- Awareness among all stakeholders: Lack of awareness in the general public about the seismic vulnerability of the area has led to the haphazard planning of towns and construction on sites prone to landslides and sinking (ground settlement). All stakeholders, including builders, contractors, engineers, private owners, government officials and the public at large must be educated about the importance of geological setting, geotechnical issues and earthquake-resistant construction and their role in mitigating the future seismic risk.

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Recent microtremors near the Idukki Reservoir, Kerala, South India

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The continuing low-level seismicity in the vicinity of the Idukki Reservoir, Kerala, is interesting from the perspective of hydrologically triggered earthquakes. While the frequency of triggered earthquakes in the vicinity of a reservoir usually reduces with time and the largest earthquake usually occurs within a few years on the initial filling, the triggered seismicity in the proximity of the Idukki Reservoir seems to be showing a second, delayed peak, as the 1977 (*M* 3.5) tremor was followed by a slightly larger event in 2011, 24 years after the first burst of activity. Quite unprecedented in the context of reservoir-triggered sequences, we consider this delayed sequence as the hydrologic response of a critically stressed hypocentral region, to monsoonal recharging. The sustained activity several decades after the impoundment and the temporal relation with the monsoon suggest that at least some parts of the reservoir region continue to retain the potential for low-level seismic activity in response to hydrologic cycles.

Keywords: Hydrologic cycles, microtremors, reservoir, triggered earthquakes.

THE Idukki Dam built on the Periyar River in Kerala is one of the highest arch dams in Asia (169 m), which has started generating power since 4 October 1975. With a seismological network in operation since 1971, the Idukki Reservoir is among the few in India that has a pre-impoundment record of the background seismicity. This is particularly important as the reservoir is located in a region of generally low-level seismicity with no regional network to monitor the local seismicity. After the network was established, a large number of mild shocks were recorded, but only a few of these were locally felt and no large earthquakes followed the initial impoundment. The largest event in the vicinity of the reservoir occurred in 1977 (*M* 3.5; ref. 1). Based on the proximity of the microtremor locations to the reservoir, and the temporal correlation with the seasonal filling, the microseismic activity at Idukki was considered as reservoir-triggered[2]. Rastogi *et al.*[3] provide an overview of earthquake frequency subsequent to filling of the reservoir (1974–87), and the data suggest that most earthquakes are located in and around the Idukki Reservoir. Thus, the

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Idukki Reservoir is now listed as one of the known global examples of reservoir-triggered seismicity, and it belongs to the category of 53 reservoirs[4] where the maximum magnitude of the triggered event is < 4.0.

Although no significant earthquakes occurred in the immediate vicinity of the reservoir, four earthquakes in the magnitude range 4.3–5.0 occurred in Kerala during 1988–2001 (Figure 1 *a*). With the exception of the 1994. Wadakkancheri earthquake, all the other earthquake occurred in the region bound by 9.6–9.8°N lat. and 76.8–77.2°E long. (Figure 1). The 1994 earthquake occurred within the confines of the E–W-oriented Palghat Gap, a major physiographic break in South India[5]. All the other earthquakes are considered as the result of reactivation of NW-oriented faults, of which the Periyar River lineation is the most significant (Figure 1 *b*), and is considered as the source of the *M* 4.5, 1988 earthquake[6]. Later studies have suggested that the NNW-oriented faults in Kerala may host potentially active earthquake sources capable of generating moderate-sized earthquakes[7]. It is intriguing that despite the filling of the reservoir and the existence of a few NW-oriented faults/lineaments in its immediate vicinity, the maximum magnitude of the triggered earthquake is not more than 4.0. Global case-histories suggest that in most cases of reservoir-triggered earthquakes, the larger events occur within a few years of filling, mostly within five years (see Gupta[4]).

