Dear Editor and Reviewers

We have revised Manuscript NHESS-2019-227 in light of the editor's and reviewers' comments. Details of the changes are provided below. May we say that we found the reviewers and editor extremely helpful and constructive. We are glad to reaffirm that the manuscript has not been published or simultaneously published elsewhere. All changes suggested by the editor and reviewers have been incorporated or justified, as well as all new references used in the revision of the manuscript have been added.

I should like to refer some data could not be accessed until then because of the restriction of personnel at the university. Nowadays, the covid-19 policies implies home officing for everybody.

To a better understanding our answers we highlight the following guidelines; Comments/criticisms from the editor-reviewers' letter appear in black, followed by our responses, in blue, to their comments/criticisms (Re:) , which we detail the course of action taken, in red the changes done in manuscript and marked-up manuscript version showing the changes made in your File Manager.

Color legend:

(1) Comments from Referees

(2) Author's response

(3) Author's changes in manuscript

Yours Sincerely

Eveline Sayão

<u>**REVIEWER 1**</u>

The article refers to an interesting and actual research topic, however I felt limitations in how the work and decisions undertaken are explained, and an orientation toward making the results (website - as promised in the title) applicable and accessible. English is pretty sound and the chapters are divided ok. Some figures need to be enhanced. But the identification and analysis of factors leading to RTS, as well as the development of the website/GIS database and app needs better clarifications.

Specific comments

I've added my direct thoughts on the paper as comments and review inserts in the pdf supplement - please download it and have a look

COMMENTS ON THE TEXT

Title

Line 1. I don't think that "website" fits good in the title, especially since there is no link to it and it is presented more a GIS app and a database, with basic analysis of how different factors correlate with RTS occurrence; please consider a slightly different title.

Re: It is a good suggest, but the title uses website because we are implementing the site. I hope it is available at the same time as the publication. The system is to be via browser (web).

Spatial database and website for reservoir triggered seismicity in Brazil

Abstract

Line 16. worldwide (Sounds a bit odd and is maybe unnecessary)

Re: Ok, We agree with the reviewer.

Line 16. After confirming that impoundment of large reservoirs could cause earthquakes, studies on reservoir-triggered seismicity (RTS) have had a considerable scientific incentive.

Line 34. 1x10^{-4} km (Is 1X necessary and ^-4 ok (shouldn't be just 4)?

Re: We are corrected and you can see in figure 12.

Line 38. than 10^{-3} km (Shouldn't it be ^3 instead of ^-3?)

Re: The same comment was made in the previous question .

Introduction

Line 44. A reference seems needed.

Re: The references are Marza et. al. (1999); (Gupta, 2002; Wilson at al., 2017; Foulger at al., 2018) and (International Rivers, 2009).

Lines 42-49. 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 (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).

