# Sharp variations in groundwater levels at the same location: a case study from a heavily overexploited, fractured rock aquifer system near Bengaluru, South India

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**Analyses of 83 borehole camera video scans revealed that (i) measured groundwater levels show variations of up to about 200 m, even in borewells located in close proximity to each other; (ii) water-bearing joints located at shallow depths in deeper borewells often produce cascades of water which flow down-hole till they meet the water level; (iii) the downward flow of recharging waters directly through the existing borewell shafts leads to the formation of a dewatered zone below the recharge zone and above the saturated zone, and (iv) the borewells completed in the dewatered zone show a direct relationship between water level and well depth – deeper the borewell, deeper is the water level. Only the currently yielding borewells, with at least one water-yielding joint below the water level give a fair estimate of the regional groundwater table.**

**Keywords:** Borehole depth, dewatered zone, fractured rock aquifer, groundwater level.

GROUNDWATER is playing an increasingly important role in India’s economy, contributing to over 65% of net irrigated area, 85% of domestic water use and significant industrial water use[1,2]. There is increasing concern that groundwater extraction in many parts of the country is far above what can be naturally replenished. For instance, as of 2009, 26% of the area in Karnataka and 36% of the area in Tamil Nadu (both predominantly underlain by crystalline hard-rock formations) have been classified as ‘overexploited’ in the utilization of groundwater[3]. In peninsular India, hard rock or fractured rock aquifers contribute more than 50% of all water used[4]. Sharp local variations in recharge are common in areas underlain by fractured rocks, indicating preferred flow paths[5].

Obtaining an accurate estimate of the groundwater balance is particularly important in view of the severity of the problem confronting groundwater managers in India. A first step in managing groundwater resources is establishing long-term trends in the water levels, a key parameter in formulating sustainable groundwater management practices. Potentiometric maps prepared from measured groundwater levels are indispensible tools in identifying the flow directions, establishing the level of groundwater utilization and estimating aquifer properties. The continuously falling groundwater levels, due to drilling of deeper borewells in the overexploited zones, throw up a challenge to monitor the status of groundwater environment with the required accuracy. Recent studies in the Indian subcontinent have shown that hard rocks are generally characterized by dense horizontal jointing in the first few metres and their density decreases with depth[6–8]. While various aspects of hard-rock hydrogeology as well as groundwater flow therein have been studied in detail, most of these studies pertain to areas where aquifer material below the groundwater level remains saturated[9–17].

The present work was carried out as part of a larger water resources study in the Thippagondanahalli (TG Halli) reservoir catchment adjoining Bengaluru city in South India (Figure 1). In the past two decades or so, there has been significant reduction in the inflow to the reservoir leading to very little storage in the dam. A complete absence of base-flows in non-rainy periods, most probably a consequence of sharply declining groundwater levels, is suggested to be the cause of the present situation in the catchment[18]. Geologically, the major rock types found in and around the present study area include

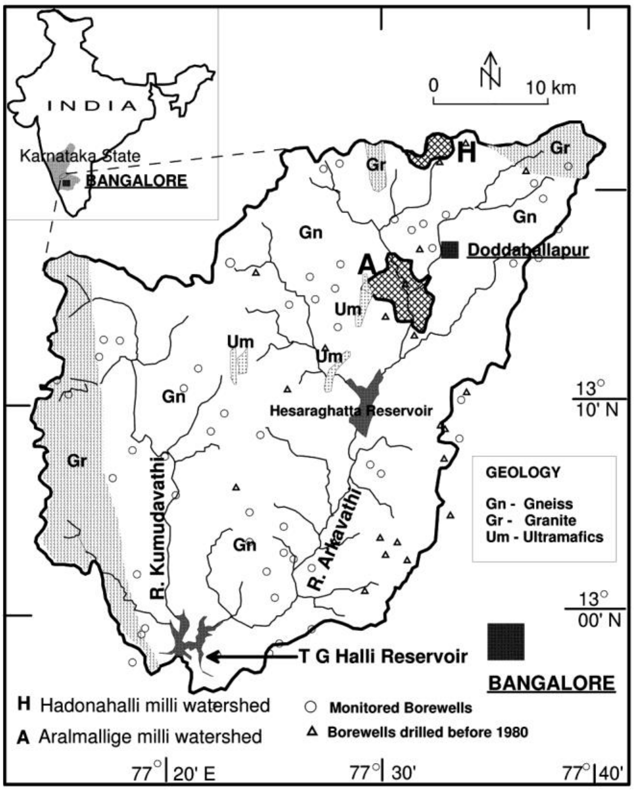

**Figure 1.** Map of the TG Halli reservoir catchment showing geology (after Geological Survey of India), drainage, location of Hadonahalli and Aralamallige mini-watersheds and monitoring borewells.

