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Website - Spatial database for reservoir-triggered seismicity in Brazil

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Abstract

After confirming that impoundment of large reservoirs could cause earthquakes worldwide, 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 effort due to the increase in pore pressure, can modify the stress regime 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 for studying RTS is to identify and correlate the factors in the area of influence of the reservoir, capable of influencing the RTS process itself. To assist the research, it was created a spatial seismicity-triggered reservoir database (BDSDR) based on the specifications of the national spatial data infrastructure (INDE), for gathering 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 with the dams that triggered earthquakes and the Brazilian dam list, which was then updated from 26 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 hydraulic behavior. The highest magnitude, 4.2, was observed for an event that occurred in 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 in the reservoirs of Hsinfenghiang (China), Kariba (Zambia), Kremasta (Greece), and Koyna (India) in the late 1960s (Figure 1). 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. 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 (MM) recorded in 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, few of them, however, correlate the physical and geological information as possible agents of the triggered earthquakes. Thus, this work proposes to present the procedures and results found in the data processing of 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. To this end, 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 corroborating the RTS requires standardizing all information, which was accomplished by following 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 Reservoir-triggered Seismicity Database (BDSDR) resulted from researching and studying the cases that happened in Brazilian Reservoirs and the realization that the pertinent data was scattered and, most important, limited to listing the cases and the occurrence sites.

The purpose of the database is to gather all the available information such as physical, structural, geological and geophysical data on each reservoir, store in a standardized way while sharing and making it accessible so that the database can assist on 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 it and maybe being 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), as shown in Figure 2.

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 dissertation. 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 (Figure 3).

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, UF, Municipality, Hydrometry, Magnetometry, Electromagnetometry, Gravimetry, Pluviometry, Regional Stress Regime, Hydrography, Crustal Thickness, Seismic Event, and Seismographic Station.

Figure 4 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 5 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 Database Management System (DBMS) used (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).

According to Medeiros (2012), the database management software (DBMS) is used for managing databases. The development of the spatial database, in a Linux environment, used the PostgreSQL 9.3 with raster extension, PostGIS 2.4, pgAdim III and Quantum GIS (QGIS) version 2.14.

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 6 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.

Update of Seismicity Triggered in Brazil 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, 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 7 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 2006-2008. 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 8 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, among them, only two events with a maximum magnitude greater than or equal to 4.0 (Table 3 and Figures 9 and 10). Regarding damages, the highest seismic intensity of VI-VII (MM) was estimated in Porto Colombia and Volta Grande while the seismicity type was mostly Initial.

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 9 and 10) 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 reservoirs, 17.8% 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

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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 studies on 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, 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, I 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 11a, and the geological province as well. The results show that igneous rocks have a higher percentage of RTS occurrence (10.1%) than sedimentary (8.4%) and metamorphic (8.1%) rocks, although the obtained difference is 2%, indicating little influence of the basement. Thus, the RTS was also compared to

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the main geological provinces that are classified by the CPRM (Figure 11b and 12) 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 13a) more likely to trigger earthquakes, corroborating Simpson (1986) findings.

According to the CBDB databank, the volume parameter is available for only 256 reservoirs. Figure 12b shows that 47% of the reservoirs with a volume greater than 1×10^{-2} km^3 triggered earthquakes, and since this percentage decreases linearly with volume, reservoirs with a volume less than 1×10^{-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 13b).

Figure 14 shows the correlation between volume and height for RTS cases. We observed that the height is not limitant, 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 14.

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 state initial 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 and the other to the more gradual diffusion of water from the reservoir to hypocentral depths. 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 15). These reservoirs can be classified according to their responses, i.e., the delayed response describes a hydraulic behavior while the initial response occurs due to the mechanical behavior of the reservoir load. However, when checking all the 26 initial cases, it is observed that most RTS have an initial response. The delayed response cases represent 43% in total, that is, almost half of them have hydraulic behavior.

Figure 16 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).

For 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 17 shows that most of the events occur in reservoirs with volumes greater than 10^{-3} and 4.2

maximum magnitude and that, for the most part, events between 3 and 4 magnitudes occur in dams up to 100 m tall.

The intensity and Highest Magnitude

Several events were either not felt or there was no micro-seismic survey defining its intensity, they were considered Intensity I here. Figure 18 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 as 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, increased monitoring and dam constructions from 2002.

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, the Northeastern region has comparatively higher relative value compared to other regions.

Although the results show a small trend for igneous rocks (rock type) and sedimentary basins (geological provinces) being more prone to RTS, there is no way to state the trend of these parameters with the current 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.

The relationship between Intensity and highest magnitude is described by the equation "I = 1.147M + 1.016 (+ -0.35)", where I is the estimated intensity and M is the determined magnitude.

The evaluation of a reservoir seismic risk is hampered by the practical difficulty of mapping a large volume of rocks located below the reservoir and, therefore, of knowing 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 overlooked while highlighting the importance of continuous monitoring, before, during and after the construction of the dam.

Data and Resources

The data used in this article was extracted 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 (UF)	Each municipality is located in a state.

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

N°	**Name**	**UF**	**Height (m)**	**Volume ($10^{-3}km^3$)**	**Max. water depth in the**	**Area (km^2)**	**Start of impoundment**	**Geological Province**	**Seismicity type**	**Largest Events**						
										Date (YY/MM/DD)	**Magnitude**	**Magnitude Type**	**I_0 (MMI)**	**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*	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	Delayed initial	2005/10/1	2,5	ML	I	0.01	Margin	Ribotta et al. (2008) and Ribotta et al.(2010)
4	Batalha	MG/GO	52	1,781	800,0	138,1	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	2,30	1954	Craton	Delayed	1972/01/23	3,7	mb	VI	18	Margin	Veloso et al. (1987) and Viotti et al. (1995,1997)
6	Campos Novos	SC	196	1,477	-	34,60	10/2005	Basin	Delayed initial	2005/10/12	1,8	ML	I	0.01	Inside	Ribotta et al. (2010)

