Detecting appropriate groundwater-level trends for safe groundwater development

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Computation of long-term linear trends of pre- and post-monsoon groundwater (GW) levels is important for the periodic categorization of regions in India according to their GW safety. For this purpose, a specific procedure has been recommended by the Groundwater Estimation Committee, 1997 (GEC'97), constituted by the Government of India. The present article points out the limitations of this procedure by providing statistical evidence from the long-term dataset in the case of Maharashtra. An improved method, having the same data requirements as the GEC'97 method and based on statistically significant recent linear trends is proposed as an alternative. Its suitability for administrative actions is demonstrated on the Maharashtra dataset. We specifically note the spatial patterns in recent linear trends obtained from our algorithm, which are otherwise difficult to detect.

Keywords: Groundwater safety, linear trends, spatial patterns, statistical evidence.

GROUNDWATER (GW) is the largest accessible source of freshwater for the people of India. However, GW resources are limited in their total storage capacity. This puts an upper limit on the maximum possible recharge and discharge from any GW regime. On the other hand, with growth in population, industry and irrigation-based agriculture, the demand for GW has risen steeply in the recent decades. This necessitates planning for sustainable development and management of GW resources. Estimation of GW resources is a pre-requisite for such planning. Periodic GW assessment (GWA) is an exercise aimed at estimating the dynamic GW resources available at the time of assessment. It is carried out roughly every five years by the Central Ground Water Board (CGWB) along with state groundwater agencies such as the Groundwater Surveys and Development Agency (GSDA) of Maharashtra, India.

The GWA methodology proposed by the Groundwater Estimation Committee (GEC)-1984, constituted by the Government of India (GoI), underwent major revision by another GEC constituted in 1997 by the GoI. The report[1] (referred to as GEC'97 in this article) submitted by the latter, now forms the basis of the national GWA exercise.

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According to GEC'97, the total area to be assessed by a GWA (GSDA in Maharashtra and CGWB centrally), has to be divided into GWA units. GWA is then done separately per unit. In Maharashtra, this basic unit is a watershed. Its average size is about 200 sq. km and roughly 3 or 4 observation wells are located in each watershed. The water level in the observation well, which is representative of the water table of the surrounding GW regime, is conventionally recorded by GSDA in metres below ground level (m bgl). The elevation of the location of a well (ground level), above mean sea level (amsl), is noted once for all separately. Thus the GW-level at the location of a well, which is the elevation of water table amsl, may easily be calculated. In this article, by 'GW level' in a well, we mean the number recorded by GSDA in m bgl. This does not affect our arguments, as will be pointed out later in the text.

One important output of GWA is the categorization of units as SAFE, SEMI-CRITICAL, CRITICAL and OVER-EXPLOITED. Such categorization forms the basis for implementing GW regulation policies, e.g. the Maharashtra Groundwater Act-2009. This makes the correct categorization of an important objective of the assessment protocol.

The current (GEC'97) methodology of categorization involves the computation of two critical quantities. One is a stage of GW development, and the second is a linear trend, both to be calculated by clearly specified procedures[2]. We note that the words 'trend' or 'trendline' used in this article will always mean a linear trend, unless mentioned otherwise. In GEC'97, there are a few improvements in the computation of the stage of GW development compared to GEC'84, while the trend computation is an entirely new and significant addition over GEC'84. The trend procedure computes two numbers for each assessment unit, viz. a pre- and a post-monsoon trend of GW levels within the unit. These GW levels are obtained from the observation wells located within the unit. We call this the 'long-term trend computation (LTTC)' protocol since it essentially relates to the historical behaviour of GW levels. The computation of trends is a welcome addition to the assessment protocol and is the central object of analysis in this article. We do this while analysing the legacy data of GW levels gathered over the last 30 years from over 5000 observation wells of GSDA spanning entire Maharashtra, hereafter referred to as the GSDA dataset.

Most recommendations in the literature[3,4] regarding further improvements to the GEC'97 method of GWA are related to the incorporation of IT infrastructure into the GWA exercise. Various research articles[5,6], which consider region-wide GW modelling and indirect assessment also reasonably demonstrate and propound this view. Scientific reviews such as by Jha *et al.*[7] also point to the prospects of integrating remote sensing and GIS for use in GW development and management. There are a few studies which also experiment with new methods for the estimation of various components of the GW balance equations required during GWA. One such study[8] proposes the incorporation of the SWAP agro-hydrological model and other data from government agencies into a GIS to assess the effect of land use and soil on the GW budgets at sub-watershed scale. Block-wise GWA reports may be available from the monitoring agencies, like from GSDA[9] for Maharashtra. Chatterjee and Purohit[10] have reviewed the procedures and results of national GWA used for the 2004–05 exercise, while making some recommendations for improving GWA. However, as far as we know, there is no detailed analysis reported on any specific method of the current GWA procedures used in India and the suitability of results of such a method.

