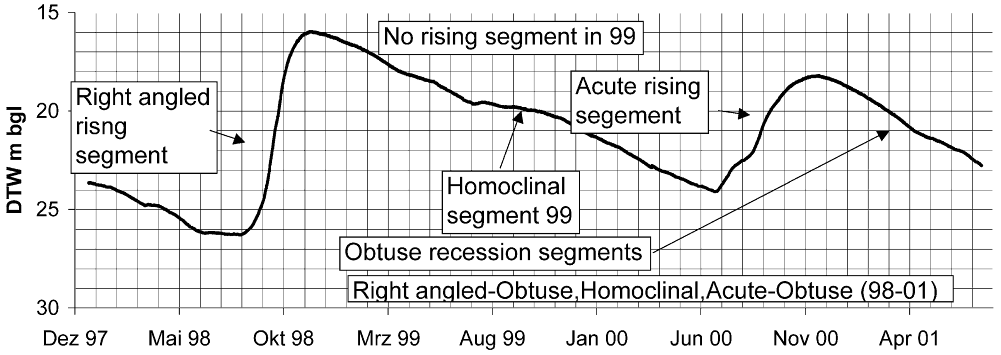

**Fig. 7**
Right angled-*obtuse*, *homoclinal*, *acute-obtuse* (98–01) hydrograph is also due to wide variations in monsoon rainfall. Note the slope of recession segments is more or less the same during the period

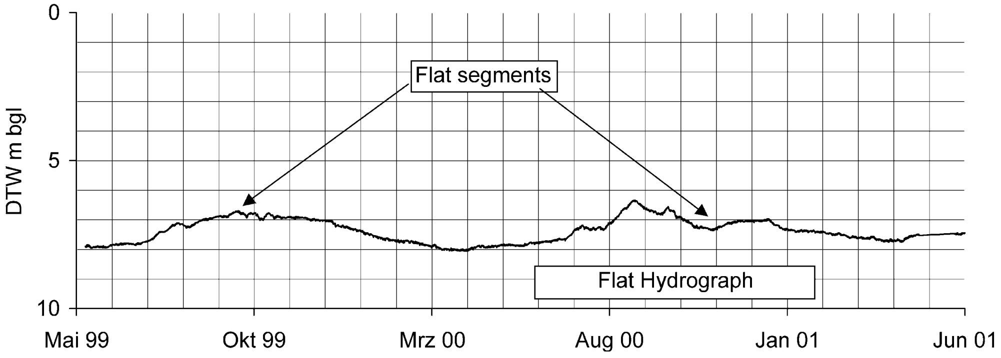

**Fig. 8**
Flat hydrograph, this confined aquifer (Mesozoic sandstone) seems to be immune to the changes, but for fluctuations of a few tens of centimetres (see Fig. 10 also)

