**ENSO modulated groundwater variations in a river basin of Central India**
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**ABSTRACT**
Several previous studies have examined the traceable regional impacts of El Niño Southern Oscillation (ENSO) on groundwater level (GWL) but it remains a question whether the ENSO impacts on groundwater can be established in smaller basins using statistical techniques. The present study attempts to record the ENSO impacts on the groundwater availability in Venna basin, Maharashtra by proposing a combination of statistical and spatial analysis. Utilizing the GWL, the study estimates the spatial variability of GWL, groundwater anomalies, groundwater recharge and discharge using geographic information system (GIS) and quantitative variations in groundwater using statistical techniques. The study also highlights the applicability of the Kolmogorov–Smirnov test in hydrometeorological studies. Analyses reveal the association of deeper GWLs and higher discharge with the El Niño, as opposed to shallower GWLs and higher recharge with La Niña. The two-sample Kolmogorov–Smirnov test confirms the discrepancy in the cumulative distribution of GWL between different ENSO phases. Mann–Kendall, Sen slope and Mann–Whitney tests ascertain the variation of GWL and recharge as well as ENSO impacts in the command area (area irrigated by reservoir using the canal networks) and non-command areas. A significant difference in recharge between El Niño and La Niña is observed in the command as well as in the non-command areas.

**Key words** | climate change, discharge, ENSO, GIS, groundwater, recharge

**INTRODUCTION**
In recent decades, interannual climate variability such as El Niño Southern Oscillation (ENSO) has become one of the major concerns for agriculturists and water resource managers globally. Imprints of ENSO on regional monsoon, groundwater levels (GWL), streamflow, droughts, flood frequency, vegetation spread, crop growth and crop yield have been confirmed by many researchers in different parts of the world (Chiew et al. 1998; Legler et al. 1999; Peters et al. 2003; Shao et al. 2016), including India (Kulkarni 2000; Rishma & Katpatal 2016a, 2016b).

Compared to other nations, India is one of the largest groundwater extractors for irrigated agriculture (Scott & Shah 2004). However, human-driven factors such as overexploitation and increased rate of pumping combines with climate change which amplifies the groundwater depletion (Treidel et al. 2012). The changes in temperature and precipitation may alter the groundwater recharge and result in shifts of the regional water tables.

The response of the groundwater system to interannual climate variability like ENSO has not been studied extensively; however, previous works and key findings are given below in Table 1.

Nevertheless, the impacts of interannual to multidecadal climate variability on recharge rates and other subsurface hydrologic processes need more studies in various parts of the world (Treidel et al. 2012) for deeper understanding of the scenario.

The earlier studies of the impact of ENSO on groundwater listed above employed different statistical methods. In contrast, the current study utilizes integration of GIS...
and statistical techniques to analyse the impacts of ENSO on groundwater resources. Also, the previous studies examined the influence of ENSO on groundwater by only observing the variations in GWL, which does not completely depict the hydrological impacts due to ENSO. To sufficiently relate the hydrological changes to ENSO, the present study analyses other prerequisite impact parameters like deviation of GWL from long-term average (anomaly), change detection (year-to-year variation) of groundwater, net discharge, and net groundwater recharge in the area. The study also analyses the different impacts of ENSO in the command area (CA) and non-command area (NCA).

Therefore, the specific objectives of the present study are as follows:

- To analyse the spatial annual variations in the groundwater occurrence using spatial interpolation techniques such as inverse distance weighted (IDW) and to generate groundwater anomaly maps using geographic information system (GIS) techniques to establish the relationship of groundwater occurrence to different ENSO phases.
- To estimate the net groundwater discharge and recharge in the study area during 1996 to 2015, and to understand its harmonisation with ENSO events.
- To observe the difference in GWL of El Niño and La Niña years using a two-sample Kolmogorov–Smirnov test to understand the deviation in the distribution of two GWL series.
- To perform trend analysis of GWL and temporal analysis of groundwater recharge in the CA and NCA using different statistical methods.
- To observe the significant variation in the impacts of ENSO in CA and NCA using the Mann–Whitney test.