Preliminaries: GEC'97 categorization method and GSDA GW-level dataset

The categorization method recommended by GEC'97 (ref. 1), assigns a GW-safety tag (category) to each assessment unit, to indicate the type and scale of actions to be taken for sustainable GW development in that unit. For this purpose, GEC'97 prescribes the calculation of indices representing the GW-development in the unit. The data obtained during GWA are used for this purpose. The values of these indices are used to assign the tag by following a given set of rules. This categorization process[2] is briefly presented below.

Indices of GW development and categorization rules

Indices of the stage and trend of GW development are obtained to judge the safety and sustainability of the GW regime in the near future. The calculation of these two indices is briefly presented below.

Stage of GW development: The first objective in GWA is to assess the current stage of GW development. This is calculated as a percentage

$$\text{Stage of GW development (\%)} = \frac{\text{Existing gross GW draft for all uses}}{\text{Net annual GW availability}} \times 100.$$

Both the numerator and the denominator are estimated using thumb-rules from secondary data obtained from other government agencies and departments. For example, recharge from return flow from irrigation is one component in net annual GW availability. Its calculation is based on rough estimates of area of cultivation of various crops and the norms recommended for the return flow factors for these crops. Similarly, the gross GW draft for irrigation in the GWA unit is one component of the existing gross GW draft for all uses, which also is roughly estimated. The cropping and irrigated-agriculture data themselves are obtained from the Directorate of Soil Conservation and Watershed Development Department in Maharashtra. Thus the stage of GW development is only an estimate whose accuracy may vary.

GW-level trends: The second index is the pair of pre- and post-monsoon GW-level linear trends associated with each assessment unit. These trends are computed by first tabulating a time series (y_i, z_i) for each unit, where y_i is the observation year and z_i is a suitably weighted average of GW levels from observation wells within the assessment unit. GEC'97 prescribes using GW-level data available from at least the last 10 years to obtain this time-series. The next step is to use simple regression to compute the slope (referred to as 'trend') b of the best-fit line $z = a + by$ for the time series. The formula for b is easily obtained and is reproduced here

$$b = \frac{\left(N\sum_{i=1}^{N} y_i z_i\right) - \left(\sum_{i=1}^{N} y_i \sum_{i=1}^{N} z_i\right)}{\left(N\sum_{i=1}^{N} y_i^2\right) - \left(\sum_{i=1}^{N} y_i\right)^2}. \quad (1)$$

A trend is significant according to GEC'97, if the magnitude of trend b is greater than B, where it is recommended[11], that B be between 0.1 and 0.2 m/year, the specific value being decided based on local hydrogeology. Note that the statistical significance of b is ignored and only its magnitude is considered. To distinguish this form of significance from statistical significance, we will refer to it as GEC significance.

As already mentioned, each of the two time-series of pre- and post-monsoon GW levels for the unit, is obtained by an averaging computation done over the respective GW-level time-series from the observation wells within the unit. This computation is expected to account for the areas of the watersheds which fall within the assessment unit while disregarding other factors like varying aquifer thickness and varying times-of-observation for different wells within the unit. Actual observation-well data may have many years where observations are missing, which further complicates these calculations.

In this study, we compute trends for each observation well separately and analyse these results. Without

Table 1. Categorization of units

Stage of groundwater development (S; %)	Significant long-term decline (pre-monsoon, post-monsoon)	Category
$S \le 70$	(No, no)	SAFE
$S \le 70$	(Yes, no), (no, yes), (yes, yes)	To be re-assessed
$70 < S \le 90$	(No, no)	SAFE
$70 < S \le 90$	(Yes, no), (no, yes)	SEMI-CRITICAL
$70 < S \le 90$	(Yes, yes)	To be re-assessed
$90 < S \le 100$	(No, no)	To be re-assessed
$90 < S \le 100$	(Yes, no), (no, yes)	SEMI CRITICAL
$90 < S \le 100$	(Yes, yes)	CRITICAL
$S > 100$	(No, no)	To be re-assessed
$S > 100$	(Yes, no), (no, yes), (yes, yes)	OVER EXPLOITED