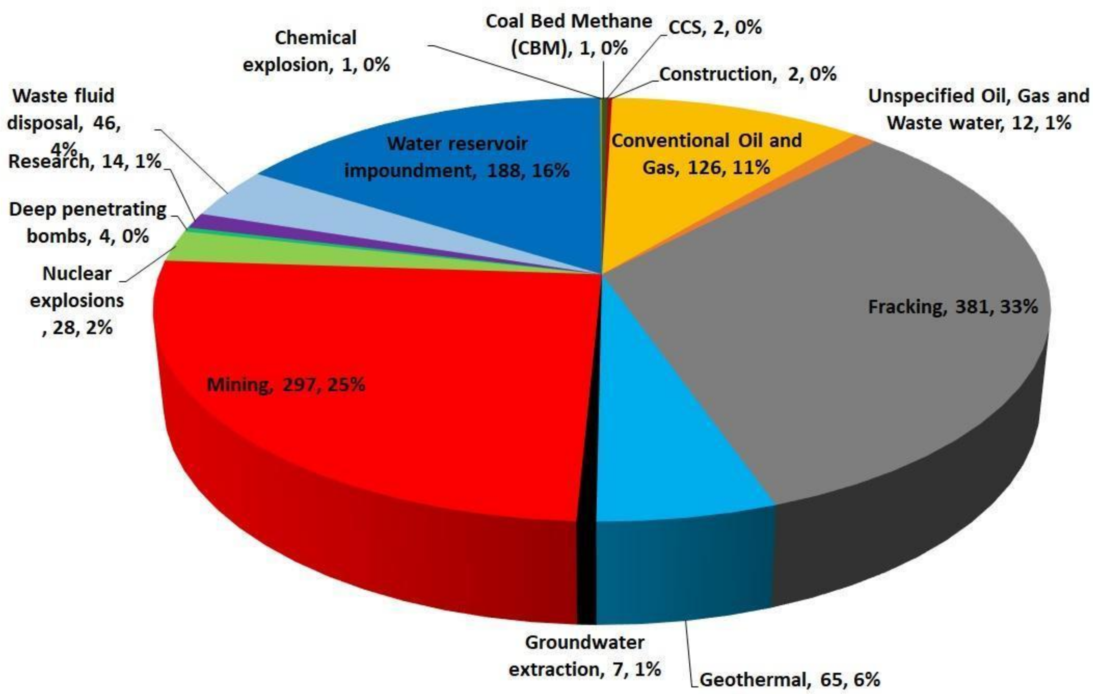
Line 46-. A reference seems needed

Re: The reference is Simpson (1986).

Line 49-52. 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).

Line 50. Any damage statistics, worldwide or for some important events (such as the ones mentioned earlier)?

Re: Yes, we should cite the site (www.inducedearthquakes.org), that show that the human induced earthquake website, there are 188 cases of RST, totaling 16%.



Lines 45-49. 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).

Line 54. Could you present some of the most relevant?

Re: The sentence was rewritten.

Line 57-59. 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.

Line 55. 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.
(Could be useful to add one-two sentences explaining why is this correlation important (and is important).

Re: Yes, we agree. The sentence was rewritten.

Lines 57-60. 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.**

National Spatial Data Infrastructure (INDE/ NSDI)

Line 103. as shown in Figure 2 (I don't consider Figure 2 really necessary, since you already provide the text description in the text - more useful.)

Re: Yes, we agree. We removed the figure.

Line 106. dissertation (paper/article)

Re: Yes, we agree, We will change dissertation by paper.

Lines 109-111. 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.

Designing the Spatial Database

Line 121. Figure 3 (Figure is probably not necessary.)

Re: Yes, we agree. The description in the text is sufficient to understand the steps involved in the construction process of the project in space database system.
We removed the figure.

Third Phase: Physical Modeling

Line 150. Sounds quite obvious to be "According to..."

Re: Ok, We agree and we can change the sentence.

Line 155. Database management software uses database management software (DBMS), p. e.: Medeiros (2012).

Line 153. This version is now a bit old; any comment on implementation capabilities for 3+ version?

Re: We are currently using version 3.12

Lines 155-157. 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.

Web viewer

Line 163. RISBRA (Reservoir Induced Seismicity in Brazil) (Is the webviewer publicly available? Where can it be found?)

Re: Yes, it is hosted on the site http://obsis.unb.br/portalsis/ in test phase.

Reservoir-Triggered Seismicity List updated for the database

Line 185. By who and with what method? Which were the detection limitations (e.g. number of stations monitoring seismicity near the dams)?

Re: Who? The catalog used was produced by the Seismology Center at the University of São Paulo and the Seismological Observatory at the University of Brasília in partnership with other reference centers in seismology in Brazil, we can access in http://www.moho.iag.usp.br/rq/ or www.obsis.unb.br. What method? In general, They used Geiger's method.

Lines 189-192. 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.

Line 191. The histograms are not enough to show swarms, especially since data is for all of Brazil; maybe maps for the mentioned dams would pin-point better the swarms and the time history of events in the areas.

Re: We agree and inserted stars in figure 5. We affirm that these swarms, in particular, they were well monitored by local seismic networks, it happens very rarely. Initially, as it is an analysis of general cases (across the country), we are not interested in addressing either case due to time constraints and objectivity.

RTS

Line 217. Beside intensity, couldn't it be provided an estimation of PGA (acceleration), based on recordings or GMPE's? Could also be relevant, as also an important parameter in seismic design of structures.

Re: We thought about this possibility but due to the lack of data coverage for all or most of the reservoirs, we did not address it on paper. We are doing a detailed study for reservoirs with PGA data for another paper. However, we inserted the estimated values of PGA in table 2 by USGS,2011. We have also added the text below.

Lines 220-224. 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).

Correlation of RTS with geological characteristics

Line 243. characteristics, ~~I~~ was compared…

Re: Ok! We were correct.

Line 250. 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).

Line 247. A short comparison with literature article findings explaining potential implications and correlations between rock types and RTS seems adequate.

Re: Yes, we agree.The sentence was rewritten.

Lines 253- 259. 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).

Dimensional physical properties and their correlations

Line 259. Dam height or reservoir depth?

Re: Dam height

Line 266. Maybe also other filters (such as geology, initial seismicity existence or swarm effects) could provide more insights to these statistics.

Re: Yes, we agree. And we can do the analyzes with the filters at the same time and not only separately, but some of them were treated in the research.

