

Preliminary Study of Reservoir Triggered Seismicity in the Vicinity of Tarbela Dam

Babar, A.¹

Abstract

Tarbela dam is situated on the lesser Himalayas of northern Pakistan which is a very active tectonic region. On regional scale the Main Boundary Thrust, Punjal Thrust Structure, Indus Kohistan Seismic Zone and Hazara Kashmir Syntaxis are major active fault systems which increase the vulnerability of this region to catastrophic earthquakes. Hazara, Salkhala, Kingriali and Tanawal formations exist in the region around the dam. Seismic data from 1973 to 2012 from a specialized network of seismic stations are incorporated in this study in order to carry out an investigation based upon the reservoir triggered seismicity (RTS). The hydrological data of Tarbela dam reservoir is also used to find out whether a relationship exists between the rate of earthquake occurrence around the lake of Tarbela dam and the fluctuation in water level during various seasons throughout the year. An extensive work in this article deals with the various aspects of the *b*-value. Three concentric circular regions, encompassing the reservoir of Tarbela dam, are defined to identify geological boundaries of the study region and filtering of the seismic data. Although the number of earthquakes vary significantly from larger to smaller zone the *b*-values does not deviate much from an average value of 0.64 for the whole period between 1973 and 2012. The difference of *b*-value on seasonal basis as well as on yearly basis, throughout any given year in vicinity of the dam, could not be attributed to the occurrence of a medium to large earthquake. However, the influence of water level in reservoir and seismic energy released on difference in *b*-value is settled. The water level fluctuation in the reservoir has strong correlation with the *b*-value. During the months when reservoir level is minimum *b*-value is smallest and when the reservoir approaches its optimum level *b*-value is highest. The relationship between difference in *b*-value and variation in water level on annual basis is ambiguous. Contradictory instances of fine correlation and an inverse relation are observed between these two quantities. Depth and magnitudes of various reservoir triggered earthquakes is also scrutinized to find the existence of any relationship of these with water level. No clustering or swarm activity of earthquakes is discovered in vicinity of Tarbela dam reservoir. The whole earthquake activity around Tarbela dam cannot be associated with the RTS.

Key Words: Reservoir Triggered Seismicity, Tarbela Dam, MBT, MMT, *b*-value, seismic energy.

Introduction

The earthquakes that occur in the surrounding area of any artificial water reservoirs due to its loading and unloading are categorized as “reservoir triggered seismicity” (RTS). This term was formulated by McGarr and Simpson (1997) who moreover differentiated RTS from “reservoir induced seismicity” (RIS). They defined RIS as the causative activity responsible for most of the stress changes. In this article the term RTS is used to signify earthquake activity associated with reservoir impoundment, following the above criteria.

The phenomenon of RTS was discovered at Lake Mead, USA by Carder (1945). In some cases e.g., Selim et al. (2002) the number of micro earthquakes increased after the impoundment and swarms occurred near the reservoir. While others e.g., Srivastava, (1990) and Shukla et al. (2012) reported absence of any definite relationship between the occurrences of earthquake around the dams and seasonal variation in water level in the reservoirs. Mostly earthquakes associated with the RTS have small to medium magnitude. According to Lay and Wallace (1995), earthquakes triggered by human activity, loading and

¹ agha_babar@yahoo.com

Pakistan Meteorological Department, Pitras Bukhari Road , Sector H-8/2, Islamabad, Pakistan.

unloading of reservoirs for instance, are intraplate in nature. Some examples of significant earthquakes associated with the RTS are mentioned in Table 1.

Table 1: Some notable reservoir triggered earthquakes.

Magnitude	Date	Region	Source
6.1	March 20, 1962	Hsinfengkiang, China	Gu02
5.5	September 23, 1963	Kariba, Zambia–Zimbabwe Border	GG70
5.8	September 23, 1963	Kariba, Zambia–Zimbabwe Border	GG70
5.8	September 25, 1963	Kariba, Zambia–Zimbabwe Border	GG70
6.5	1966	Kremasta, Greece	PP89
6.3	December 10, 1967	Koyna, India	Gu02
5.7	August 01, 1975	Oroville, CA, USA	Si88
5.2	November 14, 1981	60 km S of Aswan dam, Egypt	Se02
5.9	April 22, 1983	Thailand and the adjacent Myanmar	CL92
4.6	September 18, 2004	Pyrenees, Spain	Ru06

Gu02 = Gupta (2002),

Si88 = Simpson et al. (1988),

GG70 = Gough and Gough (1970 b),

Ru06 = Ruiz et al. (2006),

CL92 = Chung and Liu (1992),

PP89 = Papazachos and Papazachou (1989),

Se02 = Selim et al. (2002),

According to Guha (2000) only 21 percent amongst the deep reservoirs (having depth more than 140 m) all over the world could generate RTS. However, it is a well established fact that triggered earthquakes by large water reservoirs have capability of damaging the dams as well as claiming human lives. On the other hand the construction of dams cannot be prevented as it is vital for power generation, flood control and irrigation purposes. Hence there exists a matter of concern between the benefits associated with economy and finance versus the risks put together by the RTS.

Tarbela dam is constructed on the River Indus in the lesser Himalayas of northern Pakistan. It is the world's largest embankment dam (Chao, 1980). The reservoir of the dam was filled to some extent for a few weeks after completion of its construction in 1974 for the first time (Ibenbrahim et al., 1989); later in 1975 it was fully impounded (Jacobs et al., 1979). The main embankment of dam is 2.75 km long and 143 m high having gross capacity of 13.7 km³ (Mahdi, 1988). The area of the dam reservoir is almost 260 km² (Khan et al., 2012). Several studies have been carried out in order to quantify and associate the seismicity around the dam with a seismogenic source, geology and seismotectonic interpretation around the dam region. Notable examples among those are mentioned in the preceding lines.

Methodology

An authentic and reliable earthquake catalogue in terms of preciseness of magnitude, location of epicenters and focal depth is required for analysis of the RTS. Authenticity and reliability of earthquake catalogue used in this study is ensured by various plots including catalogue completeness graph, depth versus magnitude plot, depth categorization and histogram showing number of earthquakes occurred on yearly basis. The aforementioned analysis was necessary to be performed because several further analyses were to be performed based on b-value. Gutenberg and Richter's (1954) proposed a relationship that actually defined the concept of the b-value, which is as follows:

$$\log N = a - b M \quad (1)$$

The same is used herewith. Furthermore, the difference in b-value is estimated on seasonal (for three months time span) as well as on yearly basis by incorporation of seismic data from 1973 to 2012.

Three concentric circular regions, having center at 34.1419°N and 72.8400°E (two among those are shown in Figure 1), are defined in order to put together the geological boundaries of the study region and seismic

data filtering out of the earthquake database for the estimation of seismic energy release and b-value. These circular regions have radii equal to one degree ($1.0^\circ \approx 111$ km), half degree ($0.5^\circ \approx 55$ km) and 20 km, henceforward referred to as 1.0° radial zone, 0.5° radial zone and 20 km radial zone, respectively.

The criterion of defining a 1.0° radial zone is adopted in order to filter out only those tectonic features that have potential to generate a significant earthquake effecting the structure and facilities installed at the dam and its vicinity. The idea of considering this radial zone was adopted from Shukla et al. (2012), (their Figure 6). When the heterogeneity of geological conditions and presence of another source of the RTS namely Mangla dam come across, the region for studying RTS shrunk to only a 0.5° radial zone. In this way the other source of the RTS is excluded and hence the analysis is more focused on that associated with Tarbela dam. In his study on number of seismic events and energy release around Tarbela dam, Mahdi (1988) also considered an area of 50 km radius ($\approx 0.5^\circ$). Most results are presented from analysis of earthquake data within the 0.5° radial zone. Another circular zone of 20 km radius following Ibenbrahim et al. (1989) is considered to increase the preciseness and accuracy of the results.