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*For correspondence. (e-mail: ballukraya@hotmail.com) granites, granitic gneisses, granulites, migmatites and ultramafics. Jointing is a common feature of most of the rocks. The weathered rock zone at the surface (saprolite/regolith) is followed by a partly weathered rock zone, which gradually changes to fresh unweathered rock (which may also have 2–3 sets of joints cutting across it). Monitoring of groundwater levels in 70 borewells (Figure 1), using the electrode method, over a two-year period (2013–15) showed that the measured groundwater levels were spatially very uneven. Very deep levels (>200 m) were noticed in borewells located in close proximity (<100 m) to wells having significantly shallow levels (<50 m). In order to understand this anomaly, detailed studies were planned and carried out using borewell scanning cameras in two mini-watersheds in order to get accurate water-level measurements as well as other hydrogeological data. Several scans were also carried out in the vicinity of these two mini-watersheds, including Bengaluru city.

The TG Halli catchment area is a heavily overexploited zone from the point of view of groundwater. Borewells remain the preferred source for irrigation water in this area and their depths have presently reached up to about 400 m. The diameter of the borewells in this area is generally 153–165 mm (nominal), with the weathered rock portion at the top lined by casing and the rest of the borehole being open. Thousands of borewells have been drilled in the last 50 years or so, with a vast majority of the older/shallower borewells having been abandoned due to declining yields. The necessity of drilling deeper borewells every few years, partial or complete dewatering of the weathered and partly weathered rock zone, as well as the availability of economically extractable groundwater exclusively from deeper aquifers indicate the overexploited nature of the area[14,15]. Data from a group of 20 borewells drilled in the catchment area between 1970 and 1980 show that the static water levels recorded were largely in the range 6–15 m bgl (below ground level)[13].

An inventory of all the existing borewells was carried out in two mini-watersheds, namely Hadonahalli and Aralamallige (Figure 1), located in the northern part of the Arkavathi catchment area. The second mini-watershed (Aralamallige) was included in the study in order to verify the data that were obtained from the first (Hadonahalli) watershed. A total of 472 borewells, 294 in Aralamallige and 178 in Hadonahalli were inventoried during July–August 2014. Of these, 294 (62%) were failed or abandoned wells and only 198 (38%) were still functioning. Generally, the irrigation borewells are abandoned as uneconomical when the yield falls below 2–3 $m^3$/h. Currently, the minimum depth of freshly drilled borewells in these two areas is in the range 250–300 m. Figure 2 shows the sharp increase in borehole depths over time in these two areas. Borewells drilled prior to 2001 (as ascertained from the well owners) were all less than 100 m, while majority of borewells drilled after 2010 are deeper than 300 m.

In order to obtain accurate details on current groundwater levels, 83 borehole scans (all in agricultural borewells) were carried out in the two mini-watersheds. Borehole camera scanning was found necessary for measuring the water levels, since the traditional electrode method often resulted in incorrect/unreliable measurements. The scan videos enable accurate measurement of water levels in the borewells and also give a complete picture of the hydrogeology – thickness of weathered rocks (as indicated by the lined part of the well, beyond which the borehole is unlined), presence and depth of water-producing or dewatered joints, nature of rock formation and presence of seepages and cascades, to name a few. Majority of these borewell scans were carried out during August 2014 to March 2015 (a few were carried out during May–July 2015 and later). The large time spread is necessitated by the fact that scanning could only be undertaken when the farmers remove the pump sets from the borewell – either for repairs or due to reduced well yields. Of the 83 borewells scanned (62 in Hadonahalli and 21 in Aralamallige (Supplementary Table 1), currently 40% are producing wells, 33% were recently abandoned, 21% were wells abandoned during 2011–13 and the rest 6% were wells abandoned earlier than 2010 (the year of abandoning was ascertained from the well owners).

The scanning was done using a camera which could be lowered into a borehole. The camera is connected to a monitor-cum-video recorder by optic-fibre cables. The area around the camera is illuminated using light sources. A continuous video is generated as the camera is lowered into the borehole and details of depth are noted against the video time. An example of the information that can be obtained from the scanning is shown in the form of scan photographs (Figure 3; scan shots from the video for a specific time/depth). Supplementary Table 1 details the salient hydrogeological data obtained from the scanning exercise. It is observed from the scans that a large

