Spatial database and website for reservoir triggered seismicity in Brazil

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Abstract

After confirming that impoundment of large reservoirs could cause earthquakes, studies on reservoir-triggered seismicity (RTS) have had a considerable scientific incentive. Most of the studies determined that the vertical load increase due to reservoir load, and the reduction of effective force due to the increase in pore pressure, can modify the stress field in the reservoir region, possibly triggering earthquakes. In addition, the RTS is conditioned by several factors such as pre-existing tectonic stresses, reservoir height /weight, area-specific geological and hydromechanical conditions, constructive interaction between the orientation of seismotectonic forces, and additional load caused by the reservoir. One of the major challenges in studying RTS is to identify and correlate the factors in the area of influence of the reservoir, capable of influencing the RTS process itself. A spatial seismicity-triggered reservoir database was created to facilitate the research in this field, based on the specifications of the national spatial data infrastructure (INDE), assemble data pertinent to the RTS study in the area of reservoirs. In this context, this work presents the procedures and results found in the data processing of seismotectonic factors (dam height, reservoir capacity, lithology and seismicity) and compared first to the dams that triggered earthquakes and secondly the Brazilian dam list. The list has been was updated with 4 more cases adding to 30 cases. The results indicate that the occurrence of RTS increases significantly with dam height since dams less than 50 m high cause only 2% of earthquakes while those higher than 100 m cause about 54%. The reservoir volume also plays a role and it was estimated that RTS occurrence requires a limiting minimum value of $1x10^{-4}$ km^3. There was no clear correlation between the geology and geological provinces with RTS. The delayed response time of the reservoirs represents 43% of the total, that is, almost half of them have a hydraulic behavior. The highest magnitude, 4.2 was observed at a reservoir with a volume greater than 10^{-3} km^3. As a practical result to assist the analysis by the general community, the web viewer RISBRA (Reservoir Induced Seismicity in Brazil) was developed to serve as an interactive platform for BDSDR data.

Introduction

The reservoir-triggered seismicity (RTS) phenomenon was first observed during the filling of Lake Mead at the Hoover Reservoir (United States) in the mid-1930s, and occurrences of RTS in case of the following reservoirs: Hsinfenghiang (China), Kariba (Zambia), Kremasta (Greece), and Koyna (India) in the late 1960s (Marza,1999). Currently, there are more than 150 identified as RTS (Gupta, 2002; Wilson at al., 2017; Foulger at al., 2018) and the worst case may be the major earthquake in May 2008 in Sichuan, China. The 7.9 magnitude earthquake, about 80.000 people, broke nearly 300 miles of fault and damaged 2.380 dams, including a 156-meter-high Zipingpu Dam (International Rivers, 2009). (Figure1). Filling large reservoirs, mining underground mines, injecting high-pressure fluids into deep wells, removing fluids during oil exploration, and the after-effects of large nuclear explosions can cause earthquakes (Simpson, 1986). Among these, we highlight the RST phenomenon related to geoengineering works that can have major social, economic, environmental, legal, impacts, among others.

In Brazil, the first STR case was a 3.7 magnitude earthquake with intensity V-VI (MMI) recorded at the reservoir of Carmo do Cajuru, MG, in 1971. Approximately 185 RTS cases are known worldwide, of which 30 happened in Brazil (Foulger et al., 2017; Wilson et al., 2017) (Figure 1). There are several studies on reservoirs capable of triggering earthquakes (Assumpção et al., 2002; Ferreira et al.,2008; Veloso and Gomide., 1997), few of them, however, correlate the physical and geological information as possible agents of the triggered earthquakes. Making this correlation expands the ability to understand this phenomenon. Thus, this work presents the procedures and results found in the data processing concerning the following parameters (height, volume, area, geology, and local seismicity level) and comparing them with the dams that triggered earthquakes and the Brazilian dam catalog. Finally, a spatial database model of the reservoirs and their geological and geophysical characteristics was developed.

This work is based on the work developed by the Comissão Nacional de Cartografia (CONCAR, 2010) and the Technical Specification for the Structuring of Vector Geospatial Data of Defense of the Earth Force - ET-EDGV (Brazil, 2015, 2016). Because these specifications are still being developed, the diagrams of the dam systems are not yet adequately represented. The amount of information and probable effects RTS causing requires the standardization of information, which was accomplished according the National Spatial Data Infrastructure (INDE).

The work is based on the OMT-G (Object Modelling Technique for Geographic Applications) model (Davis Jr., 2000; Borges et al., 2001; Borges et al., 2005) also used in these documentations. This model aims to be more faithful to the modeled reality by using a smaller set of graphic objects than would be used in other models for geographic data.

Database and web viewer

The motivation for creating the Seismicity Database Triggered by Reservoir (BDSDR) arose from the research in the cases that occurred in Brazilian Reservoirs when observing the lack of cohesion of information, pertinent to the study, presenting only isolated cases or listing with the locations of occurrences.

The purpose of the database is to gather all the available information such as physical, structural, Geological and geophysical data on each reservoir, and to store in a standardized way while sharing and making it accessible so that the database can assist in RTS studies.

National Spatial Data Infrastructure (INDE/ NSDI)

The body responsible for developing spatial data structures is the Comissão Nacional de Cartografia (CONCAR) that is linked to the former Ministry of Budget and Management Planning. CONCAR is responsible for elaborating the technical specifications related to the spatial data that make up the Infraestrutura Nacional de Dados Espaciais (INDE), regulated by Decree No. 6,666/2008. According to this decree, INDE is an integrated set of technologies, policies, mechanisms and procedures for coordinating and monitoring, standards and agreements, necessary to facilitate the storage, access, sharing, dissemination and use of geospatial data that belong to the federal, state, district and municipal spheres of government (Brazil, 2008).

The spatial data infrastructure defines the standards for the data composing and can be presented as a Technical Specification. In 2006, CONCAR set up the Specialized Committee for the Structuring of the Digital National Map (CEMND), which developed the Technical Specifications for the Structuring of the Geospatial Vector Data (ET-EDGV) for application in the National Cartographic System and INDE (CONCAR, 2017).

The specifications proposed for the EDGV (CONCAR, 2017) divide the Brazilian geographical space into two groups. The first group consists of the object classes usually produced in the Small-Scale Mapping (MapTopoPE), elaborated in the Systematic Mapping of the SCN (scales of 1: 25,000 and smaller). The second group consists of the object classes usually acquired in the topographic mapping of large scales. This work will use only the small-scale topographic model.

MapTopoPE is divided into 14 categories: Energy and Communications (ENC), Economic Structure (ECO), Hydrography (HID), Boundaries/Limits and Localities (DML), Reference Points (PTO), Relief (REL), Basic Sanitation (SAB), Vegetation (VEG), Transport System (TRA), Transport System/Airport Subsystem (AER), Transport System/Duct Subsystem (DUT), Transport System/Rail Subsystem (FER), Transport System/Hydro Subsystem (HDV), and Transportation System/Road Subsystem (ROD).

In conceptual modeling, the object classes are grouped into categories with common functional aspect. Among the categories, the hydrography package covering the dam class is the class of interest for this paper. However, the other classes inserted in the proposed model do not have definitions pre-established by the INDE. According to the INDE Action Plan (CONCAR, 2017), the data or datasets associated with each of these EDGV classes are considered as reference geospatial data in the INDE.

The Action Plan for implementing INDE classifies the data into thematic and reference data. Thematic data are sets of data and information on a phenomenon or a theme, such as climate, education, vegetation, industry, among others, in a region or across the country. Whereas, according to CONCAR (2010), the reference data are defined as:

"Datasets that provide general information of non-particular use, elaborated as indispensable bases for the geographic referencing information on the surface of the national territory and can be understood as basic inputs for georeferencing and geographical contextualization of all the specific territorial themes".

Designing the Spatial Database

For implementing the data in the database management system, three phases are required: conceptual modeling, logical modeling and physical modeling or implementation. This same method is used for modeling spatial databases.

First Phase: Conceptual Modeling

Conceptual modeling is not directly linked to implementation, its main objective is to capture the semantics of the problem and the needs of the study in question (Cardoso and Cardoso, 2012).

The OMT-G (Object Modelling Technique for Geographic Applications) data model was used to create the conceptual model of the Reservoir-Triggered Seismicity Database (BDSDR). This model was chosen following the NSDI specification.

From the studies on the metadata of the archives of the seismological data, it was initially defined a model consisting of 20 entities: Stress Regime, Fault Orientation, Fault Mechanism, Chronostratigraphy, Structure, Lithology, Reservoir, Dam, Federative Unit, Municipality, Hydrometry, Magnetometry, Electromagnetometry, Gravimetry, Pluviometry, Regional Stress

Regime, Hydrography, Crustal Thickness, Seismic Event, and Seismographic Station. Figure 2 presents the conceptual model based on OMT-G, developed in the StarUML 5.0.2.1570 software while Table 1 explains each relationship of the OMT-G model.

Second Phase: Logical Modeling

Creating the Reservoir-triggered Seismicity database in a Database Management System (DBMS) required transforming the conceptual model into an implementation model. This transformation consists of converting the OMT-G model into the relational model (MR) that represents the data in the database as a collection of relationships (tables).

At this stage, key attributes such as imposing relational integrity, creating unique indexes, attributing data types, and the height of the fields to store information are defined and identified. The logical model was created using the StarUML 5.0.21570 software.

Figure 3 shows the BDSDR relational model that was created from this conversion.

Third Phase: Physical Modeling

The last phase of the database design consists of creating a physical schematics, which depends on the used Database Management System (DBMS) (Cardoso and Cardoso, 2012). DBMS is the set of computer programs that can change the logical and physical structure of the database. The degree of freedom of the data is higher than in the older systems (Teorey et al., 2014).

Database management software uses database management software (DBMS), p. e.: Medeiros (2012). For the development of the spatial database, in Linux environment, postgreSQL 9.3 with raster extension was used, PostGIS 2.4, pgAdim III and Quantum GIS (QGIS) version 3.12.

Most database management systems do not support the spatial data implementation natively, requiring the use of spatial extensions. The extension used in the implementation of BDSDR was PostGIS 2.4. The PostgreSQL is an open source object-relational database management system, that allows to study, modify and distribute the software free of charge for any purpose to anyone. Object-relational refers to the spatial database system optimized for storing and querying data related to objects in space, including points, lines, and polygons (Elmasri and Navathe, 2011).

Web viewer

A web viewer is an interactive map in an application that allows the user to interact with elements on the map and obtain information on these elements.

The web viewer, named RISBRA (Reservoir Induced Seismicity in Brazil), was created using the leaflet, Node.js and Redis libraries. The leaflet is an open source JavaScript library for interactive maps that provides great tools for implementing map applications for browser interaction (Leaflet, 2018). Redis is an open source network application, in-memory data structure store, used as a database, cache and message broker (Redis, 2018). Finally, Node.js is an open source JavaScript interpreter that focuses on migrating client-side JavaScript to the server side (Node.js, 2018).