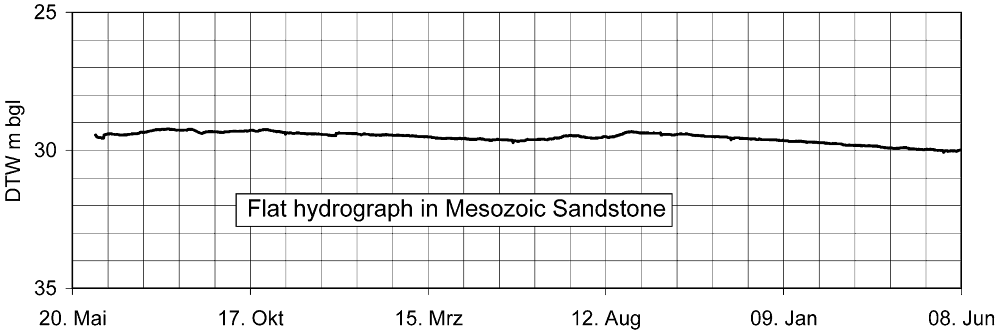

**Fig. 9**
Flat hydrograph with seasonal fluctuation of around a metre or one and half metre

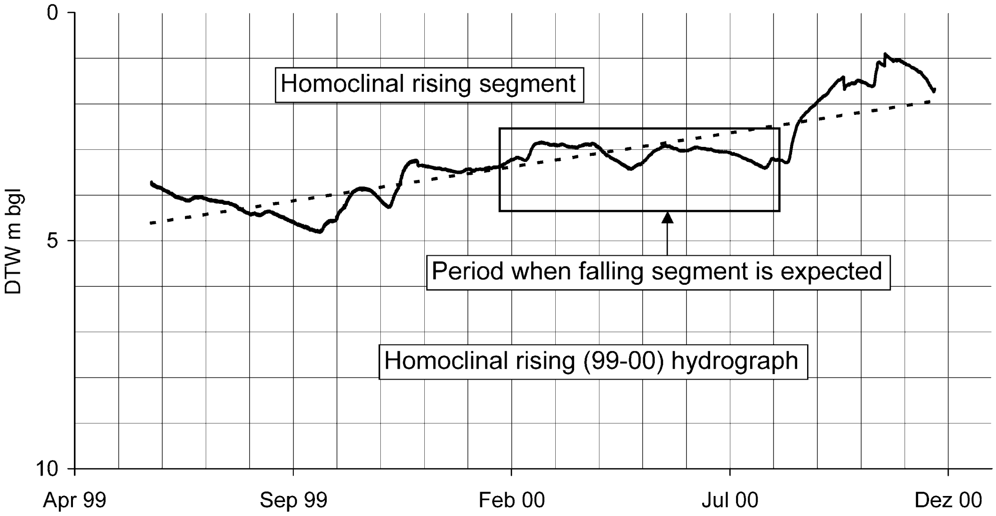

**Fig. 10**
A homoclinal rising hydrograph under the influence of recently commissioned surface water irrigation system

**Table 2**
Category names and short names of the hydrographs

| Category name | Category short name | Category Code | Segment's inclination |
|---|---|---|---|
| *Flat* | Fa | 1 | 0 to 20° |
| *Obtuse* | Ob | 2 | 20 to 45° |
| *Acute* | Ac | 3 | 45 to 80° |
| Right angled | Ra | 4 | 80 to 90° |
| *Homoclinal* falling | ho | 5 | – |
| *Homoclinal* rising | hr | 6 | – |
| Plateau | Pa | – | – |
| Concentric | Co | – | – |
| Wavy | Wa | – | – |
| Jagged | Ja | – | – |

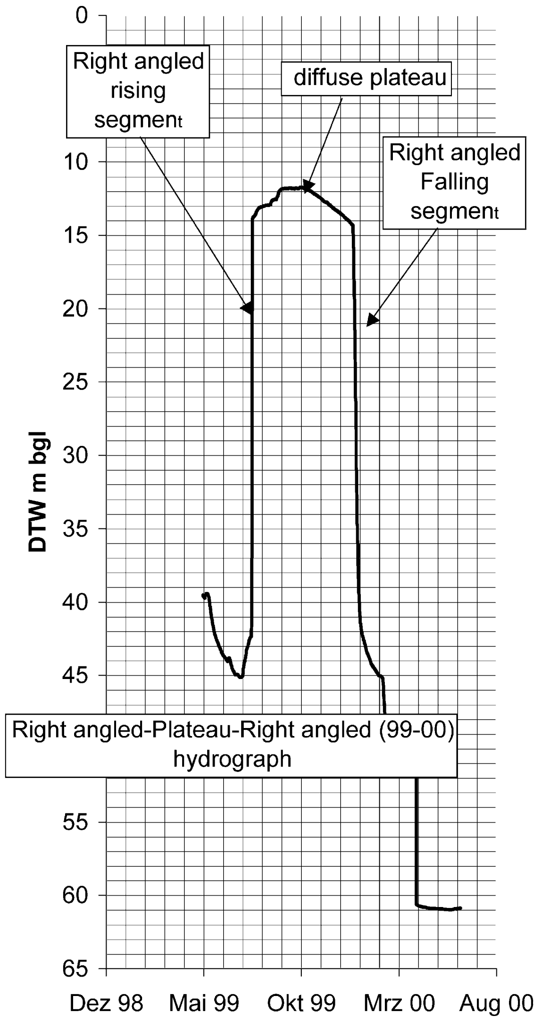

**Fig. 11**
Right angled-plateau-right angled (99–01) hydrograph showing a steep rise due to a sudden contribution from the overlying aquifer, (which are dry in the summer period) in layered basaltic rocks of the area

