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Research article

Recent seismic activity in the vicinity of Sidi Salem dam, Beja, Tunisia

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Abstract

Induced seismicity is a case of seismicity which needs to be studied given the damage caused by it in many places in the world. There are several types of induced seismicity for example seismicity linked to fluid injections, induced seismicity flowing the exploitation of mines, seismicity induced by dams. There are several factors that favor the triggering of induced seismicity. Among these factors, we can cite the seismotectonic context. The Sidi Salem dam is located in the north of Tunisia, this region is an area known for significant seismic activity. The main aim of this work is to demonstrate the important role of seismotectonic studies in the preliminary analyzes of the seismicity induced by the Sidi Salem dam in Tunisia for the period of time (1982 - 2010). The results show that there is a relationship between compression deformation which characterizes the studied region and the seismic activity near the studied lake. Preliminary analyzes carried out by Matlab show that there is a close relationship between the increase in water level in the dam and the triggering of seismic activity around the dam. The seismic activity related to the Sidi Salem reservoir serves as an exemplar of initial seismic events. Nevertheless, a rise in seismic activity surrounding the reservoir has been observed since its impoundment in 1982.

Key words: *Triggered earthquake, Compressive deformation, Sidi Salem dam, Tunisia.*

1. Introduction

Natural seismicity refers to the seismic activity that occurs globally in response to the movements of tectonic plates (Chattopadhyay et al., 2020). Typically, natural seismicity occurs at greater depths, ranging from tens to hundreds of kilometers. Induced seismicity differs from natural seismicity, it is seismicity caused by human activity. The damage caused by this type of seismicity is not at all negligible; it can even cause more damage than a natural earthquake. We can take the example of the Koyna earthquake (1967), the magnitude of this earthquake exceeded 7.5 on the Richter scale, the energy released exceeded the energy released by Hirochima atomic bomb. Studies on induced seismicity are prominent due to the elevated likelihood of causing destruction to infrastructure and posing risks to human lives (Bommer, 2022; Bal, 2021; Yenier et al., 2017).

The study of induced seismicity can be approached using several methods (Krietsch et al., 2019). Seismic monitoring involves using instruments to detect and record ground vibrations that human activities may cause. Deformation measurement using instruments such as GPS can provide information on changes in pressure and stress in the subsurface, which may be related to induced seismicity (McGarr et al., 2002). Also, seismic data can be used to identify induced seismic events, locate them, and estimate their magnitude (Pena Castro et al., 2019). It is important to carry out continuous monitoring and regularly assess the risks associated with human activities to minimize the potential negative effects of induced seismicity (Scanlon et al., 2019; Vilarrasa et al., 2019). Several types of induced seismicity include:

- Natural induced seismicity:

There are cases of seismicity induced by natural phenomena. There are earthquakes triggered by lunisolar tides. The physical phenomenon involved is a weak disturbance of the constraints, generating instabilities that can trigger events.

- Seismicity related to fluid injections:

The first instances of human-induced seismicity were observed in the 1960s in Lake Colorado, specifically with injections at Rocky Mountain in Colorado as reported by Healy et al. in 1968. Evans (1966) documented that over 1,300 events were recorded in the surface. These events were induced by fluid injection at Arsenal. Zoback and Healy (1984) estimated that an increase in fluid pressure of 3.2 MPa was enough to trigger seismic activity.

- Induced seismicity in mines:

Some mines may be prone to sudden collapses, which are not necessarily related to explosions. Slow extraction of a large volume of rock generates stress instability and subsequently can trigger induced earthquakes. Fluid transfers and geological (mechanical) discontinuities are all influential factors that control these phenomena.

- Seismicity induced by the exploitation of hydrocarbons:

Since the onset of extensive hydrocarbon exploitation, numerous cases of seismic activity have been associated with deposits. Examining small to medium-sized earthquakes in oil and gas fields offers a distinctive opportunity to establish connections between earthquakes and the physical conditions under which they occur. Many instances of induced seismicity have been documented in the literature (e.g., Dost et al. 2020).

- Seismicity related to dams:

Studies on dam-induced seismicity began in the 1960s. Currently, the number of reservoirs that have been identified as artificial lakes that can trigger seismicity exceeds 90. Huge artificial reservoirs are being constructed worldwide for various purposes such as hydroelectric power generation, flood control, and irrigation. The occurrence of induced earthquakes due to water reservoirs was observed at Lake Mead in the United States of America for the first time.