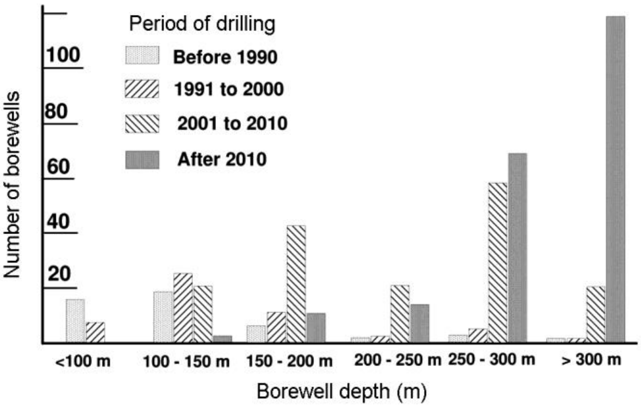

**Figure 2.** Histogram of borehole depths and year of drilling.

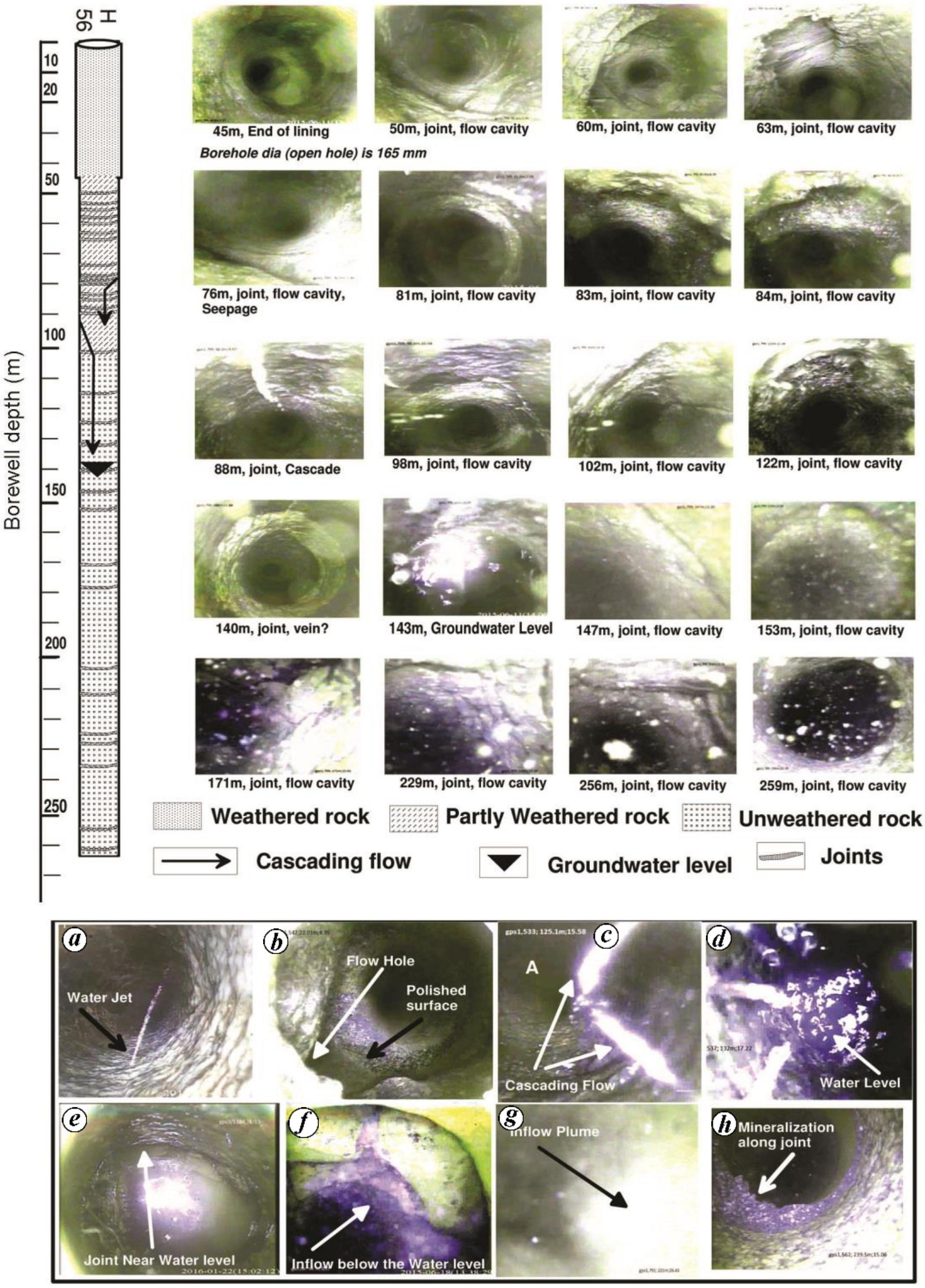

**Figure 3.** (Top) Sample photographs from the borehole scan video (Hadonahalli, no. 56) along with the constructed borehole section. Note the horizontal disposition of most joints, presence of cavities and flow openings in the joints. Also note that almost all these joints opening to the borewell are de-watered, except for the ones at 76 and 88 m depth. (Bottom) Scan photographs of (***a***) Jet-like seepage, (***b***) flow holes and polished surface in a cavitated joint, (***c***) cascading seepage from a joint, (***d***) cascading flow joining the water level, (***e***) joint near water level, (***f***) joint below water level indicating inflow into the well, (***g***) inflow plumes formed below water level and (***h***) mineralization along a joint.

number of joints are encountered in the borewells, sometimes as many as 20 of them in a deep well. However, only 1 or 2 of these joints located above the water level show inflow of groundwater (as seepages or cascades) into the borewell while the rest, both above and below these water-producing joints, are seen to be presently dry. A