15	14	13	12	11	10	9	8	7
Itapebi	Itá	Irapé	Furnas	Funil	Emborcação	Castanhão	Capivari-Cachoeira	Capivara
BA	RS/SC	MG	MG	MG	GO/MG	CE	PR/SP	PR/SP
120	125	209	127	50	158	85	60	60
1,633	5,100	5,964	22,950	0,258	17,588	6,700	0,178	10,540
-	370,0	470,8	-	808,0	653,0	100,0	-	-
61,58	141,0	137,0	1,44	33,46	473,00	458,0	13,10	576,00
12/2002	12/1999	12/2005	1963	2002	08/1981	2003	07/1970	01/1976
Craton	Basin	Thrust and Folding Range.	Thrust and Folding Range	Craton	Thrust and Folding Range.	Thrust and Folding Range.	Thrust and Folding Range	Basin
Initial	Delayed initial	Initial	Initial *	delayed	Initial	Initial	Initial	Delayed initial
2003/08/0	1999/12/15	2006/05/14	1966/11/15	2011/08/14	1982/05/20	2007/08/07	1971/05/21	1979/03/27
1,5	2,5	3,0	3,2	3,2	1,6	2,3	3,9	3,7
M_D	ML	mR	mI	mR	ML	mD	ML	mb
I	III-IV	III-IV	IV-V	IV-V	I	I	VI	VI-VII
~0.01	0.01	0.01	~1?	8	~1	1?	~1	~3
Margin	Margin	Inside	-	Margin	Inside	Initial	-	Margin
Barros (2008)	Ribotta et al. (2006b,2010,2017)	França et al.(2010)	Berrocal et al. (1984) and Barros et al. (2005)	Barros et al. (2014)	Viotti et al. (1997,1995)	Ferreira et. al. (2008)	Berrocal et. al.(1984) eand Mioto et.al. (1991)	Assumpção et.al (1995)

24		23		22	21	20	19	18	17	16
Porto Colômbia e Volta Grande		Paraibuna-Paraitinga		Nova Ponte	Miranda	Marimbondo	Machadinho	Lajeado	Jirau	Jaguari
MG/SP		SP		MG	MG	MG/SP	RS/SC	TO	RO	SP
55	40	105	84	142	79	90	126	31	62	77
2,300	1,525	1,270	2,636	12,792	1,120	6,150	3,339	5,190	2,746	0,793
-		-		-	-	-	-	212,3	90,0	-
19,50	143,00	47,00	177,00	443,00	70,00	438,00	79,00	630,00	361,60	56,00
09/1973	04/1973	1976	1974	10/1993	08/1981	1975	28/08/2001	2002	2014	12/1969
Basin		Thrust and Folding Range.		Basin	Basin	Basin	Basin	Basin	Basin	Thrust and Folding Range
Initial		Initial		Delayed initial	Delayed initial	Initial	Delayed initial	Delayed initial	Initial	Delayed
1974/02/24		1977-11-16		1998/05/22	2000-05-06	1978/07/25	2001/09/08	2012/04/01	2014/11/07	1985/12/17
4,2		3,3		4,0	3,3	2,0	1,8	2,2	3,2	3,0
mD		mb		mR	mR	ML	ML	mD	mR	ML
VI-VII		IV		VI	V-VI	I	I	I	IV-V	V-VI
~1		~1		4.5	2.7	~3	0.01	10	0.8	16
Margin*		Inside		Margin	Margin	Margin	Margin	Margin		
Berrocal et al. (1984), Veloso (1992a) and Gomide (1999)		Mendiguren (1980) eand Ribotta (1989)		Chimpliganond (2002), Marza, Barros, Soares et al. (1999) and	Barros e Caixeta (2003) e Assumpção et al. (2002)	Veloso et al. (1987)	Ribotta et al.(2006a) e Ribotta et al. (2010)	Technical Report of the UnB Seismological Observatory	Barros et.al (2015)	Veloso et al. (1987)

25	Serra da Mesa	GO	154	54,400	-	1,78	10/1996	Thrust and Folding Range	Initial	1999/06/13	2.2	mD	I	~3	Margin	Veloso et al. (1987) and Assumpção et. al (2002)
26	Sobradinho	BA	43	34,116	-	4,12	1977	Craton	Initial	1979/07/05	1,9	ML	I	~2	Inside	Berrocal eand Fernandes (1996)
27	Quebra-Queixo	SC	75	0,136	549,0	5,60	2002	Basin	Initial	2003/03/01	0,1	mD	I	-	-	Technical Report of the UnB Seismological Observatory
28	Três Irmãos	SP	82	13,800	-	785,00	1990	Basin	Initial	1990/11/01	0,5	mD	I	~0.1	-	Relatório Técnico do Observatório Sismológico da UnB
29	Tucuruí	PA	95	45,500	-	2,43	09/1984	Craton	Delayed initial	1998/03/02	3,6	-	IV-V	14	Inside	Assumpção et. al (2002)and Veloso et al. (1992b)
30	Xingó	AL/SE	150	3,800	-	60,00	06/1984	Thrust and Folding Range	Initial	1994/07/20	1,7	ML	III-IV	~0.1		Berrocal and Fernandes (1996)

ΔT, time interval (years) since the beginning of filling; MMI, Modified Mercalli Scale; * Doubtful cases.

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

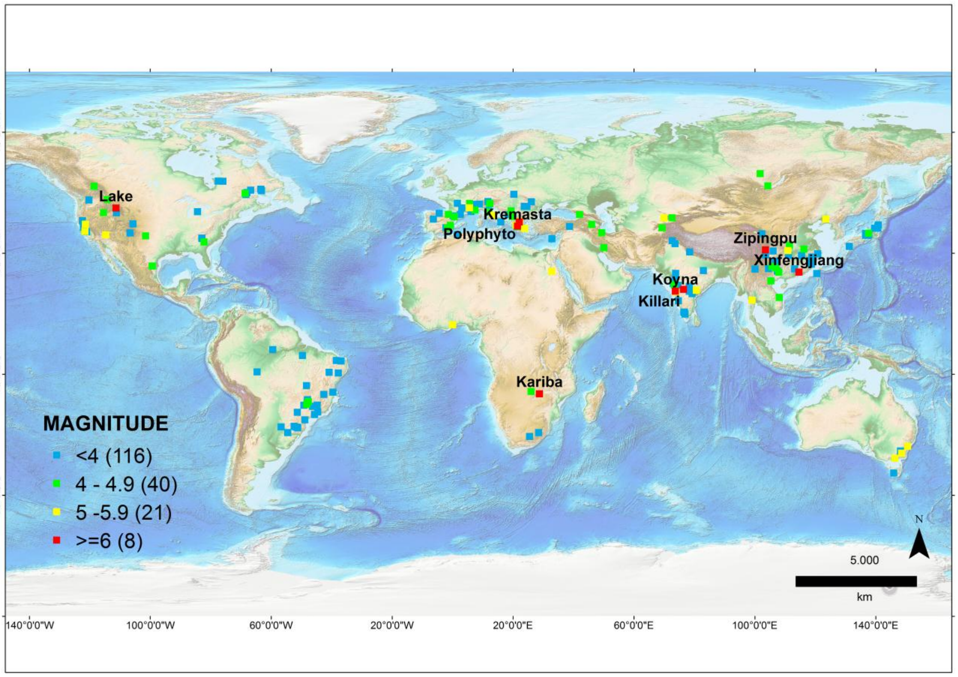


Fig 1 - World map of events triggered by reservoirs.