Although three earthquakes in the magnitude range 4.5–5.0 occurred in the area, the frequency and size of tremors in the immediate vicinity of the Idukki Reservoir had declined after its initial burst of activity in 1977. This is not surprising and is in conjunction with the general observations in most known cases of reservoir-triggered seismicity. However, there was an increase in the frequency of earthquakes during 2011, and this sequence included one earthquake of *M* 3.9. The renewed activity near this reservoir has raised questions about the sensitivity of the area and the most important question is why the reservoir continues to generate earthquakes, and whether the low-level activity observed in the recent periods are forerunners of a larger earthquake. The proximity of the Idukki Dam to the 116-year-old Mullaperiyar Dam (see Figure 1 *b* for location) upstream of the Periyar River makes these questions more compelling. Clearly, the answers can only be based on the existing data and knowledge gained from experiences in similar geological situations elsewhere. Our studies of the seismicity of Kerala have suggested that the central mid-land region is more prone to low–moderate earthquakes[7]. Further, we had proposed that many of the mircoearthquakes observed in different parts of Kerala occur in response to increased rainfall, following the hydroseismicity model[8]. In this communication, we examine the recent microseismicity observed near the Idukki Reservoir from the context of reservoir-triggered and hydroseismicity models, and suggest that the recent spurt of activity in the vicinity of the reservoir is the hydrologic response of a critically stressed region in the vicinity of the reservoir.

Although the Idukki Reservoir had been in existence since 1975, concerns about its seismogenic status were perhaps revived when an earthquake of magnitude 4.5 occurred near Nedumkandam, about 20 km to its east (see Figure 2 for location). The 1988 earthquake sequence shared no characteristics of the reservoir-triggered earthquakes and based on the absence of foreshocks, low *b*-value of aftershocks, and its time of occurrence when the reservoir level was at its lowest, Rastogi *et al.*[3] treated this event as part of the peninsular shield seismicity. In an earlier study, Singh *et al.*[6] had reached the same conclusion and attributed the earthquake to failure on the WNW–ESE-oriented Periyar lineation (see Figure 1 *b*). The next significant activity in the area occurred as two low–moderate doublets ($M \sim 5$) during December 2000 and January 2001, sourced near Palai, about 25 km southwest of the Idukki Reservoir. The *M* 5.0, 12 December earthquake, the largest to have occurred in Kerala in the documented history, was followed by a series of aftershocks, including one of *M* 3.9. The *M* 4.8 earthquake occurred on 7 January 2001, which was also followed by a series of aftershocks, including one event of *M* 2.7 (see Figure 1 *b* for locations).

The source parameters of the 2001 earthquakes suggested reactivation of a NW–SE-oriented structure[9,10]. Based on the appreciable difference between the instrumental and field evidence of the source, which included felt reports, damage to structures, secondary rupture (~15 m long, with a maximum horizontal offset of 17 cm) and significant changes (increase by ~1 min water level in some open wells), Rajendran *et al.*[7] suggested that the two sources are independent and separated by 15 km. These authors considered that both the sources are to be related to NW–SE structures, parallel to the west coast and defined also by a series of dykes, possibly the southern outliers of the Deccan Trap volcanism. Their review of the historical and recent seismicity of the region further suggested that the NNW–SSE trending faults in central Kerala might host potentially active sources that may generate low–moderate earthquakes.

Excluding the 1988, 2000 and 2001 earthquakes, which were 25–40 km away from the Idukki Reservoir and were attributed to reactivation of pre-existing WNW–ESE to NW–SE trending faults, the Idukki Reservoir area experienced only very low-level microseismic activity. According to the records of the Kerala State Electricity Board (KSEB), which monitors the local seismicity around the reservoir, no tremors of $M > 3$ were recorded in the area after the 1977 tremor of *M* 3.5 (see also Rastogi *et al.*[3]). The broadband observatory at Peechi, located 120 km away from Idukki and operational since 1999, also maintains a record of local and regional events. This observatory has also not reported any tremors of $M > 3$ originating from the Idukki area since its operation in September