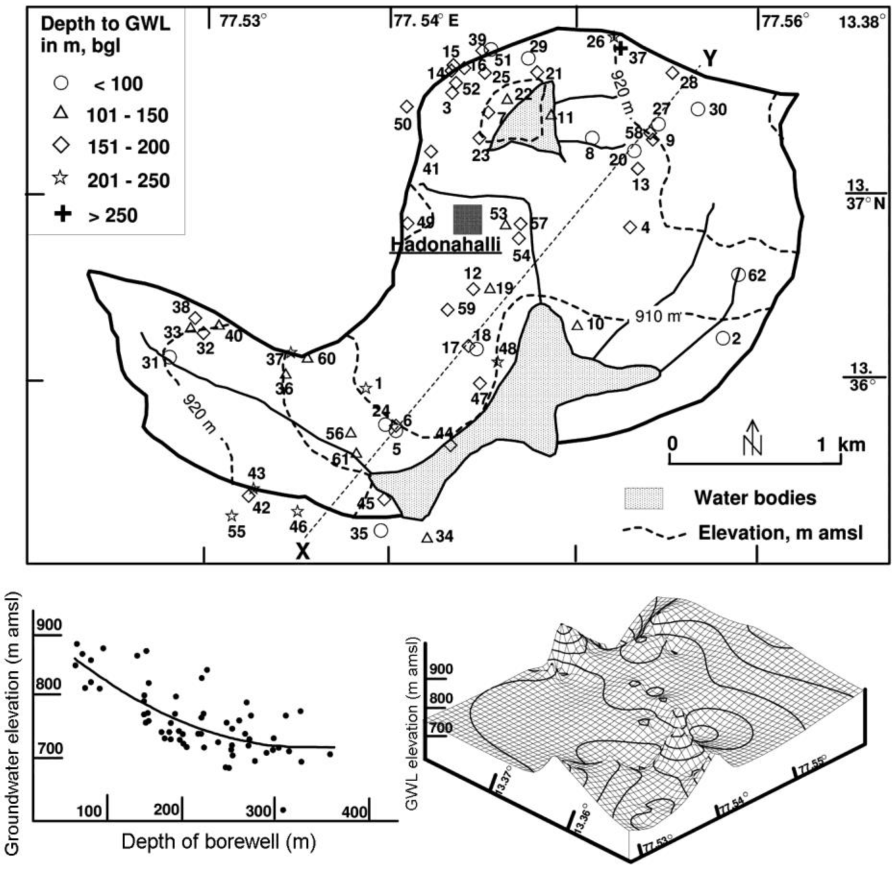

**Figure 4.** (Top) Map of Hadonahalli mini-watershed showing location of scanned borewells (classified into five categories based on depth to water levels). (Bottom, left) Scatter plot of borewell depth versus elevation of groundwater levels. (Bottom, right) 3D wireframe of the measured groundwater elevation (based on 62 wells) in the mini-watershed.

large percentage (89%) of the seepages/cascades observed in the borewell scans from Hadonahalli is located at depths between 40 and 90 m, while only 11% is found in the zone 91–150 m. In Aralamallige too, the same pattern is prevalent (87% of seepages are shallower than 90 m, while only four seepages are beyond that depth). Many of the deeper seepages are observed to be like jets (Figure 3 *a*) emanating from point sources in the bedrock. In the currently productive borewells, one or more joints are found below the water level, which contribute to the well yield. The thickness of these joints is normally in the range 20–30 cm, and they are generally filled with weathered/partly weathered rocks. Occasionally, several such joints may occur close to each other. Most, if not all, of these joints are interconnected by a network of vertical/inclined joints cutting across the entire rock matrix. A vast majority of joints exposed in the borewells are seen to be horizontally (or nearly so) disposed.

Figures 4 and 5 show the locations of the 83 borewells scanned (these borewell scans can be accessed, on request, from www.atree.org/accuwa/hydrology) in Hadonahalli and Aralamallige respectively. It may be noted that the scanning was spread over a period of 6–8 months, and hence the water levels measured are subject to seasonal fluctuations due to recharge and discharge conditions. Groundwater recharge in the area occurs from rainfall, rainfed surface reservoirs as well as (and mainly) return of irrigation waters. In order to have an idea of the magnitude of fluctuations in the area during the study period, a few working borewells were monitored for monthly (sometimes even bimonthly) water-level variations. It is seen that for deeper wells, the fluctuation during this period is about 20–25 m while for the shallow wells it is barely 1–2 m (Figure 6).

Borewells having shallow water levels are found in close proximity to those having very deep water levels (Figures 4 and 5). The spatial variations in the measured water levels in the two mini-watersheds are shown in the form of 3D wireframes in the two figures. It must be emphasized here that these water-level elevation maps do not in any way represent the potentiometric map of the area; they are based only on the measured levels and are presented only to highlight the very sharp spatial variations in the measured groundwater levels – from a shallow 28 m to a very deep 222 m bgl. In Hadonahalli, of the nine borewells showing levels of less than 75 m, eight are