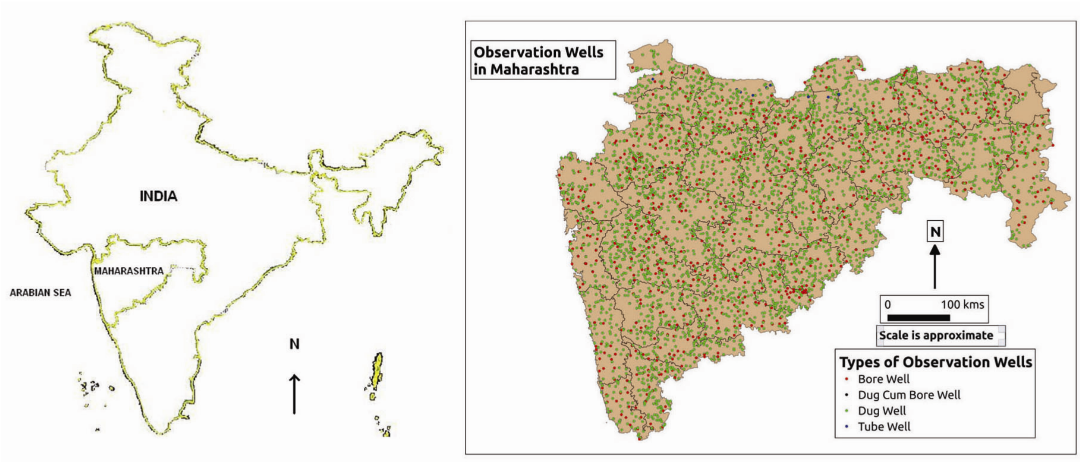

Figure 1. Location of observation wells in Maharashtra, India (location map source: bhuvan.nrsc.gov.in).

compromising the validity of our arguments regarding trend (temporal) analysis, this will bring into focus the issues in the use of trends, instead of extraneous issues of the spatial-averaging mechanism.

The categorization rules in Table 1 state the precise way of using the pre- and post-monsoon GW-level trends along with the stage of GW development to decide the category of the unit. When the stage of GW development and the trends in GW levels are not consistent in their GW-safety implications, the unit is tagged for re-assessment of GW-resource computations as well as for the reliability of GW-level data.

GSDA GW-level dataset

We now describe those features of the GSDA dataset which concern this study. GSDA began monitoring GW levels in Maharashtra starting with merely four observation wells (also called 'sites') before 1970. The number of sites gradually rose to about a 1000 by 1980 and is 5383 as available in our dataset (year 2011).

Among the 5383 wells, 4260 are dugwells, 1108 borewells, 14 tubewells and 1 dug-cum-borewell (Figure 1). Observations in dugwells are usually recorded in January, March, May and October, while those in other types of wells are recorded monthly. In Maharashtra, the May GW level is considered as the pre-monsoon level and the October GW level as post-monsoon level[2].

GSDA has conventionally recorded GW levels as the depth to water level in the well (m bgl). If the well is at elevation E m amsl and the observation records water level at z_i m bgl for year y_i, then the elevation of water level is $E - z_i$ m amsl for year y_i. It is easy to see that the linear trend in z_is is statistically significant (i.e. high likelihood of being different from zero), if and only if the linear trend in $E - z_i$s (an affine transform of z_is) is statistically significant. Since we will be primarily concerned with detecting significance of linear trends, the method of recording GW levels, whether in m bgl or in m amsl, will not alter our conclusions. We will thus use the recorded values, i.e. m bgl.

When an observation well is dry, its reading is recorded to be same as the well depth. These readings have been plotted as 'dry obs.' (coloured red) in the graphical plots in this article.

Limitations of LTTC for periodic GWA

Here, we will focus on examining the procedure of computing GW-level trends. To this end, we present the limitations of LTTC, using statistical evidence obtained from the GSDA dataset. Some of these limitations may be appreciated even without any reference to the actually observed GW-level behaviour.

Time-span ambiguity in LTTC

For GWA, although the last year of data is usually known, viz. the year of GWA, the first year of data to be used is not clearly prescribed in GEC'97. The trends calculated using different 'first' years for LTTC may give different trend values and lead to a different categorization.

This issue is illustrated in the case of Andrud dugwell (Figure 2), which exhibits abrupt changes in GW levels. The long-term trend calculated using the data from 1989 to 2010 is falling at 0.13 m/year. However, had the monitoring of the well begun in 1992, the trend calculated using the data from 1992 to 2010 would have been rising at 0.16 m/year. Even if data from 1989 were available, there seems to be no reason to believe that the trend from 1989 is more correct for assessment purpose than the one from 1992.

Considering the observed high variation and abrupt changes (see later in the text) in GW levels and multiple reversals in their short-term trends, a (unqualified) 'long-term trend' may become meaningless for GWA.

Is the linearity assumption of LTTC valid?

In using LTTC, GEC'97 assumes[2], that the (pre-/post-monsoon) GW level (z) varies linearly with the year of observation (y), so that

$$z = a + by,$$

where a and b are to be determined from the observed data. However, with up to three decades of GW-level data

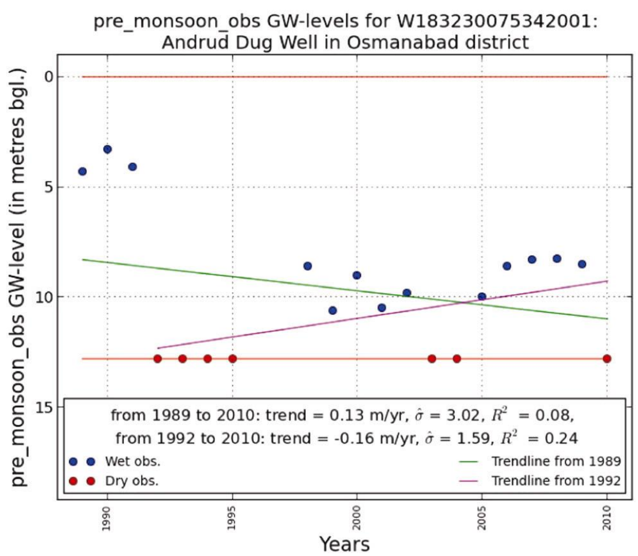

Figure 2. Example of dependence of long-term trend on monitoring span.

now available in the GSDA dataset, it is seen that this linear model is statistically inadequate.