We developed a menu, named LAYERS, which contains all the tables of the bank that can be represented in the map. Figure 4 shows the RISBRA interface and the earthquake icon selected. The image shows the table *layers*, where the data that can be accessed by the user at any time (Reservoir, Dam, Crustal Thickness, Seismographic Station, Structure, Seismic Event, Hydrography, Lithology, Fault Orientation, Pluviometry, Stress Regime, Triggered Earthquakes, Chronostratigraphy, and Fault Mechanism). The data are arranged in the interactive map using icons with the conventional symbology of different formats and colors. All elements are georeferenced on the map of Brazil. The zoom tool in the lower right corner of the screen allows expanding the map to the street level.

Reservoir-Triggered Seismicity List updated for the database

Data linked to geology and/or geophysics are dispersed, varying from reservoir to reservoir. The Brazilian bibliography of dam studies presents isolated cases and general listing of the cases. Marza et al. (1999) pioneered the creation of the Reservoir-Triggered Seismicity List, which was later updated by Assumpção et al. (2002), França et al. (2010) and Barros et al. (2018). However, a systematic database containing this information has not yet been established.

From 1966 to 2018, 626 events were classified as RTS using Geiger's method (data from the seismic bulletin of the IAG-USP and SISBRA-Brazilian bulletin cataloged by SIS-UnB), with seismic recurrence in several dams, the largest being 4.2 recorded in the dams of Porto Colombia and Volta Grande, at the border between the states of Minas Gerais and São Paulo. Figure 5 shows a histogram for the 367 events with a magnitude greater than 1, according to the data from the seismic bulletin of the IAG-USP and SISBRA (Brazilian bulletin cataloged by SIS-UnB). This histogram clearly shows the seismic swarms in the Itapebi and Carmo Cajuru dams in 2003, and Lajeado and Nova Ponte in 2006. These swarms were well monitored by local networks. The histogram also shows the increased monitoring and dam construction since 2002 (Oliveira, 2018).

In this work, the RTS cases are compared using the unified list (Table 2), where the maximum magnitude recorded in each dam is considered from the reviewed list of all Brazilian dams. The objective is to calculate the potential for triggering an earthquake according to dam height, reservoir capacity, lithology and seismicity. Therefore, we use the data available in the National Register of Dams from the Brazilian Committee of Dams which lists a total of 1413 dams with different purposes. We selected a total of 348 reservoirs, at least 20 m high, built for producing electricity (hydroelectric), except for the Açu and Castanhão reservoirs that fight drought and irrigation, respectively. Dams lower than 20 m high were discarded since these dams have low probability of triggering earthquakes, refer to previous works (e.g. Assumpção et al., 2002).

Table 2 and Figure 6 present the updated RTS cases, which increased from 17 (Marza et al., 1999) to a total of 30 cases. Table 2 is based on the work of Marza et al. (1999), to which we added other data such as area of reservoirs, type of seismicity, maximum magnitude, predominant geological type of the reservoir (Craton, Fold and Thrust Belt and Basins), location of the event in relation to the reservoir, and the references.

Results and Discussions

The known RTS cases have significant common features, especially during the initial filling phase of the reservoir, when reservoir-triggered earthquakes generally begin to occur. Factors such as dam height, volume, area, local geology, maximum magnitude, and seismicity in the region may interfere with RTS, each one of these factors are addressed below.

RTS

In general, from the total of 348 reservoirs, only 8.6% of those presented RTS, and only two events with a maximum magnitude greater than or equal to 4.0 (Table 3 and Figures 7 and 8). Regarding damages, the highest seismic intensity of VI-VII (MMI) or Peak Ground Acceleration (PGA) of 0.08 - 0.25, was estimated in Porto Colombia and Volta Grande while the seismicity type was mostly Initial (Table 2).

Geographically, Brazil is divided into five regions; North, Northeast, Southeast, South, and

Midwest. From the regional viewpoint, the southeastern region has the highest number of cases, which is directly related to the high number of reservoirs in the region that accounts for 43% of the country's reservoirs. Additionally, the southeast also concentrates the largest number of reservoirs higher than 50 m (Table 3 and Figures 7 and 8) and the greatest occurrence of natural earthquakes cataloged in Brazil, thus explaining the highest number of RTS in the Southeastern region. However, compared to the number of RTS, 17.8% of the total number of Reservoirs in the Northeast shows that although there are fewer cases in the region, the relative value is comparatively higher. Surprisingly the North region also has a considerable percentage indicating a potential region for RTS whereas the Midwest region has the lowest percentage.

Correlation of RTS with geological characteristics

The hydromechanical properties of the rocks related to the RTS phenomenon were discussed by Snow (1972), Brace (1974), Howells (1974), Bell and Nur (1978) and Do Nascimento (2002). Despite the laboratory test determining these properties, little progress has been made, especially due to the great practical difficulties to map the huge number of rocks below and in the vicinity of a reservoir in terms of porosity, permeability, existence of faults, cracks, etc. (Assumpção et al., 2002). It is known that permeability determines the diffusion velocity of the fluid pressure and controls the volume of affected rocks while possibly being one of the most important factors in the change of seismicity level in the vicinity of a reservoir (Do Nascimento, 2002). The existence of fractures and faults, besides generating a weakness zone due to the low resistance to rupture, it also facilitates liquid penetration all the way to the deepest and most distant reservoir zones, increasing the pressure in the pores. Thus, depending on the orientation of the natural efforts in relation to the fault system, a small effort/stress, even a very small one, of the reservoir may be sufficient to trigger earthquakes (Assumpção et al., 2002).

In order to correlate the probability of RTS with the geotectonic characteristics, was compared the local number of reservoir-triggered seismicity cases with the local lithology (types of rocks): igneous, metamorphic and sedimentary, as indicated in Figure 9a, and the geological province as well. Baecher and Keeney (1982) were among the first to propose to compare the number of cases of RTS with local lithology. The results we had with the same correlation show that igneous rocks have a higher percentage of occurrence of SDR (10.1%) than on sedimentary (8.4%) and metamorphic (8.1%) rocks. This is contrary, for example, to what Baecher and Keeney (1982) estimated for deep, very deep or very large reservoirs (that is, height> 100 m or volume> 10 km^3): sedimentary rocks are slightly more likely (16%) compared to metamorphic or igneous (about 10% each).

Thus, the RTS was also compared to the main geological provinces that are classified by the CPRM (Figures 9b and 10) into three categories: Craton, Basins, and Fold and Thrust Belt. The values were again very close, with the tendency of a higher number of RTS in the region of basins (10.65%).

Although the results show a slight tendency toward igneous rocks in the geological context and basins in geological provinces, it is impossible to determine with certainty the trend of these parameters. Therefore, we suggest an in-depth study on the local structural geology of the dams so that the geological influence can be determined more clearly.

Dimensional physical properties and their correlations

Simpson (1986) observed that the higher the dam the greater the probability of triggering an earthquake, and that the most common RTS occurrence is observed in reservoirs with a maximum height greater than or equal to 100 m. The tectonic, geological and hydrogeological environment of the reservoirs is most affected by the increase of the vertical efforts, via its own weight and/or via the increase of water pressure that infiltrates through pores, faults, and fractures.

Thus, in Brazil, the comparison between the RTS cases and the dam heights indicates that dams smaller than 50 m are only 2% likely to trigger seismicity while those higher than 100 m are approximately 54% (Figure 11a) more likely to trigger earthquakes, confirming Simpson (1986) findings.

According to the CBDB databank, the volume parameter is available for only 256 reservoirs. Figure 11b shows that 47% of the reservoirs with a volume greater than $1x10^{-2}$ km^3 triggered earthquakes, and since this percentage decreases linearly with volume, reservoirs with a volume less than $1x10^{-3}$ km^3 have a low estimated probability for triggering earthquakes. This result demonstrates the influence of volume (pressure) that is clearly related to the type of RTS in Brazil, which are mostly of the initial type (Table 2 and Figure 11b).

Figure 12 shows the correlation between volume and height for RTS cases. We observe that the height does not have a limit between 20m and 209m, which is the height of the largest dam. However, regarding volume, we estimate a minimum value of $1x10^{-4}$ km^3 for generating a RTS, which is represented by a black bar in Figure 12.

Response Time

Seasonal variations in the water level of the reservoir can trigger earthquakes. Simpson (1986) and Talwani (1995) divided the seismic response of a reservoir into two categories, depending on the spatial and temporal pattern of RTS: (i) initial seismicity and (ii) steady state/ initial or delayed response seismicity.

The initial seismicity occurs with the initial damming/impounding of the water or large oscillation of the water level in the lake, which is observed more frequently. Cases of steady state or delayed response seismicity occur at a certain time after the filling/impoundment when the steady-state is reached and presents a more lasting associated seismicity. These different responses may correspond to two fundamental mechanisms by which a reservoir can modify the force in the crust - one related to the rapid increase of elastic stress due to the reservoir load (mechanical behavior) and the other to the more gradual diffusion of water from the reservoir to hypocentral depths (hydraulic behavior). The force may decrease as a result of changes in the elastic stress (decrease of normal stress or increase in shear stress) or reduction of effective normal stress due to increased pore pressure. The pore pressure at hypocentral depths can increase rapidly, from a coupled elastic response due to the pore compaction, or more slowly, with the diffusion of surface water.

Of the 30 RTS cases, only 4 were considered as a delayed response while 17 cases had only an initial response (Figure 13). These different responses may correspond to two fundamental mechanisms by which a reservoir can modify the force in the crust - one related to the rapid increase of elastic stress due to the reservoir load (mechanical behavior) and the other to the more gradual diffusion of water from the reservoir to hypocentral depths (hydraulic behavior). Figure 14 shows reservoir height, volume, and area versus the delay time. The dispersion of the results indicates that correlating any of these parameters with time delay is impossible.

Highest Magnitude

It is known that in large reservoirs, the chances of pressure in the rock pores to affect the existing seismic structures in the area below the reservoir increase; however, there are cases in the literature of small reservoirs triggering earthquakes that released stresses with magnitudes far exceeding the sum of all additional stresses resulting from the lake. As an example, in 1974 in Brazil, the largest RTS event (4.2 mb magnitude) occurred near the Porto Colombia and Volta Grande reservoirs, with 40 and 55 m high and 19.5 and 143 km^2 respectively (number 24 in Table 2). Furthermore, short reservoirs such as Açu and Carmo Cajuru with dams only 31 and 23 m high, triggering earthquakes with magnitudes higher than 3.0 (Veloso and Gomide, 1997; Ferreira et al., 1995).

Based on Klose (2013), the reservoir volume showed a small tendency to generate higher magnitude events compatible with the affected area of the reservoir, depending on its dimensions. Figure 15 shows that most of the events occur in reservoirs with volumes greater than 10^{-3} and with a magnitude of 4.2 in most cases, events between 3 and 4 magnitudes occur in dams lower than 100 ml.

The intensity and Highest Magnitude

Several events were not felt, or there was no micro-seismic survey to define its intensity, for these we consider Intensity I. Figure 16 shows a linear correlation between magnitude and Intensity, disregarding the Intensity I data. Thus, a linear least squares adjustment was performed and resulted in the equation below:

$$I = 1.147M + 1.016$$ (0.35 standard deviation)

The correlation coefficient of 0.66 reflects the small number of data available. It is characteristic of the Intraplate Intensity that the value estimated for Intensity is greater than that estimated for magnitude.