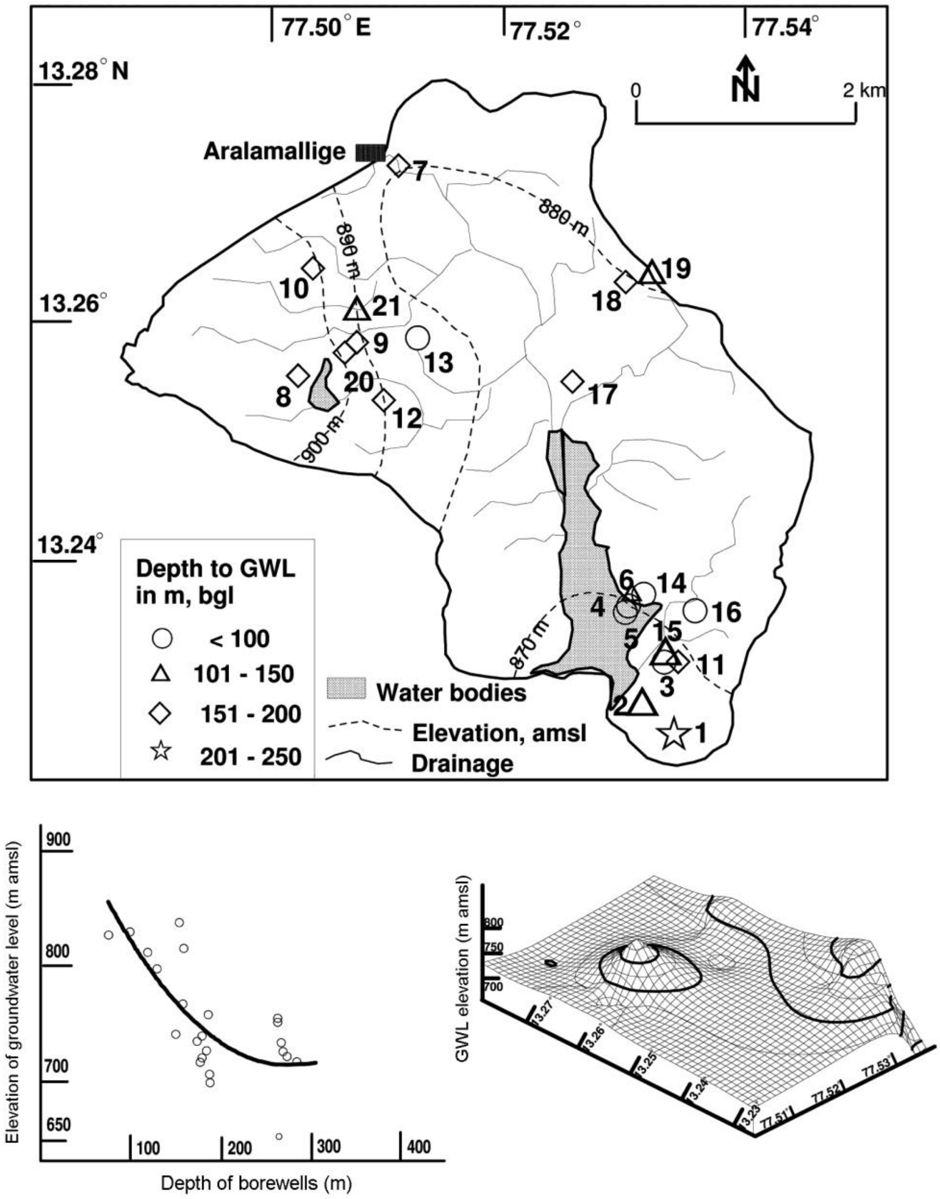

**Figure 5.** (Top) Map of Aralamallige mini-watershed showing location of scanned borewells (classified into five categories based on depth to water levels). (Bottom, left) Scatter plot of the borewell depth versus elevation of groundwater levels. (Bottom, right) 3D wireframe of the measured groundwater elevation (based on 21 wells) in the mini-watershed.

shallow to moderately deep (<165 m depth); all of them were drilled prior to 2005 with a few of them still yielding limited quantities of water. In the immediate vicinity of these shallow borewells, there are several recently drilled deep to very deep borewells, which are currently working and having significantly deeper groundwater levels. For example, in Hadonahalli, borewell no. 51 (90 m deep) shows a water level of 28 m bgl; while very close to it are two deeper borewells nos 25 and 39 (256 and 294 m deep), in which the measured water levels are 195 and 200 m respectively. Similar instances are observed in Aralamallige as well.

The general subsurface hydrogeology of the area can be understood from Figure 7, which is a cross-section prepared for the Hadonahalli watershed (along *X*–*Y* of Figure 4). The ground surface has a southwesterly slope with elevation varying from 610 to 624 m amsl. Only one (no. 46) of the ten borewells is presently working; two (nos 5 and 27) are seasonally productive while the rest have all been abandoned due to poor yields. Three shallow borewells (nos 18, 20 and 27 – depth varying from 99 to 105 m) show water levels lower than 97 m. Four moderately deep borewells (nos 6, 9, 28 and 54; 165–195 m deep) have water levels at or near the bottom of the well, indicating that in all probability they do not represent the real groundwater levels (stored/stagnant water). It is also seen that in these four borewells, there is a joint at or just below the water level, which apparently allows the cascading waters to flow outward and downward, preventing the water level from rising in the borewell. Moreover, no joint is noticed beyond this depth, which could act as a source of water to the well. A recently drilled and presently productive borewell (no. 46), is very deep at 315 m with the water level at 204 m bgl. Several joints are also seen exposed below the water level in this borewell, which are all yielding, as indicated by flow movement and/or plumes. This water level could therefore be considered as the representative groundwater level of the area as the presence of water-yielding joints, below the water level, signify saturated conditions beyond this depth. In borewell no. 5, which is moderately deep (158 m), the water level is found at a very shallow depth of 44 m. This is probably due to the absence of joints below 73 m depth, thus preventing any loss of the cascading water into the dry joints. Similarly, borewell no. 61 which is 195 m deep, has water level at 135 m and this well also does not have any joints exposed below the water level. Considering the fact that the area is a compact one, has uniform lithology, no known lineaments and without significant elevation differences, structural geology or land elevation does not seem to apparently control the depth at which the groundwater levels are found.