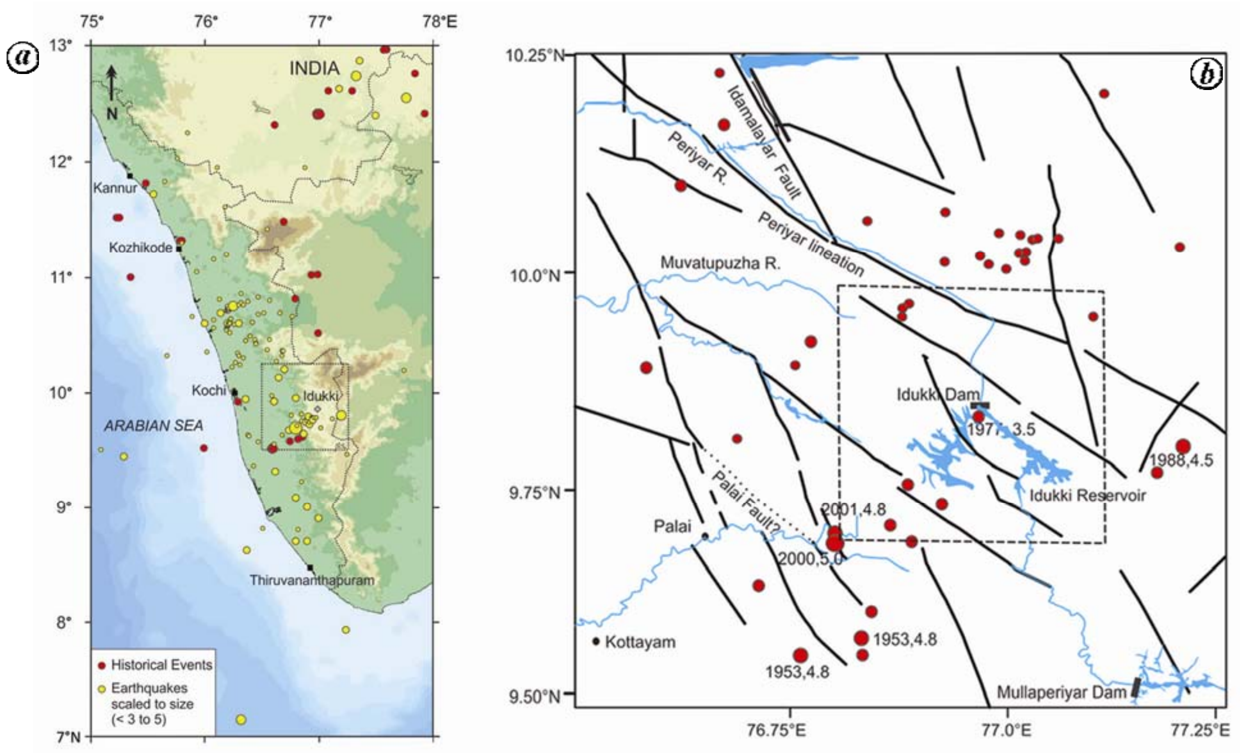

Figure 1. ***a***, Historical and recent seismicity in Kerala and its neighbourhood (updated from Rajendran *et al.*[7]). Red dots: Historical earthquakes (magnitude uncertain, mostly < 4.5). Yellow dots: Earthquakes from 1980 to August 2011. Dots are scaled to size. Rectangle identifies the area shown in ***b***. ***b***, Area around the Idukki Reservoir showing faults and lineations (modified from Rajendran *et al.*[7]). Significant historic earthquakes and the recent earthquakes of $M \geq 4.5$ are identified. The M_L 3.5 (1977) earthquake that occurred very close to the Idukki Dam is the largest previously reported earthquake[1]. Idukki and Mullaperiyar reservoirs are also shown. Earthquakes until 2011 are plotted. Rectangle identifies area shown in Figure 2.

1999, until the 2011 spurt of activity (see also Rajendran *et al.*[7]). Thus the vicinity of the Idukki Reservoir was going through a long period of low-level activity, and it was presumed as an indication that the region had attained a hydrologic equilibrium. Starting July 2011 microtremors were felt in the area and the sequence included at least three earthquakes of magnitude $M_L \geq 3.0$. Twenty tremors were recorded until November 2011 by the KSEB network as a part of this sequence; three of these were of $M_L \geq 3.0$ and the maximum magnitude was M_L 3.8, which occurred on 26 July 2011 (Figure 2 *a*). The broadband seismic station at Peechi also recorded these tremors, but their magnitude estimate is slightly different in that there are four earthquakes of $M_L \geq 3.0$ (Figure 2 *b*). The largest event was assigned magnitudes 3.8 and 3.9 respectively, by these sources of data (Figure 2). These minor differences between the magnitude estimates (M_L), by the Peechi and KSEB stations could be due to the variations in the computational algorithms used.

We believe that the epicentral locations provided by KSEB are likely to be more precise as they are based on data from local stations, whereas the Peechi station locations are based on the single-station method using the SEISAN software. The epicentre of this tremor, which occurred on 26 July 2011 is close to a NW-oriented fault, located southwest of the Idukki Reservoir, and both the seismic stations at Peechi (KFRI Campus) and KSEB sources place it at the same point.