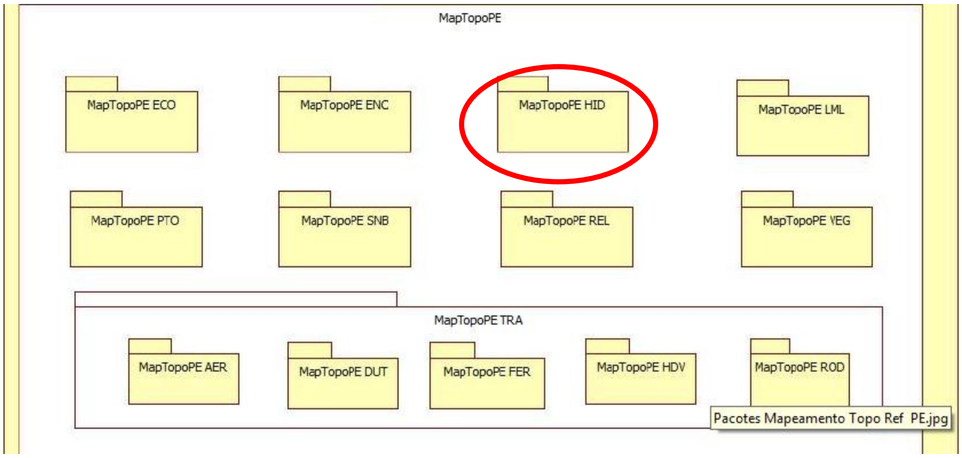


Fig 2 - Package with the information/data categories proposed by the *EDGV*, small scale topographic mapping MapTopoPE. The package is divided into information categories: Energy and Communications (ENC), Economic Structure (ECO), Hydrography (HID), Limits and Localities (DML), References (REL), Basic Sanitation), Vegetation (VEG). The Transport System (TRA) and its subsystems: Airport Subsystem (AER), Transport System/Duct Subsystem, Transport System/Railway Subsystem (FER), Transport System/Waterway Subsystem (HDV) and Transport System/Road Subsystem (ROD). Highlighted with the circle is the Hydrography category used in this dissertation (CONCAR, 2017).

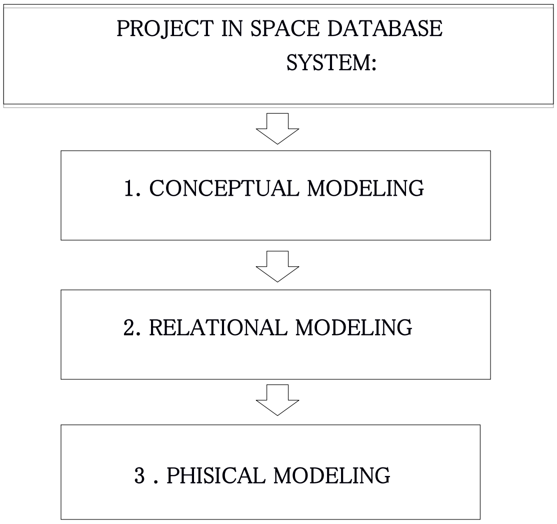


Fig 3- Flowchart to create the BDG Project.

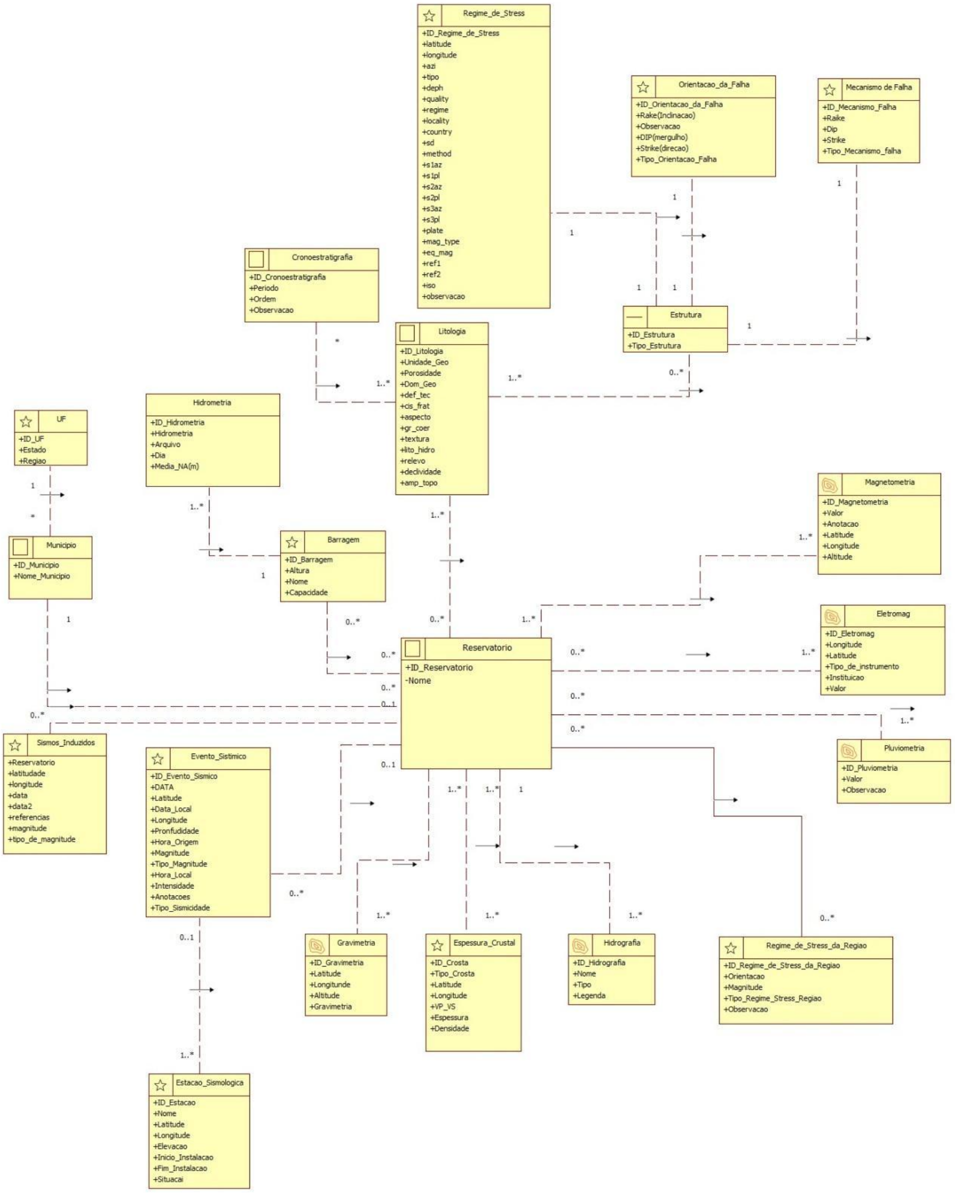


Fig 4- OMT-G Model of Reservoir-triggered Seismicity Database.