There have been several cases of dams inducing seismic activity have highlighted the potential risks associated with large-scale dam construction and operation. One prominent example is the Koyna Dam in western India, which has been linked to a series of earthquakes since its construction in the 1960s (Mikhailov et al. 2017). The largest earthquake, with a magnitude of 7.9, occurred shortly after the dam's construction and resulted in over 80,000 deaths (Lei 2011). These cases underscore the importance of careful monitoring and assessment of the potential risks associated with continuous monitoring and these risks, we can minimize the potential for dams to induce seismic activity and mitigate the impacts of any earthquakes that do occur.

The Tunisian territory occupies a geologically significant position in Africa, located between the highly deformed craton Saharan domain and the Alpine domain in the North, which was deformed during the Mesozoic and Cenozoic periods. The seismicity catalog of Tunisia shows moderate magnitudes for most events. However, some events have been highly destructive. The analysis of seismic records from the establishment of the National Seismological Network, indicate that the region remains seismically active.

The Sidi Salem reservoir is an embankment dam. The height of the artificial lake is 73 m and its volume is 814 Mm3. The studied dam is located in Béjà which is situated in Noth West Tunisia. This region is known as most important seismic activity in the country. The impoundment of the dam was in 1982. The chosen period in this study is from 1976 until 2022. Seismic activity around the dam is monitored by the National Institute of Meteorology (INM) network of seismic stations. This time period was selected because the network significantly improved after 1976 with the installation of numerous seismic recording stations. All events included in this study have a magnitude greater than 2.

2. Material and methods

We obtained the water level data from the Department of Large Dams in Tunisia, which operates under the Ministry of Agriculture, Water Resources, and Fisheries. We used seismic catalog provided by the National Institut of Meteorology to compile the events. We then used Matlab to analyze the data.

- Representation of the Study Dam

The Sidi Salem dam is situated 70 km southwest of the city of Tunis and 4.5 km northwest of the city of

Testour. The coordinates of the dam are as follows: 36°35'27" North and 9°23'51" East (see Fig. 1).

Fig. 1. Location of the Sidi Salem dam

The Sidi Salem dam is strategically situated at the confluence of the Medjerda River with the El Melah, Khalled, and Siliana Rivers (see Fig. 1). It serves as a linchpin in the Medjerda valley, playing a crucial role in water resource management for northern Tunisia. This integrated system ensures the safety and long-term sustainability of the country's economic infrastructure. Completed in 1981, the Sidi Salem dam is an embankment structure, standing at a height of 73 meters, with a total volume capacity of 814 million cubic meters. Its primary objectives encompass flood protection for the lower valley, water supply, irrigation, and power generation (Gaieb et al. 2019).

3. Material and methods

3.1. Seismotectonic Context of the Studied Area

In examining the seismotectonic context of the study area, it becomes evident that the active fault directions, represented by the two nodal planes of most focal mechanisms, indicate a compressive deformation oriented in the NE-SW direction (Gaieb et al.2017) (see Fig.2).

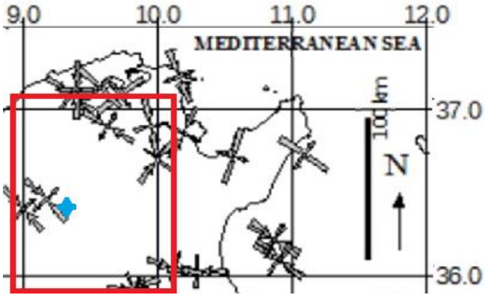

Fig. 2. Seismotectonic context of the studied area: the blue star represents the Sidi Salem dam; the red square represents the studied area

The dam is located at the final topographic narrowing of the Medjerda Valley, within an inter-diapiric synclinal structure of the Oued el. Melah. The presence of Triassic deposits in this tectonic structure which represents the retaining sides of the dam indicate that the reservoir's full pressure exerted itself on these tectonic contacts. This seismotectonic context is highly significant and has had a major impact on inducing seismic activity caused by the reservoir.

