J. Ind. Geophys. Union (January 2015)
v.19, no.1, pp:55-61

Deciphering the seismicity pattern from MEQ study atIndira Sagar reservoir area, Madhya Pradesh, India.

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ABSTRACT

Indira sagar reservoir, one of the largest reservoirs ofthe country located in seismically active Central India Tectonic Zone (CITZ), witnessed significant seismic activity sincerecent past. Seismicity monitoring began in 1995 to study the local seismicity in and around the reservoir site, and it is being continued till today. Impoundment started in 2003 and seismicity of the region has been studied for the period of 1995-2009 with the help of microearthquake data by ten seismic observatories.The results of seismological investigations have facilitated in assessing seismic potential of the area and its possible impact on the dam. In addition, role of crustal scale seismotectonic features in triggering the seismicity is assessed with the help of magnetotelluric (MT) study. MT study delineated the major geological formations and fault features, which are responsible for seismic activity in the proximity of the reservoir. A total of 16 seismic events have been identified within the 50 km radius from the dam site with hypocentral depths of <15 km during study period of 1995-2009. Seismicity was found to be decreasing after water impoundment in the reservoir, contrary to reservoir triggered seismicity. Reduction in seismic activity indicates that seismicity may not be associated with reservoir dynamics.It is interpreted that seismicity of the regioncould be associated withlocal adjustments in the crustal blocks along a series of parallel gravity faults towards north and south of the Narmada Riverand other existing seismogenicfaults near the dam site. Seismicity,as a whole,is inferred as due to regionaltectonic forceswithin the Central India Tectonic Zone (CITZ) and reservoir has little impact.

INTRODUCTION

The peninsular shield of India was considered to be seismically stable intra-plate region, far away from the Himalayan plate boundary (Khan, 2009). However, several isolated areas of the Peninsula are known to have experienced low to moderate level of seismicity in the recent past and the Central India Tectonic Zone (CITZ)is one of them. One of the largest earthquakes in the study area was the Satpura earthquake of 14th March 1938, with magnitude (M_s) 6.3, which occurred near Khandwa within the CITZ. The CITZ is a conspicuous feature in India and at present is under the compressional forces of the Himalayan orogeny (Kaila, 1986).It is a zone of fractures belonging to early Precambrian, Cretaceous and post Deccan trap period (Kaila et al., 1989). This zone is dissected by several E-W/ENE–WSW trending faults. The Son Narmada South fault (NSF) is one of them and is considered to be seismically active (Fig.1).Indira Sagar reservoir is one of the major reservoirs ofIndia located approximately at latitude 22° 17′ N and longitude 76° 28′ E, andlying at a distance of~40 km from the Son-Narmada south fault in the CITZ. It waspostulated that impoundment of water in the reservoir can trigger the micro to moderate level seismicity (Simpson, 1986; Simpson et al., 1988). Since geological faults and formations play a major role in triggering the seismic activity, it is necessary to delineate the crustal architecture and monitor the seismicity in the proximity of the reservoir and its surroundings. Taking the known surface geological and seismotectonicfeaturesinto consideration, a network of 10 seismological stations has been established in and around the reservoir area to assess the seismic potential.

In addition, a magnetotelluric study carried out in the past has been used to delineate the crustal architecture across the reservoir site. The recorded seismic events and delineated crustal scale geological and tectonic features are used in the present study to infer the seismic potential of the area, stability of the reservoirand also to understandthe role of reservoir in generating recorded seismic events.

Magnetotelluric (MT) studies

Magnetotelluric (MT) study is a passive electromagnetic geophysical technique, which can be used to delineate the subsurface electrical resistivity structure(Tikhnov, 1950; Cagniard, 1953).The source signals (natural electromagnetic waves) are generated through interaction of Solar wind-magnetosphere and worldwide thunderstorm activity in the period range of 10^{-5} to 10^{5}s (*Kaufman, 1981; Vozoff, 1991; Campbell, 2003)*. The signals are sensitive to both vertical resistivity changes as well as lateral variation of resistivity, and so help to map the lateral heterogeneities along a profile. The data, natural variation of electric and magnetic field signals, are recorded using electric field sensors – usually non-polarized electrodes- and magnetic field sensors – induction coil magnetometers.