Conclusions

The complete compilation of reservoir-triggered seismicity occurrences, including spatial/temporal behavior, allow a better evaluation of the seismic risk of future reservoirs. Thus, the database allows to present systematically and in one place all the pertinent data regarding RTS cases in Brazil, including all the known parameters that interfere with the RTS process.

The created web viewer, RISBRA, presents an interactive platform with easy access and great potential to improve knowledge on the RTS in Brazil.

The histogram of the RTS cases reflects seismic swarms, greater monitoring and construction of dams since 2002. We highlight that, as of 2011, Brazilian Seismographic Network (RSBR) was established, which improved the acquisition of seismic monitoring data. The RSBR is the joint work of four different institutions: Universities of São Paulo (USP), Brasília (UnB), Rio Grande do Norte (UFRN) and National Observatory (ON). The network consists of more 90 stations (in January 2020) operated by these four institutions (Bianchi et al., 2018).

From the regional viewpoint, the considerable percentage of RTS in the Northern region indicates a potential RTS region, considering the exploratory growth. Despite having a small number of RTS, 5 cases, the Northeast region has a comparatively higher relative value of RTS compared to other regions.

Although the results show a trend with higher number of RTS in case of igneous rocks (rock type) and sedimentary basins (geological provinces) being more prone to RTS, however trends cannot be backed up with the currently available data. Therefore, we suggest an in-depth analysis of the structural geology at the dam sites in order to understand and identify in more detail the geological influence.

The dam height has been confirmed as one of the main indicators of the dam capability of triggering earthquakes. Dams less than 50 m high are only 2% likely to cause seismicity while those more than 100 m high are about 54% more likely to cause an earthquake.

The reservoir volume also strongly influences its capability for causing an earthquake and we estimate the limiting minimum value of $1x10^{-4}$ km^3 for the occurrence of RTS.

The delayed response of the reservoirs represents 43% in total, indicating hydraulic behavior for almost half of the reservoirs. For higher magnitudes (4.2, the highest recorded), we found that most events occur in reservoirs with volumes larger than 10^{-3} km^3.

An equation "$I = 1.147M + 1.016$ (+ -0.35)" has been determined to describe the relationship between Intensity and highest magnitude. Where “I” is the estimated intensity and “M” is the determined magnitude.

Practical difficulty of mapping soil layers below the dams hinders the evaluation of the seismic risk of an reservoir and, therefore, it is essential to obtain key parameters such as local stresses, rock mass permeability, and fracture system geometry. Thus, studies of previous cases are useful when trying to assess the seismic risk posed by future reservoirs. Most importantly, this work shows that the possibility of RTS occurrence in Brazil cannot be neglected while highlights the importance of continuous monitoring, before, during and after the construction of a dam.

Data and Resources

The data used in this article was extracted from the seismic bulletin and SISBRA. Data and information from the SISBRA can be downloaded from the Seismological Observatory of the University of Brasília (SIS / UnB), Center of Seismology of the University of São Paulo (USP):

www.obsis.unb.br; www.sismo.iag.usp.br; (last accessed December 2018). Information on the dams was taken from the Brazilian Committee of Dams (CBDB) http://www.cbdb.org.br/ (last accessed in October 2018).

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TABLES

Table 1. Explanation of the OMT-G model for the Reservoir-triggered Seismicity Database.

Relationship	Description
Lithology and Structure	The structure is the fault characteristic that is associated with lithology.
Lithology and Chronostratigraphy	Lithology (rock type) has one or more chronostratigraphy data.
Reservoir and Lithology	The reservoir area has one or more types of lithology.
Structure and Stress Regime	The stress regime focuses on the structures
Structure and Fault orientation	Fault orientation refers to diving, direction and inclination information of the structure (fault).
Structure and Fault Mechanism	Failure mechanism refers to information on the characteristics of the structure.
Reservoir and Crustal Thickness	The area of the reservoir has information on Crustal thickness.
Reservoir and Seismic Event	The seismic event may occur in the area of reservoir influence.
Seismic Event and Seismographic Station	Seismic station detects seismic event.
Hydrometry and Reservoir	The reservoirs have daily hydrometric data.
Reservoir and Magnetometry	The reservoir has magnetometry information in its area of influence.
Reservoir and Electromagnetometry	The reservoir has Electromagnetometry information in its area of influence.
Reservoir and Gravimetry	The reservoir has gravimetric information in its area of influence.
Reservoir and Region Stress Regime	The area of reservoir influence has forces acting on the stress regime.
Reservoir and Hydrography	The reservoir is part of the hydrography.
Reservoir and Rainfall	The reservoir area is influenced by rainfall
Reservoir and Dam	The reservoir has a dam.
Municipality and State	Each municipality is located in a state.

572 **Table 2- Seismicity Cases triggered in Brazil.**

										Largest Events							
N°	**Name**	**Federative unit**	**Height (m)**	**Volume ($10^{-3}km^3$)**	**Maximum water depth in the Reservoir (m)**	**Area of the reservoir (km2)**	**Start of impoundment**	**Geological Province**	**Seismicity type**	**Date (YY/MM/DD)**	**Magnitude**	**Magnitude Type**	**Io (MMI)**	**PGA (g)**	**ΔT (year)**	**Location**	**References**
1	Açu	RN	41	2,400	55,0	195.0	1985	Thrust and Folding Range	Delayed	1994/08/26	3.0	mR	IV*	0.03 and below	9.5	Inside	Do Nascimento (2002) and Ferreira et al. (1995)
2	Balbina	AM	31	9,755	51,0	2.36	10/1987	Basin	Initial	1990/03/25	3.4	mb	I	-	2.5	Margin	Assumpção et al. (2002) andVeloso et al. (1991)
3	Barra Grande	RS	185	5,000	-	93.40	12/1999	Basin	Initial- Delayed	2005/10/10	2.5	ML	I	-	0.01	Margin /Inside	Ribotta et al. (2008) and Ribotta et al.(2010)
4	Batalha	MG/GO	52	1,781	800,0	138.13	2014	Thrust and Folding Range.	Initial	2015-08-01	2.1	mD	I	-	-	Margin	Chimpliganond et al. (2015)
5	Carmo do Cajuru	MG	22	0,192	749,7	2.3	1954	Craton	Delayed	1972/01/23	3.7	mb	VI	0.08 - 0.15	18	Margin	Veloso et al. (1987) and Viotti et al. (1995,1997)

										Largest Events							
N°	**Name**	**Federative unit**	**Height (m)**	**Volume ($10^{-3}km^3$)**	**Maximum water depth in the Reservoir (m)**	**Area of the reservoir (km2)**	**Start of impoundment**	**Geological Province**	**Seismicity type**	**Date (YY/MM/DD)**	**Magnitude**	**Magnitude Type**	**Io (MMI)**	**PGA (g)**	**ΔT (year)**	**Location**	**References**
6	Campos Novos	SC	196	1,477	-	34.6	10/2005	Basin		2005/10/12	1.8	ML	I	-	0.01	Inside	Ribotta et al. (2010)
7	Capivara	PR/SP	60	10,540	-	576.0	01/1976	Basin	Initial- Delayed	1979/03/27	3.7	mb	VI-VII	0.08 -0.25	~3	Margin	Assumpção et.al (1995)
8	Capivari- Cachoeira	PR/SP	60	0,178	-	13.1	07/1970	Thrust and Folding Range	Initial	1971/05/21	3.9	ML	VI	0.08 - 0.15	~1	-	Berrocal et. al.(1984) eand Mioto et.al. (1991)
9	Castanhão	CE	85	6,700	100,0	458.00	2003	Thrust and Folding Range.	Initial - Delayed	2007/08/07	2.3	mD	I	-	1?	Margin -Inside	Ferreira et. al. (2008)
10	Emborcação	GO/MG	158	17,588	653,0	473.0	08/1981	Thrust and Folding	Initial	1982/05/20	1.6	ML	I	-	~1	Inside	Viotti et al. (1997,1995)
11	Funil	MG	50	0,258	808,0	33.46	2002	Craton	Delayed	2011/08/14	3.2	mR	IV-V	0.03 -0.15	8	Margin	Barros et al. (2014)

N°	Name	Federative unit	Height (m)	Volume ($10^{-3}km^3$)	Maximum water depth in the Reservoir (m)	Area of the reservoir (km2)	Start of impoundment	Geological Province	Seismicity type	Largest Events: Date (YY/MM/DD)	Magnitude	Magnitude Type	Io (MMI)	PGA (g)	ΔT (year)	Location	References
12	Furnas	MG	127	22,950	-	1.44	1963	Thrust and Folding Range	Initial *	1966/11/15	3.2	mI	IV-V	0.03 -0.15	~1?	-	Berrocal et al. (1984) and Barros et al. (2005)
13	Irapé	MG	209	5,964	470,8	137.0	12/2005	Thrust and Folding Range.	Initial	2006/05/14	3.0	mR	III-IV	0.03 -below	0.01	Inside	França et al.(2010)
14	Itá	RS/SC	125	5,100	370,0	141.0	12/1999	Basin	Initial- Delayed	1999/12/15	2.5	ML	III-IV	0.03 -below	0.01	Margin -Inside	Ribotta et al. (2006b,2010,2017)
15	Itapebi	BA	120	1,633	-	61.58	12/2002	Craton	Initial	2003/08/03	1.5	M_D	I	-	~0.01	Inside - Margin	Barros (2008)
16	Jaguari	SP	77	0,793	-	56.0	12/1969	Thrust and Folding	Delayed	1985/12/17	3.0	ML	V-VI	0.03 -0.15	16	Margin	Veloso et al. (1987)
17	Jirau	RO	62	2,746	90,0	361.6	2014	Basin	Initial	2014/11/07	3.2	mR	IV-V	0.03 -below	0.8	Inside	Barros et.al (2015)

										Largest Events							
N°	**Name**	**Federative unit**	**Height (m)**	**Volume ($10^{-3}km^3$)**	**Maximum water depth in the Reservoir (m)**	**Area of the reservoir (km2)**	**Start of impoundment**	**Geological Province**	**Seismicity type**	**Date (YY/MM/DD)**	**Magnitude**	**Magnitude Type**	**Io (MMI)**	**PGA (g)**	**ΔT (year)**	**Location**	**References**
18	Lajeado	TO	31	5,190	212,3	630.0	2002	Basin	Initial- Delayed	2012/04/01	2.2	mD	I	-	10	Margin	Technical Report of the UnB Seismological Observatory
19	Machadinho	RS/SC	126	3,339	-	79.0	2001/09/08	Basin	Initial- Delayed	2001/09/08	1.8	ML	I	-	0.01	Inside -Margin	Ribotta et al.(2006a) e Ribotta et al. (2010)
20	Marimbondo	MG/SP	90	6,150	-	438.0	1975	Basin	Initial	1978/07/25	2.0	ML	I	-	~3	Margin	Veloso et al. (1987)
21	Miranda	MG	79	1,120	-	70.0	08/1981	Basin	Initial- Delayed	2000-05-06	3.3	mR	V-VI	0.03 and 0.15	2.7	Margin	Barros e Caixeta (2003) e Assumpção et al. (2002)

