Journal of Geography, Environment and Earth Science International

21(2): 1-10, 2019; Article no.JGEESI.49100
ISSN: 2454-7352

Relationship between Observed Seismicity and Water Level Fluctuations in Polyphyto Dam Area (North Greece)

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/JGEESI/2019/v21i230122
Editor(s):
(1) Dr. Suvendu Roy, Assistant Professor, Department of Geography, Kalipada Ghosh Tarai Mahavidyalaya, India.
Reviewers:
(1) Orhan Polat, Dokuz Eylul University, Turkey.
(2) Ali Amasha, Arab Academy for Science Technology & Maritime Transport, Egypt.
Complete Peer review History: http://www.sdiarticle3.com/review-history/49100

Original Research Article

Received 05 March 2019
Accepted 21 May 2019
Published 28 May 2019

ABSTRACT

The spatial-temporal seismicity in Aliakmona river area is presented for the period 1974-2010 (NW Greece). This study area, which was classified as low seismicity, presents a particular interest due to the unexpected strong earthquake of Ms=6.6 which occurred between the cities of Kozani–Grevena, at a distance of 18 km from the southern edge of Polyphyto lake in 1995. According to [1], seismic hazard changes have been identified SE of the Polyphyto dam after the impoundment of the lakes. In this study, we examined the possible correlation between the impoundment and the water level fluctuations due to the three artificial lakes which are established in the region and the observed seismicity using data from the catalogues of the National Observatory of Athens (NOA) (see details for seismological data on Mc, RMS, etc. in [2,3]). For the latter purpose, spatial and temporal distribution maps were developed as well as correlation diagrams between water level variations in respect to monthly seismicity for distances 10 Km, 20 Km, 30 Km, 40 Km and 50 Km around the artificial lakes using the ESRI ArcMap 10 software. A remarkable change is observed in seismic activity in the vicinity of reservoirs for the period commencing 10 years prior to the first filling in comparison with the period 10 years after. This increased seismicity is correlated to the daily rate of water level fluctuations (dh/dt) for the period 1984-2010 reveals the presence of mainly shallow seismic activity with focal depths of 0-5 km in a high percentage (67%). This

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protracted seismicity which is mainly located in the SW area of Polyphyto lake, has characteristics of the second type of induced seismicity according to Talwani [4], and seems to be controlled by the water level fluctuations of Polyphyto reservoir due to the mechanism of pore pressure diffusion.

Keywords: Triggering seismicity; induced seismicity; dams; North Greece.

1. INTRODUCTION

Many study cases worldwide have been associated with many strong earthquakes and the reservoir impoundment as well as water fluctuations in lake levels, such as in the region of the Leak Mead in Arizona, USA [5], Hsinfengkiang, China, [6,7], Kremasta, Greece, [8,9], Koyna, India, [10,11,4,12], Pournari, Greece, [13]. This association is known as Reservoir Induced seismicity (RIS) or Reservoir Triggering Seismicity (RTS). According to Talwani [4] two main types of RIS are observed. The first type is known as initial seismicity and the second one as protracted seismicity.

The main factors which have been associated with the RIS are the maximum height of water level, the permeability of background, the amplitude of the reservoir water level fluctuations as well as the periodicity [14], the impoundment rate, the value of pore pressure increase [15], and the exceedance of lake levels over previous maxima, a phenomenon known as ‘‘stress memory’’ [7,16,6].