Discrepancies in location accuracy notwithstanding, the general epicentral area identified using both these data is close to the western limb of the reservoir. Focal depth estimates of these earthquakes are generally not precise due to inadequate station coverage and poorly constrained velocity models. Further, the stations of the Idukki network belong to the earlier generation analog type, and compared to the digital broadband station which uses a GPS clock for timekeeping, synchronized timekeeping of the analog network can be less precise, giving rise to location and hypocentral depth inaccuracies. We consider that the activity is restricted to the shallow crust (usually less than 10 km), as is commonly observed in southern India, and also noted previously based on local networks installed for aftershock monitoring[3,9].

Previous studies have noted spatial and temporal correlation of microseismicity at Idukki with the reservoir activities and the tremors were generally located in and around the reservoir[3]. The recent activity is also close to the reservoir and in regions that have generated low-level activity in the past. We have examined the reservoir level, rate of filling and rainfall data (from Idukki) from

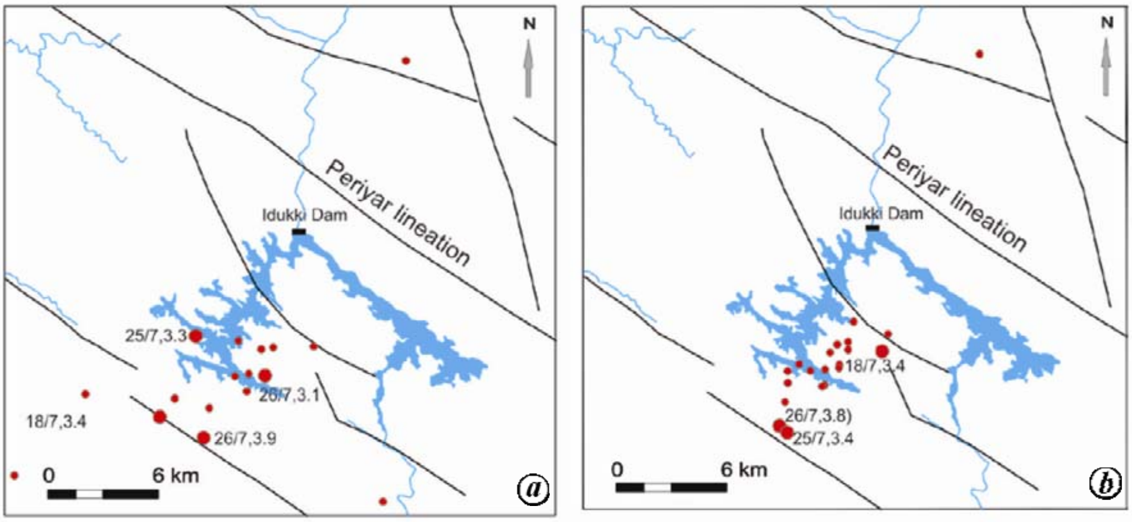

Figure 2. ***a***, Epicentral locations of earthquakes located by the Kerala State Electricity Board network during January–November 2011. ***b***, Epicentral locations of earthquakes located by the Peechi station during the same period. Earthquakes of magnitude > 3.0 are identified.

this region for the last five years starting with 2007 (Figure 3). It should be noted that there was no significant change in any of these parameters during these five years, and there was nothing unusual about the rate of reservoir filling or rainfall intensity. However, there was an increase in the level of seismicity during 2011, which followed the monsoon when the weekly rate of refilling increased to about 3–4 ft/week (Figure 3 *e*). The frequency of earthquakes has reduced since August 2011.

Here we explore the causal relation between the increased rainfall and the onset of localized low-level activity. Earthquakes induced by increased pore-fluid pressure in the proximity of reservoirs or other regions vulnerable to hydrologic changes fall in the general category of 'hydroseismicity'[11]. In fact, the 'hydroseismicity model' introduced by Costain *et al.*[12] is an extension of the concept of reservoir-induced seismicity, wherein the hydrologic cycle plays an important role in the generation of intraplate earthquakes, and the sources are not necessarily in the proximity of the reservoirs. The hydroseismicity model was later broadened to include artificial as well as natural changes in crustal pore-fluid pressure that may trigger earthquakes[13]. Hydrologic changes occur through various processes–reservoir loading and unloading, fluid injection and withdrawal from aquifers (oil reservoirs), and pressure changes induced by earthquake occurrence. Under these special circumstances, seasonality of earthquakes has been interpreted as a consequence of downward propagation of pore-fluid pressure, thereby changing the failure conditions.