Two statistics calculated for the GSDA dataset are sufficient to establish this.

- Table 2 shows that linearity explains only a small component of the total variation on the average and more than half of the variation is left unexplained in most observation wells.
- The values of standard error of GW levels about the best-fit trendline are also high (Table 3) (compare, for example, with the maximum GEC-significance threshold of 0.2 m/year). Compounded with poor R^2 values, this magnifies the issue of inadequacy of the linear model.

LTTC may not appraise recent GW-level changes

Long-term GW water behaviour in a region typically consists of many regimes which depend on the agricultural cycle, construction of key assets (such as dams and canals) in the vicinity, population growth and so on. On the other hand, the outcome of an assessment is put to immediate use by the district and state administrations as an input in implementing GW policy. Thus, it is the currently active regime that is more relevant to the administrator in designing corrective actions for GW safety and sustainability. The LTTC, on the other hand, produces a trend value corresponding to the overall long-term behaviour which will be an average over all past regimes. This value can be substantially different from that of the currently active regime.

In the GSDA dataset, there are 2270 wells whose pre-monsoon GW-level trend in the latest 5 years is significant in magnitude using the 0.2 m/year minimum threshold recommended by GEC'97, while the overall long-term trend is not. For post-monsoon GW levels, there are 1927 such wells. Even worse, there are 342 cases, 241 of pre-monsoon and 101 of post-monsoon GW levels, where the trend in the latest 5 years as well as the overall long-term trend are both significant in magnitude (using the 0.2 m/year threshold), but oppositely inclined. Thus, the LTTC is likely to lead to many false positives and false negatives compared to the currently active trend. Figure 3 shows two examples of such behaviour.

Abrupt changes in GW levels

Abrupt changes are observed in many wells of the GSDA dataset. This limits the use of any continuous model (linear model being one example) that assumes smooth variation in GW levels. We point to two examples. The pre-monsoon GW level in Jamthi dugwell of Akola district, dropped by 10 m from 2000 to 2001 (Figure 4). Similar abrupt change was seen in Kilaj borewell of

Table 2. Results of coefficient of determination (R^2) based on linearity assumption

Season	Average R^2 over all sites	No. of sites where $R^2 < 0.5$
Pre-monsoon	0.24	4500 (out of 5347)
Post-monsoon	0.21	4553 (out of 5258)

Table 3. Results of standard error based on linearity assumption

Season	Average standard error over all sites (m)	No. of sites where standard error > 1 m
Pre-monsoon	1.90	3669 (out of 5347)
Post-monsoon	1.88	3669 (out of 5258)

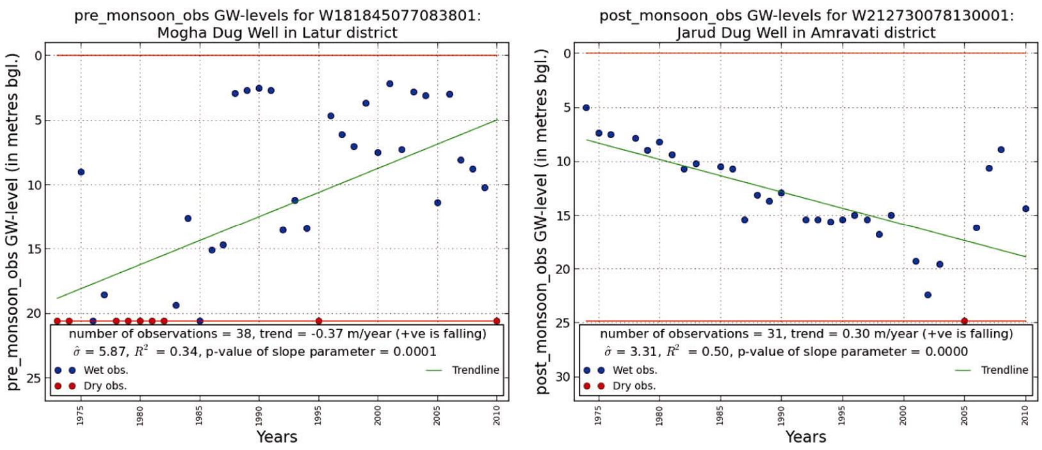

Figure 3. Examples where recent trend is significantly opposite to the overall long-term trend.