In order to unearth any correlation in case of Tarbela dam, the reservoir water level data on daily basis at the dam are obtained from Tarbela Dam Project, WAPDA. An average of water level each month from 1974 to 2012 is calculated from these data. Earthquake data around Tarbela dam reservoir comprising of 40 years from 1973 to 2012 is enormously large. Plotting of such large amount of epicenters seems unrealistic. Therefore, the spatial distribution of epicenters is examined after breaking up the whole time span of 40 years into four decades, viz. 1973 to 1982, 1983 to 1992, 1993 to 2002 and 2003 to 2012. The earthquake data is further divided into two categories by taking into consideration the reservoir level. From February to April the reservoir remains at a minimal level while from August to October it remains at its optimal level, each year. This scheme is followed to examine the spatial distribution of earthquake epicenters with respect to depth and magnitude. Remaining months correspond to transitional period during which the water level attains maxima or descends to minima.

The correlation of released seismic energy, b-value and number of earthquakes in a year with water level in reservoir is also examined herewith. The release of seismic energy is quantified in this study by using an empirical relationships derived by Gough and Gough (1970). The spatial distribution of seismic activity is examined in order to find any swarm like activity or clusters of earthquakes in space and time. Depth and magnitudes of various reservoir triggered earthquakes is also scrutinized to find the existence of any relationship of these with water level.

It is important to mention here that the 1.0° radial zone is also a source of assistance for development of a good understanding of the geology and seismotectonics of the study region. Salient features of fractures, like length, characteristics of seismicity and nearness to the dam are also critically examined by the help of this radial zone. The geological structures and fractures are considered on regional as well as micro scale. The dimensions of various fractures are estimated by using geo-referencing technique in a software meant for GIS.

Geology and Seismotectonics

A fold and thrust belt extends from the Main Mantle Thrust in the north to the Salt Ranges in the south. It is termed as Himalayan fold and thrust belt (Khwaja et al., 2003). Tarbela dam is located in the Himalayan fold and thrust belt region in proximity of west of the western Himalayan syntaxis. This fold and thrust belt is the most dominant feature, formed as a result of collision between the continental portions of the Indian and the Eurasian tectonic plates. One of the tectonic features in this belt is Hazara region which has also been termed as Hazara seismotectonic province by Quittmeyer et al. (1979). In the northern parts of Pakistan, the upper crustal layers have undergone folding and thrusting near/ around the Indian-Eurasian plate margins, whereas, left lateral shear in addition to folding and thrusting is seen southwestern and western parts of Pakistan (Quittmeyer and Jacobs, 1979).

Fracture Zones

The leading feature responsible for the cause of RTS are those fractures which lie underneath the comparatively deep parts of the lakes of the large dams (Guha, 2000). Numerous significant fractures exist along the direction of flow of the River Indus near Tarbela dam. According to Kazmi (1979) these fractures are responsible for controlling the passage of water in the River Indus. Only those geological structures and fractures are discussed in this section, which exist within the 1.0° radial zone. A brief account of some of these faults is presented as follows:

Main Boundary Thrust (MBT)

Main Boundary Thrust (MBT) on a regional scale is a very important and seismically active geological feature, as compared to the other faults, situated in the vicinity of Tarbela dam. It comprises of Hazara fault, Parachinar fault, Kalachita fault and Murree fault (Iqbal et al., 2008). In conjunction with these faults, the MBT forms a sharp prominent syntaxial bend namely the Hazara–Kashmir syntaxis which is regarded as the most dominant tectonic feature of the area.

Punjal Thrust Structure (PTS)

Punjal Thrust Structure (PTS) is another active feature parallel to the MBT. It is a reverse fault with strike-slip component (Iqbal et al., 2008). It is situated about 70 km NNE of Tarbela dam (upstream of the River Indus) near Balakot with a total length of 224 km. The value of maximum credible earthquake assigned to it is Mw 7.2.

Indus-Kohistan Seismic Zone (IKSZ)

Indus-Kohistan Seismic Zone (IKSZ) is a northwest striking zone, situated in the vicinity of the Hazara Kashmir Syntaxis and around 50 km from Tarbela dam in northwest. The zone encompasses the dam from north, northeast and east. It continues northwest across Kashmir into the KPK province of Pakistan having an alignment with the zone of seismicity along the Himalayas (Yeats et al., 1992; Bilham, 2004).

Hazara Kashmir Syntaxis (HKS)

Hazara Kashmir Syntaxis (HKS) is a north-south trending tectonic zone famous for its complexity (Khwaja et al., 2003).

Hazara Lower Seismic Zone (HLSZ)

Hazara Lower Seismic Zone (HLSZ) is a right lateral strike slip fault located in south of Tarbela dam.

Punjal–Khairabad Fault (PKF)

Punjal–Khairabad Fault (PKF) passes very close to Tarbela dam. It is almost 12 km away from the dam. Its outcrop is believed to be 80 km on the surface exposed from the Hazara syntaxis, where it splays off the Himalayan thrust system, to Attock area, where the former rejoins the latter again.

Darband Fault (DF)

Darband Fault (DF) is a left lateral strike slip fault with sharp dip and passes just beneath the main abutment of Tarbela dam forming a 214 m near vertical escarpment in the dam foundation (Mahdi, 1988). The fault makes a steep slope or escarpment at the base of dam abutment perpendicularly. Total length of the fault line is approximately 100 km.

Jehlum Fault (JF)

Jehlum Fault (JF) is a strike-slip fault the lateral extension of which is between two cities of Azad Jammu and Kashmir namely Balakot and Bagh. That is the reason some workers e.g., Thakur et al. (2010) term it as Balakot–Bagh fault. It is a NNW striking fault (Monalisa et al., 2005) with a total length of almost 100 km and approximately 70 km away from Tarbela dam settlements.

Rawalakot Fault (RF)

Rawalakot Fault (RF) is 100 km away from Tarbela dam. It is almost 20 km long, strike slip fault with a northwesterly trend. It passes 10 km away from the Bagh city of Azad Jammu and Kashmir.

Khair-e-Murat Fault (KMF)

Khair-e-Murat Fault (KMF) is 175 km long (Monalisa et al., 2005) east-west trending structure. It advances near south of Kohat city parallel to the MBT keeping a separation of 20 to 25 km until it reaches Islamabad and takes an ENE turn and terminates or conceals beneath quaternary deposits.

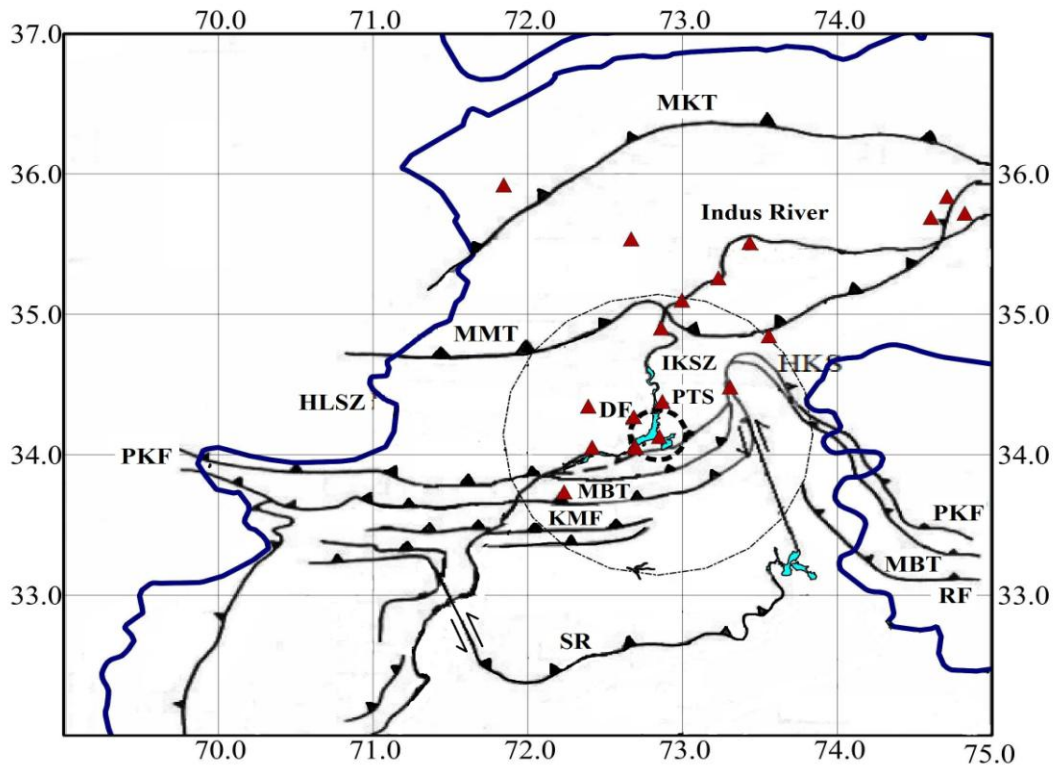


Figure 1: Map showing the northern and northwestern part of Pakistan (modified from Monalisa et al., 2005; their Figure 1).