3.2. Studied Area from Geological Perspective

From a geological perspective, the Sidi Salem dam is situated in the northern Tunisian Atlas, specifically within the diapir zone. Upstream of the site, the Medjerda River flows in an east-west direction, passing through the Triassic extrusions of Jebel el Melah, which predominantly trend in a NE-SW direction over a distance of approximately 8 km. At the confluence with the Oued Zerga, a left bank tributary of the Medjerda, the river changes its course to a north-south direction until Testour.

The geological formations in the study dam are presented by an anticline formed by alterning Miocene marl-sandstone series. Downstream of the site, on the left bank, the complex structure of the Teboursouk alignment is bounded by Eocene Nummulite limestone formations of Jbel Skhira. These structures are more prominently exposed further north and are compressed within the Miocene terrains, forming distinct layers. On the right bank, the Miocene formations about the intricate structure of the Triassic Teboursouk mountains, which are punctuated by the Oued Melah diapir (Ben Mammou 1998). However, a regular monoclinal structure is present upstream from the dam site. The layers corresponding to the northwestsoutheast alignment of the dam are parallel to the straight course of the valley. These layers dip slightly towards the left bank at an angle of approximately 20°.

The Neogene facies in the geological survey of the Sidi Salem reservoir constitute the most extensive deposits in the Triassic diapir zone. These deposits are predominantly lagoonal-continental and are characterized by thick layers of conglomeratic, clayey-sandy sediments. Notably, several formations can be distinguished: the HAKIMA Formation, OUED MELAH Formation, and KECHABTA Formation:

- HAKIMA Formation:

It consists of sandstones, clays, conglomerates, and variegated breccias, mostly of lagoonal origin.

- OUED MELAH Formation:

These are predominantly Helvetian marls.

- KECHABTA Formation:

This formation corresponds to Tortonian sandstones and clays. Vertically and laterally, they transition into the marls of the Oued Melah.

The HAKIMA, OUED MELAH, KECHABTA formations of the detrital Pliocene underwent folding deformation during the Villafranchian.

The geological formations present at the site originate from the Miocene age and are attributed to the Kechabta formation, which is a thick marl-sandstone series exceeding 1000 m in thickness. The sandstone beds' thickness and their proportions relative to the marl layers also vary from the base to the top. The alternating layers, cut obliquely by the valley, exhibit an upstream dip ranging from 45° to 60°.

3.3. Seismic activity in the vicinity of the artificial lake

Seismic activity around the dam is controlled by the National Institute of Meteorology (INM) which is the national seismic monitoring center in Tunisia. The events analyzed in this part of the study span from 1976 to 2010. This time period was selected because the network significantly improved after 1976 with the installation of numerous seismic recording stations. All events included in this study have a magnitude greater than 2.

Seismic activity in the vicinity of our studied dam is not insignificant. Before the reservoir impoundment, between 1976 and 1981, a total of 248 events were recorded within a radius of 100 km from the dam (see Fig. 3). The seismic activity is relatively low, with most earthquakes having a magnitude almost equal to 2. Notably, to the east of the dam, there is a higher occurrence of seismic events compared to the west. This can be attributed to the influence of the major accident at Teboursouk, the active Sidi Thabet fault, and the Utique fault. Furthermore, during the 1980s, the Mejezel Bab region experienced several earthquakes near Jbel Bou Mousse (Gaieb et al. 2022) (see Fig. 3).

Alternatively, seismic activity increased significantly after the reservoir impoundment, with a total of 684 events recorded between 1982 and 2010. These events occurred near to the dam, within a 10 km radius around the reservoir, and had magnitudes ranging from 2 to 4. During this period, there was a notable increase in the number of earthquakes especially to the west of the dam. The heightened seismicity observed west of the reservoir following the impoundment suggests that the Sidi Salem dam induces seismic activity. Additionally, it thinks that two earthquakes with magnitudes of 3 and 4 occurred within 5 km of the dam (see Fig. 4).