N°	22	23		24		25
Name	Nova Ponte	Paraibuna-Paraitinga		Porto Colombia e Volta Grade		Serra da Mesa
Federative unit	MG	SP		MG/SP		GO
Height (m)	142	84 /105		40	55	154
Volume ($10^{-3}km^3$)	12,792	1,270	2,636	2,3	1,525	54,400
Maximum water depth in the Reservoir (m)	-	-		-		-
Area of the reservoir (km2)	443.0	47.0	177.0	19.5	143.0	1.78
Start of impoundment	10/1993	1976	1974	09/1973	04/1973	10/1996
Geological Province	Basin	Thrust and Folding Range.				Thrust and Folding Range
Seismicity type	Initial- Delayed	Initial				Initial
Largest Events						
Date (YY/MM/DD)	1998/05/22	1977-11-16		1974/02/24		1999/06/13
Magnitude	4.0	3.3		4.2		2.2
Magnitude Type	mR	mb		mD		mD
Io (MMI)	VI	IV		VI-VII		I
PGA (g)	0.08 - 0.15	0.03 and below		0.08 - 0.25		-
ΔT (year)		~1		~1		~3
Location	Margin	Inside		Margin?		Margin
References	Chimpliganond (2002), Marza, Barros, Soares et al. (1999) and Marza et al. (1997)	Mendiguren (1980) eand Ribotta (1989)		Berrocal et al. (1984), Veloso (1992a) and Gomide (1999)		Veloso et al. (1987) and Assumpção et. al (2002)

										Largest Events							
N°	**Name**	**Federative unit**	**Height (m)**	**Volume ($10^3 km^3$)**	**Maximum water depth in the Reservoir (m)**	**Area of the reservoir (km2)**	**Start of impoundment**	**Geological Province**	**Seismicity type**	**Date (YY/MM/DD)**	**Magnitude**	**Magnitude Type**	**Io (MMI)**	**PGA (g)**	**ΔT (year)**	**Location**	**References**
26	Sobradinho	BA	43	34,116	-	4.12	1977	Craton		1979/07/05	1.9	ML	I	-	~2	Inside	Berrocal eand Fernandes (1996)
27	Quebra-Queixo	SC	75	0,136	549,0	5.6	2002	Basin	Initial	2003/03/01	0.1	mD	I	-	-	-	Technical Report of the UnB Seismological Observatory
28	Três Irmãos	SP	82	13,800	-	785.0	1990	Basin	Initial	1990/11/01	0.5	mD	I	-	~0.1	-	Technical Report of the UnB Seismological Observatory
20	Tucuruí	PA	95	45,500	-	2.43	Set/1984	Craton	Initial	1998/03/02	3,6	-	IV-V	0.03-0.08	14	Inside	Assumpção et. al (2002)and Veloso et al. (1992b)
30	Xingó	AL/SE	150	3,800	-	60.0	06/1984	Thrust and Folding Range	Initial	1994/07/20	1,7	ML	III-IV	0.03 and below	~0.1	Margem	Berrocal and Fernandes (1996)

573 ΔT, Time interval (years) since the beginning of filling;MMI, Modified Mercalli Scale;

574 Doubtful cases; PGA(g), Peak Ground Acceleration; Adapted by Marza et al. (1999).

575 Table 3- Number of dams, RTSs and natural earthquakes by country regions.

Region	Total number of dams	RTSs	Percentage of RTS cases (%)	Number of natural earthquakes
Midwest	48	1	2 %	1821
Northeast	28	5	17.8%	2393
Southeast	167	14	8.4 %	3475
North	29	4	13.8 %	1814
South	76	6	8.9 %	139

Figures

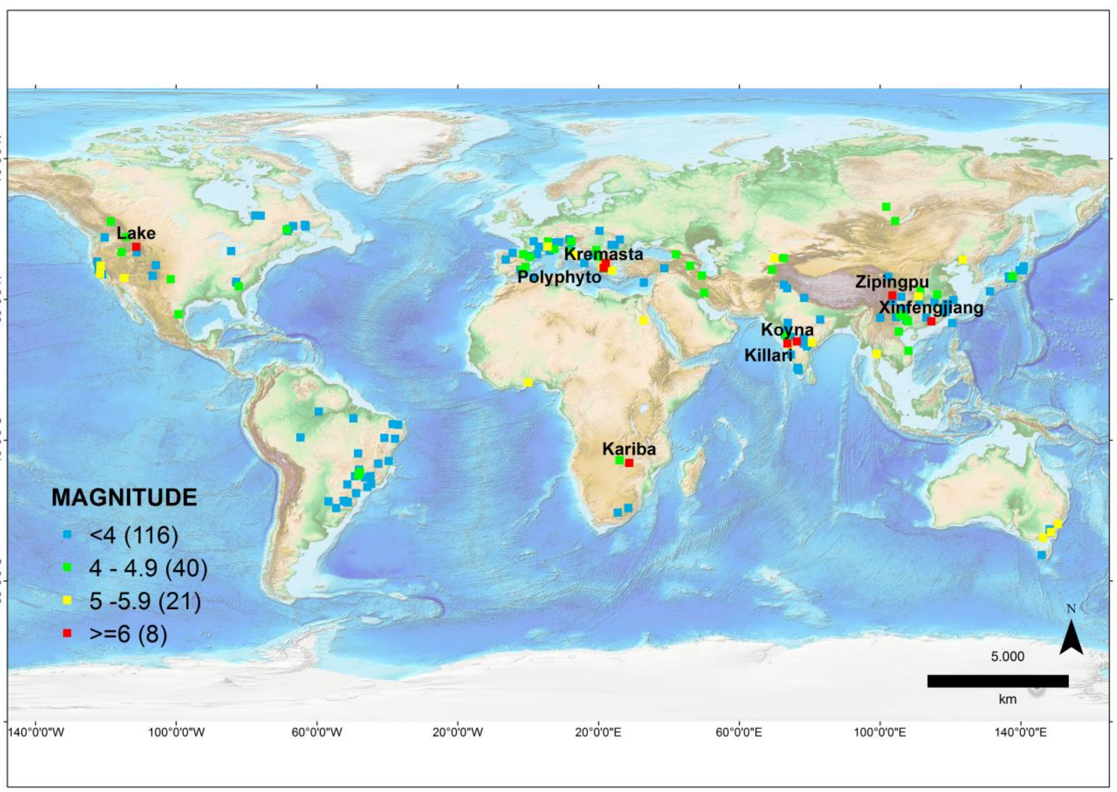


Fig 1 - World map of events triggered by reservoirs. (Data from the www.inducedearthquakes.org. Last accessed 10 May 2020)

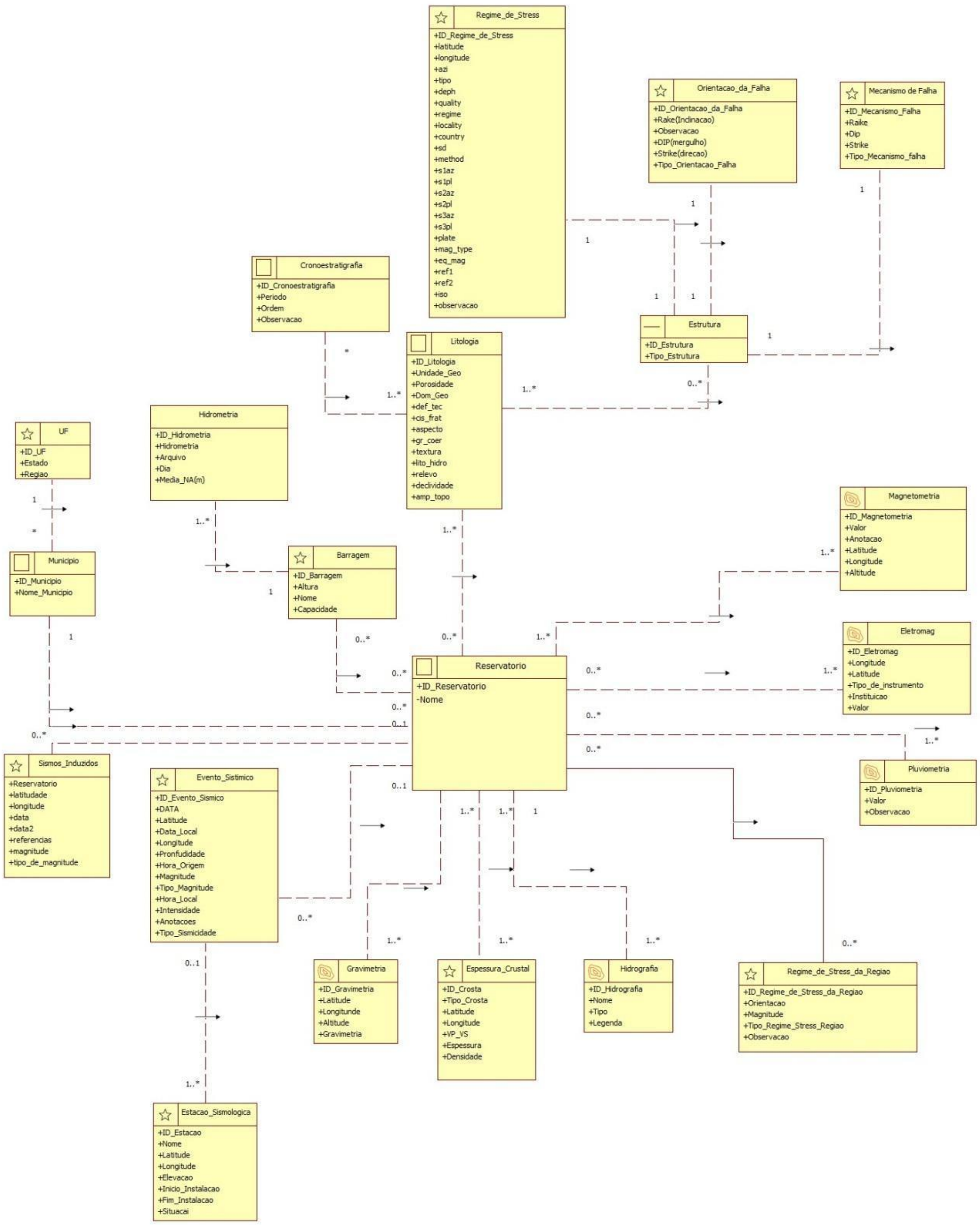


Fig 2- OMT-G Model of Reservoir-triggered Seismicity Database.