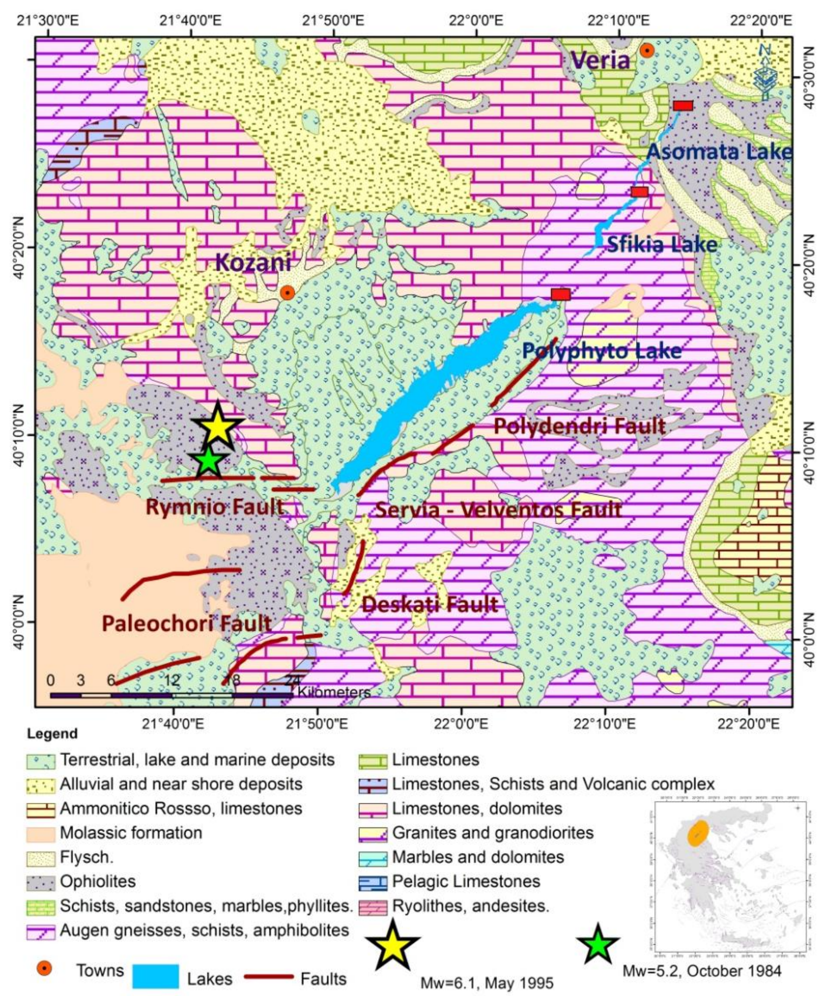

Fig. 1. Geological map of study area

The study area belongs to the Pelagonian zone which consists of metamorphic rocks (crystalline substratum) covered by carbonate rocks and flysch. The major geological structures which trend NW -SE along the Dinarides are intersected by the Servia active fault with ENE-WSW direction [17,18]. The south-west part is covered by ophiolites (Jurassic-Upper Cretaceous) and molassic formations of the Meso- Hellenic Trench while the northern part of the broader area (up to 50 Km around the artificial lakes) is covered by carbonate rocks that belong to the Axios zone and ophiolites. Plio-Pleistocene deposits occupy the basin of Kozani which is located on the west of the lakes.

The main faults that dominate the broader Polyphyto reservoir area are: a) a 70 km long fault zone which consists of several subparallel faults with ENE-WSW to NE-SW direction, parallel to the Polyphyto (Polydendri, Servia-Velventos and Deskati fault) and b) the Rymnio, Paleochori, Chromio-Vari, Pontini- Pilori and Feli faults located SW of the edge of the lake, striking in a E-W direction (Fig. 1.).

The observed seismicity of Aliakmona river area (N Greece), upon which the Public Power Corporation (PPC) has established three reservoirs downstream of each other, with Polyphyto Dam being the first largest with a dam height of 112m, maximum water level height h=289m, maximum volume V=1.220X106m3 and first filling in January 1974, was investigated.