Hydrograph segments were used for rapid statistical grouping and analysis (Fig. 13). The dominant rising segment is the *acute* type followed by the *obtuse* type, except in the confined aquifers belonging to Mesozoic strata, where *flat* segments are dominant. *Right-angled* rising hydrograph segments are few in number. The dominant recession segment is *obtuse*. Departure from the dominant categories could be due to a number of reasons. Some of these are discussed below:

1. Variation in rainfall:
    a. In a poor monsoon year the rising segments instead of being *acute* tend to be *obtuse* or altogether absent. Thus, many of the hydrographs are *homoclinal*, as in 1999.
    b. *Right-angled* rising segments or departures towards steeper-rising segments occur due to high rainfall in a short duration, either in one spell or in several closely spaced precipitation events.
    c. Wavy forms are due to short spells of recharge and discharge during most parts of the year.
2. Aquifer characteristics:
    a. *Acute* recession segments with either *acute* rising segments or *right-angled* rising segments are due to

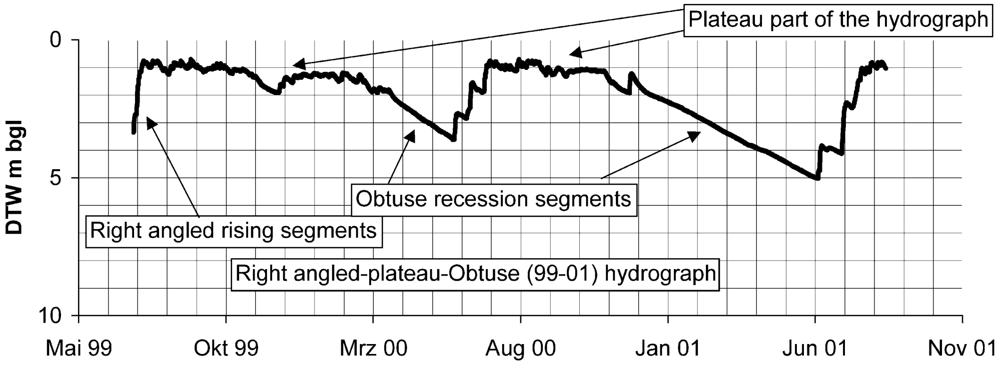

**Fig. 12**
Another hydrograph showing plateau due to induced recharge as water is released to the canal

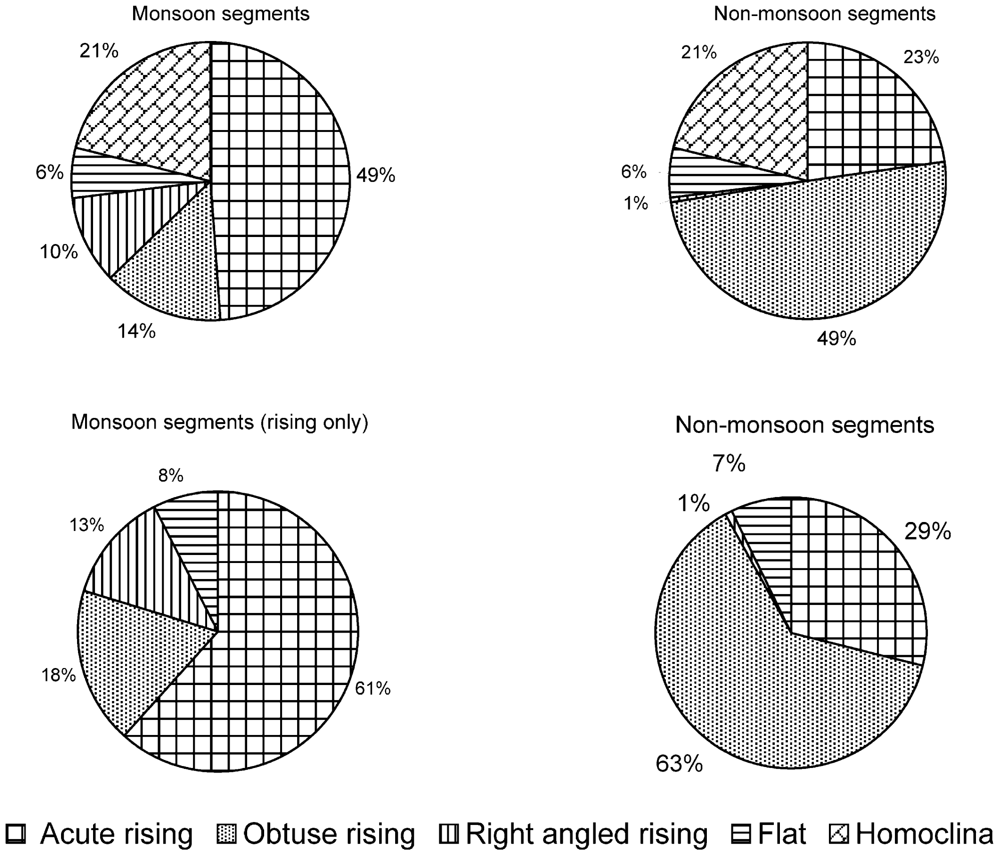

**Fig. 13**
Percentage of different classes of segments in different rock types during monsoon and non-monsoon periods

relatively poor aquifers. These are observed in hard rocks comprising shales of Proterozoic strata where water table fluctuations are very high (about 10 m) when the rainfall remains more or less the same and also in a large percentage of the wells in a granitic terrain. *Acute* recession segments are also common in an aquifer comprising weathered residual granulites, gneisses and schists in the eastern parts of the study area (Fig. 4). They are also noticed in Recent alluvial aquifers, which are clayey and hence reflect relatively low specific yield.

b. *Flat* segments are noted in aquifers with large transmissivities and aquifers that are confined, such as in Mesozoic sandstone aquifers (Fig. 8)
c. Plateau forms separated by *right-angled* or *acute* segments occur in multi-aquifer systems, when the overlying aquifers dry up and are saturated seasonally (Figs. 11 and 12).

3. Induced recharge:
   *Homoclinal* rising and plateau forms of hydrographs are observed in areas where canal irrigation is introduced. The water levels in the piezometers stabilise in response to the head in the canal when water is released into the canals (Fig. 9).