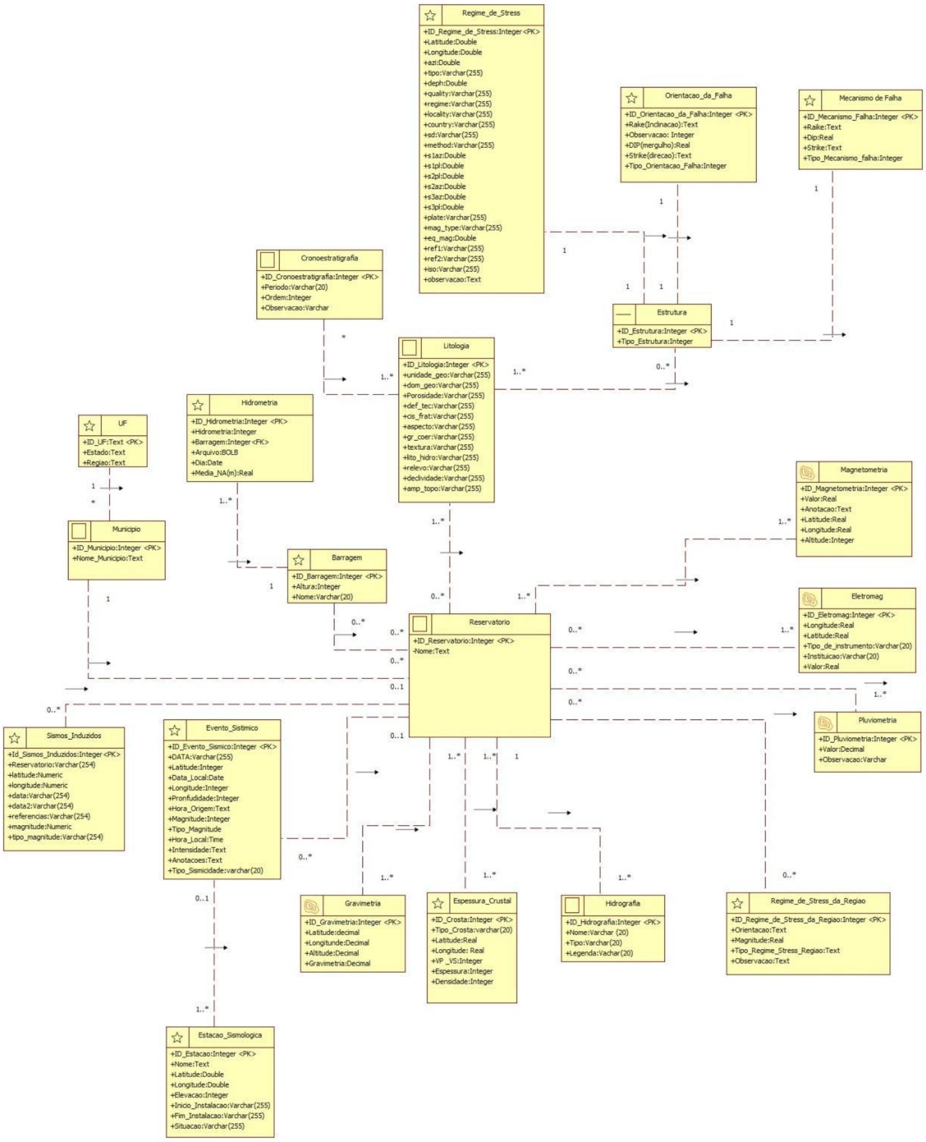
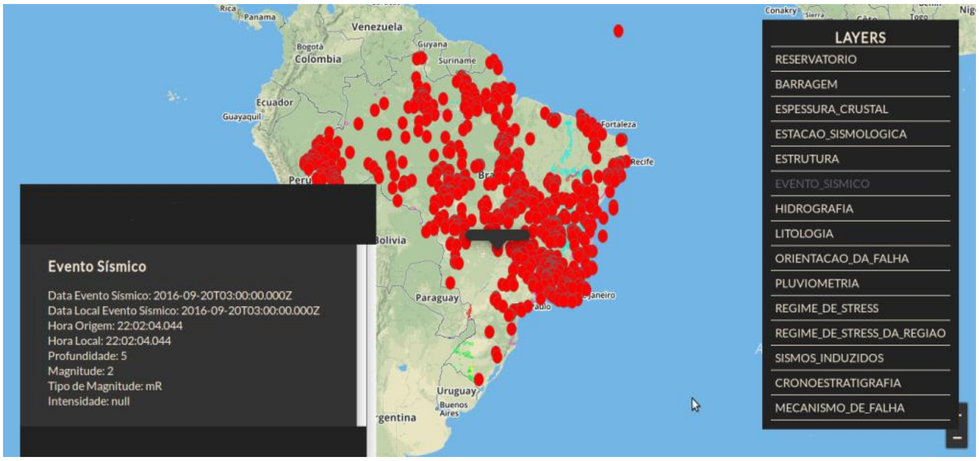


Fig 5- Relational model of Reservoir-triggered Seismicity Database.



Evento Sísmico

Data Evento Sísmico: 2016-09-20T03:00:00.000Z
Data Local Evento Sísmico: 2016-09-20T03:00:00.000Z
Hora Origem: 22:02:04.044
Hora Local: 22:02:04.044
Profundidade: 5
Magnitude: 2
Tipo de Magnitude: mR
Intensidade: null

Fig 6- 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.