The intensity and Highest Magnitude

Line 319. Please rephrase these sentence - it's unclear.

Re: The sentence was reformulated.
Line 328. Several events were not felt, or there was no micro-seismic survey to define its intensity, for these we consider Intensity I.

Conclusions

Line 332. What is the policy regarding open "easy" access to RISBRA? I don't find on google any link or in this paper.

Re: The RISBRA is hosted on no Seismological Observatory website (http://obsis.unb.br/portalsis/). Access to the website and data is free. It is currently in the testing phase.

Line 333. Should be better highlighted, not just by histograms. Also, seismic monitoring increased capabilities (not discussed) are important when referring to an increase of RTS.

Re: We agree. The sentence was rewritten.

Lines 343-348. 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).

References

Lines 427, 429, 437, 440. available.

Re: Corrections have been made.

Line 445. CBDB - Comitê Brasileiro de Barragens, Available at: http://www.cbdb.org.br/, last access: 23 October 2018.

Line 447. Centro de Sismologia da USP – Available at: http://www.sismo.iag.usp.br/eq/bulletin/, last access: 15 October 2018.

Line 455. CONCAR – Comissão Nacional de Cartografia. Plano de ação para implantação da infraestrutura nacional de dados espaciais (INDE). Rio de Janeiro, 2010. Available at: https://www.concar.gov.br/pdf/PlanoDeAcaoINDE.pdf . last access: 03 April 2018.

Line 458. CONCAR – Comissão Nacional de Cartografia. Especificações técnicas para estruturação da infraestrutura nacional de dados espaciais digitais vetoriais. Edição 3.0, 2017. Available at: https://www.concar.gov.br/temp/365@ET-EDGV_versao_3.0_2018_05_20.pdf. . last access: 04 April 2018.

TABLES

Line 551. Wouldn't be a good link also between Reservoir and temperature variations (for evaporation etc.), or Reservoir and Water release (if not reflected by hydrometric data already)?

Re: Great suggestion. We are seeing a possibility of inserting climatological data on the platform and we will do some analysis for already known cases of RTS. For water release we use hydrometry data already available and analyzed in the Response Time approach.

Table 2-

Line 552. Seismicity Cases triggered in Brazil.

What does UF stands for?

Re: Federative unit.

Area of the reservoir?

Re: Has been run to:Area of the reservoir (km^2).

Area of the reservoir (km^2)

Some text appears to be missing

Re: Has been run to: Maximum reservoir water depth (m).

Maximum reservoir water depth (m).

Figures

Line 563. I don't consider Figure 2 really necessary, since you already provide the description in the text - more useful.

Re: The figure was deleted.

Line 584. I don't consider this figure necessary, since you already provide the description in the text.

Re: The figure was deleted.

Line 588. It would be useful to include all attribute names in english.

Re: Answered in next question

Line. 590. Please, use english names for the text to make the schema applicable and traceable

Re: The OMT-G and Relational Model are models made in softwares for use in the application of the physical model. It is in Portuguese because the database was developed in that language. However, we will have the English version of the page.

Line. 598. Histogram of the RTS numbers with a magnitude greater than 1, per year.

Re: Removed the word than.

Fig 5- Histogram of the RTS numbers with a magnitude greater 1, per year.

Line 598. Citing a datasource would be good also here (not just in the text).

Re: The correction was made.

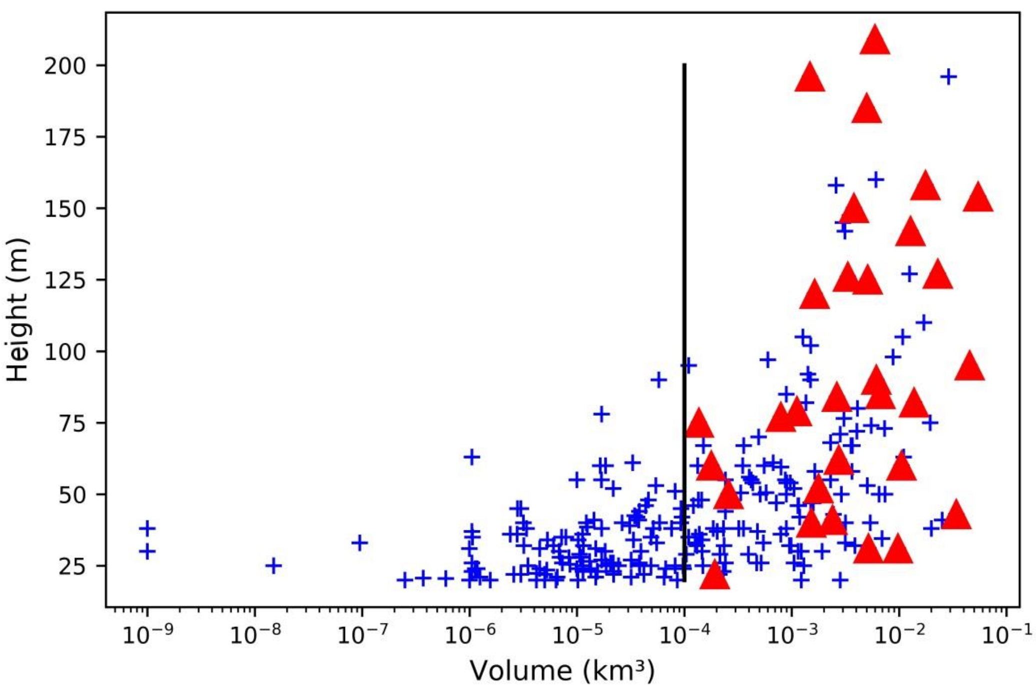
Fig 5- Histogram of the RTS numbers with a magnitude greater 1, per year (Data from the Brazilian bulletin cataloged by SIS-UnB).