Results of MT study along a profile(Naidu and

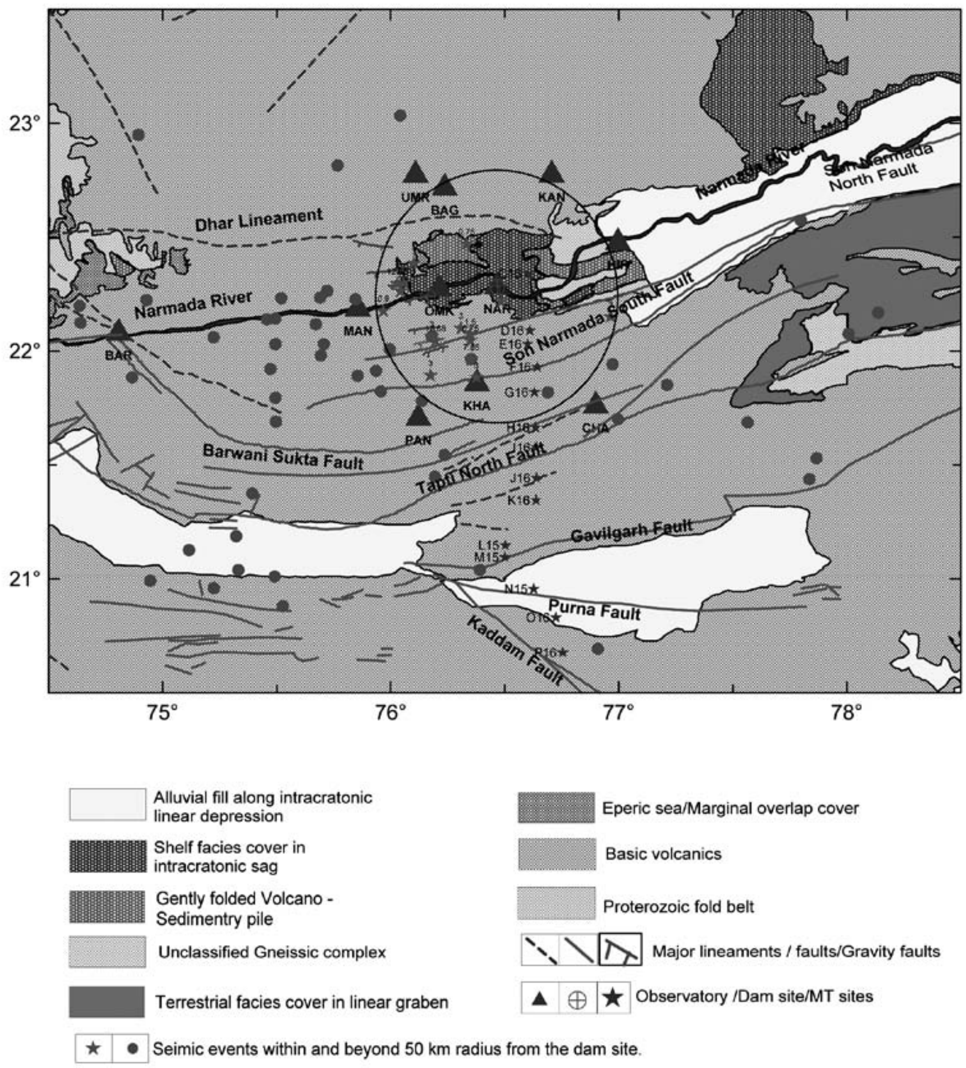

Figure 1. Detailed geological map of the study area, showing major seismotectonic and geological features along with the epicenters of recorded seismic events in the area of Indira Sagar reservoir site, Madhya Pradesh (GSI, 2000). Seismic events (stars in red color) within the radius of 50km from the dam site are shown in the black circle.

Harinarayana, 2009) have been used to elucidate the crustal architecture as it is cutting across the reservoir site and its adjoining fault features.A shallow depth section up to 7 km derived from the modeling study is shown in figure 2. We focus on mainlythe crustal structure towards northern part of the profile as it is passing through the reservoir site. The top most moderately resistive (~ 100 ohm-m) layer is delineated as volcanic rock (trap) with a thickness of about ~250m. This layer is underlain by high resistive (>500 ohm-m) basement structure towards northern part of the profile across the reservoir site.Basement structure is clearly demarcated in the section at varying depths. There is a sharp variation in the basement depth (basement fault) from ~250m to ~3 km between the stationsE16 andF16. This sharp variation in basement configuration indicates presence of Narmada South fault (NSF).This fault is lying at a distance of ~40km away from the reservoir site and divides the section into two parts.Towards north of this fault, a thin trap layer (~250 m) is delineated underlain by the basement whereas south of this fault, a basin like structure with subtrappean sediments underlain by the basement is delineated.