The concentric circles have radii 20 km and 0.5 degree, while the red triangles show the location of TSN stations.

DF–Darband Fault; HKS–; HLSZ–Hazara Lower Seismic Zone; IKSZ–Indus Kohistan Seismic Zone; KMF–Khair-e-Murat Fault; MBT–Main Boundary Thrust; MKT–Main Karakoram Thrust; MMT–Main Mantle Thrust; PKF– Punjal Khairabad Fault; PTS– Punjal Thrust Structure; RF–Rawalakot Fault; SR–Salt Range.

Geological Formations

Geological conditions around the area encompassing Tarbela dam are heterogeneous. The Hazara and Salkhala formations consist of slate and both belong to the late Precambrian eon. The Hazara formation, in addition to slate, consists of phyllite and shale. It forms bedrock base of the Indus valley. The Salkhala formation is located near Salkhala village, Kishan Ganja River Kashmir. In context to Tarbela dam, this formation is on right side of the Indus river channel near dam. The Kingriali and Tanawul formations belong to the middle Triassic epoch and Cambrian period of the Paleozoic era respectively. The Kingriali formation is located near Zaluch Nala, western Salt Range and Tappan Wahan, Khisor Range and consists of dolomite, dolomite limestone, marl and shale. Regarding the geological framework of Tarbela dam and surrounding region, this formation is on left side of the Indus river channel near dam. The Tanawul formation consists of biotite, muscovite quartz schist and andalusite staurolite schist. It is also located on right side of the Indus river channel near Tarbela dam (Shah, 1977).

Analysis and Results

The database filtering criteria plays a fundamental role in any study related with quantification of earthquakes. Three radial zones with 1.0° , 0.5° and 20 km radii are considered for data filtering. The circumference of 1.0° radial zone touched the adjoining areas of Muzaffarabad and Murree in east while Mardan and Peshawar in the west. Furthermore, in the southeast, the extent of that circle touched territories of Mangla dam which itself is a source of RTS. These areas have different geological conditions and trend of seismicity which cannot be attributed to the RTS associated with Tarbela dam, the scope of this study. The foremost significance of 1.0° radial is to examine or study the geological as well as seismotectonic setting of the study region. However, in this section the earthquakes occurred in 1.0° radial zone are also taken into account for the estimation of b-value which is obtained from data of those earthquakes which occurred during 1973 to 2012. Other analyses are performed on date within a concentric 0.5° radial zone and a 20 km radial zone encompassing the reservoir of Tarbela dam.

A substantial part of results deal with b-value including assessment of b-value being a precursor to a large reservoir triggered earthquake, effect of water level in dam reservoir on b-value and comparison of water level variation and seismic energy release with difference in b-value. The spatial distribution of earthquake epicenters with respect to depth and magnitude is also examined, afterwards.

Earthquake Database Analysis

The earthquake database used in this study is compiled by Tarbela Seismic Network (TSN) deployed by the Water and Power Development Authority of Pakistan (WAPDA). It comprises of earthquake data recorded from 1973 to 2012. According to Ibenbrahim et al. (1989), the TSN initially consisted of six stations around the Tarbela reservoir in August, 1973 and within a year the number increased to 15. Each station comprises of a short-period, vertical component and high-gain instruments. Presently the network, as shown in Figure 1, consists of 19 stations (Shehzad, pers. communication). The catalogue completeness for WAPDA earthquake database is examined for 0.5° radial zone, as shown in Figure 2.

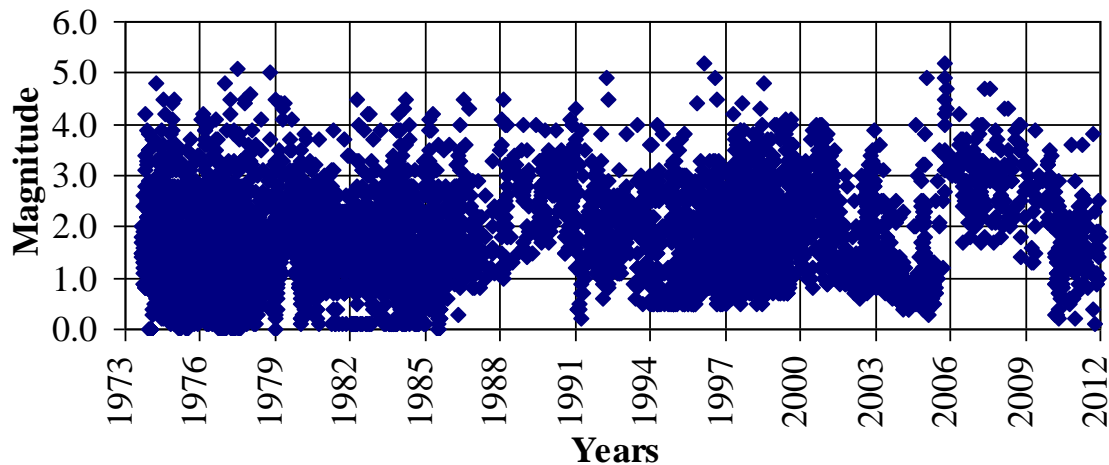


Figure 2: Catalogue completeness for earthquakes that occurred within 0.5° radial zone.

As mentioned in preceding section that Tarbela dam is situated in a very active tectonic region. Many medium to large earthquakes occurred in the adjoining areas of Tarbela dam region after its construction and deployment of the TSN. The time-magnitude distribution around the study region is non-homogenous as indicated in Figure 2 drawn on the basis of available database. The presence of aftershocks data, in the catalogue under consideration, associated with any one of the aforementioned medium to large earthquakes is questionable. The epicenter of M7.6 earthquake of October 08, 2005 was merely 80 km away from Tarbela dam. It occurred in the middle of two well populated cities of Azad Jammu and Kashmir namely Muzaffarabad and Balakot. This devastating earthquake was

followed by numerous aftershocks. The principal reason to examine the catalogue completeness is to check whether the aftershocks data of October 08, 2005 earthquake are included in the catalogue. Apparently from Figure 2 as such no aftershock activity followed the aforementioned earthquake. No unusual increase in seismic activity is observed in the year 2006 or any other year. It is, therefore, established from Figure 2 that the database is free from anomaly of after shock activity.

Mostly the RTS is shallow and has a hypocentral depth around 10 km (Gupta and Rastogi, 1976). The RTS is manifested at micro level i.e., constitutes 3.0 or lesser magnitude earthquakes.

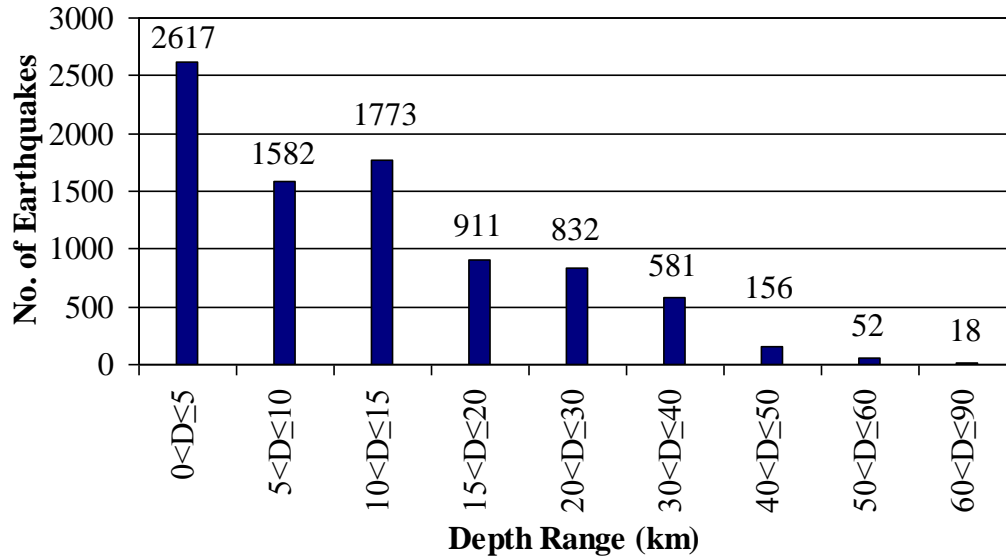


Figure 3: Depth distribution for WAPDA catalogue for 0.5° radial zone.