4. High abstraction:
   *Homoclinal* forms are observed in areas where the rate of groundwater extraction throughout the year is higher than the rate of recharge. At present this happens only during a poor monsoon year (Fig. 6).

Coarse grained weathered and fractured granite aquifers show *acute-obtuse or 32* signature, but during a poor monsoon year shows an *obtuse or 22* signature while in some cases where groundwater withdrawal is relatively high their signatures could be *homoclinal or 55*. Fine grained weathered granites or clayey weathered granites or weathered residual granulites, gneisses and schists show *acute* or a *33* signature irrespective of the deviations in rainfall. Mesozoic aquifers and aquifers in alluvium show *flat* segments.

### Seasonal trends

Rising segments of the monsoon period are somewhat difficult to classify as they are erratic, suggesting irregular recharge surges and the co-efficients of determination ($R^2$) of their hydrographs are less than 0.5. The shape of the monsoon limb is influenced by the intensity, interval and duration of precipitation. Rainfall appears to primarily determine the shape of the rising limb, as even a hydrograph of a well in a good aquifer in an alluvial tract shows an *acute* or *right-angled* (steep) rising limb during a period of particularly good rainfall and conversely well hydrographs tend to be *obtuse* in a poor monsoon year. Not all hydrographs show the same class of rising limb but react differently, which is due to the character of the aquifer. However, the trends observed during a non-monsoon period generally show linear or curvi-linear trends with the co-efficient of determination being nearly equal to unity. It indicates a lack of irregular abstraction around the piezometer and this would help in predicting the groundwater stage during the recession period by using a spreadsheet program. The shape of the hydrograph during a non-monsoon period is a reflection of the character of the aquifer. Linear recession could be due to rapid discharge from the aquifer. Curvi-linear trends in hard rock may be due to the complex nature of the aquifer, which may be reflecting a phenomena similar to de-watering during stress. De-watering during stress is attributed to slow release from the matrix comprising the weathered rock and faster release from the fractured rock (Barenblatt and others 1960).