This area was classified as low seismicity until 1995, when a strong earthquake of MS=6.5 occurred between the cities of Kozani and Grevena, at a distance of 18 Km from the southern point of the reservoir [19,20,21]. This focal area is near to the earthquake ML=5.2 that took place on 25 October 1984 during the Asomata reservoir initial filling [8,22,23,24,25]. According to several author [26,27,17], many parts of Kozani and Grevena cities and a number of villages had been damaged by the mentioned 1995 earthquake. The latter event caused the disagreement about it was induced due to the first filling of the Polyphyto artificial lake or caused by tectonic movements [28,29,30,31,32, 25].

The impoundment of the third downstream reservoir (Asomata Dam, initial water level height 44m, and maximum 78m), which commenced on 10 October 1984, was accompanied by an earthquake ML=5.2 on 25 October 1984, NW of the edge of Polyphyto lake with focal depth 18Km, while the first filling of the second downstream reservoir (Sfikia Dam, initial water level height 88 m and maximum 112m, maximum volume V=17.6X106m3) started on 12 March 1985 and was completed at the end of August 1985.

2. DATA AND METHODS

We detailed investigated the correlation between the recorded seismicity and the daily rate of water level fluctuations (dh/dt) for the period 1974 – 2010, using the seismological data from National Observatory of Athens catalogues (NOA), and the spatial and temporal distribution of observed seismicity was studied for distances 0-10 km, 0-20 km, 0-30 km, 0-40 km, 10-20 km, 20-30 km, 30-40 km and 40-50 km around the reservoir using the ESRI software ARCGIS 10 (see details for seismological data on Mc, RMS, etc. in several author [2,3].

2.1 Background Seismicity and Seismicity after Impoundment

This area was classified as low seismicity until 1995, when a strong earthquake of MS=6.5 occurred between the cities of Kozani and Grevena, at a distance of 18 Km from the southern point of the reservoir [1]. This focal area is near the earthquake ML=5.2 that took place on 25 October 1984 during the Asomata reservoir initial filling [27,23,24].

During the period up to 1900, five major earthquakes occurred in the broader area with epicenters close to Veria (ML=6.0, 896-904 and ML=6.4, 1211-1236), Edessa (ML=6.7, 1395) Kozani (ML=6.5, 1695) and Katerini (1889) [22] [33,34]. In the 20th century, only two major events (1922 December 7, M=5.4 and 1943 March 25, M=5.5) are located close to Preveza and Kozani respectively [34,30].

The spatial distribution of epicenters for the period commencing 10 years prior to the impoundment of Polyphyto dam (first filling in 1974) in comparison with the distribution for the period 10 years after, indicates a noticeable change in seismic activity in the vicinity of the artificial lakes for a distance up to 50Km. (Fig. 2.a.). The increase of seismicity is remarkable after the first filling of Polyphyto Dam (early 1974).

