Reservoir Triggered Seismicity (RTS) and well water level response in the Koyna–Warna region, India

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Abstract

Water level fluctuations in twenty-one observation wells have been monitored for the last 10 years around the seismically active Koyna–Warna region, western India where earthquakes continue to occur even after four decades of the initiation of the seismic activity in the region. Fourteen of the observation wells act as volume strain meters as their water levels show earth tidal signals. Our analysis suggests three types of response of the well water levels to seismo-tectonic effects, i) one to local earthquakes, ii) to regional and teleseismic events, and iii) to local fluctuations in rock strain on regional scale. We observed five cases of co-seismic step-like well water level changes, of the order of few centimeters in amplitude, related to earthquakes in the magnitude range 4.3 ≤ M ≤ 5.2. All these earthquakes occurred within the network of wells drilled for the study and within 25 km distance of the recording wells. In three cases, drop in well levels preceded co-seismic step-like increases, which may be of premonitory nature. The second type of response is observed to be due to the passing of seismic waves from regional and teleseismic earthquakes like the M 7.7 Bhuj event on January 26, 2001 and the M 9.3 December 26, 2004 Sumatra earthquake. The third type is a well level anomaly of centimeter amplitude coherently occurring in several wells. The anomalies are similar in shape and last for several hours to days.

From our studies we conclude that the wells in the network appear to respond to regional strain variations and transient changes due to distant earthquakes. The two factors which are important to co-seismic steps due to local earthquakes are the magnitude and epicentral distance. From the limited number of events we found that all local earthquakes exceeding M ≥ 4.3 have produced co-seismic changes. No such changes were observed for earthquakes below this magnitude threshold.

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Keywords: Co-seismic; Well water level; Hydrological precursors; Koyna–Warna area

1. Introduction

The National Geophysical Research Institute, Hyderabad, India has been monitoring water level fluctuations at a closely clustered network of wells to study in-situ pore pressure changes associated with earthquakes in the Koyna–Warna region in western India (Gupta et al., 2000). We undertook the investigations in an area of extensive Reservoir Triggered Earthquakes (RTS) as a part of an Indo-German research program. Changes in well water levels reflect stress changes in the medium due to several reasons such as earth tides, loading, changes in barometric pressure, passing of seismic waves or due to alterations of tectonic stresses in the crust (Bredheoeft, 1967; Bodvarsson, 1970; Sterling and Smets, 1971; Wakita, 1975; Van der Kamp and Gale, 1983; Rojstaczer, 1988; Rojstaczer and Agnew, 1989; Kissin et al., 1996; Koizumi et al., 1996; Roeloffs, 1998; King et al., 2000).

21 boreholes were drilled in and around a very well constrained seismically active zone at the Koyna–Warna region in western India. The bore wells were drilled in phases during 1995–98, to a depth range between 90 and 250 m in the Deccan trap basalts, which covers the region (Fig. 1). The location of the wells was chosen keeping in view, the aerial coverage of and nearness to the seismogenic zone, availability of pathways for drilling trucks and possibilities of maintenance through out the...
year. Also, these wells are in areas, which are not affected by human activities such as pumping of ground water. All wells were cased and the ring space sealed with concrete in their upper parts to reduce seepage and inflow from shallow aquifers. Battery powered pressure transducers (OTT-Hydrometrie, 1992) were installed in nineteen bore wells, of which four are artesian or semi-artesian. The transducers read the hydraulic pressure of the water column above the sensor element with a resolution of better than 1 mm. In addition, four barometers and three rainfall meters were set-up near some of the wells in the region.

In this paper we present well water level data of the period 1997–2004 and demonstrate that water level changes record crustal strain events and discuss the implications of our results in the light of pre- and co-seismic changes observed for a few local earthquakes.

2. Study area

The Koyna–Warana area (Fig. 1) is 225 km south of Mumbai in western India and lies 50 km east of the Arabian Sea. The Koyna and Warana dam reservoirs lie east of an elevated N–S escarpment parallel to the west coast of India. The mean elevation varies between 600 m on the escarpment to 100–200 m in the Konkan plains towards the west coast. The geological setting is characterized by the Deccan Traps of 67.4 Ma (Duncan and Pyle, 1988) comprising several sequence of lava flows. The thickness of the Deccan Traps varies from 1.5 km in the escarpment zone to less than 100 m in the peninsular shield (Kailasam et al., 1976). The massive, compact lava sequences have low permeability but there is significant migration of water through faults, fractures, columnar jointing or through vesicles. Several lineaments have been mapped from Landsat satellite imageries in the region; two NNE–SSW faults are delineated from Koyna in the north to Warana in the south.