These observations essentially support the idea that a change in the hydraulic head over the Earth's surface, when transmitted to the hypocentral depths can trigger small or moderate earthquakes, where the conditions for failure are favourable. Implicit in this statement is that every region is not prone to hydroseismicity and the hydrogeological conditions have to be favourable for failure. But the hydrogeological parameters themselves do not constitute the sufficient conditions for the earthquakes to be triggered either by man-made reservoirs or through the natural changes in hydrologic cycle.

The recent spurt of post-monsoonal activity near the Idukki Reservoir suggests that critically stressed regions in the vicinity of the reservoir may generate low-level seismicity following monsoonal filling of the reservoir and the recharge of the area in general. However, this change alone does not constitute a sufficient condition for triggering seismicity, because many such periods have been devoid of any notable activity. It appears that the hydrologic pathways and their interactions with the critically loaded faults in the vicinity play a critical role in triggering earthquakes. It is also important to note that the reservoir region remains sensitive to hydrologic changes and any increase in the rate of loading should consider this sensitivity exhibited by the region. This observation is key to deciding the filling capacity of this dam as well as construction of future large reservoirs in the area. Following the observation that the NW-oriented faults are likely to trigger earthquakes in this region, it may be noted that faults following similar trend in the immediate vicinity of the Idukki Reservoir had not been particularly active in the past. Thus, all the faults in the vicinity of a reservoir may not be activated and the presence of faults alone does not provide a sufficient condition to trigger earthquakes in a reservoir environment. It may be noted that most of the tremors in the past have occurred in the periphery of the reservoir[3]. The recent activity is located close to the western limb of the