The sediments delineated in the model have very less resistivity contrast as compared to trap resistivity. Hence, these two layers couldn't be resolved clearly in the model. In order to draw the inferences, we have integrated the model with available seismic section (Kaila et al, 1985; Naidu and Harinarayana, 2009) at shallow depths and inferred these sediments as Gondwana sediments.

Several MT studies have been carried out in the CITZ region (Rao et al., 2004; Patro et al., 2005; Naganjaneyulu et al., 2010; Abdul Azeez et al., 2013). However, we

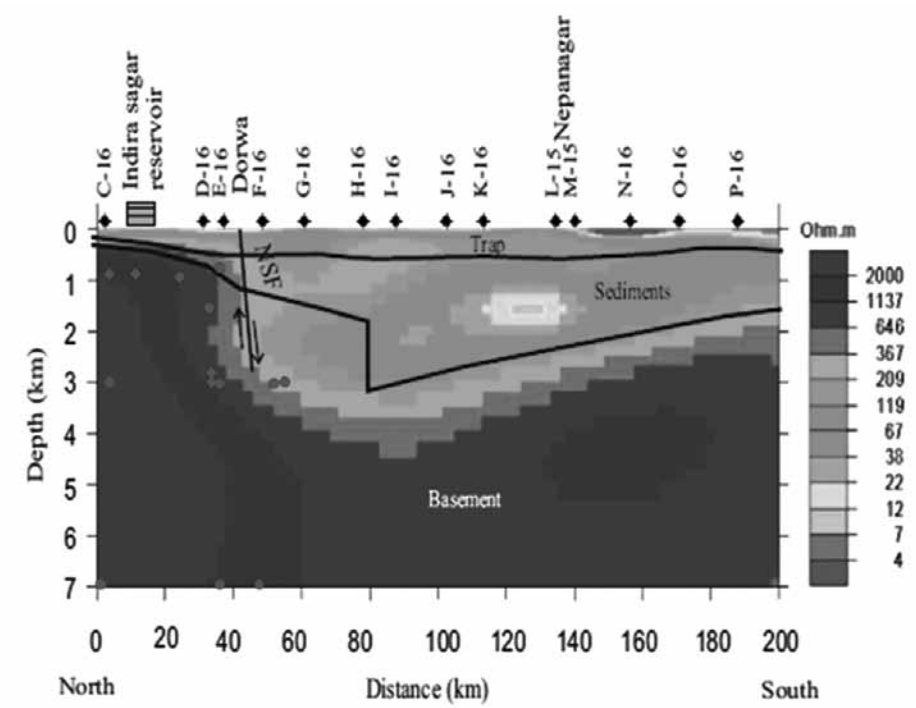

Figure 2. Depth section across the reservoir site delineated from the magneotelluric (MT) study (after modified from Naidu and Harinarayana, 2009). Solid lines indicate the boundaries oftrap and sediments given by Kaila et al, (1985). Approximate locations of the hypocentral depths within the 50km radiusfrom the dam site are shown in red circles.

have chosen the seismic section by Kaila et al., (1985) and shallow MT model by Rao et al., (2004), which are situated close to the present study area. Observations from integration of these studies indicate that north of the NSF is a thin trap layer followed by basement at a depth of about 250 m,whereas south of this fault is a thin trap layer followed by sediments and then basement at a depth of about 3km.The sudden change in the basement depth indicates the presence of fault i.e. NSF, which is the active fault situated close to the reservoir.

Since the reservoir site is not far away from the NSF and it is surrounded by some other minor faults and lineaments, seismological investigations were carried out in and around the reservoir site to evaluate the seismic potential of the area.