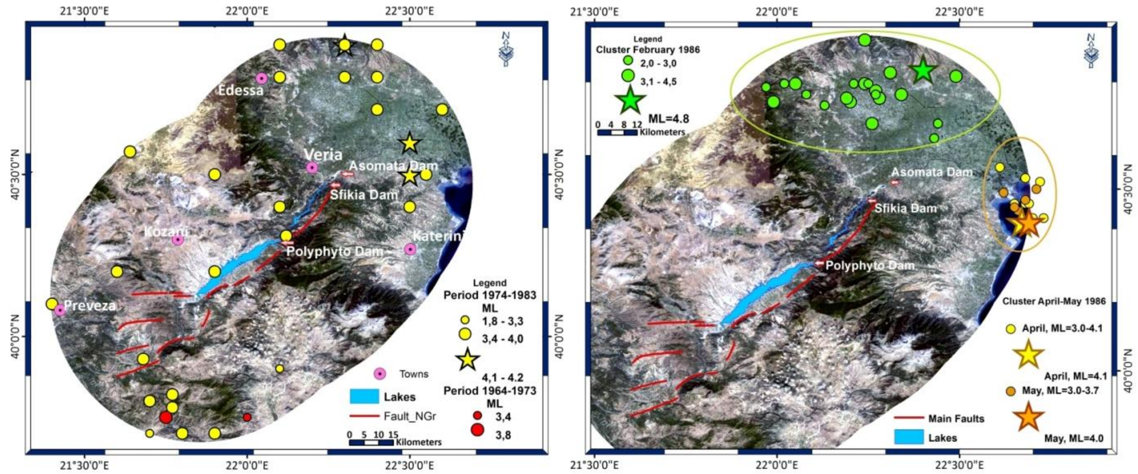

Fig. 2. Spatial distribution map for period 1964-1983 for a distance up to 50Km around the three reservoirs (Polyfyto, Sfikia and Asomata) (a). Red circles illustrate the events for the period 1964 - 1973, while orange circles illustrate the events for the period 1974 to 1983 after the impoundment of Polyphyto Dam (1974). Clusters with characteristics of induced seismicity (1986) (b)

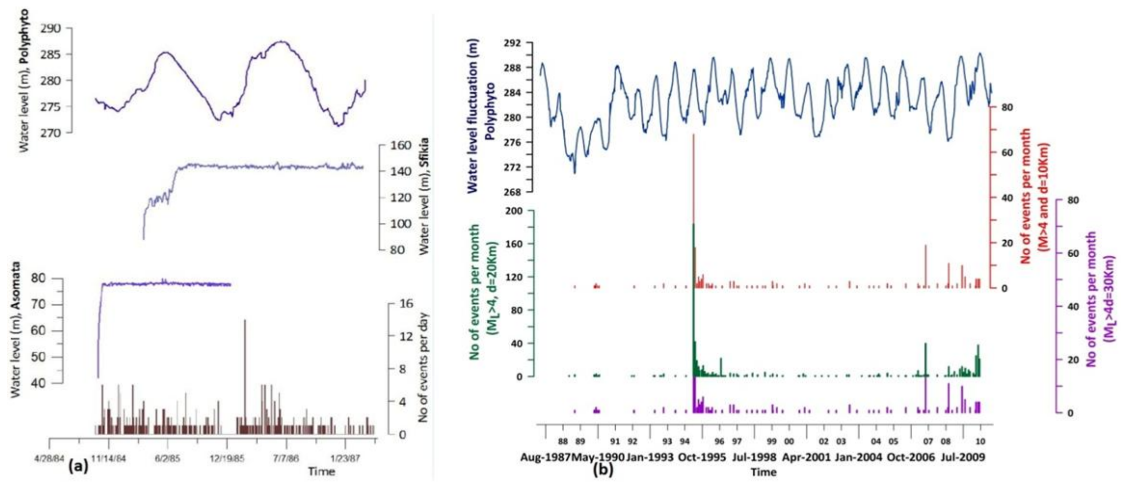

Fig. 3. Water level correlation is shown, with respect to the monthly seismicity for the period 1984- 1987 (Polyphyto, Sfikia and Asomata) (a) as well as the correlation diagram between water level fluctuations of Polyphyto with respect to monthly seismicity for distances 10, 20 and 30Km around the reservoirs (time period August 1987 to December 31, 2010) (b)

The initiation of the first filling of the Asomata reservoir took place on 10 October 1984 and an earthquake of magnitude ML=5.2 was recorded on 25 October 1984, NW of the south edge of Polyphyto lake with focal depth 18Km, which was accompanied by numerous microearthquakes. It is remarkable that in this period, the Polyphyto water level was at its lowest value. During the impoundment period of the second downstream reservoir, Sfikia Dam, few small events were observed close to the Sfikia artificial lake, in a depth range between of 5-10Km, as well as numerous microearthquakes north of Polyphyto reservoir. Noticeable seismicity was observed north of Polyphyto Dam in the period of January 1986, up to June 1986, while the water level of Polyphyto Lake was higher. This seismicity is associated with higher rate of Polyphyto water level changes.