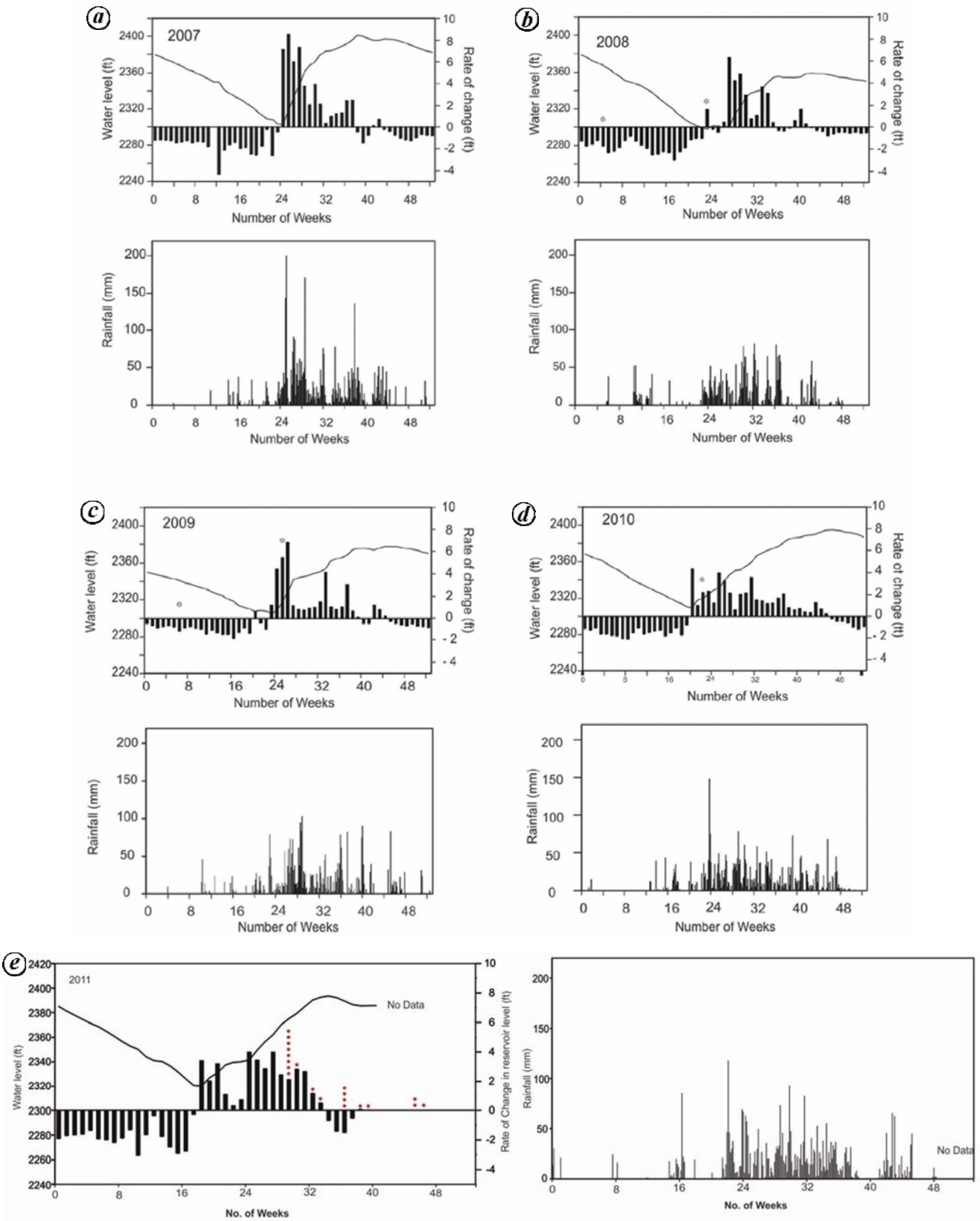

Figure 3. ***a*** (Top panel) Average lake level in the Idukki Reservoir (scale on the left), weekly change in lake level (scale on the right), and earthquakes (dots) in the area based on records from the Peechi Observatory during 2007. (Bottom panel) Daily rainfall (mm) recorded at Idukki. ***b–d***, same as in (***a***), but for the year 2008 (***b***), 2009 (***c***) and 2010 (***d***) respectively. ***e***, Same as (***a***) but for the period January–October 2011; data used are from Kerala State Electricity Board. Twenty tremors were recorded after July 2011, shown as filled grey circles, representing the time of their occurrence.

reservoir, a region that has experienced low-level activity in the past.

We conclude that the recent activity in the vicinity of the Idukki Reservoir is unusual, considering the long gap since the initial filling and the onset of activity. However, the activity occurred in regions in the vicinity of the reservoir, which have been previously activated. The current spurt of earthquakes could be related to the changes in the hydrologic equilibrium, caused by the monsoonal recharge of the region. It may be recalled that all such periods of increased rainfall may not necessarily lead to increase in micro-seismicity. Earthquakes occur where the faults are critically close to failure, and the small change in pore water pressure conditions induced by the combined effect of the reservoir and the monsoonal recharge of the area provides the trigger for failure. The hydrologic conditions of the Idukki Reservoir appear to be conducive to sustain some low-level seismic activity and there is a need to strengthen the seismic monitoring in this region. This would enable us to know the precise location of active zones, migration of seismic activity and also understand the temporal and spatial correlation with the reservoir filling and seasonal recharge. As one of the oldest reservoirs that continues to generate low-level seismic activity, the seismicity associated with the Idukki Reservoir is worth monitoring also from the point of understanding the long-term behaviour of seismogenic reservoirs.

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Social relationships among lion-tailed macaque (*Macaca silenus*) males in differently structured social units

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There is a need to study male–male relationships since models on the evolution of social relationships among primates have mainly focused on females. In this study aspects of the social relationships among lion-tailed macaque males in differently structured social units have been studied. The units include three heterosexual groups with (i) one adult, one subadult, and eight juvenile males; (ii) two adult males, one of which was castrated and (iii) two adult males and a subadult male compared under two different conditions, viz. in a small indoor and a much larger outdoor enclosure. The studies used focal animal sampling and covered minimally three months each. In the first study, over 40% agonistic interactions occurred between adult and subadult males. The interactions with juvenile males were largely of affiliative nature. The castrated male received lower aggression than the normal subadult male. The males showed more aggressive behaviour in the outdoor than in the indoor enclosure. In the latter condition, however, the males showed more disturbed behaviour. Observations from field studies, earlier attempts at establishing captive all-male groups, and the present study point to a high degree of social intolerance among adult lion-tailed macaque males. Therefore, the establishment of all-male groups in the zoos does not appear to be possible.

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