Over 100,000 earthquakes of $M \geq 0.0$ have been reported from the Koyna region with more than 100 events of $M \geq 4.0$ and 18 of $M \geq 5.0$ since 1963 (Rastogi et al., 1997; Gupta et al., 2002). Most epicenters are concentrated in an area of $15 \times 30$ km$^2$ (Chadha et al., 1997; Talwani, 1997). The epicenter of the M 6.3 Koyna earthquake on December 10, 1967 was
located 2 km south of the Koyna dam. Several ground cracks aligning in N–S directions were mapped on the surface (GSI, in press). The focal mechanism solution and moment tensor inversion for this earthquake indicated displacement along a NNE–SSW strike-slip fault (Langston and Franco-Spera, 1985; Dziewonski et al., 1988). Drilling in the NNE–SSW fault zone showed a 60° WNW dip of the fault (Gupta et al., 1999). Since then, the earthquakes in the region show consistent strike-slip movements on a NNE fault and normal faulting on a NW–SE fault coinciding with the Warna lineament. Most of the regional structures inferred from geomorphology and tectonics, supported by geophysical data suggest dominant N–S trending features (Talwani, 1997). In a recent study three fault segments in the Koyna Seismic zone were delineated (Rai et al., 1999). Since 1993, the earthquakes cluster closer to the Warna reservoir, which was impounded in the early 1990s (Gupta et al., 1997).

3. Monitoring wells

The set-up of the experimental phase and field operations that included drilling operations, initial well testing by slug and bail tests, installation of well level recorders and other sensors was completed in four campaigns. Table 1 gives details of the wells in the study area. The first well was drilled at RAS in May 1995, to a depth of 250 m; it also served as a reconnaissance well. The drilling confirmed the expected exclusive occurrence of successions of massive, vesicular and amygdoidal basalts and the Deccan trap formations. Four more wells were drilled in January 1996, down to 210 m, seven with depths between 140 m and 200 m in January 1997 and eight with depths varying between 91 m and 152 m in May 1998. Since the terrain of the wells was drilled in the periphery of the seismogenic zone. The four wells NEC, NAY, SID and MAR turned out to be artesian or semi-artesian. All other boreholes werecased in their upper parts down to depths of 30 to 60 m, to prevent distortions of the well levels from shallow aquifer effects. Inspection of early data sets provided first hand information regarding water saturation and vague expectations about the confinement of aquifers at depths where boreholes were left uncased. It was found that the water table in this region typically ranges around depths of less than 10 m. Transmissivities obtained from bailer and pumping tests vary from well to well and extend from 0.1 to 10 m²/day.

4. Data analysis

Analysis of data for the period 1996–2004 has indicated that ten out of the twenty wells that are being monitored show clear tidal signals in their well level fluctuations. Signal-to-noise ratio of the largest tidal constituent M2 are above 50 for most recordings, with peak-to-peak tidal amplitudes of up to 24 cm. Earlier, Chadha et al. (2003) analysed data for 1997–2002. Presence of tidal signals in several wells indicates that these wells are connected to confined, that is, hydraulically locked and fully water-saturated aquifers. Accordingly, these well-aquifer systems are capable of detecting weak pore pressure anomalies caused by crustal strain and hence, can act as “Strain meters”. Jannssen (1998) reported varying degrees of sensitivities for these wells ranging from 0.06 to 4.15 mm/nanostrain (Table 1).