An analysis of borewell depths and elevation (amsl) of measured groundwater levels in them shows that, in general, deeper borewells have deeper water levels as evidenced from the scatter plots for both Hadonahalli and Aralamallige (Figures 4 and 5). However, as the polynomial trend line indicates, the water levels do not increase significantly once the borewell depth is more than about 250 m. Since the measurements were made after a minimum of 10 h since the cessation of pumping (this is generally the time taken to lift the pumps from the borewells in the case of working wells for carrying out the scans), they represent as near a static groundwater level as one can get under the circumstances. An analysis of the data from Hadonahalli shows that of the 62 wells scanned, 13 have depth to water levels of less than 100 m; 12 have levels between 101 and 150 m, while in 27 borewells it is between 150 and 200 m. In 10 borewells the depth to water levels is more than 200 m, even though there are 33 borewells (53%) which are deeper than 200 m. Thus it appears that during the study period, the groundwater levels are stable at around 200 m bgl, subject to seasonal variations. This is supported by the fact that as many as 23 out of 33 deep (>200 m deep) borewells in Hadonahalli have recorded groundwater levels shallower than 200 m.

Some of the questions arising out of the analyses of the results are as follows: (1) why and how does the groundwater level decline with deepening of borewells at a given location? (2) What explains the presence of a few shallow borewells that are still functioning amidst large number of abandoned borewells? (3) Why do some deep borewells have relatively shallow water levels, while others have very deep water levels? (4) Under what hydrogeological conditions are cascades formed and why do the water levels not rise up to those from which seepage/cascade enter the borewell? The video scans indicate that the current recharge is predominantly limited to a depth zone of 40–90 m from ground surface. In the zone below the seepage-producing joints, a series of dewatered joints are observed in almost all borewells.

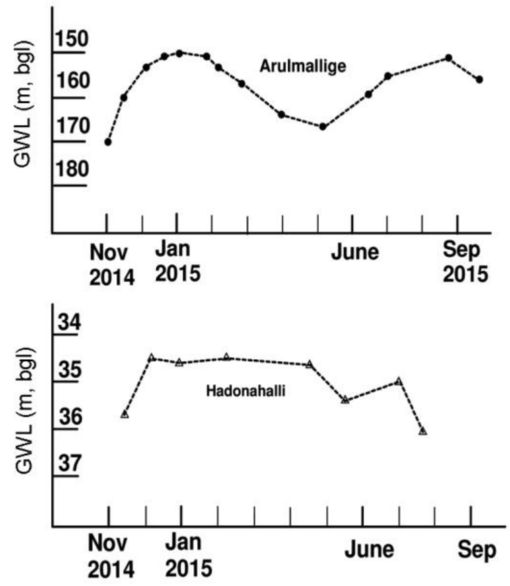

**Figure 6.** Seasonal fluctuation in measured groundwater levels.

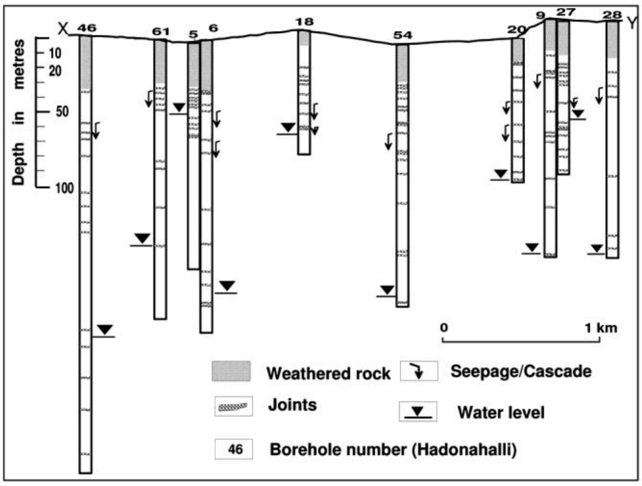

**Figure 7.** Profile along *X–Y* (Figure 4), showing subsurface hydrogeology in the Hadonahalli mini-watershed. Note the prevalence of water level close to the bottom of boreholes in moderately deep wells. Also observe the presence of several dewatered joints below the cascading flow zone and above the water level.