In Figure 3 a classification of earthquakes with respect to their hypocentral depth is presented. It is depicted from this diagram that almost 31% of the seismic activity is not more than 5 km deep and earthquakes with focal depths lesser than 20 km constitute almost 81% of the total seismicity.

Table 2: Comparison of number of earthquake and b-value for three radial zones.

Number of Earthquakes			b-value		
R=1.0°	R=0.5°	R=20 km	R=1.0°	R=0.5°	R=20 km
22853	8522	1515	0.660	0.6660	0.5969

As seen from Table 2, the consistency in b-value for the three radial zones of 1.0°, 0.5° and 20 km radii is reasonably obvious. The three b-values do not deviate much from their average value of 0.64, although the numbers of earthquakes vary significantly from larger to smaller zone. The low b-value indicates the presence of RTS in the region. Higher b-values correspond to active tectonic regions. The letter “R” in Table 2 denotes radius of the zone under consideration.

The histogram presented in Figure 4 indicates the number of earthquakes occurred every year within a time span of 40 years from 1973 to 2012. The earthquake activity reported from 1978 to 1982 remained low down. A similar trend can be observed from 1986 to 1994 and 2000 to 2012. In this context, Figure 2 does not indicate any decrease in seismic activity within the interval from 1978 to 1982. However, a slight paucity of intense earthquake activity can be seen within the intervals from 1986 to 1994 and 2000 to 2012. This fact needs some explanation on account of reservoir level fluctuation, release of seismic energy and b-value estimation on yearly basis corresponding to the intervals of high and low seismic activity.

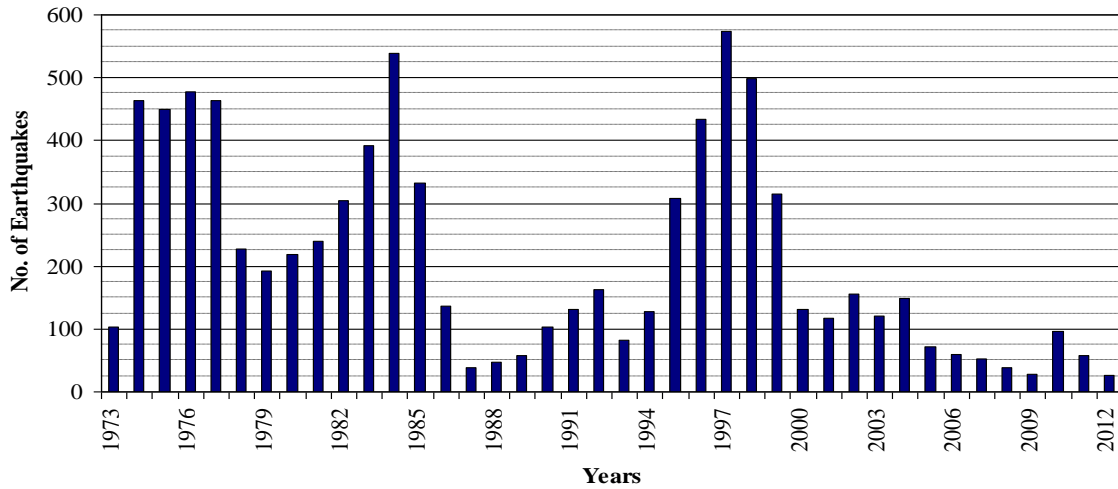


Figure 4: Histogram showing number of earthquakes occurred within a 0.5° radial zone encompassing the reservoir of Tarbela dam for each year between 1973 and 2012.

Precursor of a Large Earthquake

According to Shukla et al. (2012) and Srivastava et al. (1979) the sharp change in b-values in temporal domain, for a region around a dam reservoir, is mostly followed by an $M \geq 5.0$ earthquake. Two curves in Figure 5 show the variation in b-value; green corresponds to the 0.5° radial zone and blue corresponds to the 20 km radial zone. The diamond shaped dots show the earthquake occurrence and their magnitudes are shown correspondingly on vertical axis at right hand side of the graph. There is a reservation regarding the four events illustrated in green in the year 2005 for being the aftershocks of October 08, 2005 Muzaffarabad earthquake.

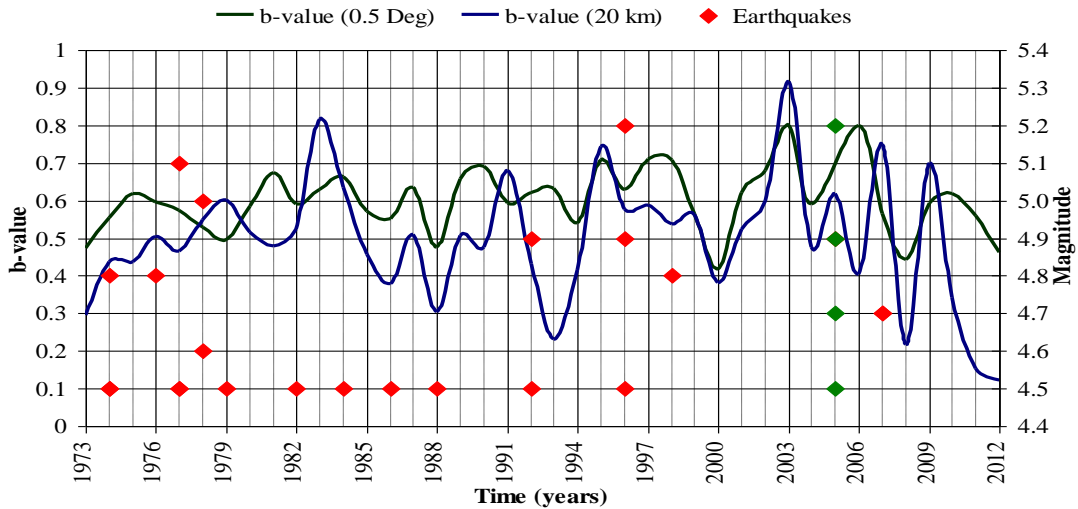


Figure 5: The curves show difference in b-value (left vertical axis) on yearly basis. Blue curve represents b-value calculated for 20 km radial zone while red curve represents that for 0.5° radial zone. The dots show earthquakes of various magnitudes (right vertical axis) in some particular years within 0.5° radial zone.

The analysis shown in Figure 5 shows b-value calculated on the basis of one year data of earthquake occurrence. The earthquakes whose details are given in Table 3 are taken into account for this validation process. Others are neglected because of their low magnitude value ($M < 4.5$) or the time gap between two consecutive earthquakes is less than six months. Considering seismic data only six months prior to any selected earthquake for calculating b-value is not adopted from an already established hard and fast rule. However, there are four cases where earthquakes of magnitude 4.5 are also taken into account because of a sufficient time (more than six months) gap between them.

Table 3: Source parameters of earthquakes with $M \geq 4.5$ within the vicinity of Tarbela dam.

Date	Origin Time (hh:mm in UTC)	Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ E)	Depth (km)	Magnitude
March 26, 1974	09:45	34.05	72.62	15	4.8
December 14, 1976	20:59	34.62	72.71	20	4.8
June 18, 1977	14:03	34.12	72.62	28	5.1
January 5, 1978	19:32	34.03	72.57	18	4.6
October 15, 1978	20:46	33.73	73.09	15	5.0
April 14, 1982	13:31	33.98	72.67	15	4.5
March 6, 1984	07:26	34.49	72.92	23	4.5
July 10, 1986	12:56	34.11	72.68	2	4.5
March 25, 1992	12:02	34.00	72.86	13	4.9
February 20, 1996	07:50	34.05	72.67	5	5.2
August 8, 1996	20:00	34.00	72.88	18	4.9
July 12, 1998	10:44	34.08	72.68	8	4.8
May 20, 2007	16:36	34.22	72.49	32	4.7

A more detailed validation is performed by focusing on the behavior of b-value six months prior to a medium to large earthquake (parameters of these earthquakes are presented in Table 3) shown in Figure 6. The horizontal axis represents time in months prior to any earthquake. An advancement of one unit in positive direction on this axis is equivalent to preceding one month with reference to any earthquake under consideration. The vertical axis shows b-value, while each curve indicates its variation, for a particular earthquake.