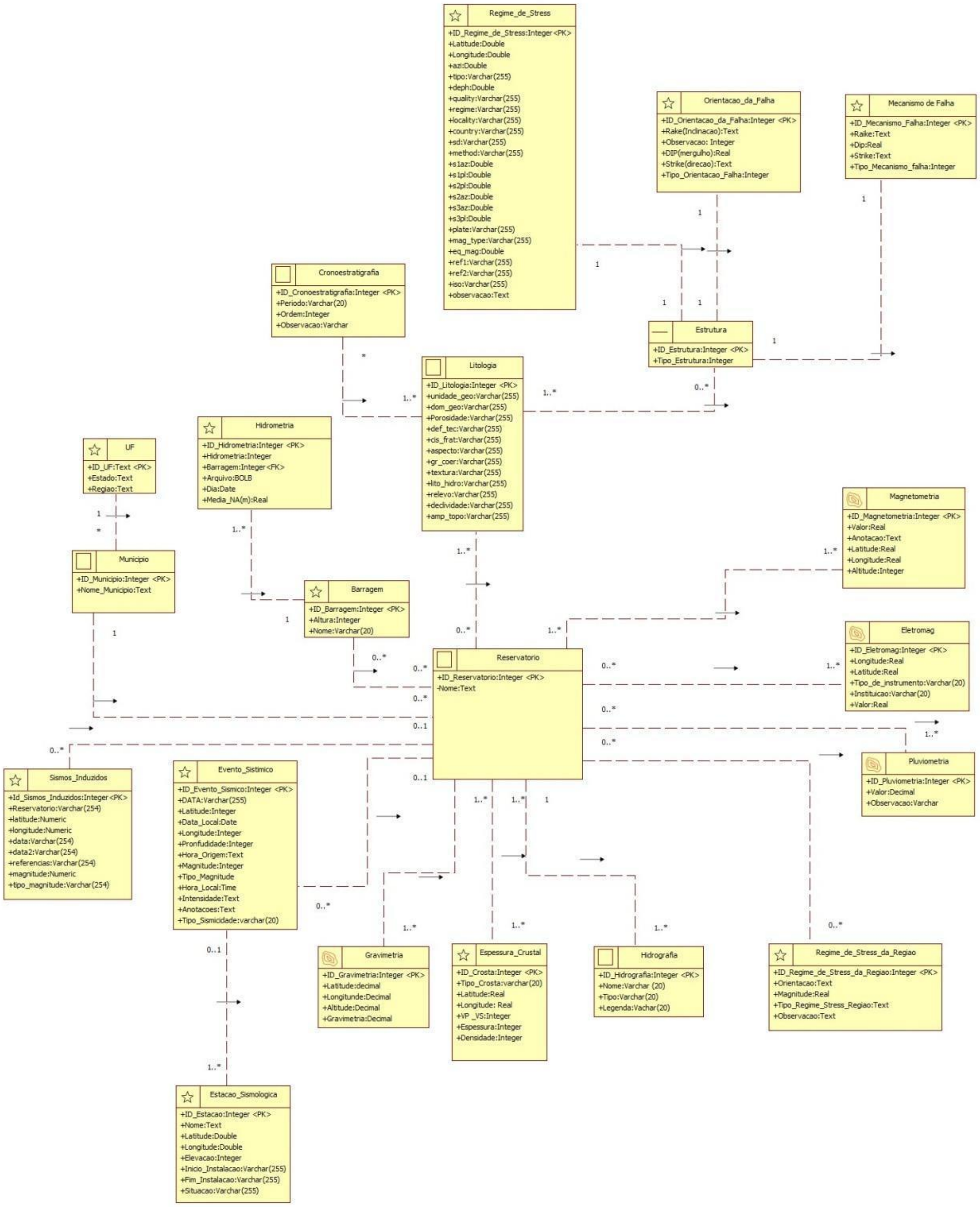


Fig 3- Relational model of Reservoir-triggered Seismicity Database.

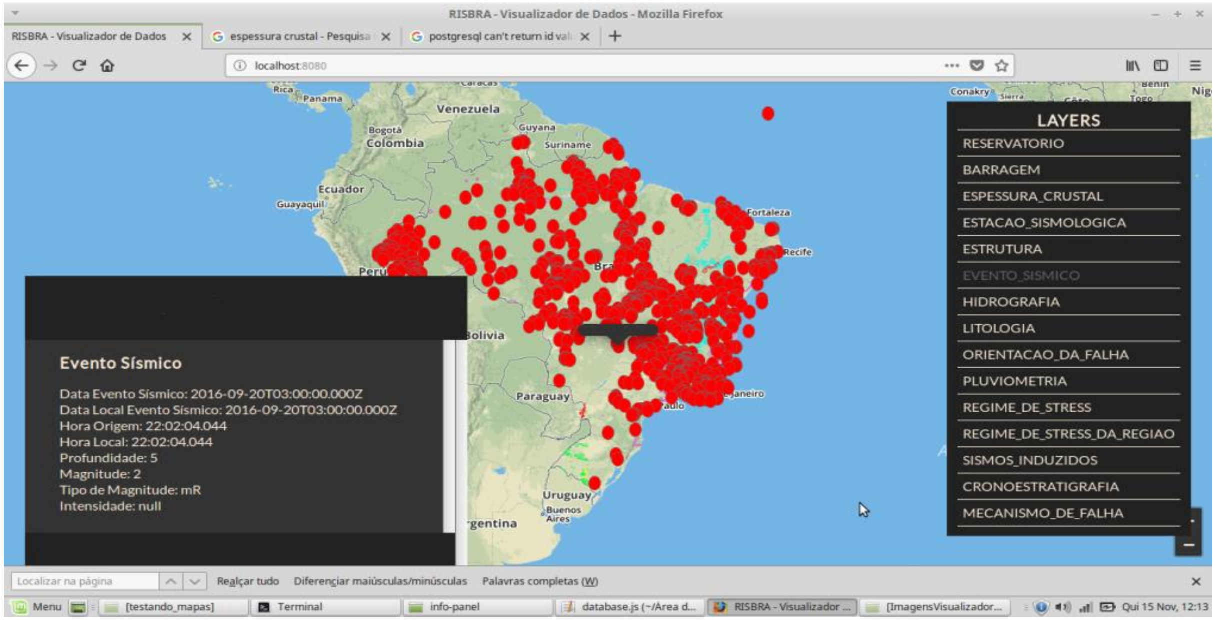


Fig 4- Example of researching Brazilian seismicity in RISBRA. The seismic events are represented by red ball and table to the left with information regarding this seismic event layer.

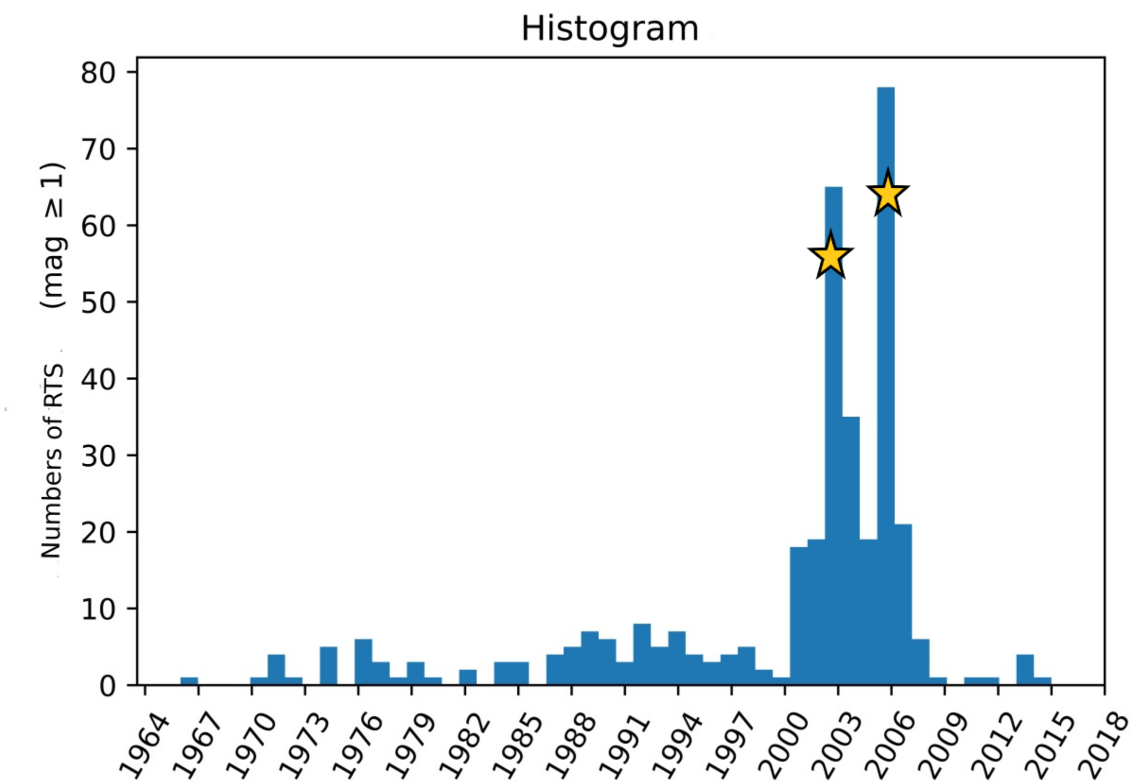


Fig 5- Histogram of the RTS numbers with a magnitude greater 1, per year. The yellow stars highlight the seismic swarms at the Itapebi and Carmo Cajuru dams in 2003 and Lajeado and Nova Ponte in 2006.

(

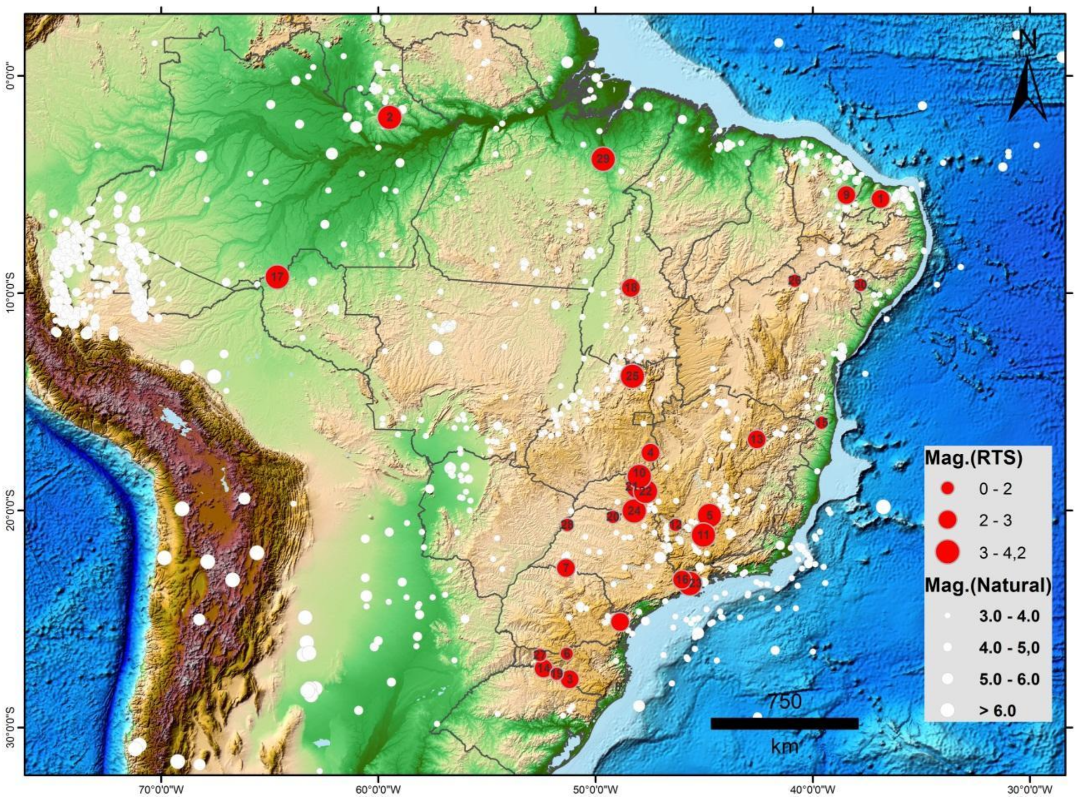


Fig 6 – Map of Brazil showing natural earthquakes (white circles, with magnitude) and RTS in Brazil (red circles, with magnitude, numbered as stated by Table 2). Data from the bulletin of the IAG-USP and SISBRA-UnB.