STUDY AREA, DATA USED AND METHODOLOGY

Study area

The Venna River basin, a sub-basin of the Wardha catchment under the Godavari basin of Maharashtra, India, has
been selected as the study area for the present study. The basin covers an area of 5,675 km² with an average annual rainfall of 1,055 mm. More than 80% of the region is covered with black cotton soil. The study area comprises 67% cultivable land and 15% forest. The three cropping seasons in the study area are Kharif (June–October), Rabi (November–February) and summer/hot weather (March–May). Kharif crops during monsoon are mainly rainfed, but the Rabi crops and summer/hot weather depend on irrigation water (either from reservoir, groundwater or river). Major crops cultivated in the region include cotton (33%), soybean (19%), jowar and wheat (22%), pulses (13%), fruits (4%) and vegetables (2%). Rishma & Katpatal (2016a) proved that ENSO has a high influence on vegetation, the phenological cycle of crops and crop coefficients of the Venna basin. They have also proved that the intensity of vegetation and crop coefficients were smaller during El Niño and greater during La Niña.

CA is considered as the area irrigated by reservoir using the canal network. There are 11 major reservoirs (Pothra, Lower wunna Wadgaon, Lower wunna Nand, Bor, Wunna, Labhansarad, Lal, Panchadhara, Dongargaon, Kanholibara and the Dham dam) in the Venna basin. There are 27 groundwater observation wells within the study area. Some of these wells are within the CA while the majority of the wells are present in the NCA. The geographical location of the study area, the spatial location of observation wells and the CA are depicted in Figure 1.

Figure 2(a) illustrates the digital elevation model (DEM) showing the elevation difference within the basin. It may be observed that the higher elevation areas are present in the northern part of the basin while lower elevation areas are present in the southern part of the basin. The figure also shows the drainage networks of different order, subwatersheds as well as the locations of the observation wells.

Figure 2(b) shows the lithological formations in the Venna basin. It may be observed that the maximum part of the basin has a basaltic formation (90%) while the rest (10%) of the area is covered by limestone, alluvium, laterite and sandstone with shale. Since the topography and lithological formations have a bearing on groundwater potential and availability, the groundwater heads and flow directions are also shown in the figure. It may be observed here that the general trend of groundwater flow in the basin is from north to south, which follows the topographical gradient. It may also be observed that the command areas (Figure 1) are generally under the groundwater flow regime, i.e., under the hydraulic heads in a profile or direction of flow.

Figure 1 | The location of the study area with spatial location of observation wells and command area.
Data used

Daily rainfall data (1985–2015) of ten rain gauge stations situated within the study area were obtained from India Meteorological Department (IMD 2015), Pune. The locations of the observation wells and depth to GWL data were obtained from the geoportal of Water Resources Information System (WRIS 2016) of India. The depth to GWL data for four major seasons, namely, premonsoon, monsoon, postmonsoon Kharif and postmonsoon Rabi for the period 1996–2015 have been analysed. Data of the years 2004 and 2012 for monsoon and postmonsoon Kharif were not available, and hence they do not appear in GIS analysis. These missing data, however, were generated and used for the statistical analyses.

The depth to GWL data for 20 years were separately grouped into El Niño, La Niña and normal years based on the Oceanic Nino Index (ONI) used by the National Oceanographic and Atmospheric Administration (NOAA 2006). The years categorized as El Niño and La Niña years on the basis of ONI values are given in Table 2.

Methodology

The ENSO–GWL relationship has been examined using both GIS and statistical analyses. Spatially interpolated surfaces of depth to GWL data of the month of October (postmonsoon Kharif season) have been generated for the period 1996 to 2015 using the IDW interpolation technique of GIS (RMSE error in the range of 1.48 to 3.01 for different years). ArcMap 10.1 software has been used for all GIS analysis as well as generation of spatial maps. Change detection analysis has been done by generating year-to-year groundwater variation maps for the postmonsoon Kharif season using the IDW interpolation technique and raster calculator of ArcMap software. These two spatial maps were then compared with the ENSO events to understand their teleconnections.

Depth to GWL anomaly maps were also generated to understand the impact of ENSO. Out of 27 observation wells in the study area, only 12 wells with continuous data available for all the seasons have been selected for this
analysis. Long-term average GWL data (Table 3) of each well (12 wells) have been calculated as the average of annual GWL data (annual GWL data means average of four seasons’ GWL data) for the period 1995–2015. Depth to GWL anomaly of each year has been calculated as the deviation of depth to GWL from its long-term average net groundwater usage and storage maps were also generated to identify the impact of ENSO on the groundwater of the study area.