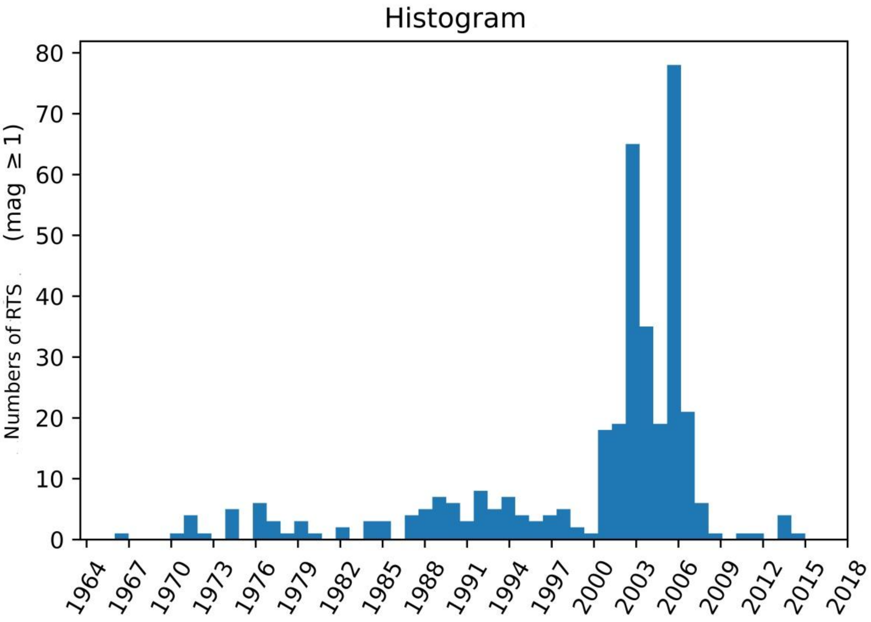


Fig 7- Histogram of the RTS numbers with a magnitude greater than 1, per year.

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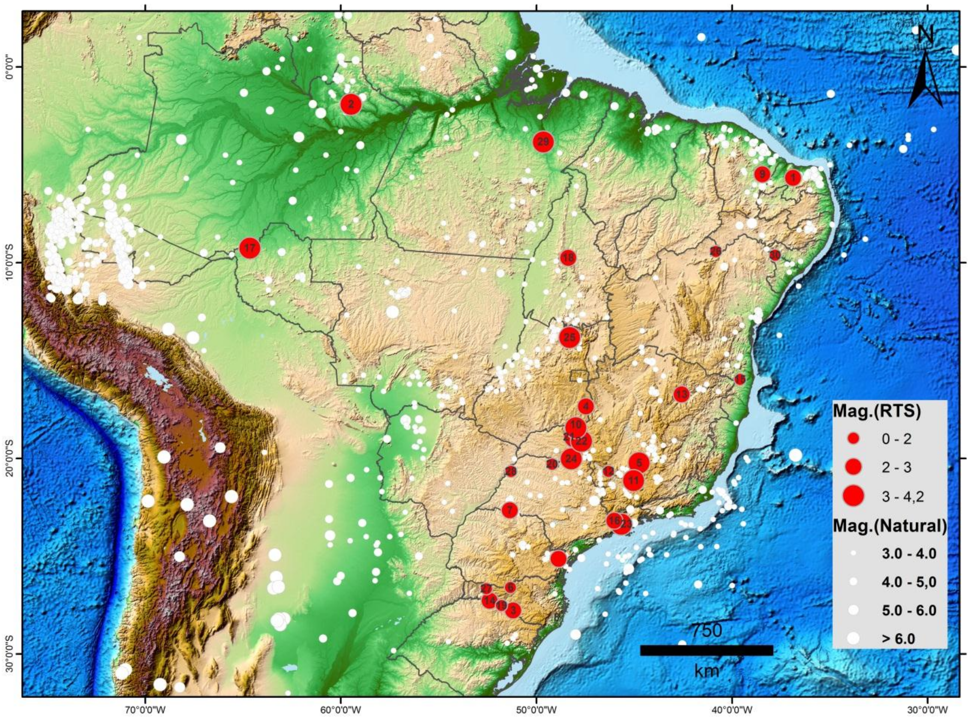


Fig 8 – Map of Brazil showing natural earthquakes (white circles, with magnitude) and RTS in Brazil (red circles, with magnitude, numbered as stated by Table 2).

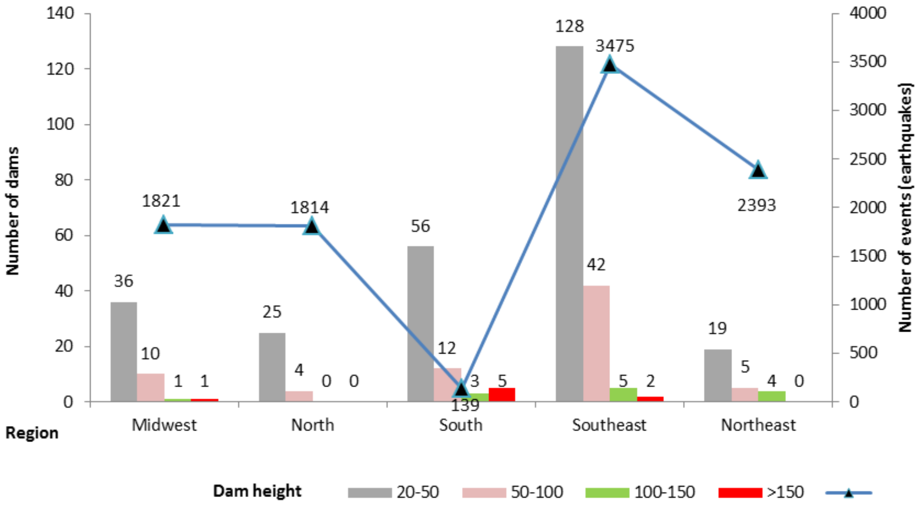


Fig 9- Graph showing the earthquakes, dams, and regions of the country. The southeastern region concentrates the highest and the most dams in the country.