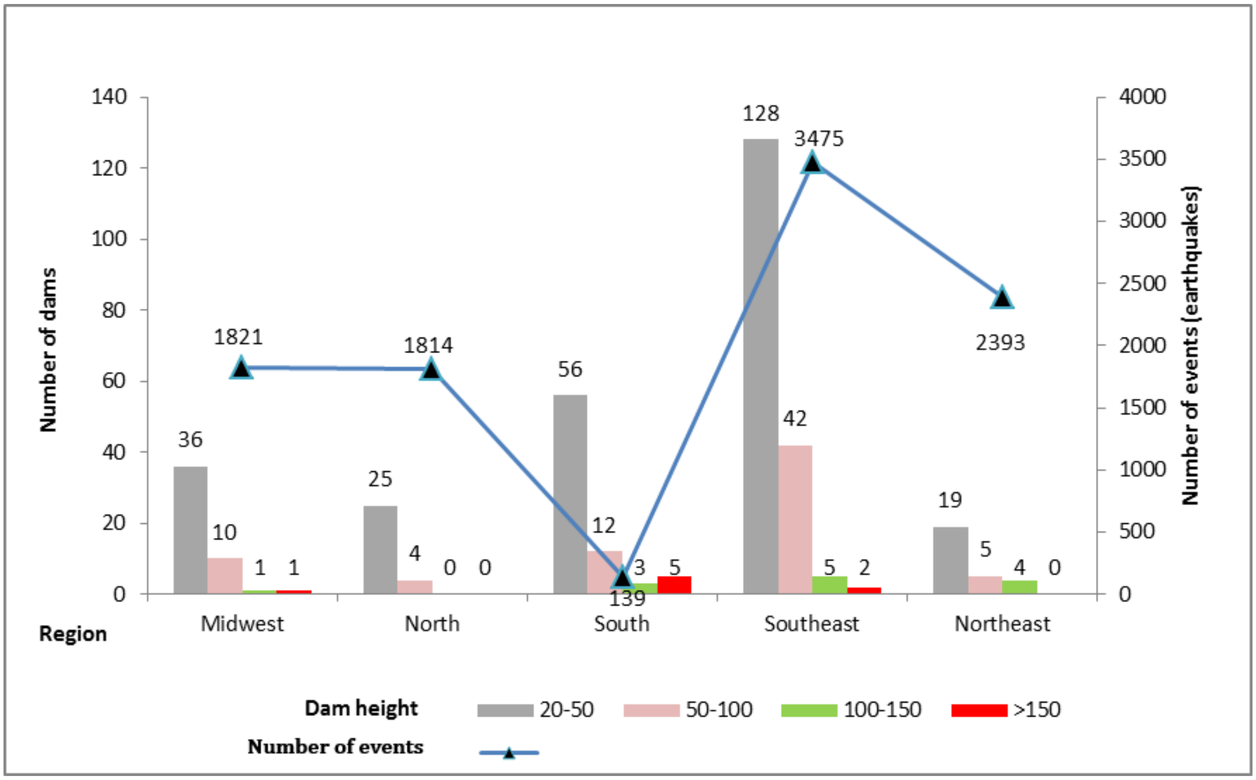


Fig 7- Graph showing the earthquakes, dams, and regions of the country. The southeastern region concentrates the highest and the most dams in the country.

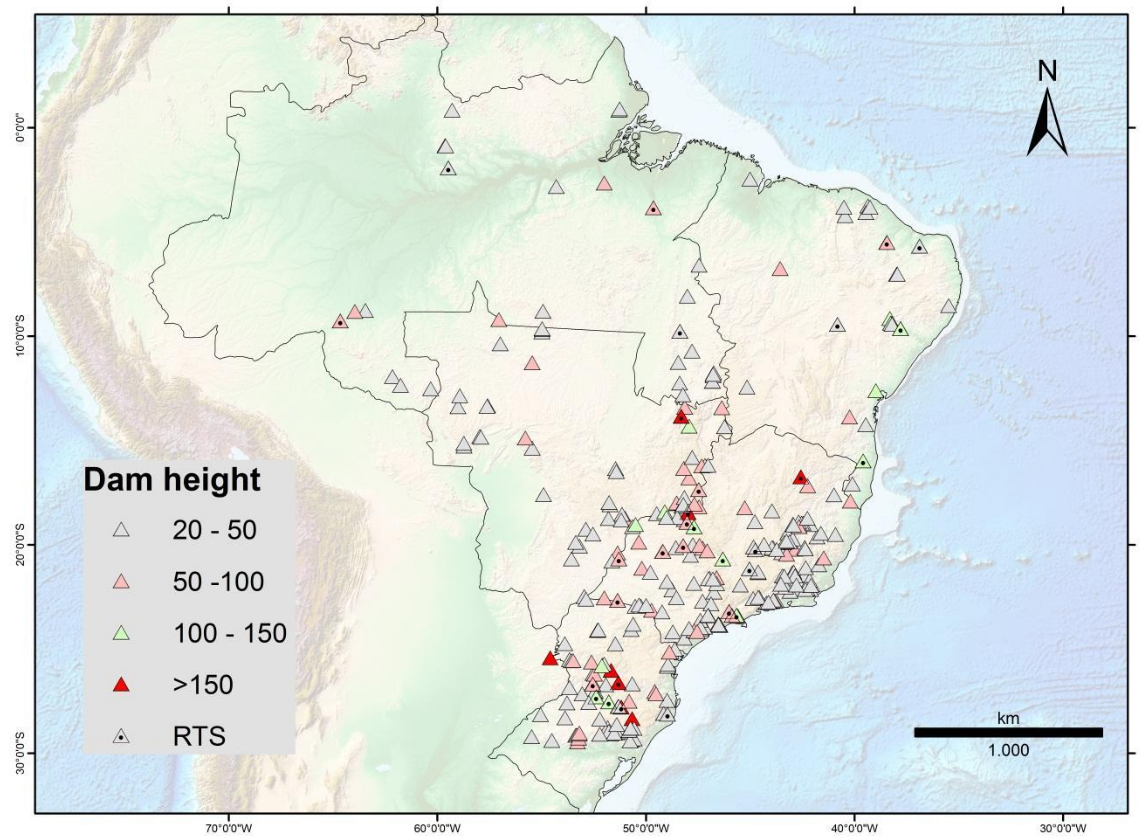
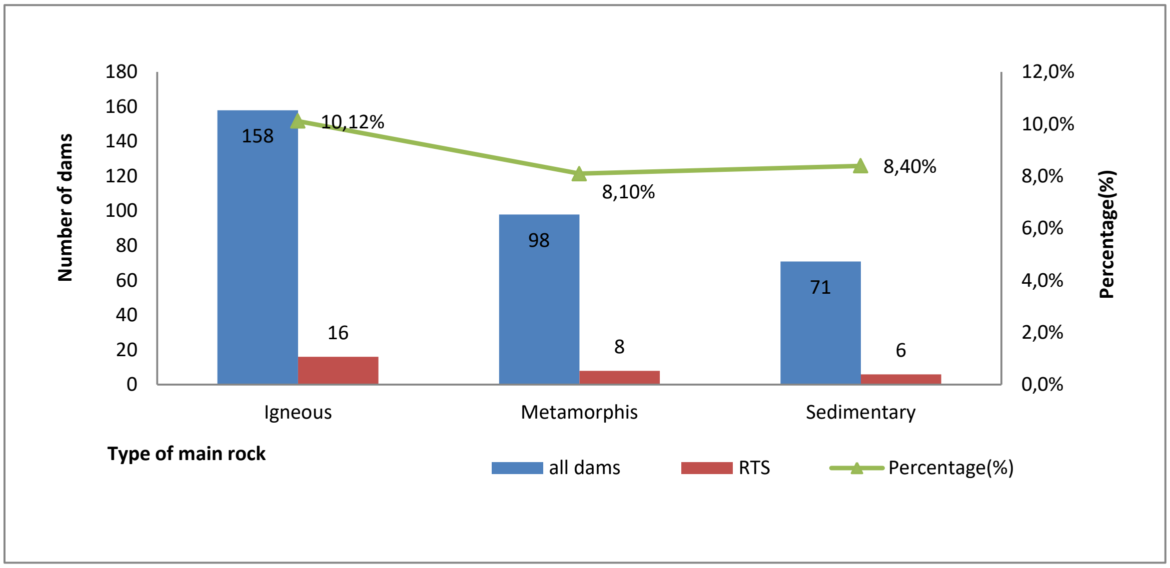


Fig 8- Map showing the location and classification by the dam height. Data by Brazilian Committee on Dam.

a)



b)

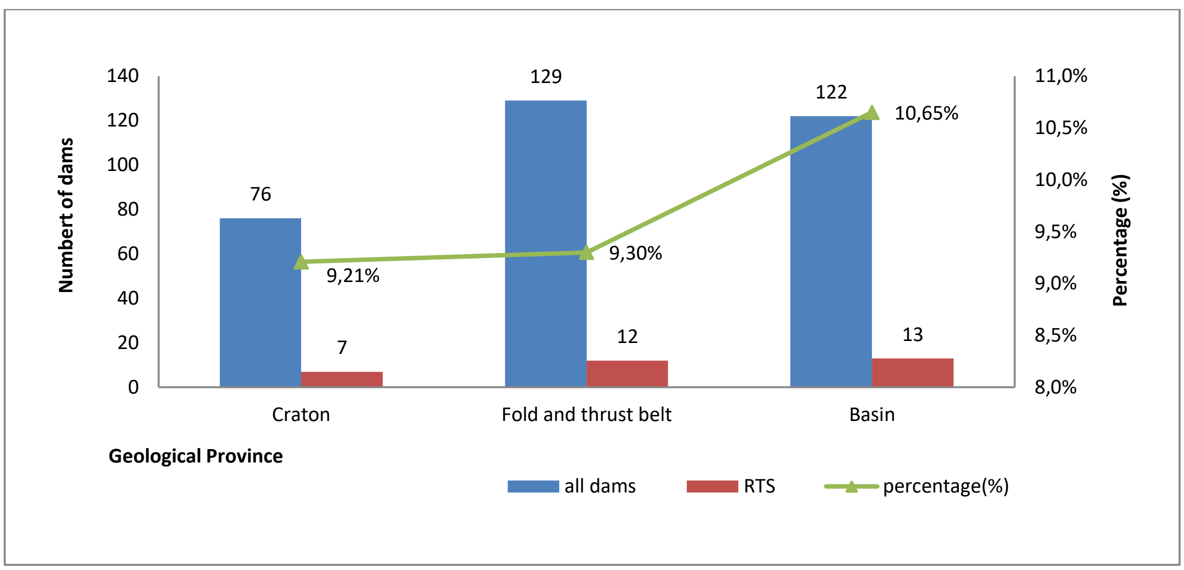


Fig 9- a) Percentage of cases of Reservoir-triggered Seismicity in Brazil as stated by main rock types (sedimentary, metamorphic and igneous) in the dam area. b) classification as stated by the main geological provinces.