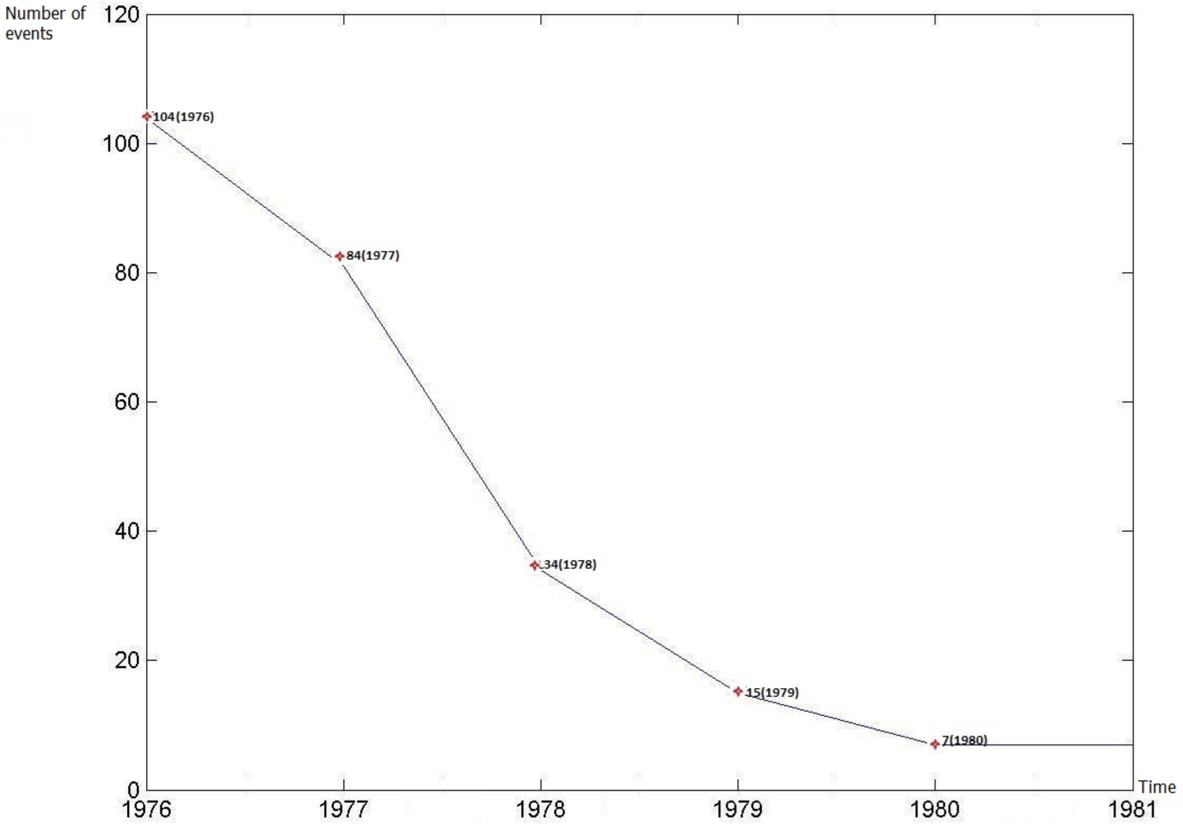

Fig. 3. Seismic events before the filling of the reservoir with different magnitudes