Variation in cumulative distribution of groundwater in El Niño and La Niña years has been studied using a non-parametric hypothesis test, namely, the two-sample Kolmogorov–Smirnov test. The Kolmogorov–Smirnov test compares the cumulative distribution function (cdf) of two datasets and computes a test statistic based on the largest discrepancy between the distributions (Smirnov 1959). The two-sample Kolmogorov–Smirnov test was carried out at a 5% significance level for all four major seasons of the study period to observe the variation in cumulative distribution of groundwater in El Niño and La Niña years. The p-value is calculated to determine the significance of the result. The p-value is the probability value in the range of 0 and 1 and interpreted in the following way: A small p-value (typically ≤0.05) indicates strong evidence against the null hypothesis, so the null hypothesis is rejected. Seasons with p-value less than 0.05 have been considered to represent the distributions of GWL with the largest discrepancy.

The analysis was also carried out separately for groundwater levels of the CA and the NCA in order to understand the variation in impacts of ENSO. Trend analysis of GWL was carried out for four major seasons using Mann–Kendall (Mann 1945; Kendall 1975) and Sen’s slope method (Sen 1968). Temporal analysis of net recharge was performed separately for CA and NCA. The differences between the net recharge in CA in El Niño and La Niña phases and the net recharge in NCA in El Niño and La Niña have been studied using the Mann–Whitney U test (McKnight & Najab 2013) at 5% significance level.

### RESULTS AND DISCUSSION

The widespread influence of ENSO on regional rainfall is well known and it has diverse impacts over different parts of the world. Most of the ENSO events resulted in above or below normal rainfall in different countries including India. The main source of aquifer recharge is the regional rainfall and hence the fluctuation of rainfall with ENSO events has an impact on the regional groundwater as well. Hence, to identify the impacts of ENSO on groundwater, several factors such as spatial distribution, anomaly maps, groundwater fluctuation, net groundwater storage and usage, etc., have been analysed separately as discussed below.

#### Temporal variation of rainfall

Average annual rainfall in the study area for the period 1985–2015 is plotted in Figure 3. A clear relationship between rainfall and ENSO can be seen. The rainfall in El Niño years is less than in normal years and greater than normal in La Niña years.
Groundwater levels

Figure 4 shows maps of the depth to groundwater in the study area in October (postmonsoon Kharif) for the years 1996–2015. They were prepared by spatial interpolation of water level data in observation wells using IDW.

Groundwater levels are deeper in the north-west (well nos. 11, 12, 14, 23, 24 and 25) in all years because this is the recharge zone with regional groundwater flow towards the south. Similarly, groundwater levels in the southern part (well nos. 2, 3, 19, 20, 21, 22) are shallower in all the years.
years since this zone receives the groundwater from the north.

A relationship between groundwater depth and ENSO phases can be observed. The groundwater is deeper for El Niño years with the greatest depth linked to strong El Niño events, increasing to 17 m below ground level (bgl). On the other hand, groundwater levels are shallower in La Niña years. In a considerable part of the study area they are less than 7 m and in some wells they can be as little as 1 m. This indicates more groundwater recharge during La Niña years.

It is worth noting that groundwater levels in the NCA, where the reservoirs have little effect, can be both deeper (e.g., well nos. 5, 6, 7 and 8 in the eastern part) and shallower (e.g., well nos. 16, 17 and 26 in the north-eastern part). Hence, it can be concluded that the groundwater levels are controlled mainly by the lithology and, because it is depths to groundwater that are considered in this analysis, the topography. Temporal changes in depth to groundwater examined in this study are however a result of rainfall and irrigation and are a meaningful representation of the ENSO effect.

**Year-to-year groundwater level variation**

Figure 5 shows the spatial maps of year-to-year variations of depth to GWL in October (postmonsoon Kharif season) for the period 1996–2015 (except for 2004 and 2012). GWL variations were classified into seven classes in the range of −10 m (rise in GWL) to 10 m (decline in GWL). The analysis shows that the locations of rising or declining zones of groundwater is not uniform every year.