Line 601. Numbers on the small circles are hard to identify. Is this data available in the webviewer - maybe make a link to the interactive version?

Re: Nice a idea. As described above, we will not be able to link to this work, but it will certainly be placed in the webviewer version.

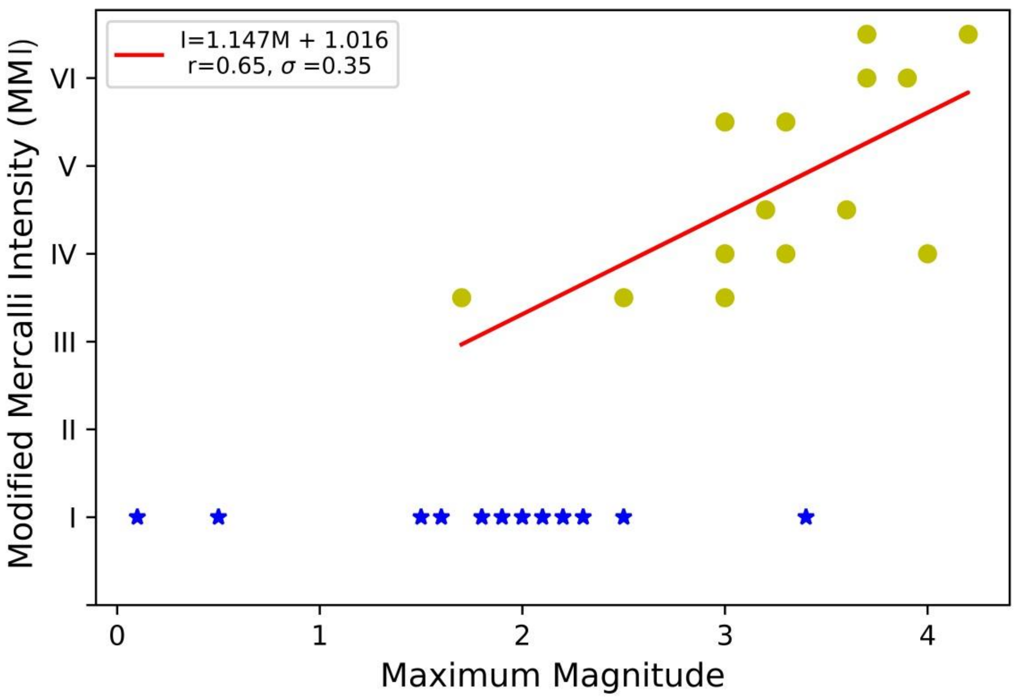
Line. 638. Height

Re: The correction was made.



Line 649. MMI

Re: The correction was made.


I=1.147M + 1.016
r=0.65, σ =0.35
Modified Mercalli Intensity (MMI)
VI
V
IV
III
II
I
0
1
2
3
4
Maximum Magnitude

REVIEWER 2

It is an interesting paper, data processing can add valuable information to this field of study. However the paper is not clear enough about the effort the authors have added to this work. It is not clear what they have performed and what was already ready to use as an input to their research. There is too much about the creation of the GIS database and to less about how the results were obtained (eg. Fig 11b). The structure of presenting the results is good however it is a question whether the results are in accordance with the referred papers or not. It is not clear how the authors have classified earthquakes to be linked to dams – ie. RST cases. The "research" itself is very simple only statistical assessment of the RTS events however it can be a kind of state of the art type of paper when compared to other research and results in this field. After revision it can be published. PS: I have added suggestions to the pdf file directly.

