An earthquake of $M \sim 5$ may occur at Koyna

Koyna, located near the west coast of India is known to be the most significant site of earthquakes triggered by artificial reservoirs[1]. Over the past 44 years, since the impounding of the Shivajisagar Lake created by the Koyna dam, the largest triggered earthquake of M 6.3 (10 December 1967) and 19 earthquakes of M 5 or larger have occurred. The number of $M \sim 4$ earthquakes is about 170, and there are several thousand smaller ones. The last $M \sim 5$ earthquake occurred on 14 March 2005, after a lapse of more than four and a half years[2].

In a series of articles[1,3,4], it has been shown that the maximum credible earthquake for the region is M 6.8; that about one half of the energy of an M 6.8 earthquake has already been released; that there is not a large enough fault segment left intact to cause an $M \sim 6$ earthquake; however smaller earthquakes will continue to occur. It has also been proposed that the occurrence of $M \sim 5$ earthquakes will be governed by Kaiser effect (Kaiser[5] reported that acoustic emission, under monotonically increasing stress, shows an appreciable increase after the applied stress exceeds the previously applied maximum stress. In our case, it implies reservoir water level exceeding previous maximum[3]), rate of loading, and duration of retention of high water levels[3]. It has also been stated that due to suitable circumstances, short-term earthquake forecast may be feasible at Koyna[4]. We have reasons to believe, based on the study of several factors, that an $M \sim 5$ earthquake may occur in the Koyna region over the next few weeks. Should it not occur till the end of December 2005, this forecast should be considered as a false alarm. We are also trying to identify precursory nucleation at Koyna[6].

The $M \sim 5$ earthquakes in the Koyna region can broadly be classified into two categories. Most of these events (16 out of 19) occurred following the start of loading of the reservoir. However, three such events occurred following the start of unloading of the reservoir[7]. The last $M \sim 5$ earthquake on 14 March 2005 also occurred in the south Koyna fault with the epicentre at (17.16°N, 73.76°E), which followed the unloading of the reservoir. Earthquakes of $M \sim 5$ associated with the loading have all occurred during September through December.

As of now (25 August 2005), we have a situation that a peak water level of 657.784 m at Koyna was reached on 17 August 2005. This is after several years that such high water level is attained as early as 17 August. It has been found that the rate of loading of the reservoir is an important factor in triggering the earthquakes. This year, the water level rose from 627.685 to 657.784 m in just 55 days (Figure 1). This is the fastest loading seen so far at the Koyna dam. Another important factor is the Kaiser effect. All $M \sim 5$ earthquakes have occurred when the previous water-level maximum had been exceeded at the Koyna reservoir. The only exception being the M 5.2 earthquake of 8 December 1993. However, during 1993, high water levels were retained for the longest duration (see table 2, ref. 3). Moreover, the Warna dam in the near vicinity had started being filled and for the first time the full pond level of above 620 m (621.8 m on 4 August 1993) was reached. Since then, the seismic activity in Koyna region is influenced by both the reservoirs. This year, the highest level of 657.784 m reached on 17 August 2005 at Koyna, has not exceeded the previous maximum of 658.3 m reached on 7 September 2002. Let us now examine the situation at the Warna reservoir. The loading of the Warna reservoir this year has been quite rapid. From a level of 594.06 m on the 23 June 2005, it has risen to 626.9 m on 15 August 2005. This has been the fastest loading when the water level rose by 32.84 m in just 53 days, compared to past several years. More significantly, for the first time, on 15 August 2005 water level at Warna has exceeded

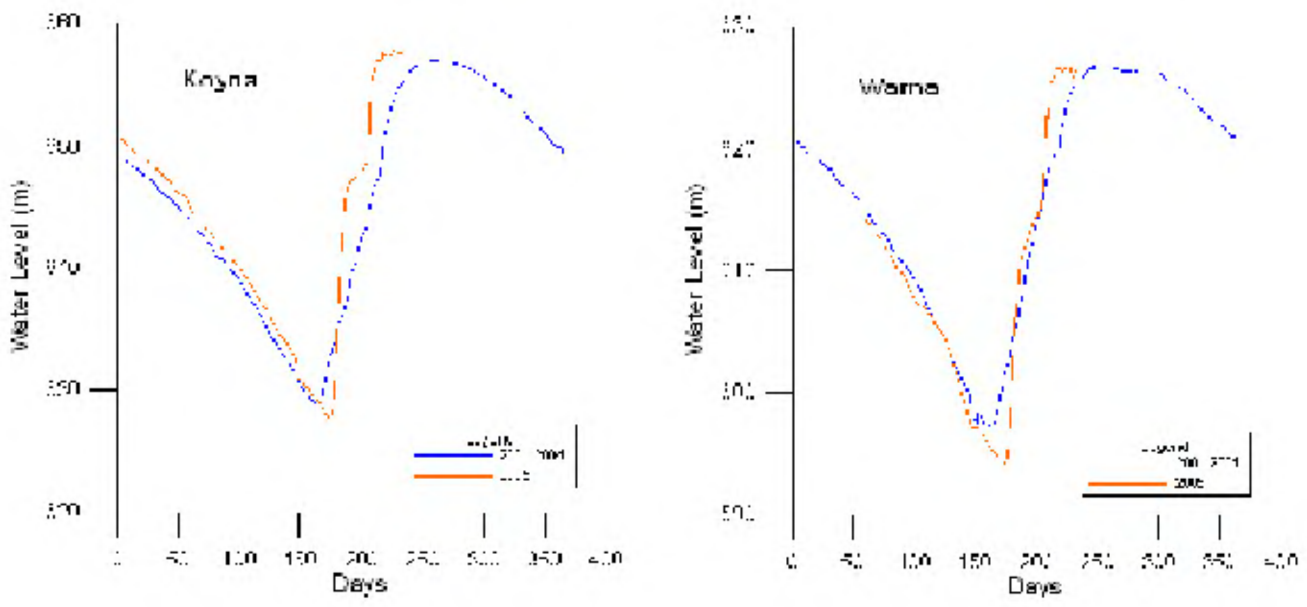

Figure 1. Reservoir water levels for 2005 (red) and averaged for four years (2001–04, blue) at Koyna and Warna. Relatively rapid loading during 2005 can be prominently seen.