The dominant fluctuations in the well water level are changes in response to earth tides and barometric pressure variations. To remove these effects from the well level recordings which could mask pore pressure anomalies caused due to tectonic reasons,

<table>
<thead>
<tr>
<th>No. location</th>
<th>Drilled mon/yr</th>
<th>Operational mon/yr</th>
<th>Depth (m)</th>
<th>Strain sensitivity a (mm/nanostrain)</th>
<th>Remarks b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CHApher</td>
<td>01/97</td>
<td>03/97</td>
<td>199</td>
<td>–</td>
<td>Lstnr</td>
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<tr>
<td>2. DHAvade</td>
<td>05/98</td>
<td>11/98</td>
<td>128</td>
<td>Unconfined</td>
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</tr>
<tr>
<td>3. DEBwadi</td>
<td>05/98</td>
<td>11/98</td>
<td>91</td>
<td>Unconfined</td>
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<tr>
<td>4. GOVare</td>
<td>01/96</td>
<td>04/96</td>
<td>210</td>
<td>0.93±0.02</td>
<td>Confined</td>
</tr>
<tr>
<td>5. HARPude</td>
<td>05/98</td>
<td>–</td>
<td>123</td>
<td>Water level&gt;100 m</td>
<td></td>
</tr>
<tr>
<td>6. INAwadi</td>
<td>05/98</td>
<td>11/98</td>
<td>91</td>
<td>Unconfined</td>
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</tr>
<tr>
<td>7. KADvai</td>
<td>05/98</td>
<td>11/98</td>
<td>110</td>
<td>Lstnr</td>
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<tr>
<td>8. KONDavalle</td>
<td>01/97</td>
<td>03/97</td>
<td>148</td>
<td>Unconfined</td>
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</tr>
<tr>
<td>9. KOYna</td>
<td>01/96</td>
<td>03/97</td>
<td>210</td>
<td>0.71±0.02</td>
<td>Confined</td>
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<td>10. MANdoor</td>
<td>01/97</td>
<td>03/97</td>
<td>153</td>
<td>Confined</td>
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<tr>
<td>11. MARleshwar</td>
<td>05/98</td>
<td>10/01</td>
<td>Artesian</td>
<td>–</td>
<td>Show tides</td>
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<td>12. MORgiri</td>
<td>05/98</td>
<td>11/98</td>
<td>123</td>
<td>Confined</td>
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</tr>
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<td>13. NAYari</td>
<td>01/97</td>
<td>06/00</td>
<td>Artesian</td>
<td>No tides</td>
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<td>14. NEChal</td>
<td>01/97</td>
<td>03/97</td>
<td>Artesian</td>
<td>Show tides</td>
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<tr>
<td>15. RASti</td>
<td>05/95</td>
<td>05/95</td>
<td>250</td>
<td>0.40±0.08</td>
<td>Semi-confined</td>
</tr>
<tr>
<td>16. SALve</td>
<td>05/98</td>
<td>11/98</td>
<td>152</td>
<td>Unconfined</td>
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<td>17. SHRingarpur</td>
<td>01/97</td>
<td>03/97</td>
<td>162</td>
<td>–</td>
<td>Lstnr</td>
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<tr>
<td>18. SIDrukwa</td>
<td>05/98</td>
<td>05/02</td>
<td>Artesian</td>
<td>–</td>
<td>Show tides</td>
</tr>
<tr>
<td>19. TALoshi</td>
<td>01/96</td>
<td>04/96</td>
<td>210</td>
<td>3.9±0.20</td>
<td>Confined</td>
</tr>
<tr>
<td>20. UKAlu</td>
<td>01/97</td>
<td>03/97</td>
<td>153</td>
<td>4.15±0.08</td>
<td>Confined</td>
</tr>
<tr>
<td>21. VAJegaon</td>
<td>01/96</td>
<td>04/96</td>
<td>210</td>
<td>0.06±0.003</td>
<td>Confined</td>
</tr>
</tbody>
</table>


b Low signal-to-noise ratio (Lstnr).
we applied the least squares regression scheme of Wenzel (1996). For pre- and post-monsoon data series, which are otherwise very stable the algorithm is used to eliminate the tidal and barometric variations. During the monsoon, heavy rainfall, significantly affect the pore pressure signals, even in the strongly confined layers. During 1997–2004, six earthquakes of M>4.0 occurred in the Koyna–Warna region. Except for the earthquake of M 4.2 on February 14, 1998, all other earthquakes induced co-seismic changes in at least one well. We grouped our observations into three categories.