### Rainfall infiltration factor in hard rock areas

The build up of the water level is mostly due to rainfall infiltration during the monsoon period. Seepages from tanks and other water bodies contribute only meagre quantities, especially at places where the piezometers are located. Piezometers were located in such a way as to minimise the effects of seepages as well as the direct interference from a pumping well. However, some piezometers were located in the zone of influence of canals (and pumping wells) to study the behaviour in these situations.

Athavale (1985), using tracer techniques, has arrived at an infiltration factor (RI) between 8 and 10% of the total annual rainfall in the study area. Gupta and others (1985), using the modelling technique, have arrived at 8.5% in Shadnagar Basin. Reddy and others (1994), using a computer-generated model estimated a 10.4% RI around Hyderabad. Considering the results of these studies, a value of 10% RI is adopted as first approximation, which is also about the same as that suggested by GEC (1997) for the computation of rainfall recharge in a granitic terrain. This value of RI is used to compute specific yield, as these computed values were found to be very low, the value of RI is then revised to bring both the values to a known range. The hydrologic budget equation given by Schicht and Walton (1961) is

$$P_a = R_w + ET + U \pm \Delta S_s \pm \Delta Sg_s \qquad (1)$$

where $P_a$ is precipitation, $R_w$ is stream flow, ET is evapotranspiration, U is subsurface flow, $\Delta S_s$ is the change in soil moisture, $\Delta Sg_s$ is the change in groundwater storage. Walton (1970) derived an equation to estimate the amount of precipitation that reaches the water table. He also suggested that groundwater recharge can be estimated from the data on significant rises in the mean groundwater stage.

Thus, Eq. (1) can be written as (Walton 1970)

$$Y_g = \frac{P_a - R_w - ET - U}{\Delta H_s} \qquad (2)$$

where $Y_g$ is gravity yield equal to specific yield (S), $\Delta H_s$ is the mean change in groundwater head or mean water table fluctuation (wtf), $P_a$, $R_w$, ET and U are as defined earlier.

$$\text{Let}\quad P_a - (R_w + ET + U) = P_w \qquad (a)$$

$P_w$ therefore is rainfall infiltration reaching groundwater body or balance of precipitation after accounting for $R_w$, ET and U.

Hence, Eq. (2) can be written as (with more commonly used notations S for $Y_g$ and wtf for $\Delta H_s$)

$$S = P_w/\text{wtf} \qquad (3)$$

and as $P_w$ is not experimentally determined in this study and its value is not known precisely, the equation is further modified as

$$S_a = P_w/\text{wtf} \qquad (4)$$

where $S_a$ is *apparent specific yield.*

Re-arranging this in terms of $P_w$ per annum (a) gives

$$P_w = S_a \times \text{wtf}/a \qquad (5)$$

This equation is similar to

$$R = S_y \times \delta h/\delta t \qquad (6)$$

given by Healy and Cook (2002), where $S_y$ is specific yield $\delta$ h is water table height, and $\delta$ t is time.

Healy and Cook (2002) state that this equation can be used over longer time intervals (seasonal or annual) to produce an estimate of “net” recharge.

### Rainfall infiltration factor and specific yields

There is a tendency to adopt the average value of water table fluctuation of an area to arrive at groundwater recharge; there is also a tendency to use the average value of water table fluctuation to arrive at the specific yield (Naik and Avasthi 2003). Groundwater draft cannot be obtained with reasonable precision and average water table fluctuation even in a small basin is dependent on the topographic positions of the sampled stations, therefore to arrive at groundwater recharge the following approach is adopted:

*Apparent specific yields* were computed using Eq. (4) and adopting $P_w$ as 10% of total annual rainfall for the net rise in the water table during monsoon for seven hydrographs from hard rocks for which daily rainfall data was available. The range of $S_a$ was from 0.003 to 0.022. This range is less than that reported from similar formations by Thangarajan (1999), Reddy and Raj (1997), Karanth (1987) and Todd (1980). GEC (1997) suggests values between 0.02 and 0.04, which are much higher than those obtained in the present study.