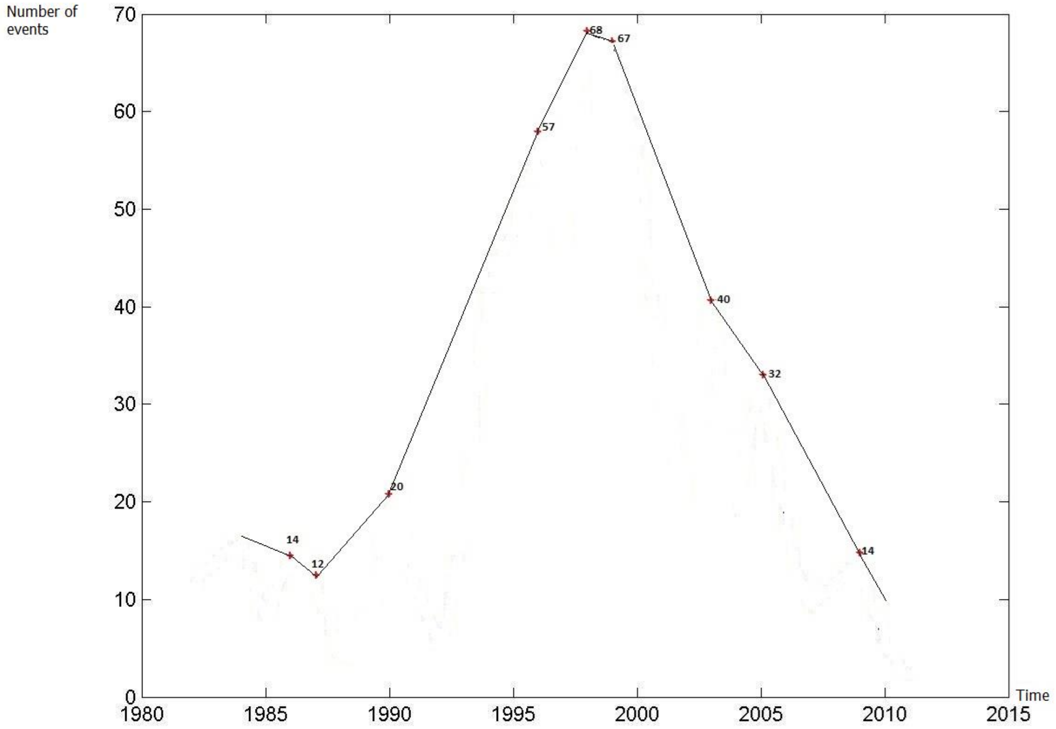

Fig. 4. Seismic events after the filling of the reservoir with different magnitudes

3.4. Relation between seismic activity and Water Level

The results in the figure 5 suggest that the triggering of earthquakes around the dam is linked to the reservoir’s full filling. However, a significant seismic event with a magnitude of 5.0 occurred in 1987 after the reservoir was completely filled. During the hydrological year 1986-1987, the total net input to Sidi Salem exceeded 725 hm3, and the water level reached 109 meters for four months (February, March, April, May). Besides, in 1991, a seismic event with a magnitude of 3.3occured, the epicenter of this earthquake was located near the Trajan Bridge at the Sidi Salem retaining tail. This year, was an exceptional wet hydrological year (1991), during which the dam's water level fluctuated between 109.96 and 108.24 meters. The normal water level of the dam reservoir, set at 110 meters by the spillway threshold (Tulipe), was raised to 115 meters in 1999. Subsequently, seismic activity experienced a significant increase from the year 2003 onward. This new level of normal water was surpassed multiple times, since the first month of 2003, when it reached a dimension of 117.51 meters. The floods during that year resulted in the accumulation of over one billion cubic meters of water in Sidi Salem's reservoir. In this particular year, the water level in the Sidi Salem artificial lake was 117.51 meters for the first time since the impoundment of the artificial lake, which was 2 meters below the highest exceptional water level recorded at 119.5 meters. In 2009, two seismic events occurred close to the dam, with magnitudes of 3.5 and 3.3. During that year, the water level in the reservoir exceeded 117 meters (see Fig. 5).

To gain a better understanding of the relationship between the water level in the dam and the occurrence of events around the reservoir, we conducted a correlation analysis using Matlab. The graph illustrates that the number of events increases whenever there is a significant fluctuation in the water level. Conversely, the number of events decreases when the water level stabilizes. The initial peak in the graph corresponds to the complete filling of the reservoir in 1987 (see Fig. 6).

However, the peak in 1998 does not align with the water's fluctuation; it represents a natural earthquake unrelated to dam-induced activity. We propose that this seismic activity is a result of the moment effect caused by the loading of the reservoir and also caused by the delayed effect of pore pressure diffusion. The occurrence of seismic events around the dam seems to be correlated with the water level in the reservoir. Monitoring micro seismic activity through a local monitoring network remains a crucial tool for managing the risk of induced seismicity. Regrettably, despite the significance of the dam as the largest one in the country, there is a lack of seismic monitoring stations in its vicinity. This limitation prevents us from accurately determining seismic activity below a magnitude of 2 and monitoring micro seismic activities.