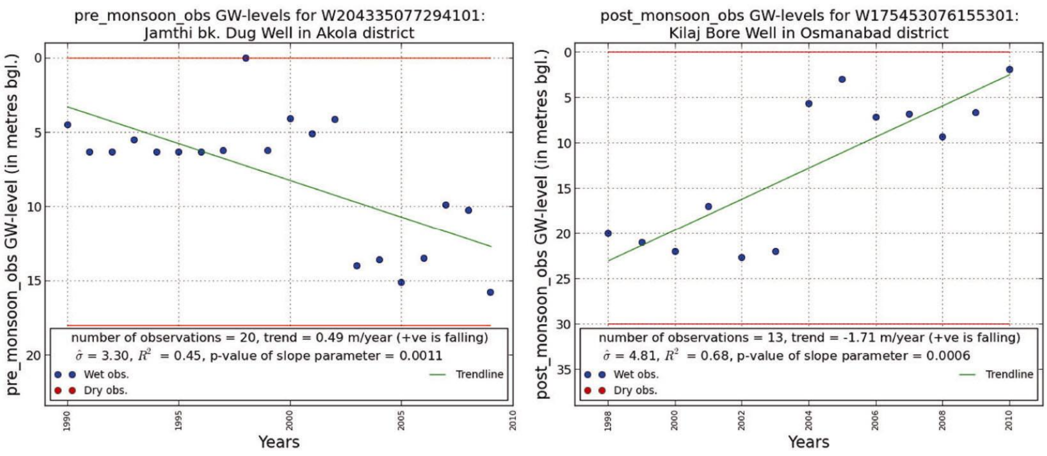

Figure 4. Abrupt changes in pre- and post-monsoon groundwater (GW) levels.

Osmanabad district, where post-monsoon GW level rose by about 15 m from 2003 to 2004.

To assess the frequency of occurrence of 'abrupt changes', we first describe a simple statistical method of detecting them. We assume that over the long term (pre-/post-monsoon) GW levels are normally distributed about some fixed mean. Suppose $D = \{d_i : i = 1, \ldots, n\}$ is the set of (pre-/post-monsoon) GW-level changes between consecutive years. These will be normally distributed with mean zero and some standard deviation, say $\hat{\sigma}_{\mathrm{d}}$. By the Student's t probability distribution, if $n \geq 6$, then all those differences d_is which are so large that $|(d_i/\hat{\sigma}_{\mathrm{d}})| > 2$, have

Table 4. Number of wells having n abrupt changes in groundwater (GW) levels over the long term

Number of abrupt changes (n)	Number of wells with n abrupt changes in pre-monsoon GW levels over the long term	Number of wells with n abrupt changes in post-monsoon GW levels over the long term
0	1382	1743
1	2110	2060
2	1276	818
3	346	179
4	78	29

only about 5% probability of occurring. Hence, this can be called an abrupt change in the GW-level behaviour of the site. In short, an 'abrupt change' is statistically an 'outlier' of large magnitude among the set of all (consecutive year) GW-level changes observed in the well.

When this detection method is applied to the GSDA dataset, we obtain the results as in Table 4, revealing the large extent of occurrence of abrupt changes.

Proposed method to detect recent trends

In this section, we propose an alternative method that detects recent trends from time-series data of GW levels. We believe that this will be more useful to administrators than the LTTC. To do this, we propose three attributes of a desirable trend calculation procedure as follows:

1. GW-level trends should detect the behaviour of the current operational GW regime. This means that in the trend computation, recent years' data should receive higher priority than past years' data. This requirement is a modification to the GEC'97 method.
2. The calculated trend should be statistically sound. This is especially important for detecting recent trends, where the sample size of recent years' data is small. This requirement is an addition to the GEC'97 method.
3. The method should be commensurate with the human resources available to the assessment agencies, their level of technical skill and available infrastructural facilities. For simplicity, it should also be limited to using only the GW-level data of the assessment unit. This requirement is met by the GEC'97 method.

A method based on the most recent significant trend

In view of the third requirement and the limitations of any smooth model, however complex, we interpret a 'trend' to mean a linear model as is done in LTTC. In order to satisfy the first two requirements, we apply a search procedure to detect the most recent statistically significant trend, when it exists. The following simple iterative algorithm clarifies the procedure; in it, M denotes the total number of latest years considered and N denotes the number of years for which pre-(post-)monsoon GW-level observation is actually available among these latest M years ($N < M$, when data for some intermediate year are missing).

1. Set $M = 4$.
2. Using the formula in eq. (1), calculate trend (b) of the N number of GW levels available within the last M years.
3. If b is statistically significant, we have detected the most recent significant trend; stop. Otherwise, increment M by 1.
4. If $M > 10$, there is no significant trend in the recent years; stop. Otherwise go to step 2.

The third step of the algorithm involves calculating the statistical significance of trend b. The standard technique of hypothesis testing can be used to judge this statistical significance. In view of the third requirement, we show the simplicity of the technique by presenting it below in a simplified table look-up form.