This anomaly is expected, and can be partly explained by the fact that the initial water levels were deep i.e., >12 m below ground level (bgl). The specific yields represent a portion of aquifer that is weathered to a lower degree and has fewer fractures per unit volume of the rock. At this depth (>12 m bgl) the rock hardly develops inter-granular (secondary) porosity and whatever little porosity that the rock has is due to sparse fractures in the rock. This fact is also reflected by *acute* rising segments, especially when the depth to water level during the pre-monsoon phase is greater than 12 m bgl, but these low $S_a$ values also suggest that rainfall infiltration (as defined here) may be much higher than 10%. For example, if the rainfall infiltration is doubled, even then the range of specific yield would be 0.006 to 0.044% which is on the lower side of the accepted standards (0.02 to 0.04).

However, if specific yields between 1.5 to 2% are adopted (which are also on the lower side of the accepted range in hard rock terrain; –see Table 2), using Eq. (6), the net recharge, which is the same as $P_w$ as defined above in the absence of other sources of recharge, works out to be of the order of 90 mm (where the rainfall is lower) to 180 mm (where the rainfall is higher) in these hard rocks. It suggests for these hard rock aquifers an infiltration factor of around 18% of annual precipitation, which is twice the value commonly adopted. As net rise was used to arrive at the value of apparent specific yield, the rainfall infiltration represents an effective addition to the groundwater body after allowing for both natural and artificial abstraction during the monsoon period. It also suggests that the gross recharge must be higher than the 18% of the annual precipitation.

### Irrigation demand on groundwater and recharge

The specific yield of the hard-rock formations is low, but the aquifers can be tapped up to a depth of 50 to 60 m, which indicates that the aquifers can hold and yield substantial quantities of water and that the limit to groundwater extraction is set by the amount of recharge. Rainfall infiltration is of the order of 90 to 180 mm. The water requirement for paddy in this area during the dry season is 1,200 mm and for irrigated dry crops like groundnut it is 600 mm (APSGWD 1977). Considering all the uncertainties involved, the probable recharge per annum is $^1/_6{}^{th}$ of the typical crop water requirement for irrigated dry crops or about $^1/_{10}{}^{th}$ for wet crops like paddy, as a result only between a sixth and a tenth of the land can be brought under groundwater irrigation. It indicates that groundwater mining is taking place wherever groundwater irrigation exceeds this factor. It is substantiated by the fact that over the last three decades three significant changes in the hydrologic regime in these hard rock areas took place in that order: (1) Base flows in streams less than 4th order have dried up completely during the 1980s, (2) Dug wells have dried up in the late 1980s and early 1990s, (3) Average yields of bore-wells have decreased from 3.5 lps to 1.5 lps or even less during the late 1990s and the trend continues accompanied by a declining potentiometric head. Further, drying up of the weathered zone has led to a decrease in reserve storage and as a result the wells (bore-wells) have become extremely sensitive to vagaries of monsoon. In a poor monsoon year their yields go down by as much as 75% and in the summer months most wells cannot sustain pumping for irrigation use. This scenario reaffirms the fact that in any area groundwater cannot be extracted beyond a certain limit as suggested earlier by Raj and others (1996). The only way to remedy is to import surface water contributed especially from areas which are under forest cover and to tap the so-called undependable flash floods.

### Cumulative rainfall needed to affect a rise in the water level

The amount of cumulative rainfall needed to affect a rise in the water level ($R_c$) varies depending upon initial moisture conditions and depth to water level with other factors such as soil type or formation characteristics remaining constant. An estimate of rainfall required to overcome a soil moisture deficit is made from the plot showing the increase in water level and the rainfall recorded for that particular day. $R_c$ is about 45 to 200 mm for the seven hydrographs in hard rocks for which rainfall data was available and analysed. Two of the analyses are illustrated in Fig. 14.

Lag time between the onset of rainfall in monsoon and the rise in water level varies from about 30 minutes to 200 rainy days. It also depends on the intensity of the rainfall. The delayed response indicates slow contribution from the overlying vadose zone towards annual replenishment of these aquifers.