Seismological studies

A local network of ten seismological observatories (Fig.1) was deployed at Narmada Nagar, Omkareshwar (Kothi), Maheshwar, Khandwa, Barwani, Indore (Umrikheda), Hirapur, Bagli (Chapra), Channera and Pandhana equipped with analog micro-earthquake (MEQ) recorders. Monitoring was started in 1995 much before the impoundment and it is being continued till today. Impoundment started in Nov, 2003 and the local seismicity for pre and post impounding stages has been studied for the period of 1995-2009. A total of 1734 local events were recorded at individual stations of all ten observatories during the present period of study, out of which 578 events were recorded during 1995-2003 (pre-impounding) and 1156 during 2004-2009 (post-impounding) period.

However, it is observed that the level of seismicity during the period 1995-2001 was very low with 211 events (fig.3a). Subsequently, there was a continuous and considerable rise in the activity since 2002, much before impounding of the reservoir (fig.3b).This rise continued for the period of 2002-2005 (1094 events). However, the level of seismicity decreased to an extent and remained steady till 2009 with 429 events (fig.3c).

From the distribution of magnitude, it is seen that the magnitudes of the events recorded for the pre-impounding period ranged mostly between 1.5 and 3.5,whereas magnitudes of the events recorded for the post-impounding period ranged mostly between 2.0 and 5.0. During the reporting period of 1995 to 2009, fifteen events having local magnitudesbetween 5.0 and 6.0 have been recorded,independently by various observatories.

DISCUSSION

The spatial distribution of 78 located events,which aresimultaneously recordedby more than threeand up to five stations have been plotted in figure1. It shows that

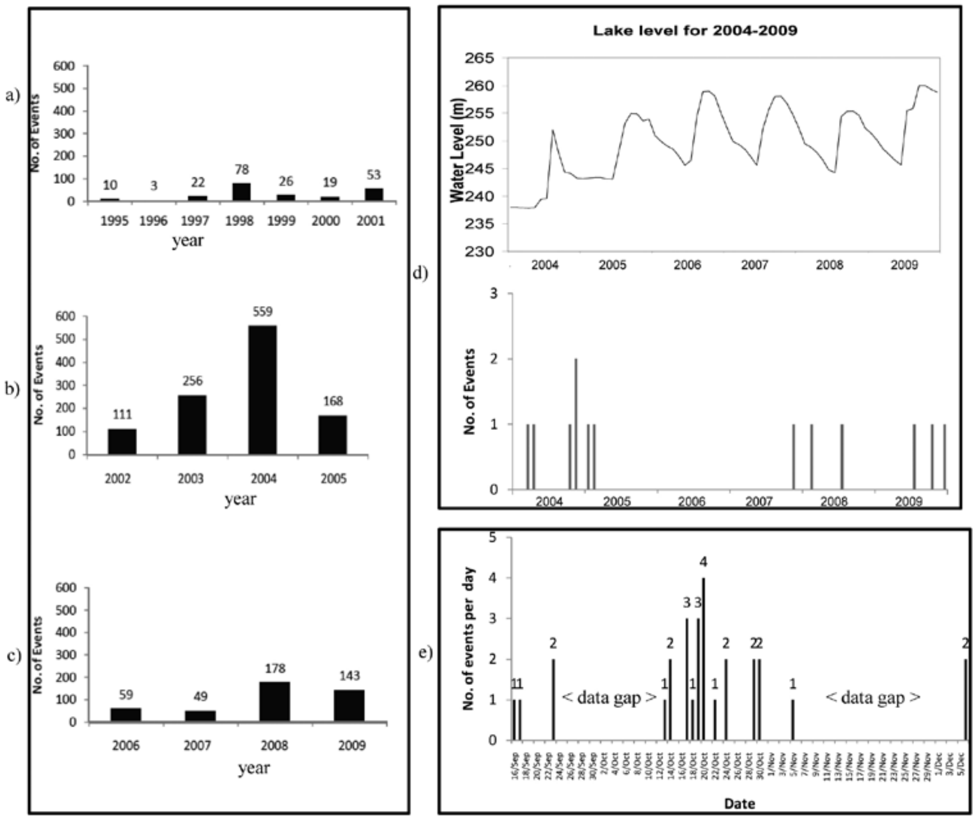

Figure 3. a) Seismic events for the period of 1995-2001. b) Seismic events for the period of 2002-05 c) Seismic events for the period of 2006-09. d) Seismic events with respect to lake level variations near Narmada Nagar stationwithin the radius of 50 km from the dam site. e) Earthquake swarm activity near pandhanarecorded by observatory at Khandwa for the period of Sep 1998 - Jan 1999.