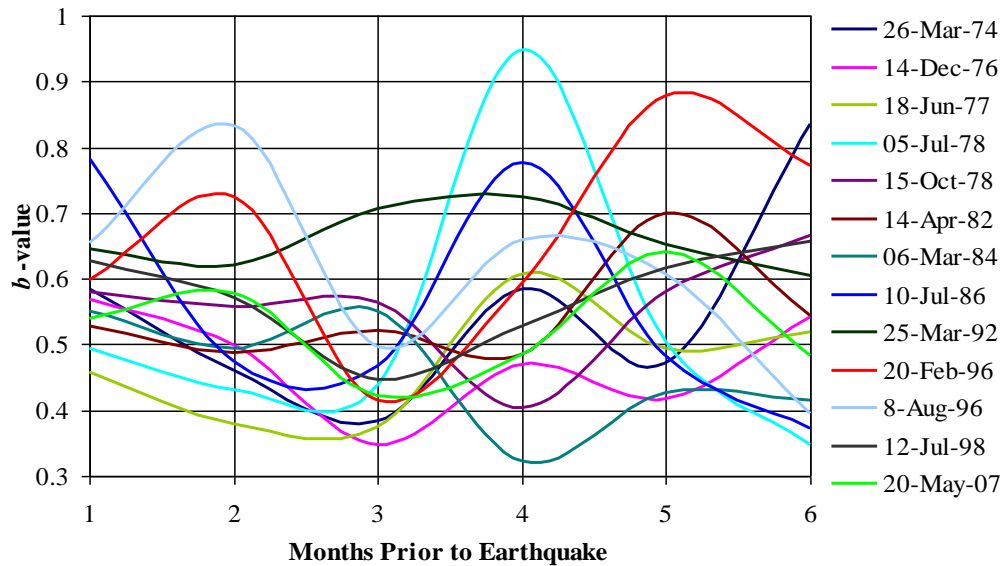


Figure 6: Difference in b-value on monthly basis.

Effect of Reservoir Level on b-value

The water column fluctuation has strong correlation with the b-value in various cases. An average of the water level each month from 1974 to 2012 is calculated from water level data on daily basis at Tarbela dam and illustrated by blue curve in Figure 7. The red and green curves show the average of maximum and minimum recorded levels, respectively. Largely, the behavior of these curves depicts that the water level remains at a maximum level between August and October; on the other hand, it remains minimum between February to April, each year. The periods from November to January and

May to July are transitional stages; reservoir level descends from maximum to minimum and ascends from minimum to maximum during these periods, respectively.

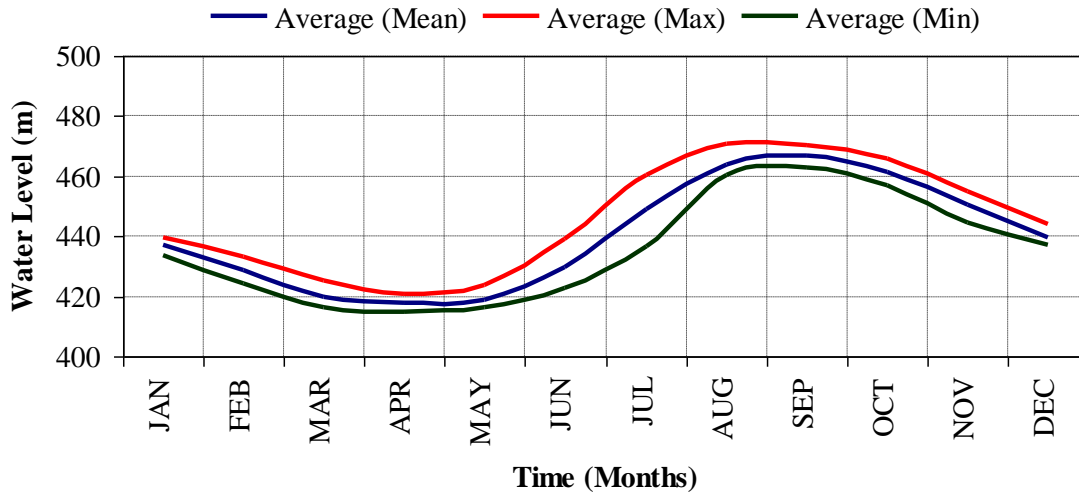


Figure 7: Seasonal effect on reservoir level fluctuation at Tarbela dam.

It can be seen from Figure 7 and Table 4, Tarbela dam reservoir undergoes large fluctuations in water level. This is in contrary to some other reservoirs that show small seasonal variations in the water levels e.g., those reported by Hassib et al. (2012) at Aswan dam. According to Dahy (2012) the local climatic conditions (around the reservoir and its catchments areas particularly) are important factors that control the fluctuation in water level of a reservoir. The climatic conditions of Tarbela dam region largely support rapid increase in water level of the reservoir and its stay to a maximum level during May to October. The variations in filling rate of a reservoir are also influenced by the type of its utilization (Dahy, 2012). In case of Tarbela dam, its reservoir is used for irrigation as well as hydro-electric power generation. These factors swiftly decrease the water level of the reservoir and are also responsible for its minimum levels during November to April.

Table 4: Water level in Tarbela dam reservoir from 1974 to 2012.

Months	Reservoir Level (m)	Remarks
May	423.64	Transition period: Minimum to Maximum
June	430.59	
July	450.50	
August	468.28	Water Level: Maximum
September	469.80	
October	461.51	
November	452.83	Transition period: Maximum to Minimum
December	433.00	
January	442.48	
February	433.00	Water Level: Minimum
March	422.70	
April	421.09	

In present study, analysis of the b-value variation with reference to the reservoir level fluctuation revealed some interesting results. It is a noteworthy point that these results are obtained on the basis of 40 years records of earthquake and water level in Tarbela dam reservoir. The seasonal variation of b-value in descending order is illustrated in Figure 8. From May to July which corresponds to a transitional period when the reservoir is on its way to attain its optimum level, b-value is highest. In contrast to this the lowest b-value is found between February to April during the minimum reservoir level. In comparison to the transitional period when the reservoir level gets to its minimum, b-value is lesser.

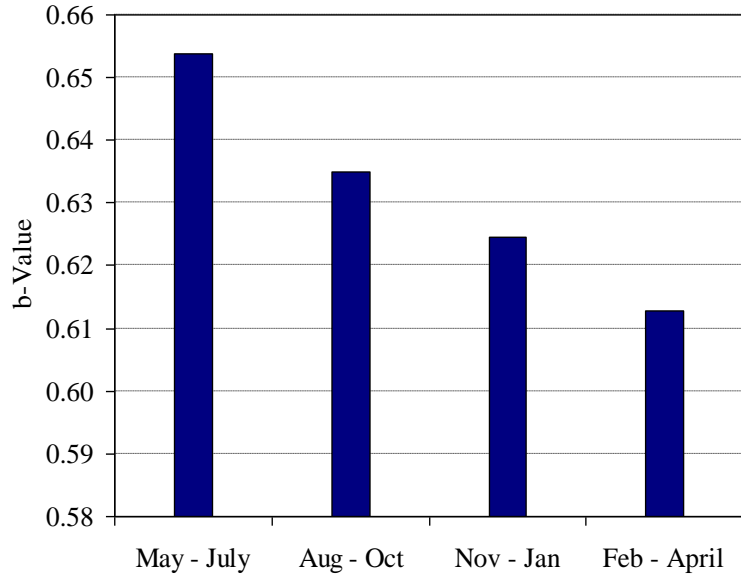


Figure 8: Sea Seasonal variation of b-value with reservoir level fluctuation

Water Level Variation and Difference in b-value

The average of daily reservoir water level data for each year is shown by the blue curve in Figure 9 while the brown and the green curves show b-value on annual basis for data within 0.5° and 20 km radial zones. Although the two radial zones have different measurements of area, however, a good correlation is found between the curves representing b-value estimated from seismic data confined within these zones. Also a good correlation between difference in b-value and variation in water level is observed from 1984 to 1986 and 1999 to 2005. However, an inverse relation is observed for 1979, 1981 and 1988.