We assume that GW levels have a normal distribution about the true trendline. Then for a given set of observations, eq. (1) produces the maximum likelihood estimate of b. The trend estimate b has a normal distribution about the true value of trend, say β. Its variance σ_b^2 is estimated as

$$\hat{\sigma}_b^2 = \frac{N\hat{\sigma}_z^2}{N\sum_{i=1}^{N} y_i^2 - \left(\sum_{i=1}^{N} y_i\right)^2}, \qquad (2)$$

where $\hat{\sigma}_z^2$ is the estimate of variance of GW levels about the trendline, calculated as

$$\hat{\sigma}_z^2 = \frac{\sum_{i=1}^{N}(z_i - ay_i - b)^2}{N-2}.$$

A statistically standardized value of b is obtained by dividing b by $\hat{\sigma}_b$. This ratio $b/\hat{\sigma}_b$ has a Student's t probability distribution with $N - 2$ degrees of freedom.

We are interested in determining the significance of the true trend, of which b is only an estimate. This is same as testing the statistical hypothesis that $\beta \neq 0$. To this end, Table 5, derived using the Student's t distribution, can be used for easy table look-up. The table entries are taken as lower thresholds on the statistic $|b/\hat{\sigma}_b|$ for trend b to be called significant. p is the probability of false positive (the 'level of significance').

We note that, if b is detected significant with p% probability of false positive, then $b > 0$ implies a rising trend with $p/2$% probability of false positive, and $b < 0$ implies a falling trend with $p/2$% probability of false positive.

Note that, for the purpose of using recent data, it is necessary to put an upper limit on M (step 4). Roughly two GWA exercises are expected to be carried out in the 10 recent years prior to the current GWA. We have limited the search for significant recent trend to 10 recent years with the consideration that any significant trend due to older data would be detected and addressed in one of the previous assessments.

Results using the proposed method

The proposed method based on recent trends was applied to the GSDA dataset using 5% significance level, with our understanding of balancing the trade-off between false positive (hence undue regulatory actions) and false negative (hence putting GW safety at risk). A total of 1887 sites were found to have significant trend in pre-monsoon GW levels during their latest years of monitoring, with 811 rising and 1076 falling. For post-monsoon GW levels, these numbers are 892 rising and 316 falling, totalling to 1208 sites having significant recent trends. The numbers already hint at a significant rise in GW development in recent years. We now use the results to provide empirical evidence for the utility of recent trends.

R^2 and $\hat{\sigma}_z$ statistics

The two statistics used to rate the linearity assumption show considerable improvement (Table 6).

Averages are taken over those wells where a significant (at 5% level) recent trend has been detected by our method. We see that the linearity assumption holds much better compared with Table 2.

Comparing recent and long-term behaviour

In the GSDA dataset, LTTC detected 677 sites to have GEC-significant pre-monsoon trend and 380 sites to have GEC-significant post-monsoon trend, when GEC-significance threshold of 0.2 m/year was used.

Table 7 presents a detailed comparison between the results of LTTC and the proposed method. Note that, here the thresholds of GEC-significance have been taken conservatively (GEC-non-significance when the magnitude is < 0.1 m/year and GEC-significance when the magnitude is >0.2 m/year) and recent trends (RT) have been detected at 5% significance level.

There are noticeably large values in the off-diagonal cells of the table. We specifically note that there are many cases (453) of recently significantly rising post-monsoon GW levels whose long-term trends are not detected GEC-significant. Similarly, there are many cases (547) of recently significantly falling pre-monsoon GW levels whose long-term trends are not detected GEC-significant.

One example of each such case is graphically shown in Figure 5. In each graphical plot of Figure 5, both the long-term trend (which is not found to be GEC-significant) as computed using GEC'97 as well as the significant recent trend detected by our algorithm have been plotted for comparison.

State-wide spatial patterns

Figures 6 and 7 show maps of wells showing recent statistically significant as well as GEC-significant trends in pre- and post-monsoon GW levels respectively.

As already noted, we see that more sites show statistically significant recent trends in GW levels, many of which are GEC-insignificant. More importantly, we notice spatial patterns in the recent trends in GW levels that do not show up in the LTTC map. The mid-eastern vertical belt of the state consisting of the districts of Buldhana, Parbhani, Latur, Hingoli, Washim, Akola, Amravati, Nanded and Yavatmal has largely seen a falling trend, while the entire region of the state to the west of this vertical belt has largely seen a rising trend in the pre-monsoon GW levels in recent years of monitoring. The central and south-central region of the state consisting of the districts of Jalna, Beed, Osmanabad, eastern part of

Table 5. Table of lower thresholds on $|b/\hat{\sigma}_b|$, for determining significance of trends

	N						
p (%)	4	5	6	7	8	9	10
10	2.92	2.35	2.13	2.02	1.94	1.89	1.86
5	4.30	3.18	2.78	2.57	2.45	2.36	2.30
1	9.92	5.84	4.60	4.03	3.71	3.50	3.36

Table 6. Average R^2 and standard error for recent significant trends (at 5% level)

Season	Average R^2 of recent trendline	Average standard error about recent trendline (m)
Pre-monsoon	0.72	1.11
Post-monsoon	0.78	1.13