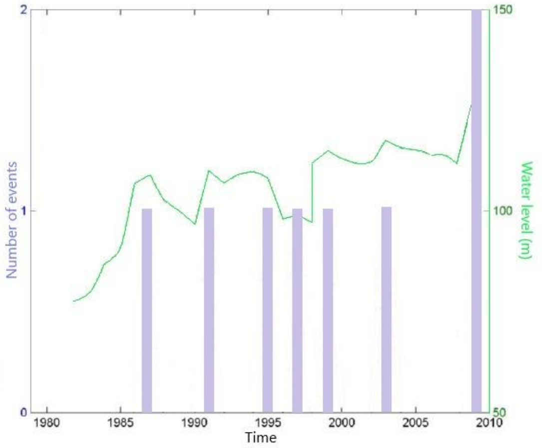

Fig. 5. Correlation plots of the seismic activity and the variation in the water level of the dam (1982-2010).

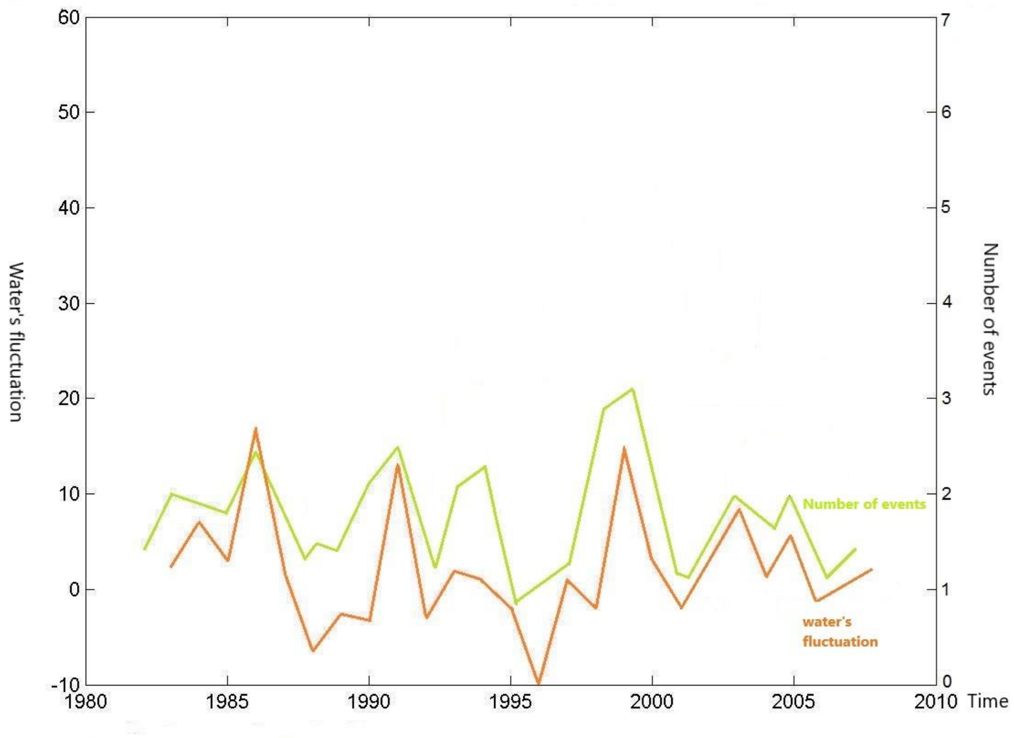

Fig. 6. Correlation plots of the water's fluctuation and the seismic activity (1982-2010)

3.5. Seismicity Around Sidi Salem's Dam During the Five Last Years

Since its impoundment, the Sidi Salem dam has consistently demonstrated its ability to induce seismicity, establishing itself as a prominent case of reservoir-triggered seismicity. The frequency of seismic events has continued to rise in recent years. In this part of our study, we conducted a comparative analysis of the seismic activity near the dam. Specifically, we examined the seismic activity before the impoundment of the lake (from 1976 to 1981), the seismic activity within the same radius five years after the impoundment, and the number of events recorded during the most recent five-year period (2018-2022). The seismic events are monitored and recorded by the national monitoring network, with magnitudes equal to or greater than 2. Before the impoundment period (1976-1982), within a 25 km radius of the dam, a total of 10 earthquakes were recorded, with magnitudes around 2 near the lake (see Fig. 7).