An earthquake of magnitude ML=4.8 occurred on February 18, 1986, north of the lakes at a depth of 25 km (Fig. 2b, green ellipse). The b value of Gutenberg-Richter relation for the aftershock sequence was calculated equal to b=1.056, while the expected b values for the region is between 0.86≤b≤0.90 e.g. [35,20,36,37,9,38,39,40]. The ratio of the largest aftershock to the main shock magnitude was calculated equal to M1/M0=0.81, while the difference between the major aftershock to the highest aftershock was calculated M0-M1=0.9. This value b could be characterized as induced seismicity b value if compared to the values that characterized the seismicity of the Koyna Dam area as induced [10]. These values for the aftershock sequence of the major earthquake M0=6.0 in case of Koyna Dam, were found M0-M1 = 0.8, M1/M0 = 0.83 and b=1.09 [9,16,10]. The same characteristics were detected in the second cluster as well (Fig. 2. b., light orange ellipse).

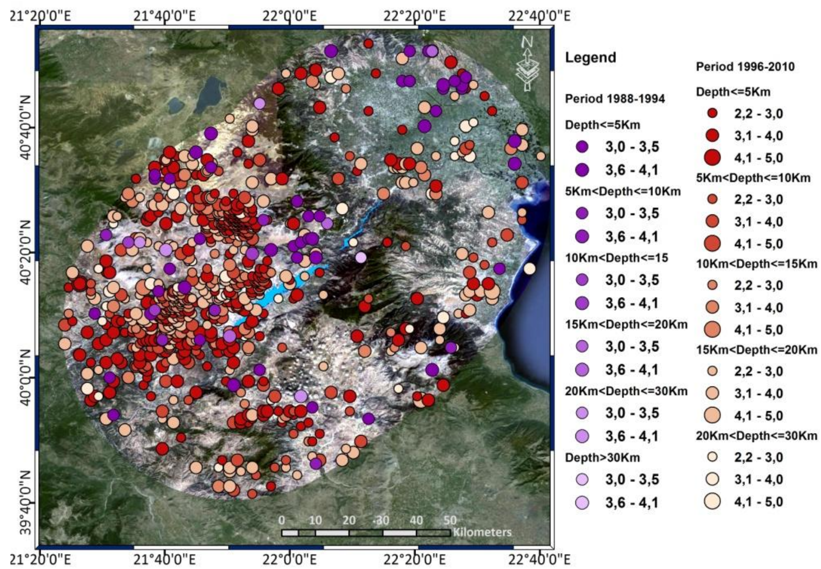

Fig. 4. Spatial distribution map for the period 1988-1994 and 1996-2010

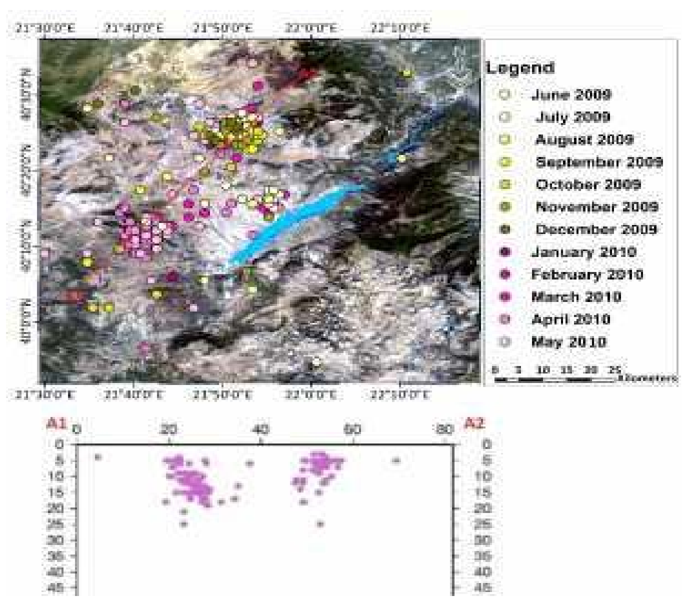

Fig. 5. Evolution of the seismicity in the study area during the period June 2009 – May 2010 (2.5<ML<=3.7) and the cross section A1A2 (strike 30°)