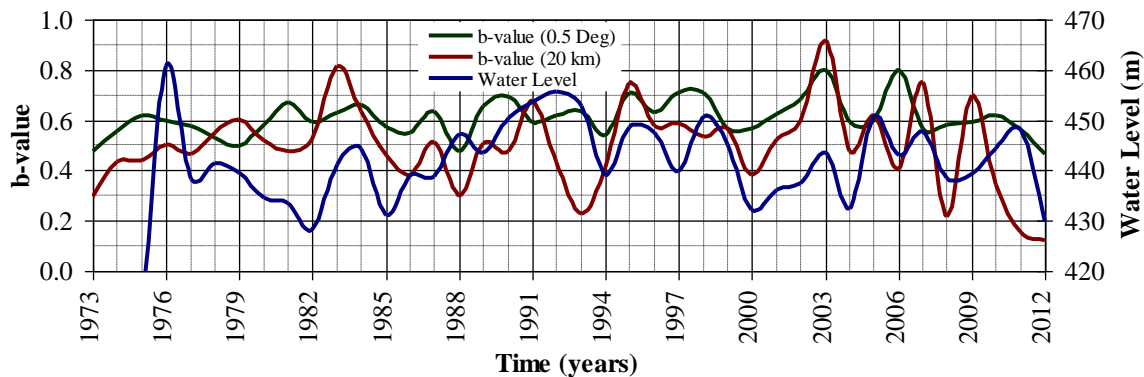


Figure 9: A comparison of water level variation at Tarbela dam reservoir with b-values calculated for circular zones of 0.5° and 20 km radii

Seismic Energy Release and Difference in b-value

In order to estimate energy released by earthquakes, Gough and Gough (1970 a) derived a relationship from Gutenberg and Richter’s relation (Gutenberg and Richter, 1942) and Bath’s relation (Bath, 1958). According to Gough and Gough (1970 a), the energy-magnitude relation is as follows:

$$\log_{10}(E) = 10.4 + 1.84 M_L - 0.023 (M_L)^2 \tag{2}$$

In this equation, E is the energy and M_L is the local magnitude. Mahdi (1988) and Shukla et al. (2012) used a slightly different relationship for calculation of seismic energy, released over a given year, as follows:

$$\log_{10}(E) = 9.9 + 1.9 M_L - 0.024 (M_L)^2 \quad (3)$$

In the present study Equation (2) is taken into account to calculate energy radiated from earthquakes in a particular year, because the references are more authentic. The earthquakes selected for this purpose occurred within 0.5° radial zone encompassing the whole lake of Tarbela dam for a period from 1973 to 2012. In Figure 10, b-value on annual basis is illustrated by thin green and blue curves estimated for circular zones of 0.5° and 20 km radii, respectively. The release of energy on annual basis is illustrated in Figure 10 by thick brown and red curves calculated for earthquakes occurred within 20 km and 0.5° radial zones, respectively. An inverse relationship is revealed in the b-value and energy curve for both radial zones of 0.5° and 20 km radii.

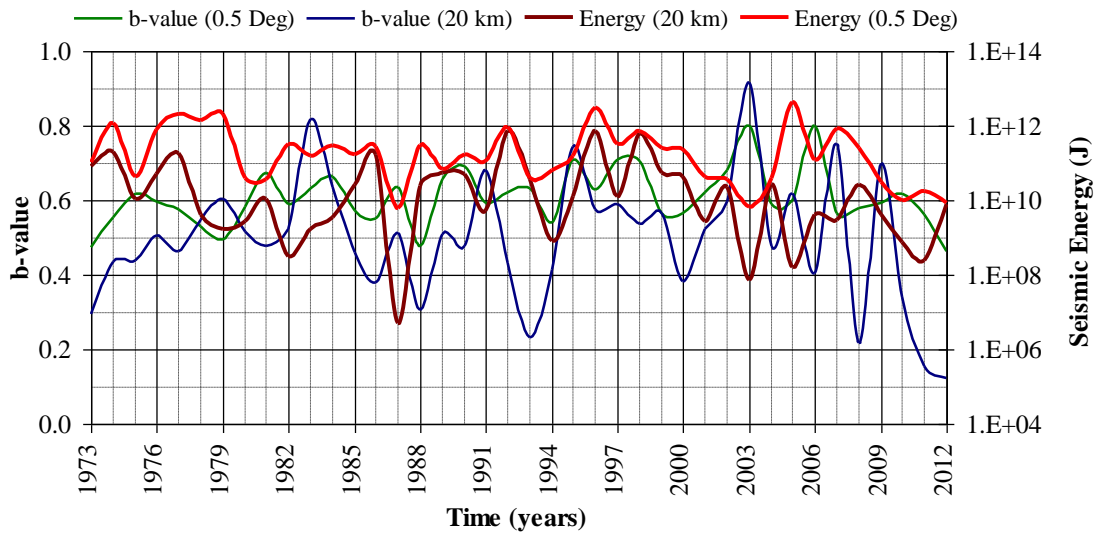


Figure 10: A comparison of seismic energy released with b-values around Tarbela dam reservoir calculated for circular zones of 0.5° and 20 km radii.

Spatial Distribution of Epicenters

In their study regarding RTS at Koyna Reservoir, Rajendran et al. (1996) reported that when the reservoir level attains maxima, the earthquakes occur in a widespread area and the spatial distribution of the earthquake activity shrinks for the other periods of year. Another observation was made by Rastogi et al. (1997) while studying RTS at Warna Reservoir. They reported that earthquakes occur in the form of a burst shortly after the reservoir level attains maxima and during times when reservoir level attains minima, the seismic activity decreases.

According to Awad and Mizoue (1995) there exists a correlation between the RTS and the focal depth. They reported that at Aswan dam region the earthquakes occur in the form of clusters with deep and shallow depths. Deep earthquake clusters had focal depths greater than 10 km. The shallow events exhibited swarm-like activity and had good correlation with water level fluctuations. Deep earthquakes showed a “fore shock–main shock–after shock” sequence and had no correlation with water level fluctuations.

The water level at Tarbela dam reservoir remains at its maximum during the month of August to October while the minimum level is observed from February to April every year. In order to follow the footsteps of Rajendran et al. (1996), Rastogi et al. (1997), and Awad and Mizoue (1995) spatial distribution of epicenters of earthquake events is examined with respect to magnitude and depth. The spatial distribution of earthquake epicenters is examined with regards to maximum reservoir level

from August to October and minimum reservoir level from February to April for the four decades 1973 to 1982, 1983 to 1992, 1993 to 2002 and 2003 to 2012. In this way, all panels of Figure 11 and 12 show only 50% seismic activity from 1973 to 2012. Separate colors are used in order to discriminate earthquake activity during maximum and minimum water level at Tarbela dam reservoir.

The tectonic setting and the RTS pattern around the reservoirs discussed by Rajendran et al. (1996), Rastogi et al. (1997), and Awad and Mizoue (1995) is different from those near Tarbela dam which is situated in a relatively more active tectonic region. Therefore, the analysis in this section may be considered as a guideline and not a comparison.