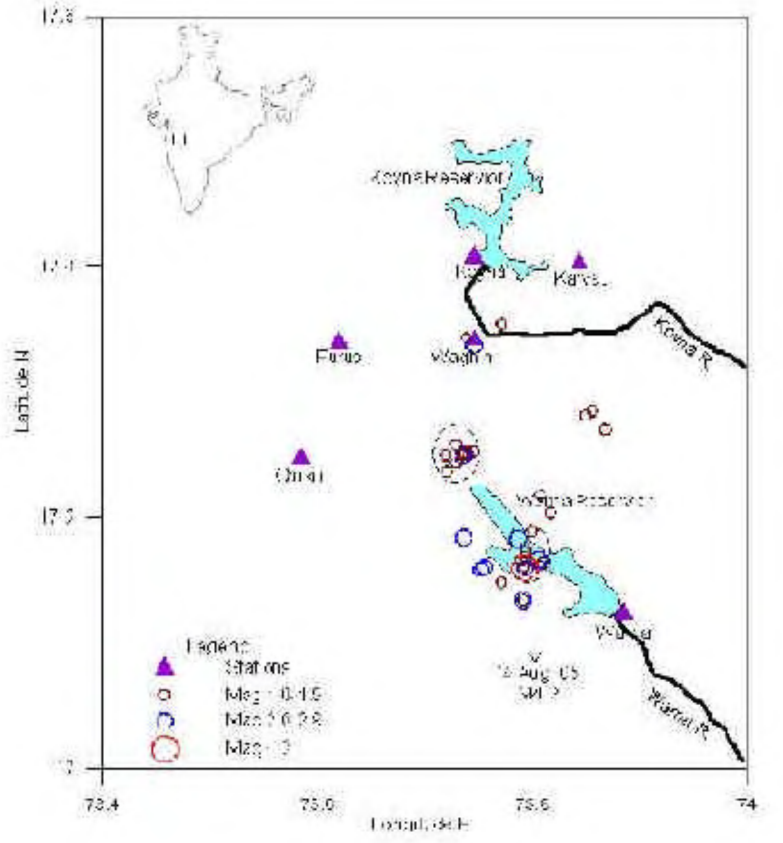

Figure 2. Seismicity of the Koyna–Warna region recorded during 9–23 August 2005 using six seismograph stations (dark triangles). Two dotted elliptical areas indicate swarms observed.

the previous maximum of 627.88 m recorded on 13 September 2003, thus satisfying the conditions for the Kaiser effect to be operative.

Figure 2 shows the current seismic activity in the vicinity of the Koyna–Warna reservoir area for the period 1 August 2005 through 23 August 2005. Only earthquakes of $M > 1.5$ are plotted. There is enhanced seismic activity. Over 30 earthquakes have been located. An earthquake of M 4.2 occurred on 14 August 2005. Two clusters can also be identified in Figure 2. In the past nucleation was found to precede earthquakes of $M \sim 4$ to 5 (refs 3, 4, 6, 8–10). We are closely monitoring seismic activity in the Koyna–Warna region, to be able to identify nucleation in real time. Our experience is that the nucleation precedes some 50 to 100 h before an $M \sim 4$ to 5 earthquake. If we succeed in identifying this nucleation when it is half-way through, we shall be able to make a short term forecast, one to two days before the event.

Thus in the Koyna–Warna region, occurrence of triggered earthquakes is influenced by several mechanical factors such as rate of water-loading, highest water-levels reached and duration of retention of the high levels, and $M \sim 5$ earthquakes occur when the previous water level maximum is exceeded. This year, loading has been the fastest ever recorded following extensive rains in the catchment area during July 2005; the water levels at the Warna reservoir have exceeded the previous maximum and there is an enhanced seismic activity. This indicates a high probability of the occurrence of an $M \sim 5$ earthquake in the weeks to follow. Typically, all $M \sim 5$ earthquakes triggered by the loading of the reservoir in this region have occurred during September through December. Should no $M \sim 5$ earthquake occur till the end of December 2005, this forecast should be considered as false alarm. If we succeed in identifying the nucleation, we may be in a position to give a short-term forecast.

Note added in the proof: Gupta and Iyer[11], from a detailed investigation of earthquakes in Koyna region, noted 'There appears to be a 50% probability of occurrence of a magnitude ≥ 5.0 earthquake, if two earthquakes of magnitude ≥ 4 are closely spaced in time (within 15 days) in the Koyna region'. In our note submitted to *Current Science* on 25 August 2005, we have inferred that an earthquake of $M \geq 5$ may occur before the end of December 2005. On 30 August 2005, an earthquake of M 4.1 occurred in the Koyna region. We had another earthquake of M 4.2 on 14 August 2005. So we have two earthquakes of $M \geq 4$ within 16 days. This implies an enhanced probability of an earthquake of $M \geq 5$ to occur at Koyna.

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ACKNOWLEDGEMENTS. We are grateful to the Maharashtra Engineering Research Institute, Nasik for providing water-level data. Seismological fieldwork was carried out under a project sponsored by the Department of Science and Technology, New Delhi. Comments by Dr Kusala Rajendran and Prof. Pradeep Talwani are appreciated.

Received 25 August 2005; revised accepted 1 September 2005

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