The distribution maps of epicenters for the period 1987 to 2010 reveal that seismicity is mainly confined to earthquakes with magnitudes ML≤4.5, with the exception of the strong earthquake that occurred on 13 May 1995 of magnitude MW=6.5, in the area of Kozani, with larger aftershocks of size ML=5.0 and ML=4.6, and earthquakes of magnitude ML=5.0 on 9 June, 2003 (18 Km depth, 49Km southeast of the Polyphyto reservoir) and ML=4.9 on 17 July, 2007 (22 Km depth, Kozani area).

2.2 Correlation between Seismicity and Water Level

The potential correlation between seismicity (for radius of 50Km around the reservoir) and water level fluctuation was investigated in two times windows. The first time window (a) concerns the initial impoundment of reservoirs Asomata and Sfikia which is April 1, 1984 until April 30, 1987, and the second time window (b) concerns the period May 1, 1987 to Dec 31, 2010.

Time window (a) During the period 10/10/1984 to 2/28/1985 112 seismic events with magnitude 1.2<ML<4.2 were recorded as well as a strong earthquake ML=5.2 which took place on October 25, 1984 (fifteen days after start filling) while the water level of Polyphyto was decreasing, recording a water level fluctuation Δh=2.46m in 44 days (Fig. 3. a.).

Several shallow earthquakes (up to 5Km) were observed during the first filling of Sfikia Dam (the second downstream of Polyphyto) with a good correlation with the water level increase. Remarkable seismicity took place during the period January 1986 - June 1986 in the northern part of Polyphyto Dam area, while the water level increased with significant daily rates of water fluctuations up to 1m. The largest daily number of earthquakes occurred on February 1986, i.e. 1 year after the first filling of the Sfikia artificial lake.

Time window (b) During the period May 1, 1987 to 2010 seismic events are observed with magnitudes ranging between 2.5≤ML≤4.1 and ML=4.9 in 2007 with a good correlation with the water level fluctuations (Fig. 3. b.).

3. RESULTS AND DISCUSSION

The statistical analysis for the study area leads to a possible case of protracted induced seismicity because of the seasonal water level fluctuations of the Polyphyto reservoir, as well as the rate of water level changes [4,7].

The correlation between the maximum or minimum water level with respect to the seismicity appears a time delay from one month to three months without systematic behavior and seems to depend on the rate changes of the Polyphyto water level.

3.1 Description of Observed Seismicity

According to the spatial distribution of the seismicity in the wider area for ML≥4.0 sizes, seismic activity is observed which is confined mainly to the SW and NE of the Polyphyto Lake. The distribution of seismic events of smaller magnitude ML≤4.0 shows sporadic seismicity throughout the area of the Polyphyto (for a distance 50Km around the lakes), which shows a higher density of seismic events south and west of the Polyphyto lake (Fig. 4.).

During the years 2009 and 2010, clusters of epicenters are observed to the Northwest of the lakes (Fig. 5.). According to the cross section A1A2, this seismic activity is linked with the activation of two normal and opposite dip direction faults with direction NW-SE, which belong to a small pull apart basin. The latter seismicity started in June 2009 while the Polyphyto water level was 289.03m and had been rising until 2010 which reached 290,37m for the first time. The epicenters of the south fault are located, in the focal area of the main event, magnitude M=6.1 which took place on May 13th, 1995 but in shallower focal depths. The seismic activity commenced in 2009 with the activation of the north fault which dips to the SW continuing during 2010 with the simultaneous activation of the south fault dipping to the NE and is close to the epicenter area of the earthquake which occurred on May 13th, 1995 (magnitudes range between 2.2≤ML≤3.7), (Fig. 5).