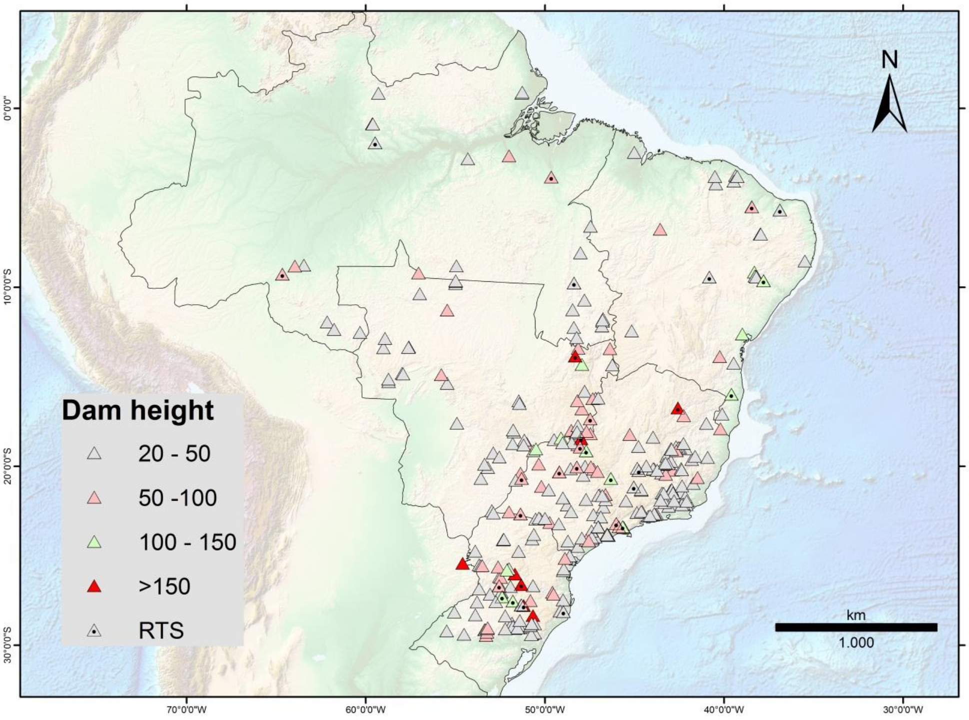
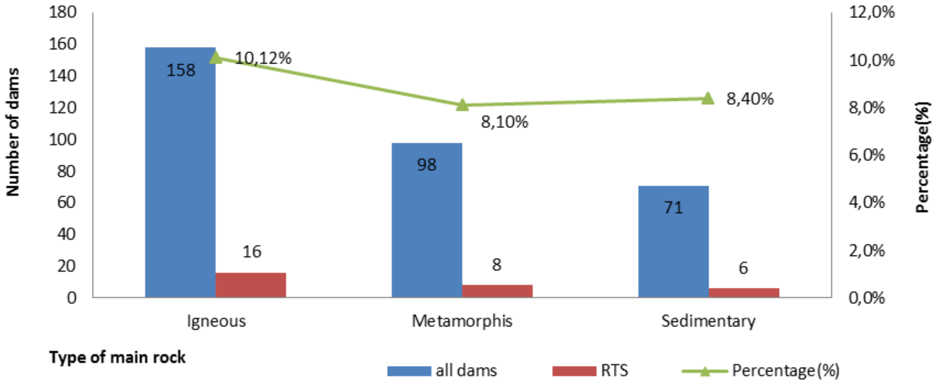


Fig 10- Map showing the location and classification by the dam height.

a)



b)

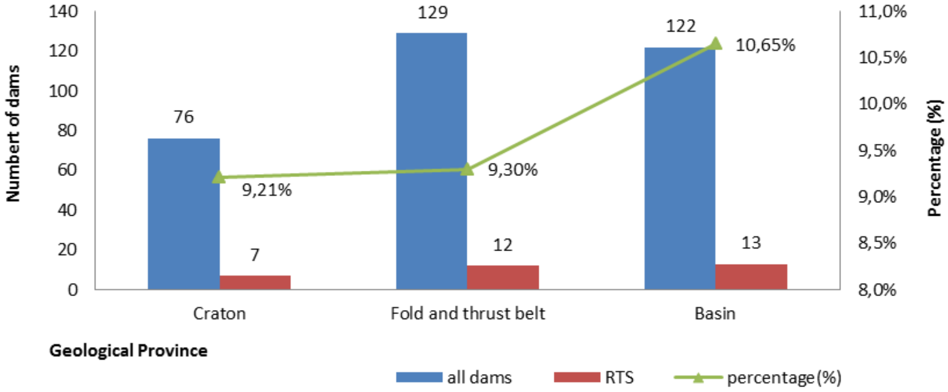


Fig 11- a) Percentage of cases of Reservoir-triggered Seismicity in Brazil as stated by main rock types (sedimentary, metamorphic and igneous) in the dam area. b) classification as stated by the main geological provinces.

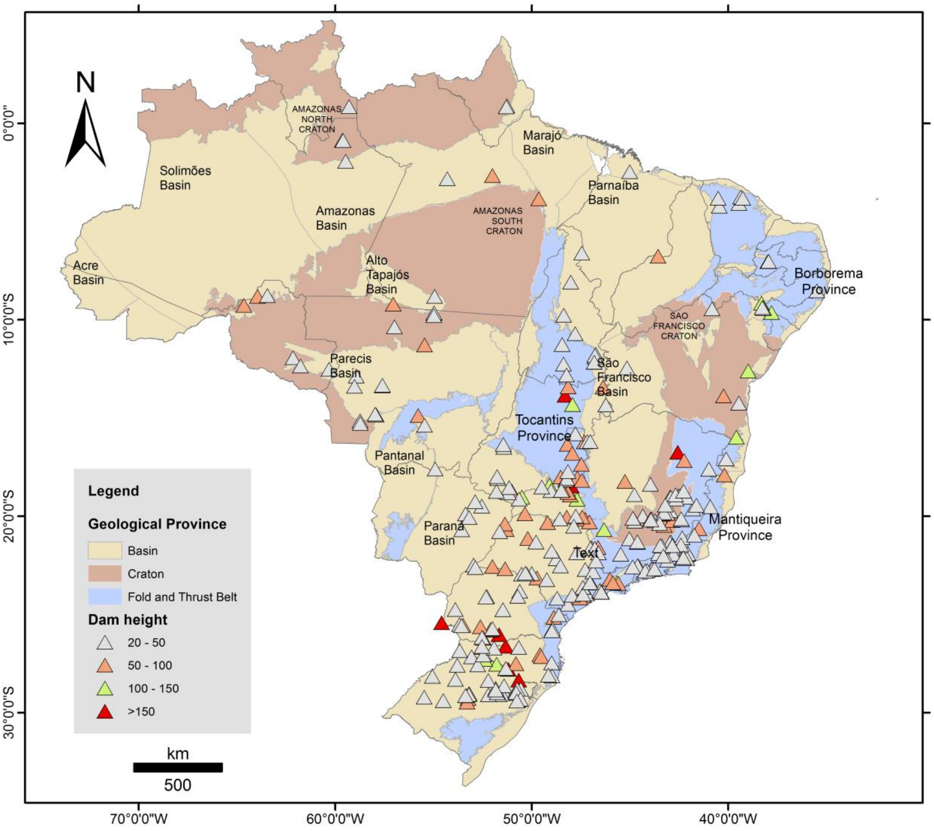


Fig 12- Map of Brazil with 348 dams with a height of 20m or more (data from the Brazilian Committee on Dams-2018). The colors refer to the main geological provinces (data from CPRM-Mineral Resources Research Company).