4.1. Co- and pre-seismic water level changes

Fig. 2 shows well water level fluctuations sampled every 15 min at GOV and TAL wells 40 days prior to an earthquake of M 4.4 on April 25, 1997; the event occurred at a distance of 1.8 and 2.4 km from these wells, respectively. Clear spring and neap tides are observed at both these wells. After the removal of earth tide and atmospheric pressure effects, still some cyclic fluctuations were observed in the time series which are mostly due to the periodic release of water in the nearby Koyna river. Fig. 2b shows clear co-seismic steps of 3 and 8 cm at GOV and TAL coinciding with the origin time of the earthquake at 16:22:52.97 (GMT). The co-seismic water level changes are measured as the maximum excursion in data corrected for tidal effects. The first anomalous water level is seen in the first data sample following the earthquake origin time. Some pre-seismic drop of 4 cm at GOV and 10 cm at TAL began 23 days before this earthquake. The well level remained low till the occurrence of the event. The phenomenon could indicate a premonitory change in crustal strain prior to the earthquake (Fig. 2a). A coincident post-seismic drop was also observed for this earthquake (Fig. 2b). No such pre-, co- and post-seismic changes were observed at other sensitive wells, however, UKA and MAN are located at a larger distance (>25 km from epicenter), VAI and KOY have a lower sensitivity, and MOR, NEC and MAR were not instrumented. No significant rainfall occurred during this period as most of the rainfall occurs during monsoon period that is from June to September, every year.

On February 11, 1998, M 4.3 earthquake occurred south of Warna reservoir (Fig. 1). This earthquake induced a co-seismic well level increase of about 5 cm amplitude at UKA well (Fig. 3a) situated at a distance of some 12 km from the epicenter. In this case, a premonitory drop of roughly 3.0 cm began 3 days before the earthquake occurred. No other wells recorded any of these changes; MAR was not operational. Another earthquake of M 4.2 followed three days later on February 14, 1998 with its epicenter some 6 km east of the February 11, 1998 event (Fig. 1). For this earthquake no anomalous changes were observed in any of the operating wells including UKA, which is at a distance of about 16 km from the epicenter.

Three moderate size earthquakes occurred close to the Warna reservoir during 2000 (Fig. 1). The first earthquake of M 5.0 on March 12, 2000 induced a co-seismic step-like increase of 6 cm at UKA and 2 cm at KOY and a decrease of 6 cm at GOV (Fig. 3b, c and d). Prior to this earthquake water level drops were observed at UKA and KOY. At UKA the water level started decreasing three days prior to the occurrence of this earthquake. Another water level anomaly was observed 21 days prior to this earthquake (Fig. 3b). At KOY a gradual 5 days drop in the water level
preceded the co-seismic step on March 12, 2002. Two water level anomalies lasting for 2–3 days were observed 14 and 18 days prior to this earthquake. The earthquake of M 4.7 on April 6, 2000 induced a sharp co-seismic increase of about 2.5 cm at MOR well (Fig. 3e) situated at a distance of 24 km from the epicenter (Fig. 1). In this case, a peculiar water level drop of 1 cm is observed 28 h prior to this earthquake. Unfortunately, for these two earthquakes we cannot present recordings from other sensitive wells because of leakage of water in pressure sensors and also because of disturbance in water level fluctuations due to pumping tests conducted during this period.

The largest earthquake for which co-seismic changes were observed occurred during the monsoon period, on September 5, 2000. This earthquake had a magnitude of M 5.2 (Fig. 1) and was different from the other four cases because, i) 7 wells showed anomalous water level fluctuations, ii) the co-seismic changes were water level drops in all responding wells, iii) it was observed at wells SHR and NAY which are insensitive to earth tides and iv) the focal mechanism for this earthquake is normal faulting along a NW–SE nodal plane which is different from the other three cases where the mechanism was strike-slip along NNE–SSW direction (Gupta et al., 2002). Fig. 4a shows water level fluctuations at four wells after the removal of tides, 5 days prior and after the earthquake on September 5, 2000. Co-seismic drops of 5.5 cm at MOR, 8 cm at UKA, 3.5 cm at TAL and 0.4 cm at NAY are evident. Fig. 4b shows water level fluctuations one day prior to and after this earthquake with co-seismic water level drops of 1 cm each at GOV and SHR and 0.5 cm at MAN. Data one-month prior to and after this earthquake reveals some precursory changes that are possibly associated with this earthquake (Fig. 5). During this period, heavy rainfall significantly affected the water level fluctuations even in some of the strongly confined aquifers. NAY is a semi-