allseismic events for the period of 1995-2009, are seen to be dispersed all over the CITZ. Seismic events as plotted in the seismotectonic map (fig.1) enable to decipher the distribution pattern of seismic events around the reservoir site. However, it is necessary to confirm whether it is reservoir triggered or due to natural phenomena. Some common characteristics of Reservoir Triggered Seismicity (RTS) have been identified based on several studies on global scale (Gupta, 2005; 1992; Gupta et al, 1997a; Hudson, 1991).One of the significant characteristics is pronounced correlation between frequency of occurrence of earthquakes and reservoir water levels.Cluster of seismic events are found tooccur, with increase in water levels,in the proximity of dam in the reservoir site (Talwani, 1997b). However,in the present case, epicentraldistribution of the recorded seismic events in the study area does not follow the above characteristics.A total of only16 seismic eventshave beenidentifiedwithin the radius of 50 km from the dam site with focal depths of <15 km during entire study period (1995-2009). Out of 16, a total of only five seismic events occurred in 2004,after water impoundment in 2003(fig.3d).The frequency and number of seismic events further reduced till 2009. In addition, the relationship between level of seismicity and the reservoir level changes shows no correlation.Water levels in the reservoir increased during 2004-2009. On contrary, seismicity has decreased (fig.3d). Thus, water level variations may not haveany role in generating the seismic events in the study region.

The NSF in central India region is believed to be thrust type of fault (Chandra, 1977; Gupta et al., 1997b; Kayal, 2000). In thrust fault environment, although reservoir load and minor principle stresses (σ_3) are vertically in downward direction, major principle stresses (σ_1) are more dominant in horizontal direction (Qiu, 2012). Hence, Reservoir load may not influence the major principle stresses σ_1 and possible occurrence of RTS activity due to elastic loadof the reservoir.

Another significant causative factor for RTS activity is pore pressure. The instantaneous increase in pore pressure in the substratum due to increase in impoundment load at the surface may cause RTS. This increase in pore pressure may decrease the normal stress that holds the fault and, thereby, induces slips along the pre-existing faults (Nur and Booker, 1972). In order to satisfy the pore pressure concept, underlying formation needs to be sedimentary with existing fault in the proximityof the reservoir. However, in the

Table-1:A list of 16 seismic events within the radius of 50 km from the dam site during the period of 1995-2009.

Sr No.	Latitude (°)	Longitude (°)	Hypocentral Depth (Km)
1	22.1505	76.9638	3
2	22.4705	76.3322	0.75
3	22.1762	75.9675	0.9
4	22.3003	76.0543	0.75
5	22.262	76.043	3
6	22.1002	76.3078	3
7	22.0455	76.196	12.86
8	22.3842	76.101	3
9	22.0463	76.3495	0.75
10	22.2952	76.0285	12.95
11	22.2162	76.4827	0.75
12	22.0642	76.18	3
13	21.9637	76.3528	7.85
14	22.0747	76.3483	1.5
15	21.8843	76.3748	3
16	21.8937	76.1737	3

present study, reservoir is located on igneous formation (basalts) in general, havingless porosity. This layer is underlined by the granitic basement, which also has low porosity.Thus, possible downward propagation of fluids towards the fault zone is negligible and cannot influence the pre-existing stresses along the fault. Hence, both reservoir load and pore pressuremay not be the probable causative factors for seismicity in the study area.

In addition, it is appropriate to compare the geological and tectonic setup of the study area with one of the most significant sites for Reservoir Triggered Earthquakes (RTS) situated in Koyna, India (Gupta, 2002). Although Koyna and Indira Sagar reservoirs are located on same type of rock (basalts), both the regions have some distinguishable characteristics.

Seismicity at Koyna was classified as delayed response, where pore pressure diffusion plays a significant role (Simpson et al, 1988). The major faults and deep fractures situated between Koyna and Warna reservoirs, extending to hypocentral depths allowed the fluids from the reservoir up to hypocentraldepths, causing the stress changes (Talwani, 1995; Talwani, 1997a; Gupta, 2005).