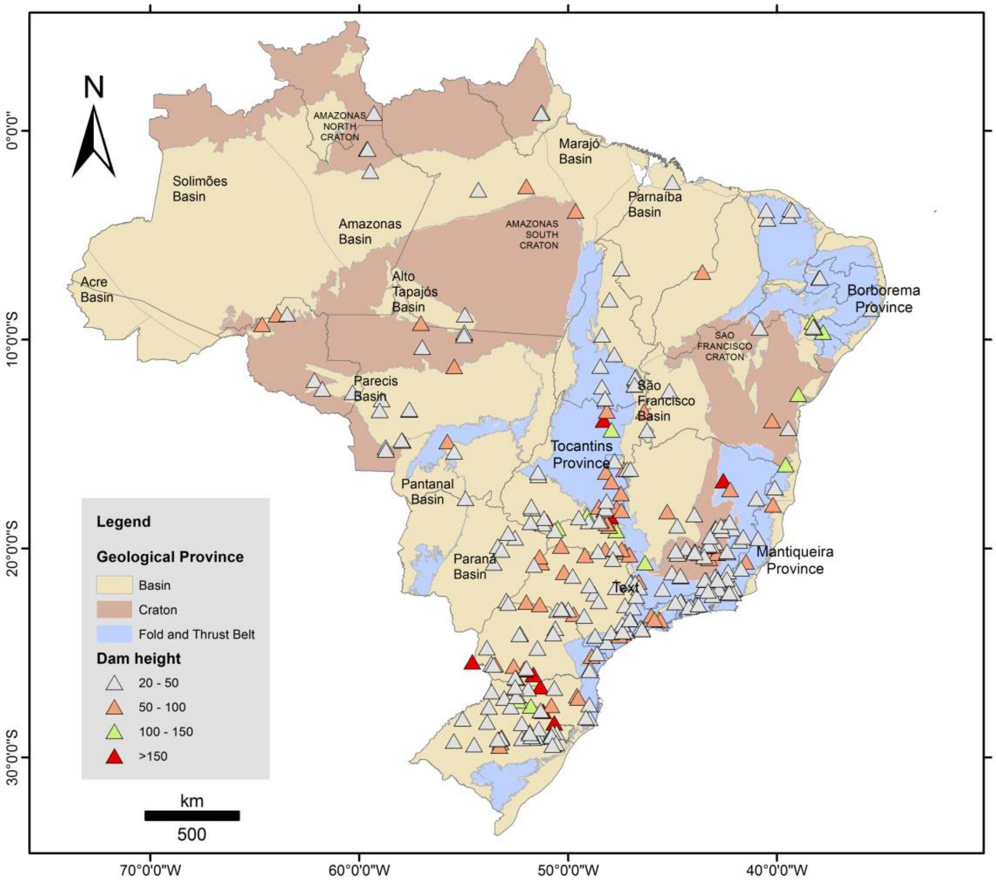
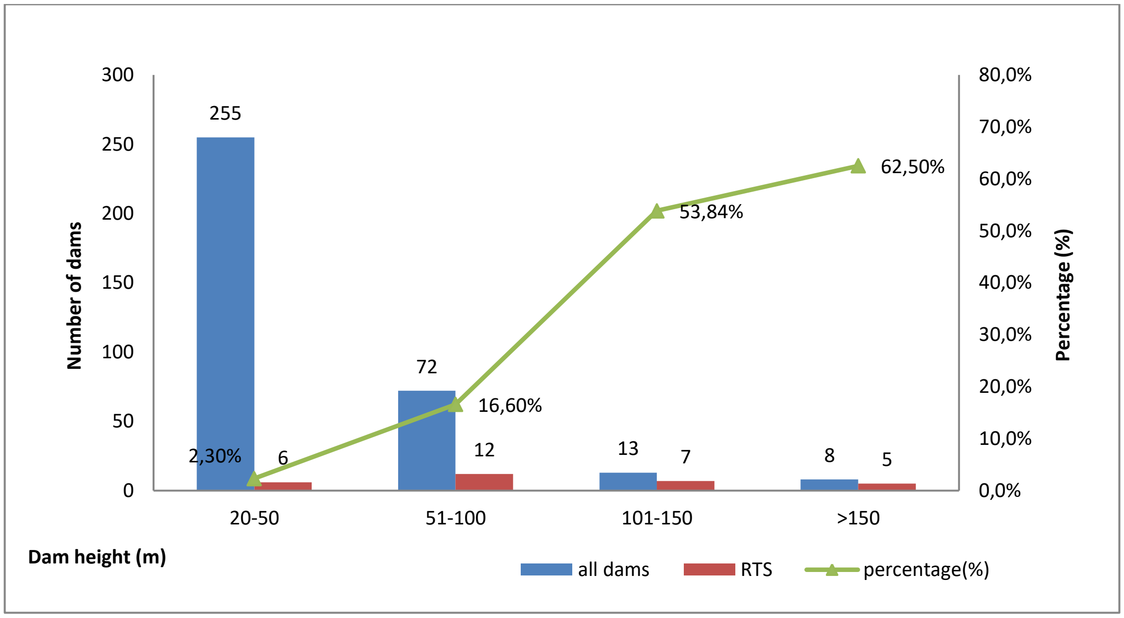


Fig 10- Map of Brazil with 348 dams with a height of 20m or more (data from the Brazilian Committee on Dams-2018). The colors refer to the main geological provinces (data from CPRM-Mineral Resources Research Company).

a)



b)

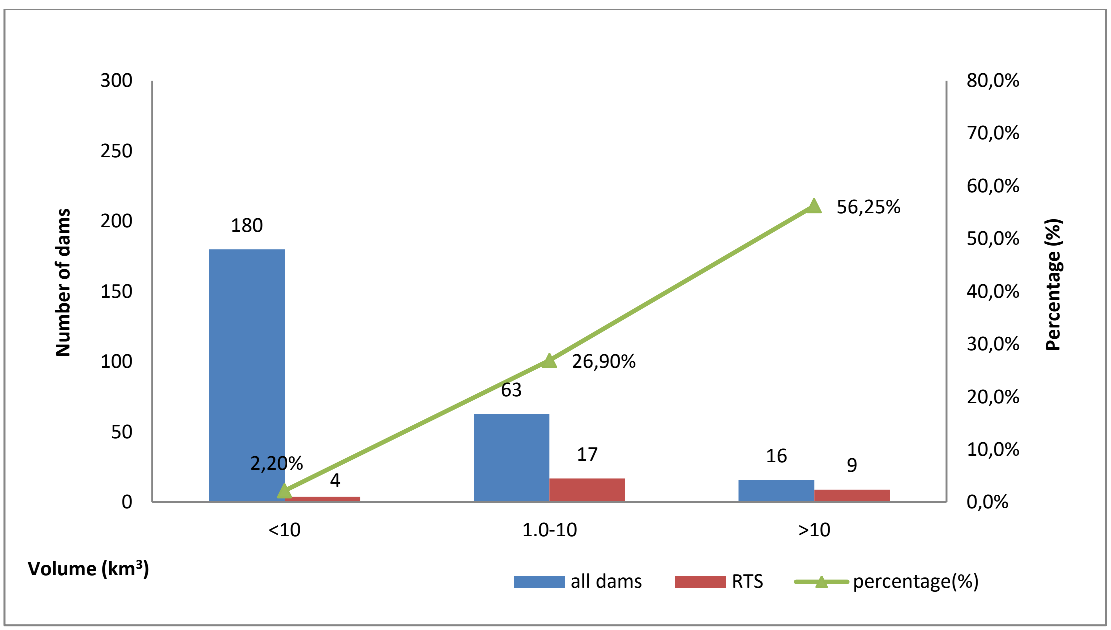


Fig 11- Percentage of cases of Reservoir-triggered Seismicity as stated by (a) dam height and (b) reservoir volume. 54% of dams taller than 100 m trigger earthquakes and 32% of reservoirs larger than $1x10^{-3}$ km^3 trigger earthquakes.

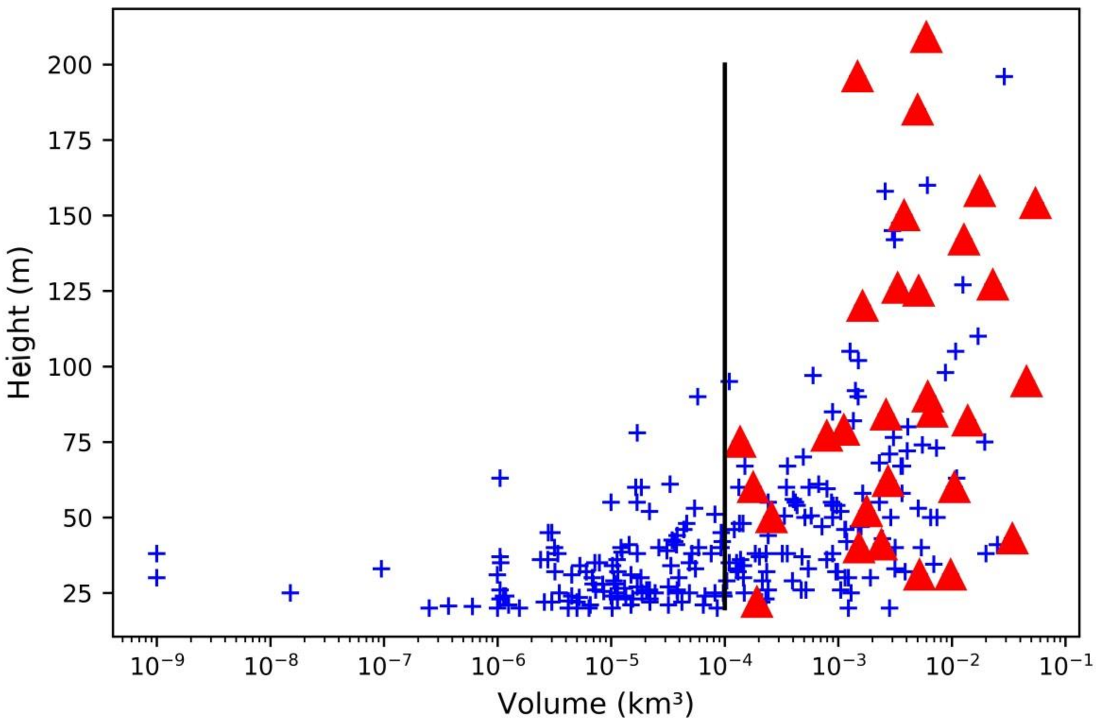


Fig 12- Graph of reservoir volume and dam height for all dams in Brazil. The triangles indicate the RTS cases and the crosses, other reservoirs. The black bar is the limit of RTS cases.