![Graph](image-url)

Fig. 3. Water level fluctuations at 5 wells after removal of tides. a) Co-seismic step rise at UKA well for February 11, 1998, shown by arrow; see also three days of precursory decrease (P.D) preceding the earthquake. b–d) Co-seismic step-like rise at UKA and KOY and drop at GOV due to the March 12, 2000 earthquake (arrow). Instants of precursory decrease (P.D) possibly associated with this earthquake at UKA and KOY are also shown. e) Co-seismic step-like rise at MOR well caused due to April 6, 2000 earthquake. A probable precursory decrease 2 days prior to the earthquake is also shown.

![Graph](image-url)

Fig. 4. Water level fluctuations at 7 wells after removal of tides. a) Co-seismic drops for the September 5, 2000 earthquake at NAY, TAL, UKA and MOR wells. The scale at NAY is exaggerated by a factor of 8 because of low amplitude fluctuations. b) Co-seismic trough-like decrease at MAN, SHR and GOV wells shown by arrow. Note different time and amplitude scales.
artesian well showing high frequency and low amplitude fluctuations. The MOR well is not much affected by rainfall. Conspicuous water level drops, which may be of premonitory nature, are observed at three wells. At MOR a water level drop occurred 28 days prior to this earthquake and continued for 3 days. At UKA two water level drops lasting for 3–5 days occurred 12 and 29 days before the event. Similarly, two water level drops occurred 8 and 29 days prior to the earthquake at TAL well. These drops recovered within 3 to 6 days. It is noteworthy that all these water level drops occurred in spite of rainfall during this period. Fig. 5 also shows well water levels at GOV, SHR and MAN wells. As can be seen from the amplitudes the water levels here are severely affected by rainfall and other factors and hence, it is difficult to resolve any precursory changes. More specifically the well level at SHR is severely affected by discharge of water in a nearby river after a heavy rain. At MAN well, the water level fluctuations are occasionally influenced by the release of water in a nearby canal from the Warna dam reservoir. More than fifteen aftershocks up to magnitude M 3.9 of this earthquake occurred. No anomalous changes that could be associated to these shocks were observed in any of the wells.

4.2. Aseismic water level changes

During April 2002, a series of conspicuous water level changes were observed which were not associated with any of the local earthquakes or with teleseismic events. Fig. 6 shows these water level changes that were recorded at 8 wells. Prominent water level drops started around 11 o’clock on April 22, 2002 at GOV, KOY, RAS, TAL, MOR and UKA, the...
amplitudes of the drops range from 1.8 cm at MOR to 4 cm at RAS. The recovery times of these water level decreases were observed to be about 3–4 h. This is much shorter than the recovery times of water level drops associated with co-seismic changes which were typically of the order of days. At the same instant of time, a water level increase was observed at two other wells, namely at MAR, an artesian well, and at CHA with amplitudes of 2 and 5 cm, respectively. Given the high strain sensitivity of most of these wells, we believe that these anomalies reflect regional volume strain with water level drop indicating extension and rise as compression. On scrutiny of data prior and after to this event, two time windows are marked in Fig. 6, where coherence in the time series of a majority of these wells is clearly seen.

4.3. Transient water level changes due to teleseisms

Transient and persistent water level changes due to the M 7.9 Bhuj Earthquake in India on January 26, 2001 and M 9.3 Sumatra earthquake in the Indian Ocean on December 26, 2004 were recorded at some of the wells in the network in the Koyna region. The epicenters of these earthquakes are located at more than 800 and 2000 km away from these wells. Fig. 7a and b show clear changes in water level due to the arrival of seismic waves at these wells at UKA, TAL, GOV and NEC. No other well in the network responded to the passing seismic waves of this earthquake.

5. Discussion

We have analyzed 7 years of water level data recorded at a network of wells drilled around the Koyna–Warna region in western India. The area is exhibiting intense Reservoir Triggered Earthquakes during the last four decades. The present analysis shows five cases of anomalous co-seismic changes in well water levels due to local earthquakes (within 25 km) of 4.3 ≤ M ≤ 5.2. The epicenters of all these earthquakes are located within the network of wells. Our results suggest that these wells also respond to aseismic events and to transient changes due to the passage of seismic waves.