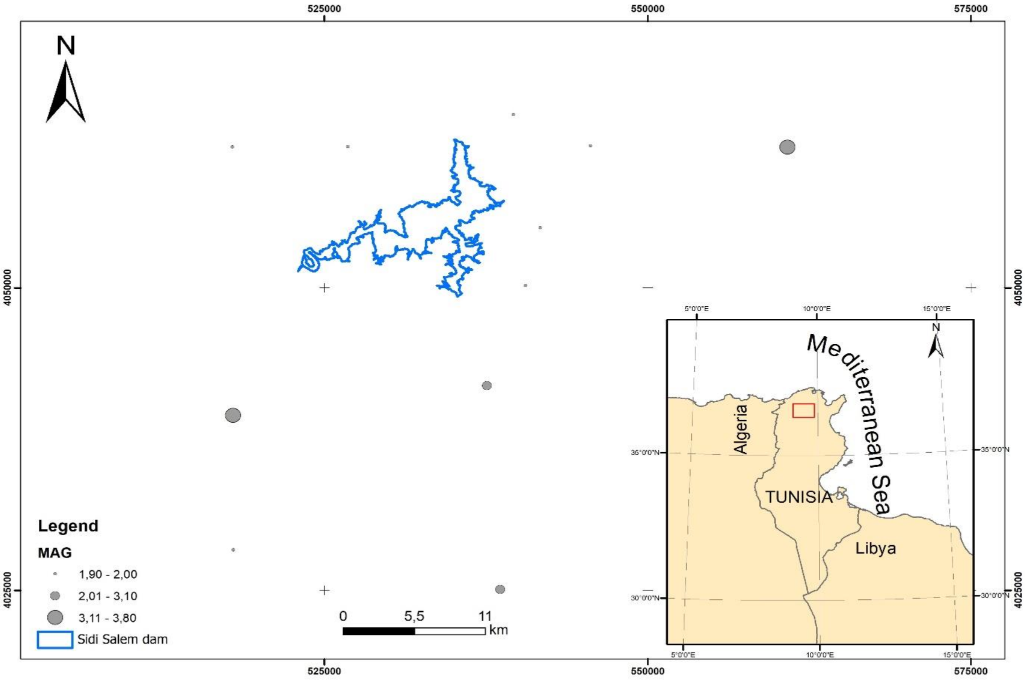

Fig. 7. Seismicity around Sidi Salem dam before the impoundment (1976 – 1982)

However, in the five years following the impoundment, the number of events increased significantly and cannot be ignored.

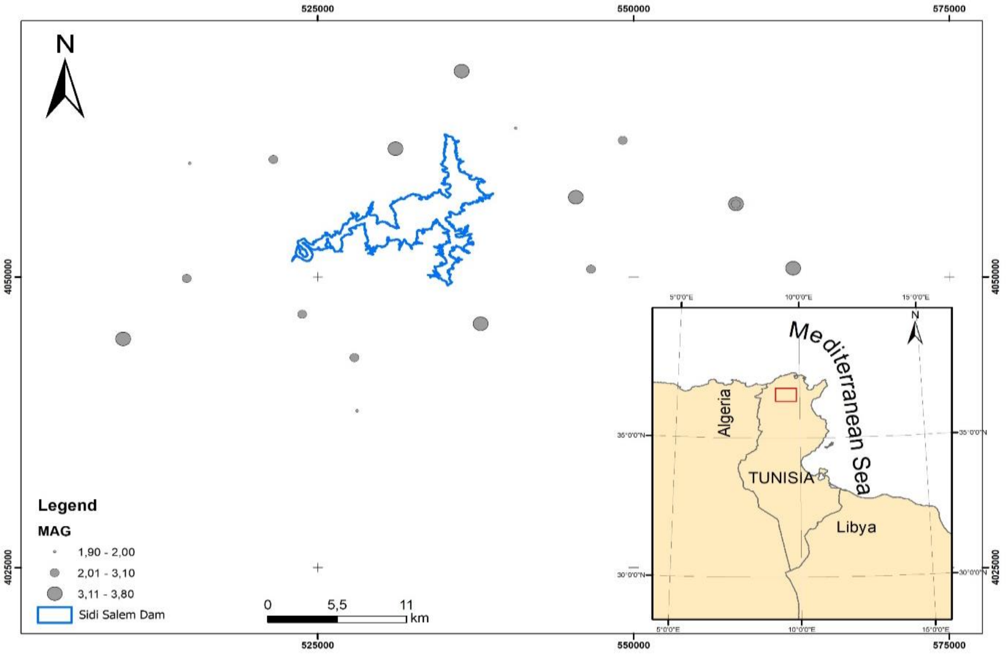

Fig. 8. Seismicity around Sidi Salem dam after 5 years of the impoundment (1982 - 1987)