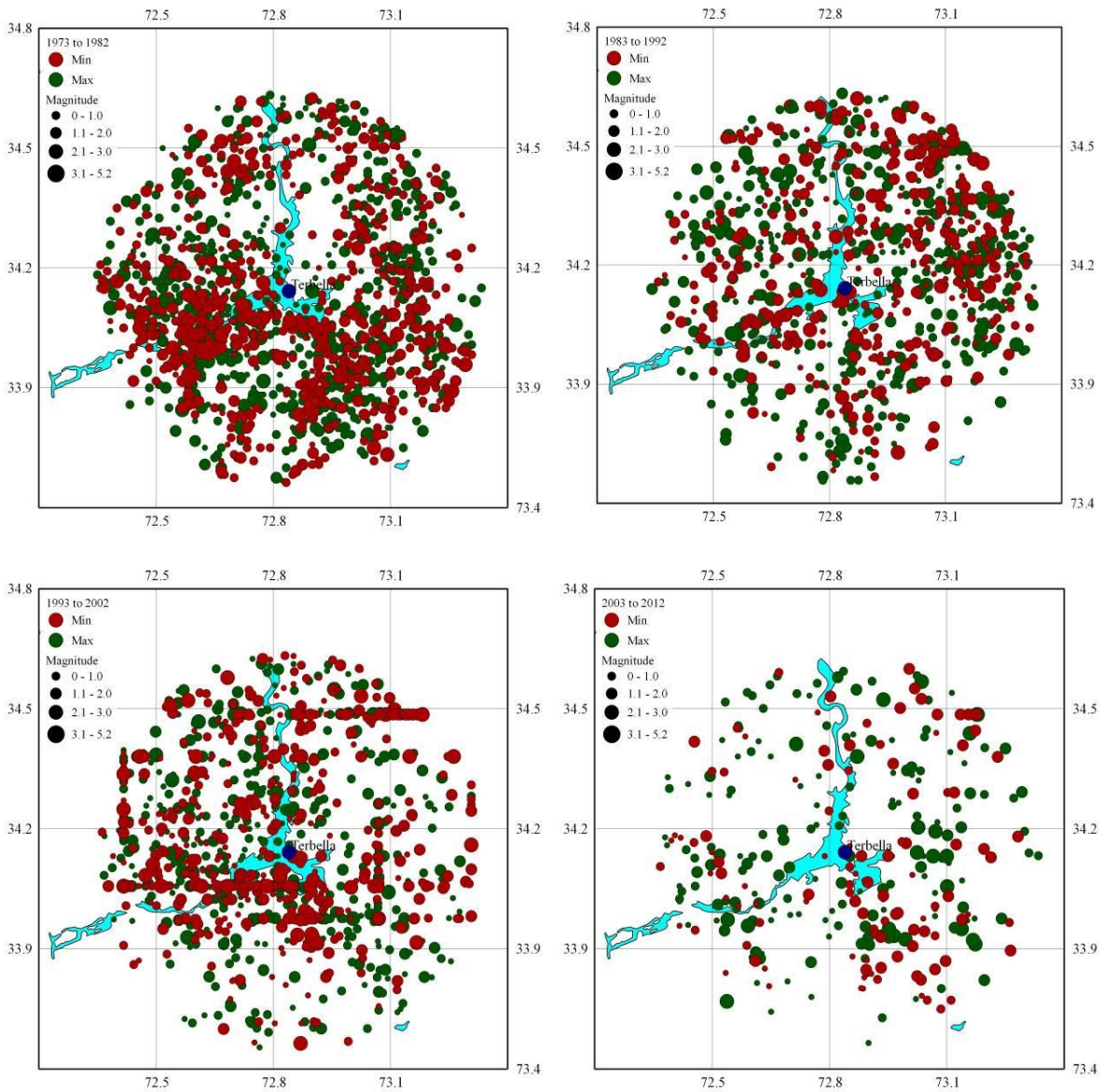


Figure 11: Spatial distribution of epicenters in the vicinity (within 1.0° radial zone) of Tarbela dam with respect to magnitude. Each panel represents seismic activity in a decade which is indicated on the upper left corner (at the first line) of respective panel. Red circles: Earthquakes during minimum water level from February to April. Green circles Earthquakes during maximum water level from August to October.

Spatial Distribution With Respect to Magnitude

All the earthquake events are categorized into four classes with respect to magnitude. The events that belong to the category with magnitude between 0 and 1.0 are represented with small dots. As the size of dot increases, the magnitude corresponding to events also increases. The maximum sized dots represent events with magnitude between 3.1 and 5.2. The colors refer to water level, i.e. red circles indicate earthquakes occurred during maximum water level in the reservoir and green ones indicate those occurred during minimum water level.

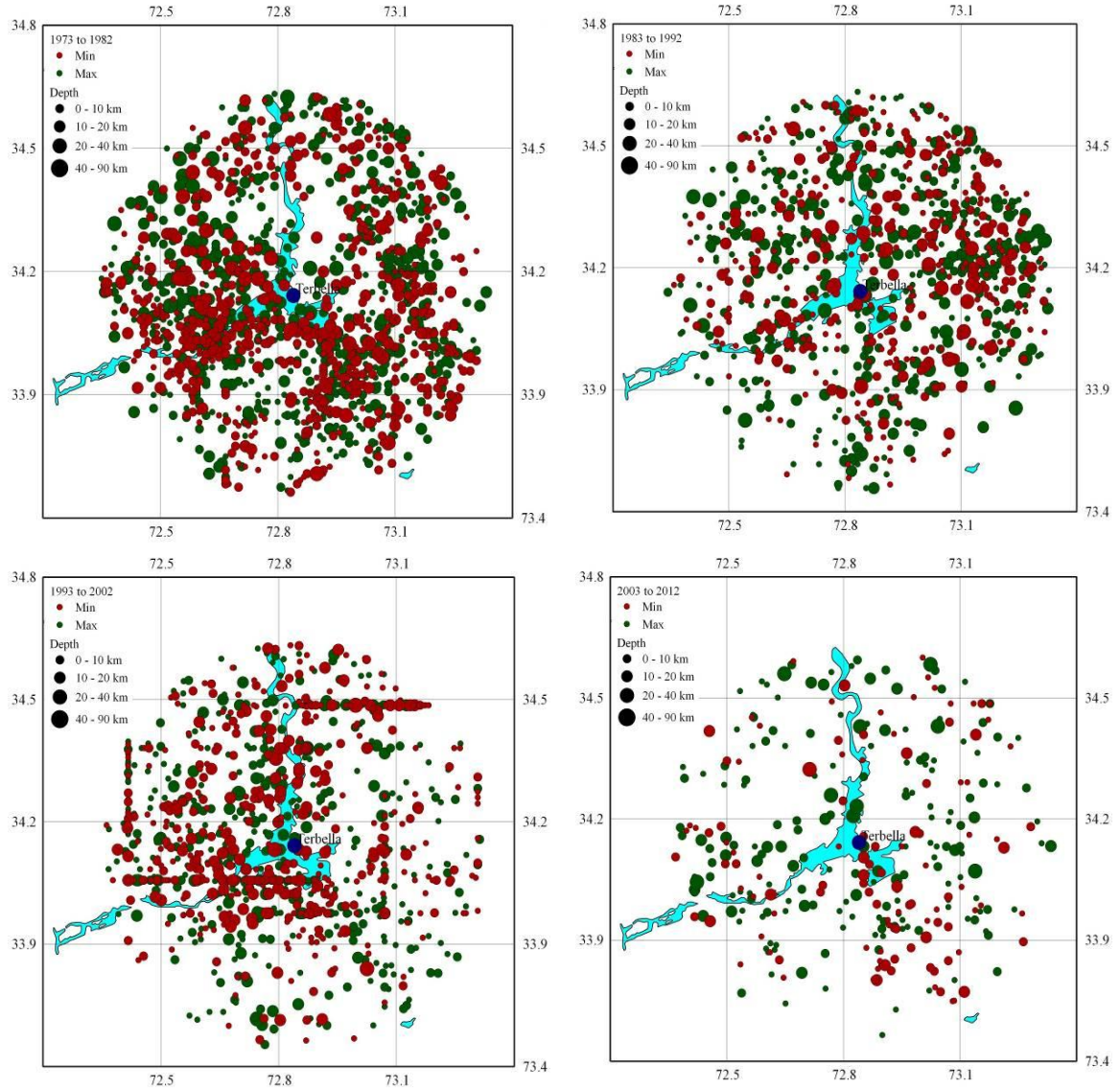


Figure 12: Spatial distribution of epicenters in the vicinity (within 1.0° radial zone) of Tarbela dam with respect to depth. Each panel represents seismic activity in a decade which is indicated on the upper left corner (at the first line) of respective panel. Red circles: Earthquakes during minimum water level from February to April. Green circles: Earthquakes during maximum water level from August to October.