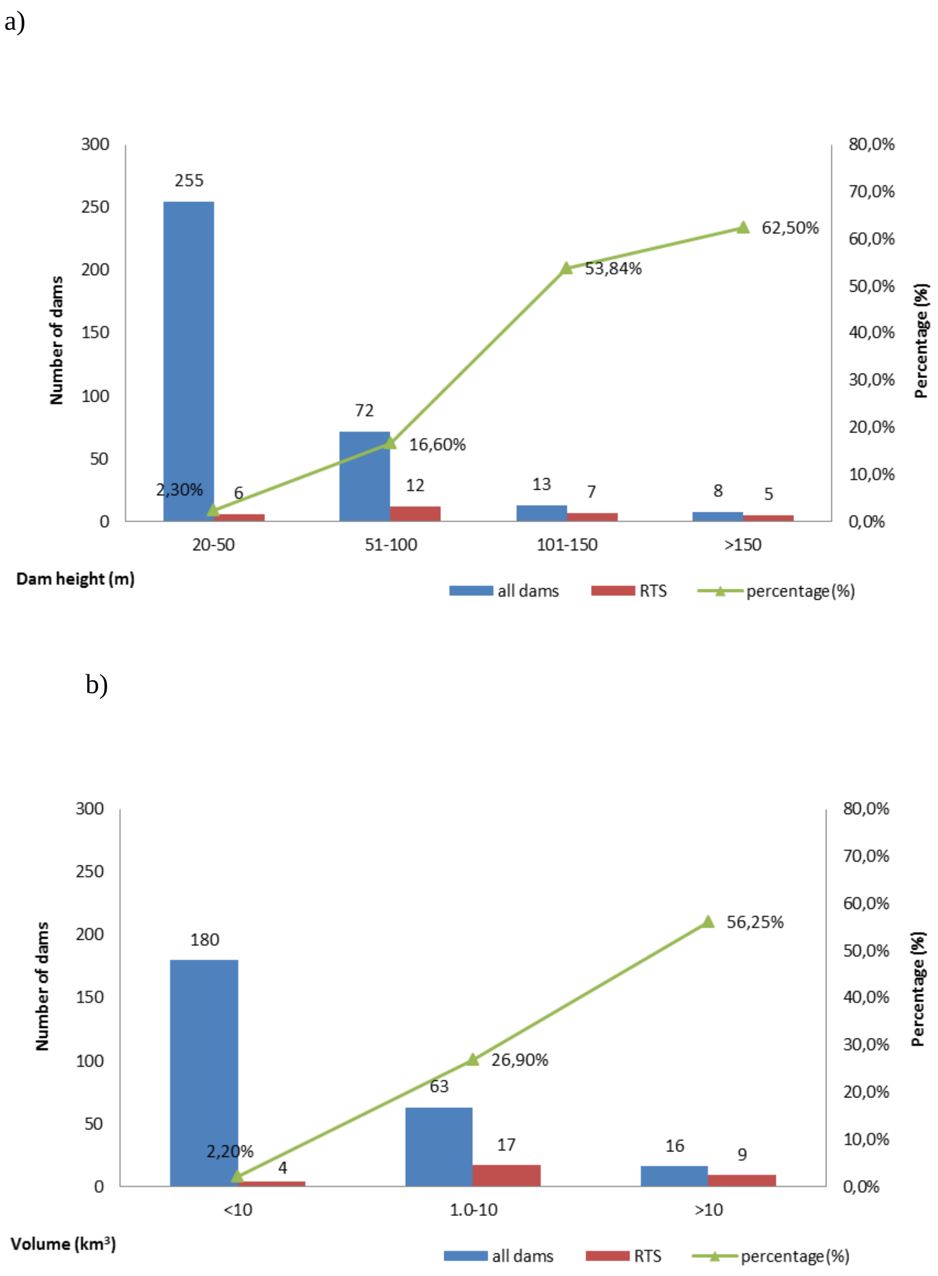
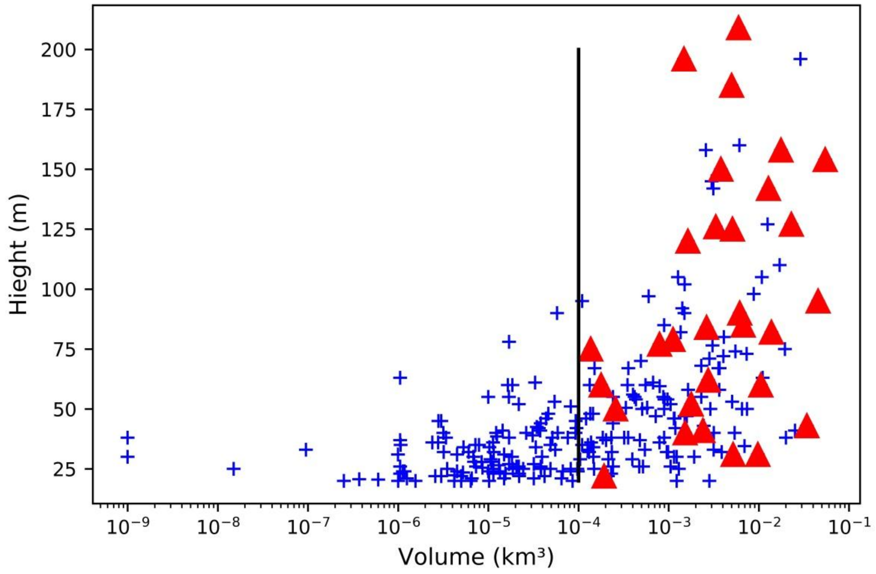


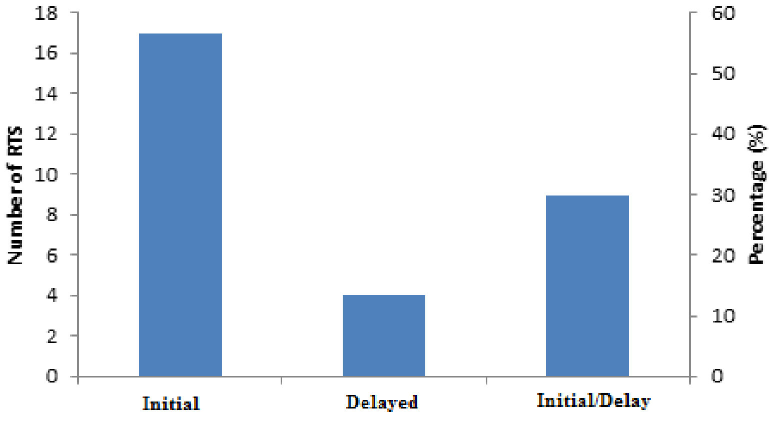
Fig 13- Percentage of cases of Reservoir-triggered Seismicity as stated by (a) dam height and (b) reservoir volume. 54% of dams taller than 100 m trigger earthquakes and 32% of reservoirs

637 larger than 1x10^{-3} km^{3} trigger earthquakes.