Whereas, near Indira sagar reservoir site, though some localized faults and lineaments are situated, they may not be connected to the Indira sagar reservoir to allow the fluids percolate into the upper crustal layersto cause the stress changes. In addition, the only fault (NSF), which is situated and extending to crustal depths close to the reservoir, is thrust type of fault (Chandra, 1977; Gupta et al., 1997b)where possibility of RTS is very less. On the other hand, Koyna reservoir is situated in strike slip fault environment where pore pressure diffusion plays a major role in triggering the seismic activity (Simpson et al, 1988).A total of 16 seismic events, within the radius of 50 km with focal depths of < 15 km are found to be located towards west of the MT profile, where a series of parallel gravity faults towards north and south of the Narmada River and other seismogenic faultsare present near the dam site. A list of seismic events within the radius of 50 km is shown in table-1.

A significant feature observed in the south-west of the reservoir site is the intermittent occurrence of swarm type of activity accompanied by blast like sound near Pandhana during 1998-1999. This phenomenon is typically related to magmatic activity in volcanic regions as well as intra continental regions like continental rifts (Ibs-von Seht et al., 2008). Micro earthquake activity of Swarm type is observed only at one observatory i.e Khandwa. Khandwa region is situated very close to Narmada south fault and it is a part of major continental rift zone – CITZ. Swarm activity is often not only confined to shallower depths (< 10km) but also to a smaller area. Shallow crustal heterogeneity and increase in pore pressure by fluid flow in to a fault system often causes the swarm activity (Kayal, 2008).In recent years, earthquake swarms also occurred in and around Khandwa during Dec 1993 – Jan 1994, Jul– Sep 1994 and Sep 1998 - Jan 1999 (Kayal, 2008). All these swarms were monitored through local seismic network by the Indian Meteorological Department (IMD) and Geological Survey of India (GSI), and consisted of several hundred tremors within the magnitude range 1.0 - 3.0. The recent Pandhana swarm activity started during Sep 1998 with a few shocks, and the acme of this activity reached during Oct 1998. This activity was recorded by one of our observatories at Khandwa and peak activity was recorded in October, 1998 with a maximum magnitude of M 3.04 (Fig.3e). Some data gaps remain there due to functioning problem of the instrument. Percolation of meteoric water to shallower depths in to a fault system, where it increases the pore pressure and causes the stress changes, may be responsible for the swarm activity in the vicinity of the Khandwa and Pandhan areas during 1998. Seismic events, located at other parts of the study area, could be purely due to regional tectonic forces within the central Indian tectonic Zone (CITZ).

CONCLUSION

We conclude that, although the level of seismicity in terms of magnitude and number of events is more for post-impounding stage than pre-impounding stage, there is, in general increase of background seismicity since 2002 before the impoundment.The level of seismicity during post impounding period is found to be increasing only till 2005 and then it has reduced to the backgroundlevel.During peak period of the seismic activity (2002-2005),most of the events were distributed away from the reservoir. Such a scenariodoes not satisfy the RTS characteristics. Hence, the local seismicity pattern in the study area indicates that accumulation of strain energy increased over the years and reached to acme at certain time periodwith the occurrences of moderate magnitude eventsand then it reducedto the background seismicity level,after releasing the strain energy. Deep crustal architecture delineated by MT study also facilitated in depicting the probable occurrence of seismicity in thevicinity of the reservoir site and its stability. A total of16 seismic events were identified within the radius of 50 km with hypocentral depths of < 15km during the study period of 1995-2009. Since these events do not satisfy the RTS characteristics, they are assumed to be natural due to local adjustments in the crustal blocks along a series of gravity faults towards north and south of the Narmada River and other seismogenic faultsnear the dam site.Hence, distribution pattern of seismicity and crustal architecture indicates that geological and tectonic conditions are not favorable for the reservoir ingenerating any significant seismic events in the reservoir area.Seismicity, as a whole, is inferred as due to regional tectonic forces within the Central India Tectonic Zone (CITZ).

ACKNOWLEDGEMENTS

Authors are thankful to NHDC for funding the seismological investigations in the study area. We wish to thankShri. S.Govindhan, Director, CWPRS for permitting to publish this work.Our sincere thanks to Dr.L.R.Pattanur, Senior Research Officer, for her guidance and suggestions in this work. Authors are thankful to anonymous reviewers and Editor of the journal, who helped to enhance quality of the manuscript significantly, through constructive comments and valuable suggestions.

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