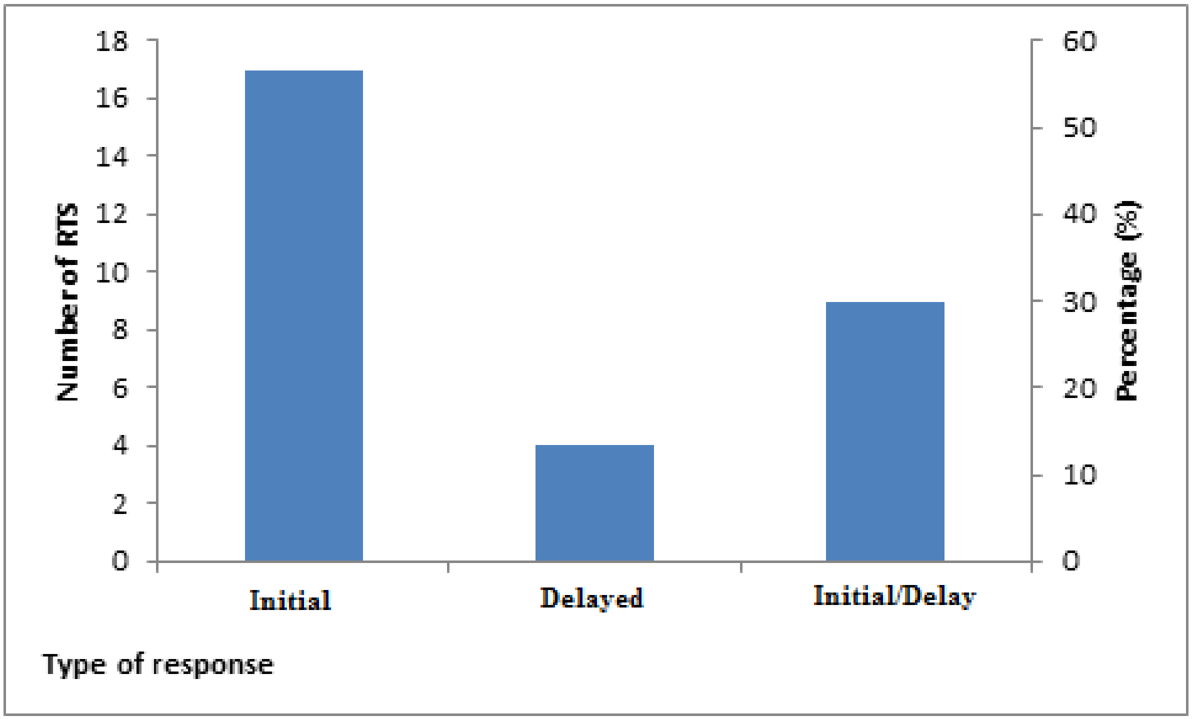


Fig 13- Graph of the type of response for RTS cases.

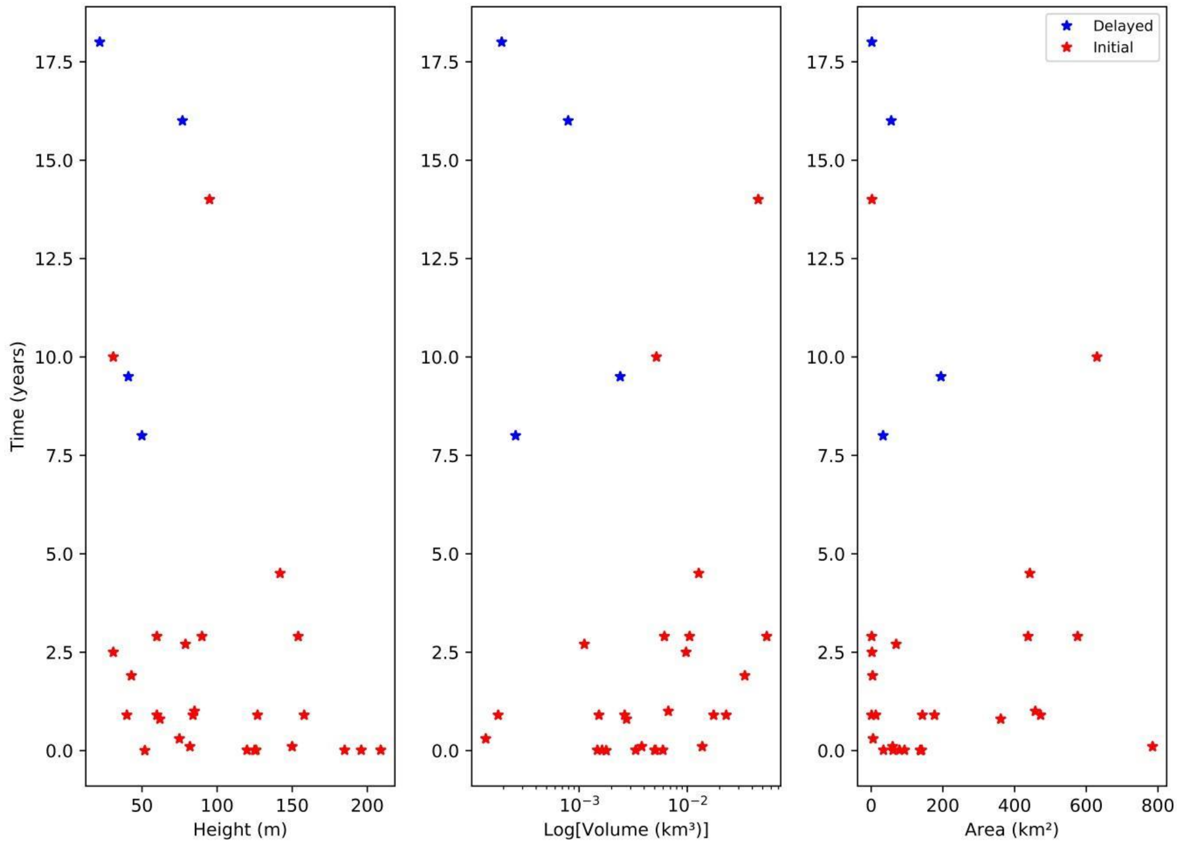


Fig 14- Graph of delay time/response versus dam height, volume, and area.

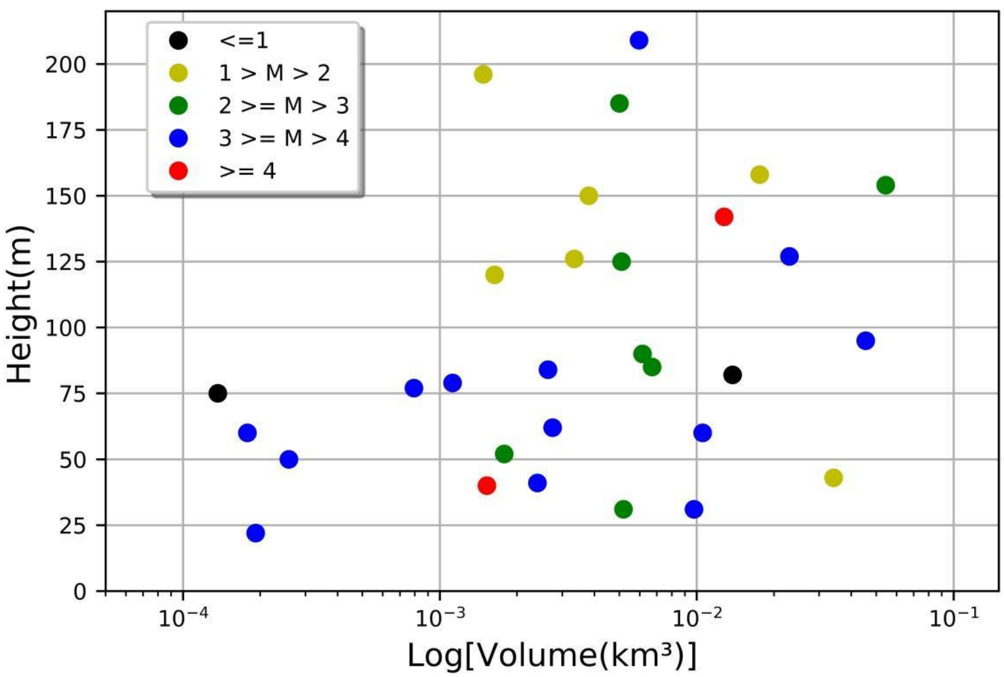


Fig 15- Distribution of reservoir volume and dam height versus the Reservoir-triggered Seismicity maximum magnitude cases.

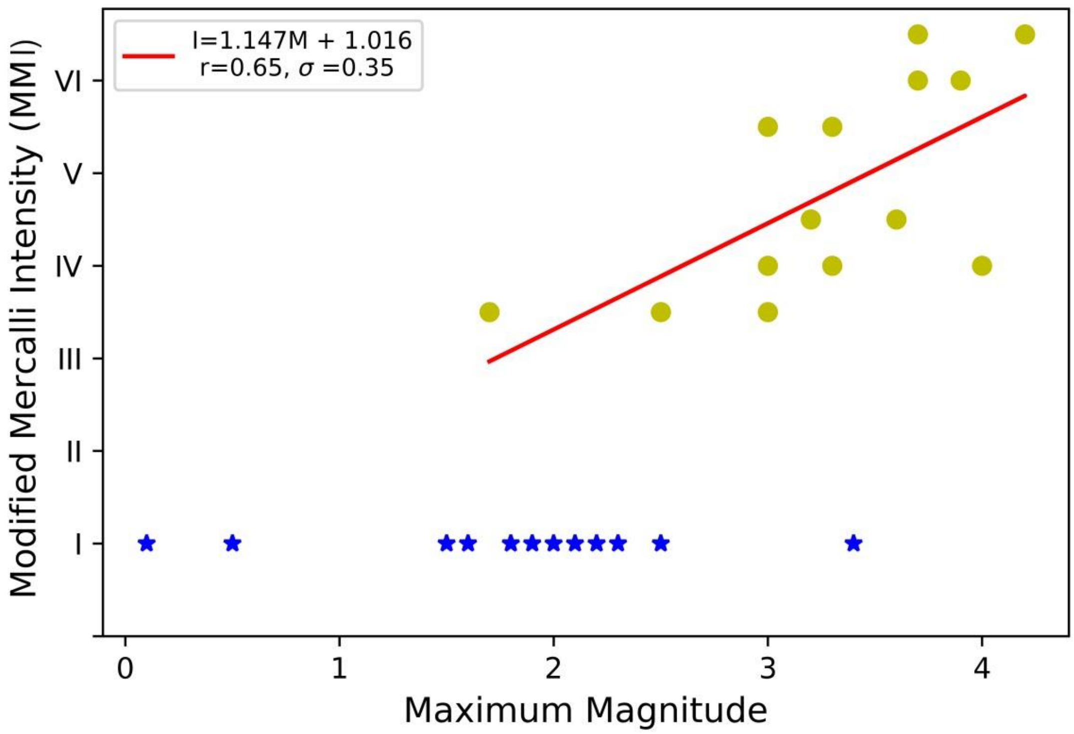


Fig 16- Graph showing maximum magnitude and intensity. The linear adjustment (bar) was performed only with data represented by circles. The blue stars indicate cases of Intensity I.