## Conclusions

Comparison of hydrographs plotted on a standardised scale and their classification using slopes of seasonal segments as elements of classification give a good relative picture of aquifers and their status. It makes the hydrographs amenable to visual and statistical analyses, which have hitherto not been attempted in groundwater studies. Data from 275 piezometers were studied and 1280 segments were classified, i.e. 640 in each season. *Acute* rising segments are dominant during monsoon and constitute more than 50% of the segments in hard rock. However, in Mesozoic and Recent sediments they constitute 20 and 36% of the segments. *Obtuse* rising or *flat* segments are

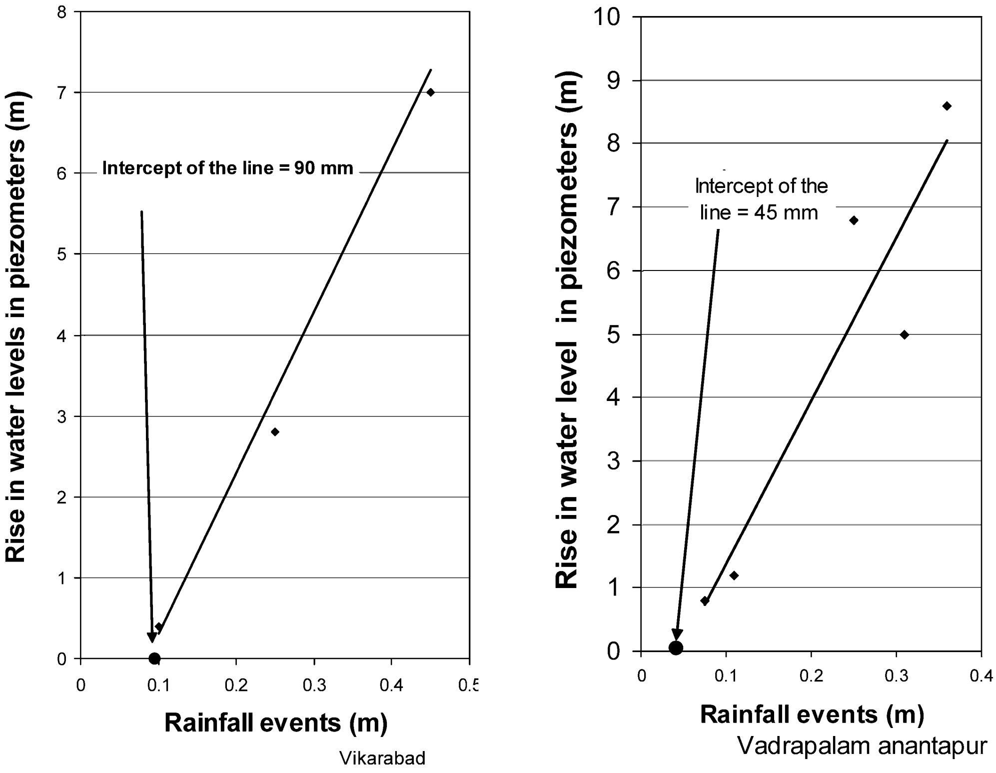

**Fig. 14**
Rise in water level in piezometer vs. a rainfall event showing threshold values of quantum of rainfall required to effect a rise in water level in the piezometer

common in Recent and Mesozoic sediments. Obtuse segments are in significant numbers in hard rocks also. *Obtuse* falling segments are dominant in a non-monsoon period; these are followed by *homoclinal* segments. However, in a normal or excess monsoon year the number of *homoclinal* segments is very few and they are replaced by *acute* rising segments during the monsoon period; and hence the *acute* rising segment far outweighs all other types in such a year. Absence of *homoclinal* segments results in the increases in the number of *obtuse* falling segments, which far outweigh all other segments in normal monsoon years.

Most of the hydrographs in this study fall under the *acute-obtuse* or *acute* category. *Homoclinal* trends implying aquifer depletion are not desirable but are noted only in a few of the piezometers or are noted in a bad monsoon year as in 1999. Recession segments are smooth and dominantly *obtuse*; they tended to be somewhat steeper in 1999–2000. This suggests whatever the recharge trend, the discharge parameter does not alter much because it is a function of the aquifer characteristics, T and S. Discharge takes place mostly through artificial withdrawal that remains more or less the same year after year or increases steadily year after year although not enough to change the category of the recession segment in many cases.