As seen in the top left panel of Figure 11, that greater concentration of seismic activity is found dominantly on the southern side of Tarbela dam reservoir from 1973 to 1982. The concentration shifted to the eastern and northeastern side of the reservoir from 1983 to 1992, as shown in upper right panel of Figure 11. However, this concentration is less dominant as compared to the previous one. The seismicity is concentrated on southern and southwestern side of the reservoir,

from 1993 to 2002, as shown in lower left panel of Figure 11. No dominance or even concentration of seismicity is found from 2003 to 2012 as seen in the lower right panel of the aforementioned figure; nevertheless, a decrease in earthquake occurrence is fairly obvious. Another apparent fact disclosed from all panels of Figure 11 is the uniformity in spatial distribution with respect to magnitude.

Spatial Distribution With Respect to Depth

All the earthquake events are further categorized into four classes with respect to depth. The events that belong to the category with depth between 0 and 10 km are represented with small dots. As the size of dot increases, the depth corresponding to events also increases. The maximum sized dots represent events with focal depth between 40 and 90 km. The color scheme of circles representing earthquakes in Figure 11 is the same as earlier adopted in Figure 12.

As seen in the top left panel of Figure 12, that greater concentration of seismic activity is found dominantly on the western and southeastern side of Tarbela dam reservoir from 1973 to 1982. A cumbersome concentration of seismicity is located on far northeastern side of the reservoir from 1983 to 1992, as shown in upper right panel of Figure 12. From 1993 to 2002, the seismicity with all ranges of focal depths is concentrated closely around the reservoir while only shallow activity is located almost 100 km away. This is shown in lower left panel of Figure 12. The overall seismic activity from 2003 to 2012 as seen in the lower right panel of the aforementioned figure remained low. Uniformity in spatial distribution with respect to depth is apparent in Figure 12 (all panels).

Discussion

Geological conditions are rigorously heterogeneous in the vicinity of Tarbela dam reservoir because four distinct geological formations namely Salkhala, Hazara, Kingriali and Tanawul formation exist at Tarbela dam site within an extent of approximately 2 km. Some potential fault zones exist merely 100 km away from the dam. On regional scale the MBT, Punjal Thrust Structure, IKSZ, Hazara Kashmir Syntaxis and HLSZ while on micro level Punjal–Khairabad fault, Darband fault, Jehlum fault, Rawalakot fault and Khair-e-Murat fault are identified as the possible source of tectonic earthquake sources around dam region. The seismogenic permeability (Talwani et al., 2007) is apprehended to be a possible cause of stimulating these fracture zones.

The anomalies like aftershock activity attributed to a large earthquake and non-completeness of catalogue (gaps in data during a span of time when seismic network remained non-operational, for example) are examined during earthquake database analysis, as seen in Figure 2. The earthquake database analysis also helped to understand nature of the seismicity around Tarbela dam region. From Figure 4, it substantiated that the seismicity is hybrid i.e., triggered by loading and unloading of the reservoir as well as tectonic in nature. The time spans of high and low seismic activity, in the 0.5° radial zone as shown in Figure 5, are also disclosed during this analysis. Spans of high activity are from 1974 to 1977, 1982 to 1985 and 1995 to 1999 and those of low activity periods are from 1978 to 1981, 1986 to 1994 and 2000 to 2012. These time spans of high and low activity cannot be pronounced as periodic because the intervals between them are not uniform to establish any thing concrete. Furthermore, the variation in released seismic energy, difference in b-value and fluctuation in reservoir water level do not show any concurrence with time spans of high and low seismic activity (average of the b-values calculated for three radial zones is 0.64).

Concerning the behavior of b-value there are two opinions. First is about the variation of the b-value being a precursor of a large earthquake. According to Shukla et al. (2012) and Srivastava et al. (1979) the sharp change in b-values with respect to time, for a region around a dam reservoir, is mostly followed by an $M \geq 5.0$ earthquake. Second opinion is about the variation of b-value with water level in a dam reservoir. It is established by Selim et al. (2002); Sameh, (1992); Gupta and Rastogi (1976); and Muco,

(1998), that the b-value is larger during the periods when water level in the reservoir increases. On the other hand the b-value is lesser during the periods of decreasing water level.

In Figure 6, the b-value fluctuates vigorously prior to every earthquake. Not even a single example is found where ascent or descent is monotonic. Therefore, nothing could be established on the basis of Figure 6 as the trend of b-value is not stable prior to any earthquake on short term (monthly) basis. The b-value of 1.0 is usually expected for regions active in terms of tectonic earthquakes. The b-values estimated in this study correspond to RTS that is why it is quiet low (highest b-value = 0.655).

Analysis of the water level variation from 1973 to 2012 in the Tarbela dam reservoir revealed that it remains at maximum level from August to October and at minimum level from February to April. Two transition periods are observed during which water level of the reservoir reaches its maximum level from minimum and vice versa and those are November to January and May to July, respectively, as shown in Figure 7 and Table 4. A correlation between water level variation in Tarbela dam reservoir on seasonal basis and b-value calculated from seismic data in the corresponding season is revealed. According to Gupta and Rastogi (1976), Muco (1998), Semeh (1992), and Salim et al. (2002) the b-value varies with reservoir level fluctuation. Higher b-value is observed during transitional periods when water level in the reservoir ascends to maximum. In the present study it is found that b-value is larger when water level increases and it is lesser during the period of decreasing water level.

The sections of this article namely “effect of reservoir level on b-value” and “the water level variation and difference in b-value” should not be confused with each other. The former one deals with the analysis of water level variation on seasonal basis and its effect on or correlation with b-value calculated from seismic data for the respective seasons. These seasons are mentioned in the preceding paragraph. The latter one deals with the quest of a correlation between average of yearly water level in reservoir and b-value calculated for earthquake data within 0.5° and 20 km radial zones. Another aspect in context of “effect of reservoir level on b-value” is the limitation of earthquake data within 0.5° radial zone in the current study. Other two radial zones have either too large or too small lateral extent which is not suitable to study such effect. Moreover, the workers mentioned previously also considered a similar extent of area to examine this effect.

It is an empirically well established fact that a big earthquake releases a large amount of energy the equivalence of which is released by too many small earthquakes. The overall energy released in the radial zones with 0.5° and 20 km radii are almost in good agreement with each other except a few instances of small energy release in 20 km radial zone e.g., 1982, 1987, 1994, 2003 and 2005 (Figure 10). This might be a shift of seismic activity out of the 20 km radial zone. The upper and lower right panels of Figure 11 and 12 (showing 50% spatial distribution of earthquake activity from 1983 to 1992 and 2003 to 2012) inadequately confirm this hypothesis for 1982, 1987, 2003 and 2005. However, no notable evidence is found for lesser seismic energy released in 1994. The other interesting feature of comparison of seismic energy release with difference in b-value is the inverse relation between these two quantities. Earlier Mahdi (1988) found a good relation between the number of earthquakes and energy release. Logically, the findings regarding seismic energy release and difference in b-value of this study and those of Mahdi (1988) are dissimilar.

Conclusion

The micro level seismic activity is mostly concentrated within 0.5° radial zone encompassing the reservoir of Tarbela dam within a depth lesser than 40 km. Phenomenon of lateral or depth wise clustering or swarms of earthquakes is not observed. Hence, the distribution of epicenters in space is even. Foreshock – aftershock sequence is absent subsequently which implies that the distribution of earthquake occurrence in time is not uniform regardless of magnitude. The water level in reservoir does not effect this uneven distribution in time. Highest b-value = 0.655 is found between months of May to July for the whole time interval between 1973 and 2012. This b-value corresponds to a transition period when water level (averaged on daily basis) proceeds from minimum to maximum. This value drops abruptly to ~ 0.61

between months of February to April, from 1973 to 2012, when water level is at its minimum. It remains intermediate for rest of the months. No clear relationship is established between difference in b-value and occurrence of reservoir triggered medium to large earthquakes. Inverse relation found between fluctuations of water level in reservoir and difference in b-value estimated on yearly basis. The release of seismic energy is quantified in this study and its inverse relationship with difference in b-value is revealed, which is a logical conflict with the findings of Mahdi (1988). Performance of the seismic network is validated by performing a sturdy analysis on the earthquake database compiled by means of this network. Consequently, the WAPDA earthquake database is the most reliable for any analysis of the RTS around dam. The absence of a clear correlation between reservoir impoundment and occurrence of medium to large triggered earthquakes implies that the entire earthquake activity cannot be associated with the RTS. Therefore, the need of studying seismogenic permeability, as done by Talwani et al. (2007), is hereby recommended for future research.

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