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**Figure 5** | Change detection of depth to groundwater in the study area for the postmonsoon Kharif season.

Groundwater level anomaly maps

Apart from understanding the year-to-year variation, long-term variation of GWL is also important for climate variability studies. Hence, the groundwater anomaly maps have been generated and related to ENSO events.

Figure 6 shows GWL anomaly maps classified into six classes ranging from much below normal (>2.5 m) to much above normal (>−2.5 m). The groundwater table in the observation wells is ‘much below the normal’ for El Niño years with a higher decline in GWL of 1.5 to 2.5 m and >2.5 m during strong El Niño years (1997 and 2015). Similarly, strong and medium La Niña years show a higher rise (much above normal) in GWL. Also, maximum deviation can be observed in the wells in the subwatersheds WRWP-1, WRWBD-3 and WRWBD-2 (Figure 2(a)). Hence, these subwatersheds may be considered as groundwater vulnerable/management zones for the ENSO impacts.

Seasonal fluctuation of groundwater level

The ‘net groundwater storage’ and ‘net groundwater usage’ have been calculated using the seasonal groundwater storage values. Net groundwater usage of Xth year has been calculated by subtracting the previous year’s postmonsoon Kharif groundwater storage (October of the (X−1)th year) from the groundwater storage in the monsoon month of the Xth year (i.e., June of the Xth year). Similarly, the net groundwater storage of the Xth year was calculated by...
subtracting the groundwater storage in the postmonsoon Kharif (October) of the Xth year from the groundwater storage in the monsoon month (June) of the Xth year (Chinnasamy et al. 2015). To estimate the groundwater storage, the GWL data have been converted to saturated thickness which is then multiplied with specific yields of the aquifer. All the wells are in basaltic terrain and have a specific yield of 2.5%.

Figure 7 shows the spatial distribution of estimated net groundwater usage for the period 1996 to 2015. The net groundwater usage values are grouped into ten classes, from $<-10$ m to $>20$ m. Negative values indicate that groundwater storage of monsoon month of the Xth year is more than the groundwater storage of postmonsoon Kharif of the $(X-1)^{th}$ year. A relationship between the groundwater usage and ENSO phases can be observed in the study area. High rate of groundwater usage is associated with ENSO warm phases with maximum rate of usage linked to strong and medium El Niño years.

Figure 8 shows the spatial distribution of estimated net groundwater storage for the period 1996 to 2015. The net groundwater storage values are also grouped into ten classes, from $-10$ m to 21 m. Negative values indicate that there is a deeper GWL in postmonsoon Kharif (October) as compared to the GWL in June, indicating a net deficit in recharge due to less rainfall or the high abstraction of groundwater during the cropping season. It can be noted that a high rate of net groundwater storage is associated with ENSO cold phases and vice versa.

Comparison of GWL of El Niño and La Niña using Kolmogorov-Smirnov test

Figure 9 shows the variation in the cumulative distribution of depth to groundwater levels during the El Niño and La Niña years generated using the two-sample Kolmogorov-Smirnov test.

The depth to GWL of each well has been averaged for El Niño and La Niña years separately, and the discrepancies
between the distributions have been observed for four different seasons, namely, premonsoon, monsoon, postmonsoon Kharif and postmonsoon Rabi. The null hypothesis for the analysis is that two samples are from the same distribution with a 5% significance level.

Figure 9 shows that the El Niño and La Niña events do not have a significant influence on the GWL during premonsoon and monsoon ($p$-value of 0.9 and 0.96, respectively) periods whereas the postmonsoon GWLs are highly affected by ENSO events ($p$-value <0.05).

GWL trends in command and non-command areas

To understand the variation in the GWL in command and non-command areas, both MK test and Sen slope methods were used. This approach has been incorporated as the MK test gives information about the significance of existing trends with their beginning and ending times, whereas the Sen slope method takes into account a non-parametric serial correlation coefficient for the possibility of a trend existence.
Table 4 and Figure 10 show the GWL trends estimated by the MK test and Sen slope method, respectively, for the period 1996–2015. The GWLs in the CA and NCA show different trends for the same period. The CA shows ‘probably increasing’ (premonsoon and postmonsoon Kharif) or ‘increasing’ (monsoon and postmonsoon Rabi) trend during the study period. However, in the NCA, GWL has no particular trend for premonsoon and postmonsoon Rabi, whereas it shows ‘increasing’ and ‘probably increasing’ trends for monsoon and postmonsoon Kharif, respectively. Since the soil formations and lithology are homogenous in the region, this difference in groundwater trend may be due to the influence of reservoirs at the upstream of the wells in the CA.