Recession segments of many hydrographs show a linear trend or curvilinear trend, with co-efficient of determination nearly equal to unity. It indicates a lack of irregular abstraction around the piezometer and would be helpful in predicting the groundwater stage during the recession period. Cumulative rainfall required to cause a rise in water table is between 45 to 200 mm and lag time varies from about 30 minutes to 200 rainy days which suggests that moisture in the vadose zone holds a part of the annual replenishment in these aquifers.

Accurate data of rainfall intensity and number of rainy days, evapotranspiration, etc, would help in further understanding the behaviour of the aquifer.

The study also shows that groundwater can sustain not more than 10% of the land for irrigation and the only way out of this is to import surface water contributed from areas that are under forest cover and to tap the flood flows by constructing medium irrigation projects or even contemplating lift irrigation. This will incidentally act as a very good source of recharge to groundwater, which can then be used in conjunction with surface water.

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## References

APSGWD (1977) Studies on hydrologic parameters in water balance computations, Andhra Pradesh. Research Series Number 6, Andhra Pradesh State Ground Water Department, Hyderabad, 151 pp

Athavale RN (1985) Nuclear tracer techniques for measurement of natural recharge in hard rock terrain. In: Proceedings of International Workshop on Rural Hydrology in Fissured Basement Zone. Dept. of Earth Sciences, University of Roorkee, pp 71–80

Barenblatt CE, Zheltov IP, Kochina IN (1960) Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks. J Appl Math Mech 24:1286–1303

Bredenkamp DB (in Lloyd JW) (1999) Water resources of hard rock aquifers in arid and semi-arid zones. UNESCO Publishing, Paris, 284 pp

Custodio E (2002) Aquifer overexploitation: what does it mean? Hydrogeology J IAH 10:254–277

Fetter CW Jr (1994) Applied hydrogeology, Third Edition. Prentice-Hall, New York, 691 pp

GEC (1997) Report of the Ground Water Estimation Committee. Ground water resource estimation methodology – 1997. Ministry of Water Resources, Government of India, 105 pp

Gupta CP, Thangarajan M, Rao GVVS(1985) Evolution of regional hydrologic set-up of a hard rock aquifer through R-C analog modal. Groundwater 23:331–335

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeology J IAH 10:91–109

Karanth KR (1987) Ground water assessment, development and management. Tate-McGraw-Hill, New Delhi, 720 pp

Krishnan MS (1960) Geology of India and Burma, Fourth Edition. Higginbothams Pvt Ltd, Madras, India, 604 pp

Naik PK, Avasthi AK (2003) Groundwater resource assessment of Koyana River Basin, India. Hydrogeology J IAH 11:582–594

Raj P, Nandulal L, Soni GK (1996) Nature of aquifer in parts of granitic terrain in Mahabubnagar District, Andhra Pradesh. J Geological Society of India 48:299–307

Raj P (2001) Trend analysis of groundwater fluctuations in a typical groundwater year in weathered and fractured rock aquifers in parts of Andhra Pradesh. J Geol Soc India 58:5–13

Reddy NT, Raj P (1997) Hydrogeological conditions and optimum well discharge in granitic terrain in parts of Nalgonda District, A.P. J Geol Soc India 49:61–74

Reddy NT, Prakasam P, Subramanyam GV, Rao NT, Goud PV, Harish K, Rao GVVS, Gupta CP (1994) Groundwater recharge process model in a granitic terrain. A long term analysis. J Geol Soc India 44:645–662

Ramam PK (1999) Mineral resources of Andhra Pradesh. Geol Soc India, Bangalore, 252 pp

Schicht RJ, Walton WC (1961) Hydrologic budgets for three small watersheds in Illinois. Illinois State Water Survey Report of Investigation, 40 pp

Taylor CJ, Alley WM (2000) Ground-water-level monitoring and the importance of long-term water-level data. U.S. Geological Survey Circular 1217, 77 pp

Taylor R, Howard K (2000) A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda. Hydrogeol J IAH 8(3):279–294

Thangarajan M (1999) Numerical simulation of groundwater flow in a weathered hard rock aquifer: A case study. J Geol Soc India 53(5):561–570

Todd DK (1980) Ground water hydrology, 2nd edition. Wiley, New York, 535 pp

Walton WC (1970) Groundwater resource evaluation. McGraw-Hill, New York, 664 pp