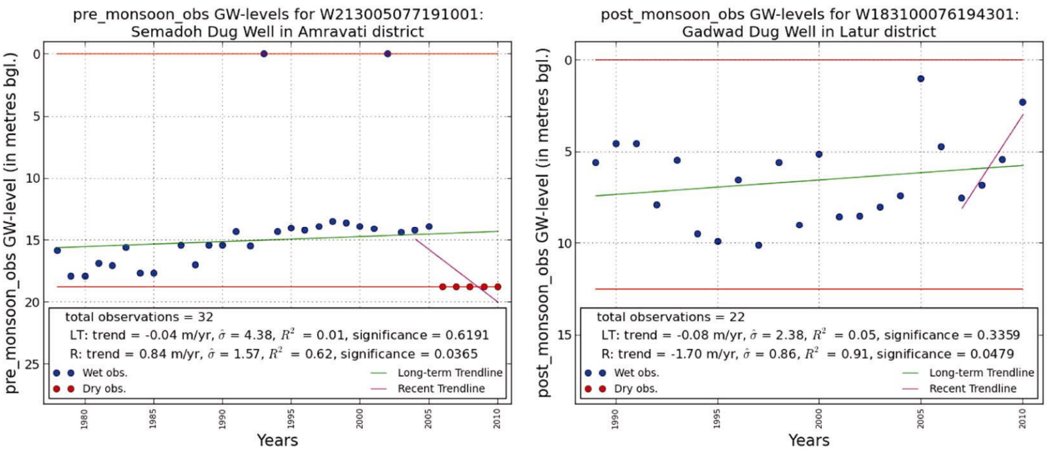

Figure 5. Examples of wells with statistically significant trend in recent years, whose long-term trend is GEC-insignificant. Green line is long-term trend (LTT) using GEC'97 and pink line is significant recent trend (RT) using the present algorithm.

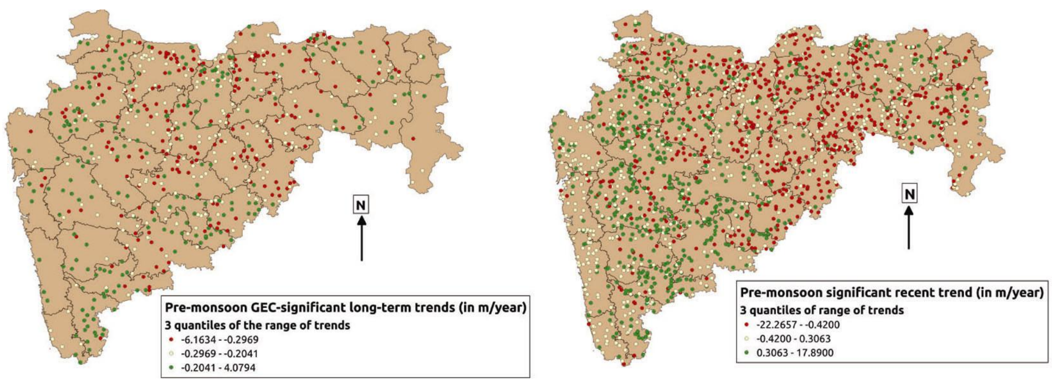

Figure 6. State-wide map of significant recent trends and GEC-significant long-term trends in pre-monsoon GW levels.

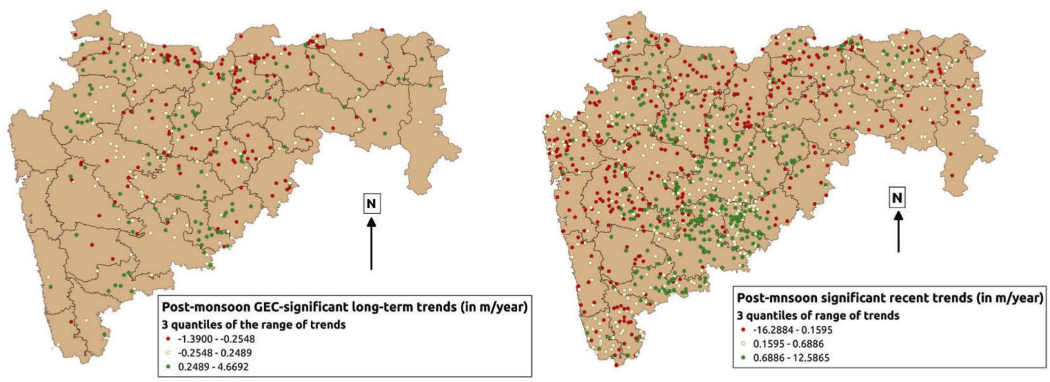

Figure 7. State-wide map of significant recent trends and GEC-significant long-term trends in post-monsoon GW levels.

Solapur and Hingoli has clearly seen a rising trend in the post-monsoon GW levels in recent years of monitoring. In passing, we note that it is easier to investigate the causes for spatial patterns in recent trends as opposed to long-term trends where many factors are involved with a complex interaction over the long term. This can help in better understanding the hydrogeology and socio-economics of GW for its management.