Variation in impacts of ENSO within CA and NCA

The variation in the impact of ENSO on CA and NCA has been studied separately by conducting the temporal analysis of net groundwater storage. Figure 11 shows the average of net groundwater storage estimated from GWL data of all observation wells.

In Figure 11, it may be observed that the net groundwater storage of CA exceeds the net groundwater storage...
of NCA which may be due to the reservoir seepage and irrigation water. It was also observed that during ENSO warm events (1997, 2002, 2006, 2009 and 2015), there is less groundwater storage (negative values indicate a net deficit in groundwater storage and overexploitation of groundwater due to low rainfall) in both CA and NCA. The groundwater storage is always more than 3 m and 2.5 m in CA and NCA, respectively, during ENSO cold events (1998, 1999, 2000, 2007, 2010 and 2011). Maximum groundwater storage of 8.23 m and 6.9 m in CA and NCA, respectively, is obtained during 2000, which was a consecutive La Niña year.

Mann–Whitney U test

The Mann–Whitney test at a 5% significance level has been performed to understand the significant difference between the net groundwater storage in CA and NCA in the El Niño and La Niña phases. Table 5 shows the results of the analysis. In command areas, the difference in maximum and minimum groundwater storage between El Niño and La Niña phases is 5.4 m and 4.5 m, respectively. Whereas, in the non-command areas, the difference in maximum and minimum groundwater storage between El Niño and La Niña phases is 6.7 m and 8.2 m, respectively.

Table 4 Trends of GWL in command and non-command areas using the Mann–Kendall test

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<tr>
<th>Trends of GWL in command and non-command areas using the Mann–Kendall test</th>
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<td>Coefficient of variation</td>
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<td>Command area</td>
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<td>Postmonsoon Kharif</td>
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<td>Postmonsoon Rabi</td>
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<td>Non-command area</td>
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Figure 10 The estimated GWL trends using the Sen slope method in the command and non-command areas.
Mann–Whitney U test at 5% significance level shows that both CA and NCA have a significant difference in the distribution of GWL during the El Niño and La Niña phases with a p-value of 0.016 and 0.008 ($\alpha <0.05$), respectively. It may also be concluded that the GWL in NCA is more affected by the El Niño and La Niña phases when compared to the GWL in CA.

**CONCLUSIONS**

The response of groundwater of the Venna River basin in Central India to different ENSO events has been analysed using integrated GIS and statistical techniques. The spatial analysis and change detection analysis of depth to GWL data reveal the association of deeper groundwater levels with El Niño and shallower groundwater levels with La Niña phases in the study area. Also, the GWL anomaly maps indicates that positive (fall) and negative (rise) anomalies are associated with the El Niño and La Niña phases, respectively.

The results of two-sample Kolmogorov–Smirnov test at a 5% significance level indicates that GWL in postmonsoon Kharif and Rabi seasons are highly affected by ENSO events, whereas premonsoon and monsoon have no impact by ENSO events. The MK tests and the Sen slope methods ascertained that GWL in CA and NCA show different trends for the same periods and this variation in trend may be due to the presence of reservoir at the upstream of the CA. Variation in the impact of ENSO on CA and NCA has been studied separately by considering the temporal analysis of net groundwater storage. A Mann–Whitney test at a 5% significance level concludes that the NCA has more variation in impacts during different ENSO events than CA.

The integration of different GIS and statistical techniques made the analyses simpler and the inferences clearer. The study also emphasizes the applicability of non-parametric tests, namely the Kolmogorov–Smirnov test and Mann–Whitney test in the hydrometeorological studies. Similar integrated approaches may be adopted to achieve clarity in analysing the impacts of interannual and interdecadal climate variability on different hydrological and vegetation parameters at regional or global levels.

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