We have divided the response of wells in three categories, viz., co- and pre-seismic, aseismic and transient changes. In the first category, a step-like co-seismic rise was observed for all the four earthquakes occurring in April 1997, February 1998, March and April 2000. The only exception was a step-like drop at GOV well for the March 2000 earthquake. This type of co-seismic steps are understood as sudden pore pressure changes related to an alteration in in-situ volume strain caused by the redistribution of stress in the brittle crust (Bodvarsson, 1970; Kuempel, 1992; Muir-Wood and King, 1993). The co-seismic steps were found to be preceded by persistent water level drops from 2 to 23 days prior to the earthquake. According to Sadovsky et al. (1979) and Monakhov et al. (1983), the most common precursor is a water level drop of a few centimeters amplitude several days before the earthquake. Typically, the drop is beginning to recover when the earthquake occurs. This type of anomaly has been referred to as ‘Rebound anomaly’ (Igarashi et al., 1992) and is believed to be related to an increase of porosity and permeability due to fracturing, with the subsequent recovery attributable either to influx of fluid or to compression (Roeloffs, 1988). Another type of precursory water level drop was observed 28 days prior to co-seismic steps, which recovered within 3 to 6 days. This type of water level
drops could be due to aseismic creep along a fault plane where the earthquake stress is building up. The co-seismic water level drop recorded at seven wells due to the M 5.2 earthquake on September 5, 2000, was not preceded by any persistent precursory decrease in water levels. Except at MOR well, where the change due to the earthquake was a co-seismic step decrease, at other wells it was either more transient or gradual. However, water level drops of 3 to 6 days duration occurred 8 to 29 days before this earthquake at three wells. We might interpret this type of water level drops and recovery to be due to small slips on the hanging wall of a normal fault prior to occurrence of the main earthquake.

Some anomalous water level fluctuations were observed which were not associated with local or teleseismic earthquakes. In two cases water level fluctuations were also found to be associated with passing seismic waves due to the M 7.9 and M 9.3 earthquakes at distances of more than 800 and 2000 km. All these observations indicate that the wells in the network respond to local/regional strain changes caused by the redistribution of stresses in the shallow brittle crust to different forcing functions. Based on our present study, we define three types of well level fluctuations associated with local earthquakes in the Koyna–Warna region (Fig. 8). In the first type, a gradual drop in the water level fluctuation, the duration of which may vary due to local factors, precedes a co-seismic step rise. This type is observed for April 25, 1997, February 11, 1998 and March 12, 2000 earthquakes. The second and third types of co-seismic fluctuations are represented by drops in water levels, which are observed for the September 5, 2000 earthquake. For April 6, 2000 earthquake no clear pattern is observed.

6. Conclusions

Nine years of systematic studies under an Indo-German collaborative research program on in-situ pore pressure monitoring provided useful data set to look for hydrological anomalies in the seismically active Koyna–Warna region in western India. So far, we have analyzed data of 20 wells for the period 1997–2004 and found 5 cases where pre- and co-seismic water level fluctuations occurred due to local earthquakes in the magnitude range of $4.3 \leq M \leq 5.2$. The wells in the network also appear to respond to regional strain variations and transient changes due to distant earthquakes. For the local events the magnitude of the earthquake and the epicentral distance to the wells appear to be the most influential parameters for recording hydrological anomalies in well water level fluctuations in addition to several local factors. In our study we found from the limited number of events that while local earthquakes exceeding $M \geq 4.3$ can produce co-seismic changes up to distances of about 24 km, no such changes were observed below this magnitude threshold (which is clearly evident from the earthquake of M 4.2 on February 14, 1998).

The study has also shown encouraging results to look for earthquake precursors in well water level changes in the Koyna–Warna region. In view of the ongoing seismicity with frequent moderate earthquakes occurring in a much localized area of $15 \times 30$ km$^2$, we feel that continued monitoring of wells for a long duration of time would provide a unique data set that will allow us to test several hypotheses and could lead to the development of earthquake prediction models.

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