638

639 Fig 14- Graph of reservoir volume and dam height for all dams in Brazil. The triangles indicate
640 the RTS cases and the crosses, other reservoirs. The black bar is the limit of RTS cases.



641 Type of response

Fig 15- Graph of the type of response for RTS cases.

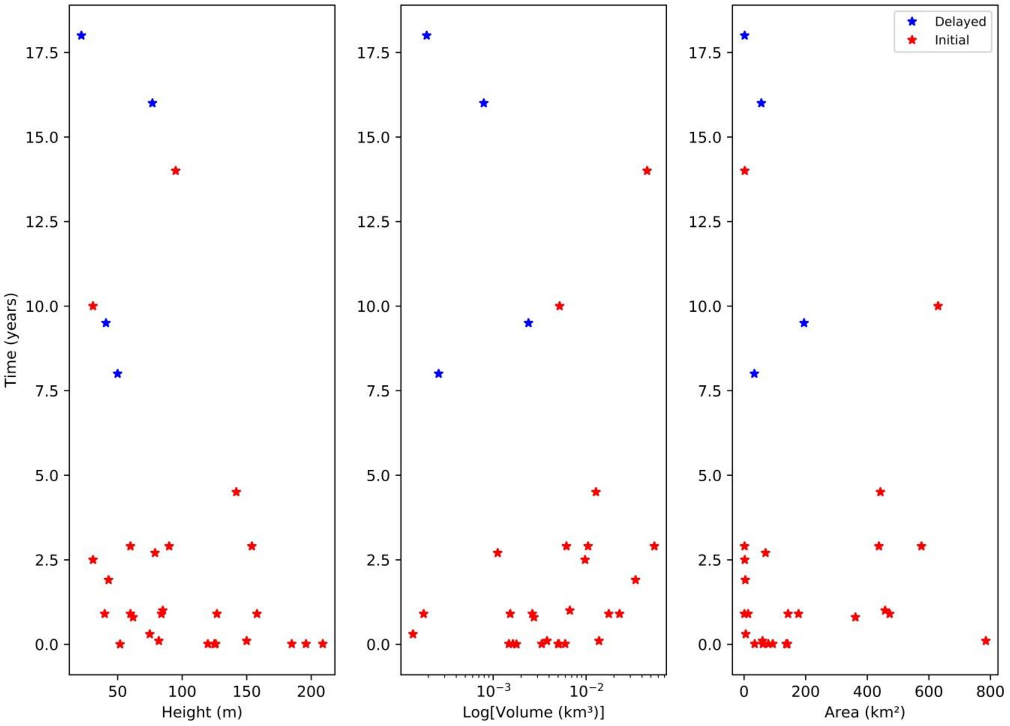
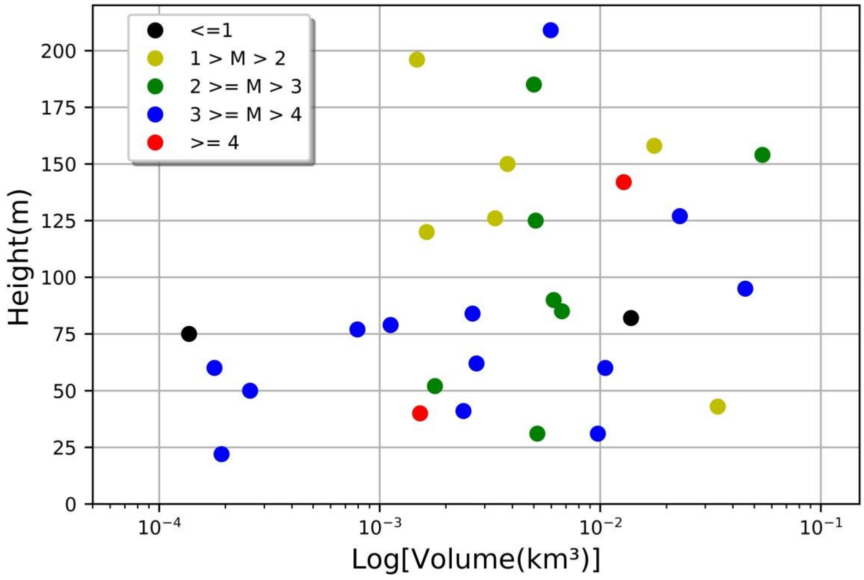
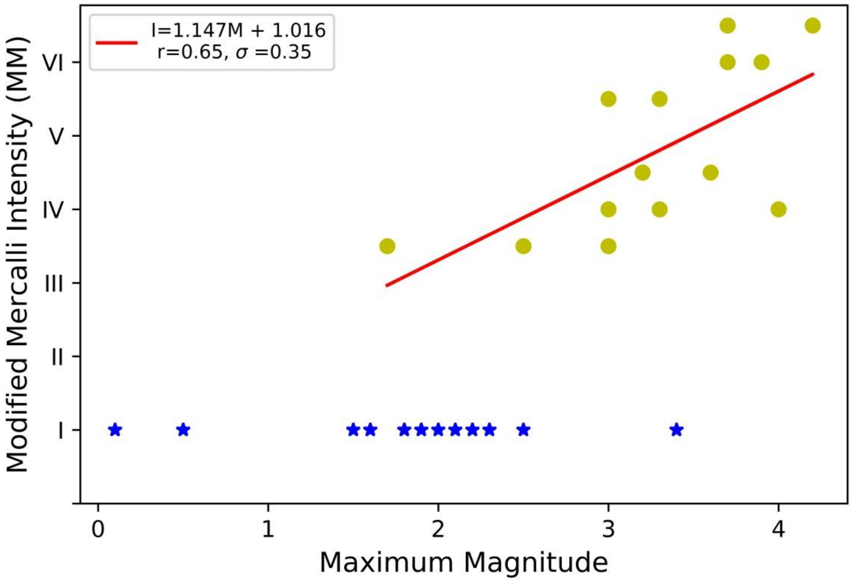


Fig 16- Graph of delay time/response versus dam height, volume, and area.

646 

647 Fig 17- Distribution of reservoir volume and dam height versus the Reservoir-triggered
648 Seismicity maximum magnitude cases.

649 

650 Fig 18- Graph showing maximum magnitude and intensity. The linear adjustment (bar) was
651 performed only with data represented by circles. The blue stars indicate cases of Intensity I.