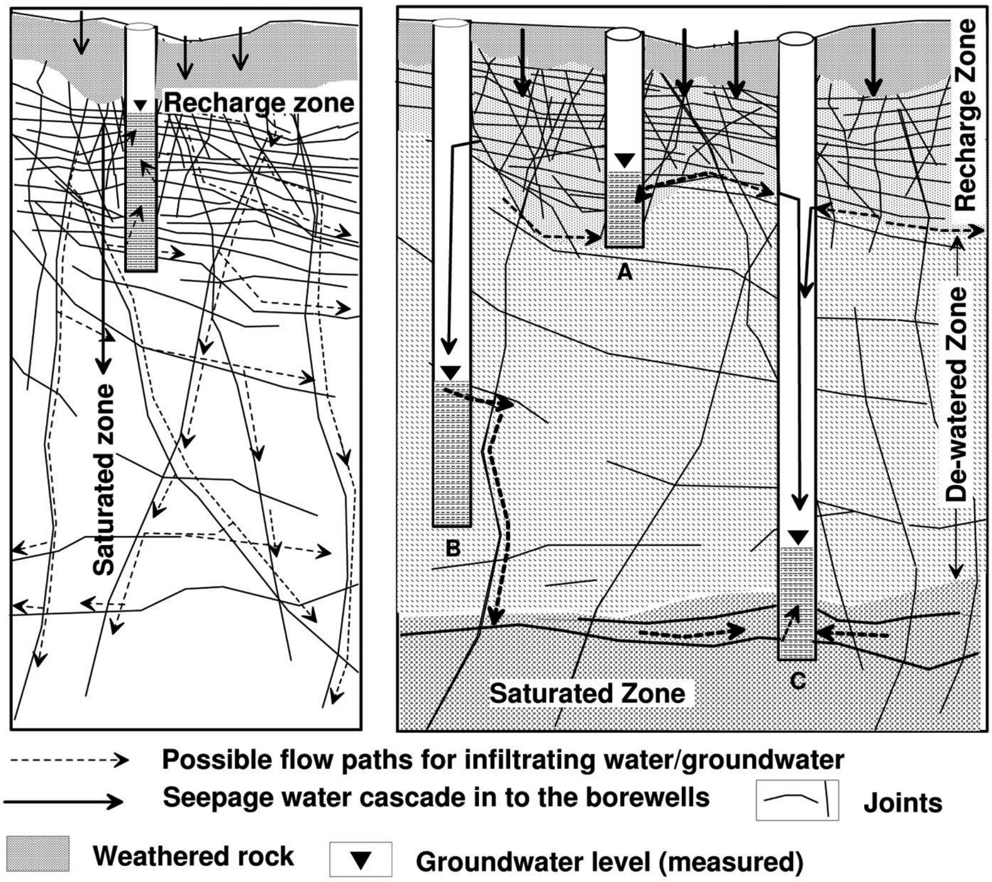

**Figure 8.** Conceptualized model explaining the hypothesis of deeper borewells showing deeper water levels in a severely overexploited, fractured rock aquifer region. ***a***, Normal hydrogeological conditions in a fractured rock system. ***b***, Conditions in a severely overexploited system. Note the flow of water from the moderately deep borewell into the fracture system through an exposed joint near the water level.

The fact that these were producing joints in the recent past is inferred from the presence of polished surfaces, cavities and flow holes (Figure 3 *b*) at the joint–borewell interface. In fact, the flow of water over long a period of time has given rise to near-circular cavities in many of these joints. The seepage from the recharge zone cascades down (Figure 3 *c*) until it intercepts the water level (Figure 3 *d*) in the borewell. This continuous free flow of water along the borehole shaft, from shallower zones directly to the saturated zone, is probably the reason why groundwater levels in the shallow borewells show only minor seasonal fluctuations.

Examination of video scans below the water level, mostly in the case of moderately deep borewells, shows that water escapes into the rock formation through joints open to the borewell (immediately below the water level) (Figure 3 *e*). This prevents any rise in the water level in the borewell despite continuous recharge through the cascading seepage waters, some of which is quite heavy. In fact, in a large number of abandoned borewells finished within the dewatered zone, the water levels are found to be just below or above a joint (well nos 6, 9, 20, 28 and 54) (Figure 7). In borewells where no joints are exposed below the cascade-producing joints, the water level rises to that of the seepage joints, as seen in the very shallow borewell no. 5. Borewells finished in the recharge zone show relatively shallow water levels (nos 18, 20 and 27) (Figure 7), since the inflow into the wells does not infiltrate further down.

Figure 8 shows a conceptualized model of the formation of the dewatered zone and the lower water levels in deeper borewells. The left side of the figure describes the conditions in a non-overexploited area with the groundwater level defining the upper part of the saturated zone. The recharging waters are shown flowing along both vertical as well as horizontal joints, depending upon the orientation of the joints in the rock formation, making up a continuum. The right side of the figure shows the hydrogeology under severely overexploited conditions. Three distinct zones are noticed here, namely the upper recharge zone, the intermediate dewatered zone, followed by the saturated zone. The presence of shallow borewells with shallow groundwater levels in them is due to the fact that the recharging waters flow into them and hence are available for exploitation. The sharply reduced vertical permeability of the rock below the recharge zone probably facilitates a near-horizontal movement of recharging water along the contact and into the existing boreholes. The presence of a large number of borewells allows for free downward flow of this water, which discourages any flow along the near-vertical joints in the rock matrix (which have significantly lower permeability), and therefore effectively preventing any fresh recharge into this intermediate zone. The water flowing into the borewells may find its way into any joint that is exposed below the water level, and the depth of that joint will thus determine the level at which the water level stands in that borewell. In a large number of borewells finished in the dewatered zone, it is observed that the water level is found to be at or near a joint (Figure 3 *e*). However, once the borewell encounters fully saturated joints (Figure 3 *f* ) at greater depths, there will be an upward flow into the well (as indicated by either water movement or by the presence of plumes (Figure 3 *g*); and therefore the water level will stabilize at or above such producing joints. Even if the bore is much deeper than these producing joints, the water level in the well may not decline significantly beyond this level. Thus the water levels in a borewell will be determined, under these circumstances, by the depth of a borewell and the presence as well as depth of dewatered or producing joints encountered in them. This results in an apparent situation of deeper borewells showing deeper measured (which may not be the real level) groundwater levels. However, it is possible that there could be some exceptions to the above hypothesis, depending on specific local hydrogeological conditions, but in general, the scans indicate the correctness of the above concept.