Significance for GW development

Table 8 shows how the average value of the magnitude of the significant recent trend detected by our algorithm varies with *M*. It shows that recent trends which are detected statistically significant at 5% level are typically also significant in magnitude, and specifically GEC-significant.

Table 7. Pre-monsoon and post-monsoon (results entries denote number of wells)

	Significantly rising RT	Significantly falling RT	No significant RT
Pre-monsoon			
Significantly rising LTT	78	26	106
Significantly falling LTT	45	173	249
No significant LTT	379	547	1667
Post-monsoon			
Significantly rising LTT	67	11	132
Significantly falling LTT	77	48	342
No significant LTT	453	148	1992

Table 8. Average magnitude of significant (at 5% level) recent trend (m/year) per M

M	4	5	6	7	8	9	10
Pre-monsoon	1.13	1.16	1.05	0.95	0.56	0.56	0.43
Post-monsoon	1.31	0.92	1.15	0.91	0.94	0.67	0.45

Table 9. Average estimated magnitude of overall GW-level change $M \times |b|$ (m) during the time-span of the trend

M	4	5	6	7	8	9	10
Pre-monsoon	4.52	5.81	6.30	6.63	4.52	5.04	4.28
Post-monsoon	5.26	4.61	6.90	6.37	7.50	6.08	4.53

$M \times |b|$ gives an estimate of the magnitude of overall change in GW level due to a trend b that has been detected statistically significant from the data of M recent years. Table 9 shows how this overall change in GW levels due to recent significant trends can be hydrogeologically important, despite the shorter time-span of recent trends.

Discussion and suggestions

GW levels being the only direct indicators of GW development used in the assessment procedure and since they can be accurately sampled, as opposed to the components of gross draft and net recharge, the optimal use of information obtained from the GW-level data should be emphasized. With this in view, we make the following suggestions for improving the categorization.

1. Increasing the density of observation wells will provide a more realistic view of the GW-level situation at regional scales. This is especially true in the fractured rock hydrogeological settings like the Deccan traps of Maharashtra.
2. The confined aquifer thickness (T) or the depth to the bottom of unconfined aquifer (D) is an indicator to decide the maximum limits of GW development. For example, shallow aquifers are more susceptible to over-exploitation than deeper aquifers having the same hydrogeological parameters. So, the use of T (or D) may be an important improvement in the categorization rules.
3. The estimate $M \times |b|$ of the overall change during a statistically significant trend b which spans M years can be used to judge the significance of the trend from GW-development perspective.
4. Existence of dry-well readings produces bias in trend estimation and hence in GW estimation. Observation wells which run dry may be deepened or a new site be chosen. More importantly, a dry well which fully penetrates the aquifer represents an empty aquifer. This may represent a grave situation of over-exploitation. So, instead of simply considering trends in GW levels, separate provisions may be made in Table 1 to address and take action regarding such severe cases.
5. As we have seen, not all wells are monitored regularly, resulting in time-gaps in monitoring. In the light of (i) high variance of GW levels, (ii) abrupt changes, and (iii) dependence of calculations on small samples of recent years' data, time-gaps can result into incorrect estimation and categorization. It is important that monitoring schedules are followed as strictly as possible.

It has to be noted that trends in GW levels and hence GW development may be a result of trends in the factors affecting the GW regime. As such, trends, both recent and long term, in rainfall, land-use pattern and other socio-economic indices can be equally important in deciding the appropriate actions for safe and sustainable GW development[12]. Calculation of trends of such important factors can make categorization (and GWA as a whole) more fruitful. However, incorporating these trends in deciding the category may require a detailed policy-level study.

Finally, we acknowledge that certain parameters in our trend detection, like the significance level used and the starting value of M in the algorithm, may be selected more suitably from the actual field experience. Furthermore, we have drawn attention mainly to the appropriate period of data to be used to calculate GW-level trends during periodic GWA. However, as GEC'97 appreciates, improvements in the GWA procedures have to be an ongoing process.

Conclusion

The purpose of categorization is to classify areas according to the actions to be taken in the immediate future for safe and sustainable GW development. Whence the period for which the trend is assessed should suit this (largely) administrative-cum-management purpose. Learning from the limitations of using long-term GW-level trends for this purpose, we have proposed an improved method of detecting more relevant and statistically significant GW-level trends.

The empirical findings in this study suggest a necessary change in perspective. In regions where the status of GW regime changes significantly within short time-spans of 5–10 years, the notion of 'gradual long-term progress to a stage of sustainable GW-development' has to be replaced by that of a 'constantly monitored, efficiently but safely used GW-regime'. Some empirical findings like the abrupt fluctuations in GW levels and existence of state-wide spatial patterns of recent significant trends in Maharashtra are worthy of more investigation and possible action by the state administration.

Finally, extending the localized and primarily temporal analysis used for categorisation by GEC'97, to a holistic spatio-temporal analysis which includes rainfall and other regional attributes may be more useful. Such analysis will eventually pave the way for safe and sustainable GW development.

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