The magnitudes of the earthquakes in proximity to the reservoir exceeded 3. The majority of these seismic events occurred in 1987, following the complete filling of the dam (see Fig. 8)

Over the last five years, seismic activity has seen a significant increase. During this period, a notable number of events were recorded, including an earthquake near the tail of the dam with a magnitude of 3.8 (see Fig. 9).

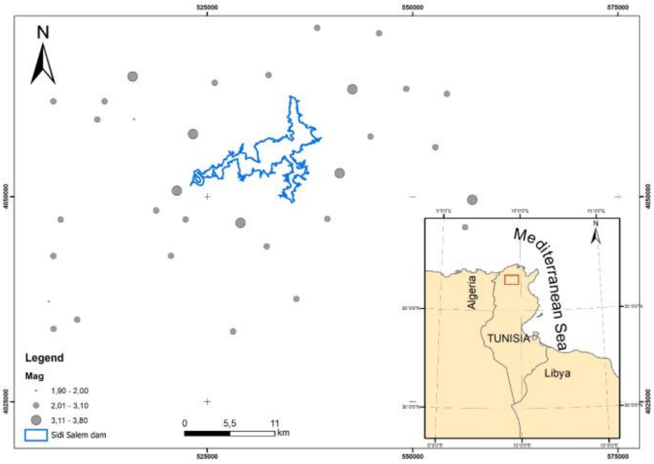

Fig. 9. Seismicity around Sidi Salem dam during the 5 last years (2018 - 2022)

This surge in seismic activity around the Sidi Salem dam can be attributed to the role of the reservoir in altering fault stability. The reservoir imposes an additional load of varying intensity on the point of the Earth's crust due to the accumulation of significant volumes of water. The influence of this load depends not only on the depth of the reservoir but also on its extent. The water accumulation in the reservoir leads to water infiltration into the ground, resulting in increased hydrostatic pressures along several permeable discontinuity surfaces near the Sidi Salem reservoir. These discontinuity surfaces can serve as pathways for water circulation. The fluid pressure within the pores and fractures of rocks, known as pore pressure, can counteract both the weight of the rock and the applied forces. The rise in pore pressure reduces the normal stress acting on the discontinuity surface because the pore pressure opposes the normal stress, thereby diminishing its shear strength. This leads to an "effective stress" that allows seismic activity to occur under low shear stresses.

4. Discussion

Over the last five years, seismic activity has seen a significant increase. During this period, a notable number of events were recorded, including an earthquake near the tail of the dam with a magnitude of 3.8 (see Fig. 9).

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The water accumulation in the reservoir leads to water infiltration into the ground, resulting in increased hydrostatic pressures along several permeable discontinuity surfaces near the Sidi Salem reservoir. These discontinuity surfaces can serve as pathways for water circulation. The fluid pressure within the pores and fractures of rocks, known as pore pressure, can counteract the rock's weight and the applied forces. The rise in pore pressure reduces the normal stress acting on the discontinuity surface because the pore pressure opposes the normal stress, thereby diminishing its shear strength. This leads to an "effective stress" that allows seismic activity to occur under low shear stresses.

5. Conclusion

Within the seismotectonic context of the studied area, it's notable that the directions of active faults align with the nodal planes of most focal mechanisms.

The increase in seismic activity around the dam, particularly over the past five years, is a clear indication of the impact of its impoundment. Additionally, a noticeable correlation exists between the water level in the reservoir, its fluctuations, and the frequency of events around the dam.

The seismicity in the region has been meticulously monitored by the seismic network established by the INM (National Institute of Meteorology). However, despite the dam's significance as the largest in Tunisian territory and its critical role in water management for northern Tunisia, there's a notable absence of seismic monitoring stations around the dam.

The installation of seismic monitoring stations around the dam is an important task for ensuring the reservoir's safety and the acquisition of valuable microseismic data. These data will serve as a crucial database for the Tunisian government and future scientific research endeavors.

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