The highest rate of observed seismicity, for the period 1987 to 2010, is due to surface earthquakes with focal depths H<=5km. From this surface seismicity, the largest percentage is observed in the zone of 10Km around the lakes.

According to the focal depths, a decrease in surface earthquakes is observed as the distance from the three reservoirs increases, with emphasis on the Polyphyto reservoir, which hosts the largest part of the seismic events that took place in the southwestern part of the wider region where it is located from May 1987 to 2010.

More specifically, the highest rate 67% of total seismicity (1616 events for period 1987-2010) occurred at depths of 0-5km, 11% at depths 6-10km and 6% at depths 11-15Km for a distance 10km around the lakes, as well as high seismicity rates with depth up to 5Km were also observed for the zones 10-20Km, 20-30Km and 30-40Km in contrast to the area zone 40-50Km (Fig. 6).

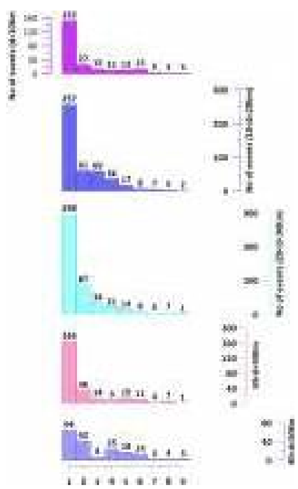

Fig. 6. Number of seismic events with magnitudes 2.2<=ML<=3.7 per depth. 1:(0-5Km), 2:(6-10Km), 3:(11-15Km) for time period 1987-2010

3.2 Correlation Results

According to the correlation diagrams, between the monthly seismicity rate and the water level variation, the presence of seismicity is detected sporadically in the time periods during which the water level has the lowest or highest water values and coincides with high rate changes (dh/dt) (Fig. 3.a, 3.b). This coincidence may be due to pore pressure diffusion that causes the reduction of background effective stress, leading to an activation of faults, which are close to failure conditions.

Specifically, during the period 2008 sporadic seismic excitation is observed consisting of small scale seismic events with values ranging between 2.5≤ M≤3.8. This seismicity is observed the second semester, with the most seismicity during the month of October. In this period the water level of Polyphyto dam was at its lowest levels with minimum height of water level h=276.12m on September 17, 2008.

As mentioned in the description of seismicity during the years 2009 and 2010 clusters of epicenters are observed to the north and south of the reservoir while the water level was 289.03m and had been rising until 2010 which reached 290,37m for the first time (Fig. 5). The above exceedance of Polyphyto water level over previous maxima (290m) caused the activation of the small pull apart basin, a phenomenon known as 'stress memory' [7,4,12,15].

A factor that enhances the effect of the pore pressure diffusion, resulting in a decrease in the shear strength of the fractures, is the fact that the earthquake of magnitude MW=6.5 occurred on May 13, 1995, ten years after the earthquake on October 25, 1984, size ML=5.2. The presence of two seismic events with ML>5 over a ten-year period is in contradiction with the region's history.

Moreover, the possibility that the earthquake of Kozani (May 13, 1995) be an accelerated event in the area because of positive coseismic stress coulomb transfer from previous strong earthquakes does not exist, since the activities of the major earthquakes from 1902 to 1995 resulted in the transfer of negative stresses in the study area according to Pavlides and Mountrakis [41].

3.3 Discussion

A noticeable change was observed in seismic activity in the vicinity of Polyphyto reservoir after the first filling in 1974 for a distance up to 50Km around the lake for the next 10 years. The spatial-temporal evolution of seismicity is examined, during the initial impoundment of Polyphyto, Asomata and Sfikia reservoirs located on Aliakmona River (North Greece), as well as for the next 30 years. The results show, despite the low seismicity which characterizes this area, a correlation between the temporal variation of seismicity and the water level fluctuations during the period 1984-2010. This correlation is due mainly to the greatest reservoir Polyphyto, which presents remarkable daily and seasonal water level fluctuations depending on the season.