It is possible that the joints below the recharge zone suffer mineral deposition (mostly carbonate material) along them and thus impeding groundwater flow. The video scans do indicate that mineralization occurs along joints, often partially or fully covering the borehole shaft (Figure 3 *h*). However, only very few instances of this nature have been observed in the present study. It is also to be noticed that open joints are present in boreholes drilled in recent periods, indicating that majority of joints have remained open despite no flow of recharging waters through them.

This leads to the question as to what exactly represents the ‘real’ groundwater level in such heavily overexploited areas. The study indicates that only the levels measured in productive borewells, with producing joints below the current groundwater level, may be considered as the representative level of the area. This necessarily leads to the exclusion of all such wells which are not currently productive (even those with low yields), and for which one does not have a video scan (required to ensure that there are productive joints below the water level) for them to be considered as monitoring wells. The continued seasonal working of a few (very old) shallow boreholes is probably due to the fact that the long period of groundwater flow into them over the years has given rise to preferred flow channels along the joints, and this facilitates easy flow of the recharging water into these wells at the present time as well. The fact that these borewells are in irrigated agricultural fields implies a continuous supply of recharge from irrigation returns.

In the severely overexploited, fractured rock aquifer regions, measured groundwater levels show extremely high spatial variability with the measured water levels generally increasing with borehole depth. Cascading flows from relatively shallow depths in borewells, reaching the water level at greater depths effectively convert all the borewells in the area into point recharge sources. As groundwater level never rises to the joint from which the cascading flows originate, a perched aquifer like condition is formed. This study suggests that in general, the presence of cascading flows, a thick dewatered rock formation below the recharge zone and deeper wells recording deeper water levels are probably good indicators of severe overexploited conditions in an area. These observations have implications on our understanding of hard-rock hydrogeology, particularly for the groundwater level monitoring programmes. It is seen that present stable groundwater level can be obtained only from currently producing borewells and not from older borewells in which water level monitors have been installed. This implies that periodic inspection of such borewells is necessary, with the help of borehole scans, to make sure that a water-yielding joints still exist below the water level. The fact that most abandoned/non-producing borewells are acting as point sources of recharge and also that the pumping well itself is partially a recharge well, needs to be incorporated into the hydrogelogical model while constructing mathematical models of aquifers for the purpose of groundwater level predictions in overexploited terrains. Since the number of abandoned borewells is in hundreds even within a few square kilometres, it becomes a critical parameter in such studies. Obviously, the entire groundwater level monitoring programme in such heavily overexploited terrains needs a thorough revision and necessary changes must be made in identifying suitable wells for monitoring, so that the existing conditions are reflected in the data collected.

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# A simple push–pull strategy to harvest earthworms from coconut leaf vermicompost produced in tanks

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**The process to recycle lignin-rich coconut leaves, produced in abundance from coconut gardens, to vermicompost, using a local isolate of *Eudrilus* sp. is an important value-addition technology from ICAR-Central Plantation Crops Research Institute helping coconut farmers and entrepreneurs to enhance their economic returns. Vermicompost is produced in cement tanks and at the end of the composting period, earthworms are hand-sorted from the mature and partially composted materials by employed workers. The scarcity of labour for earthworm sorting and non-availability of earthworms at the required time for further vermicomposting had become an impediment in sustained production of vermicompost leading to abandonment of the technology by many adopters. To overcome this situation, a simple push–pull/pull–pull strategy was developed for harvesting the earthworms, wherein freshly ground mustard solution was used as repellant (push agent) and cow dung (with or without bagasse/banana wastes) was used as an attractant (‘pull’ agent). The strategy is simple, efficient and saves on labour, eliminates drudgery, reduces production cost and time. It will pave way for sustained adoption of vermicomposting technology by coconut farmers and entrepreneurs.**

**Keywords:** Coconut leaf vermicompost, cow dung, earthworm harvesting, mustard solution, push–pull strategy.

ON average, about 6–8 tonnes of leaf biomass residues are generated from one hectare coconut (*Cocos nucifera* L.) garden each year. With close to 2 million ha under this plantation crop in India, many million tonnes of organic manure can be produced from this lignin-rich residue through the vermicomposting technology developed at ICAR-Central Plantation Crops Research Institute (CPCRI)[1,2]. The technology is implemented in tanks in batches by mixing coconut leaves with cow dung (10 : 1 or 10 : 2 ratio, w/w basis), followed by pre-decomposition for 3–4 weeks; the coconut leaf-degrading *Eudrilus* sp. are then introduced in the tanks at an average of one adult worm per kg of feed material. The earthworms digest the substrate to convert it to vermicompost in 75–90 days period. The composted material is heaped in the centre of the tanks and watering is stopped to allow the earthworms to migrate to the bottom of the heap where some moisture is available. The compost from top

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