During the impoundment of the second Asomata reservoir (October 10, 1984) low seismic activity was observed with few seismic events close to the Asomata lake as well as a seismic activity in the north edge of Polyphyto lake with maximum magnitude ML=5.2 which took place October, 25, 1984 in depth=19km in the area between Kozani – Grevena. On the other hand at the beginning of the filling of the third reservoir Sfikia (March 13, 1985) few small earthquakes are observed close to the reservoir during the third and fourth month after the impoundment, as well as a shallow seismic activity with small magnitudes which are located in the south edge of the Polyphyto reservoir.

In the first semester of 1986, aftershock sequences were detected to the North of the Asomata reservoir and to the east of the Thermaic Gulf. These aftershock sequences appear to have similar characteristics to the Koyna dam area, which has been globally characterized as a case of induced seismicity. The statistical results of the investigation of the focal depths in a 50km distance around the reservoirs show that the highest percentage took place in depths up to h=5km, with the majority of earthquakes taking place at distances between 10-30 km around the lakes. The correlation between the water level fluctuation and the monthly seismicity rate for distance 10, 20, 30 and 40km around the three (3) lakes shows that the seismicity is associated with the water level fluctuations and rate of water level change. This relationship appears with a time delay of one to three months. In the case of the Kozani earthquake (Mw = 6.5 which took place May 13, 1995) the Polyphyto reservoir high change rates of water level fluctuation during the previous seven months. Specifically, on September 10th, 1994 the Polyphyto level had a change rate of dh/dt = 0.56m/day, on September 11th, 1994 a change rate dh/dt = -0.64m/day, on January 3rd, 1995 a change rate dh/dt = 0.40m/day, on January 4th, 1995 a change rate dh/dt = 0.33m/day, on January 29th, 1995 a change rate dh/dt = 0.38m/day and on January30th, 1995 a change rate dh/dt = 0.25m/day.

Specifically on September 10th and 11th, 1994, the Polyphyto water level had a rate of dh/dt=0.56m/day and dh/dt=-0.64m/day, on January 3rd and 4th 1995 had dh/dt=0.40m/day and dh/dt=0.33m/day while on January 29th and 30th, 1995 had dh/dt=0.38m/day and dh/dt=0.25m/day respectively, a fact that leads to an increase in the effective pore pressure. The comparison of these high daily values of rate change with the usual low values leads to the conclusion that the seismicity is possible due to the change of the pore pressure owing to the high change rate of the water level of Polyphyto [16,11,15,6].

4. CONCLUSION

A relationship is observed between spatial distribution maps of epicenters as well as the correlation between Polyphyto water level and monthly seismicity. This leads us to the conclusion that there is a presence of protracted induced seismicity which is the second type of induced seismicity according to Talwani [4] and located mainly on the area SW of the Polyphyto lake.

The possible reason for this seismic activity, in this area where includes the Kozani earthquake (May 13th, 1995), isn't only due to the presence of the intensely ruptured area and the fractures limestones but also to the direction of the faults (almost perpendicular to the maximum axis of the lake) which favors the transfer of pore pressure to the neighboring rocks in greater distances through these permeable fault zones [15,6]. A factor that enhances the effect of the pore pressure diffusion, resulting in a decrease in the shear strength of the fractures, is the fact that the earthquake of magnitude MW=6.5 occurred on May 13, 1995, ten years after the earthquake on October 25, 1984, size ML=5.2 [42]. The presence of two seismic events with ML>5 over a ten-year period is in contradiction with the region's history. Moreover, the possibility that the earthquake of Kozani (May 13, 1995) be an accelerated event in the area because of positive coseismic stress coulomb transfer from previous strong earthquakes does not exist, since the activities of the major earthquakes from 1902 to 1995 resulted in the transfer of negative stresses in the study area according to Pavlides and Mountrakis [41].

COMPETING INTERESTS

Author has declared that no competing interests exist.

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