COMMENTS ON THE TEXT

Title

Line 1. ~~Website~~ - Spatial database for reservoir triggered seismicity in Brazil

Re:The title was rewritten.

Spatial database and website for reservoir triggered seismicity in Brazil.

Abstract

Line 19. of effective ~~effort~~ due to the increase in pore pressure, can modify the stress ~~regime~~ in the.

Re:Effort and regime have been replaced by force and field.

Lines 17-20. 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.

Line 24. One of the major challenges ~~for~~ studying RTS is to identify and…

Re:"For" has been replaced by in.

Lines 23-25. 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.

Lines 25-28. 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 27 to the RTS study in the area of reservoirs.

Re:The sentence was rewritten.

Lines 25-27. 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.

Lines 30-31. 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.

Re:The sentence was rewritten.

Lines 27-31. 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.

Line 36. ...of them have **a** hydraulic behavior...

Re:The correction was made.

Lines 35-37.The delayed response time of the reservoirs represents 43% of the total, that is, almost half of them have a hydraulic behavior.

Lines 37-38. The highest magnitude, 4.2, was observed for an event that occurred in a reservoir with a volume greater than 10^{-3} km^3 .

Re:The sentence was rewritten

Lines 37-38. The highest magnitude, 4.2 was observed at a reservoir with a volume greater than 10^{-3} km^3 .

Introduction

Lines 43-45. 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).

Re:The sentence was rewritten.

Lines 42-45. 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).

Line 52. ...intensity V-VI (MM) recorded ~~in~~ **at** the reservoir of Carmo do Cajuru...

Re:The correction was made.

Lines 54-55. 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.

Lines 54-55. 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. (Please redraft).

Re:The sentence was rewritten.

Lines 57-60. 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.

Line 56. Thus, this work ~~proposes to present~~ the procedures and results found in the data processing ~~of~~ the following …

Re:The sentence was rewritten.

Lines 60-63. 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

Line 58. ~~To this end~~, a spatial …

Re:The sentence was rewritten.

Lines 63-64. Finally, a spatial database model of the reservoirs and their geological and geophysical characteristics was developed.

Line 64-66. 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).

Re:The sentence was rewritten.

Lines 68-70. The amount of information and probable effects RTS causing requires the standardization of information, which was accomplished according the National Spatial Data Infrastructure (INDE).

Database and web viewer

Lines 73-74. 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**. (Please redraft).

Re:The sentence was rewritten.

Lines 76-79. 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.

Lines 76-77. ... 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.

Re:The sentence was rewritten.

Lines 81-82...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)

Line 88. The spatial data infrastructure defines the standards for the data composing ~~it~~ and ~~maybe being~~ presented as a Technical Specification.

Re:The sentence was rewritten.

Lines 93-94. The spatial data infrastructure defines the standards for the data composing and can be presented as a Technical Specification.

Lines 98-103. MapTopoPE is divided into 14 categories: ~~Energy and Communications (ENC), Economic Structure (ECO)~~, Hydrography (HID), etc ~~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. (you may list one or two but it is not necessary so far there is the Fig.2)

Re:Figure 2 was removed, keeping only the text.

Line 106. dissertation (paper/article)

Re: We did the dissertation substitution for paper.

Line 111. Among the categories, the hydrography package covering the dam class is the class of interest for this paper.

Lines 128-132. 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. (determined by the authors of this paper ?)

Re:Yes, the entities that make up the database were determined by the authors of this paper based on the research conducted.

Lines 140-142. 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. (Determined by the authors of this paper ?)

Re:Yes, this step is performed based on the objectives of using the database. It is one of the most important steps because it involves multiple search options and access to the bank's data.

Third Phase: Physical Modeling

Line 145. 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).

Re:The sentence was rewritten.

Lines 151-152.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).

Web viewer

Line 163. The web viewer, named RISBRA (Reservoir Induced Seismicity in Brazil), was created using the leaflet, Node.js and Redis libraries. (by authors of this paper ?)

Re:Yes, the name was created by the authors.

Line 179. Update of Seismicity Triggered in Brazil for the Database (Please redraft)

Re:The topic was adjusted according to the suggestion.

Line 183. Reservoir-Triggered Seismicity List updated for the database.

Reservoir-Triggered Seismicity List updated for the database

Line 203. Table 2 is based on the work of Marza et al. (1999), to which we added other data such as area of reservoirs,...

(You should indicate also at the title of the table that is based on Marza et al).

Re:The correction was made.

Line 574. Marza et al. (1999).

RTS

Line 214. In general, from the total of 348 reservoirs, only 8.6% of those presented RTS, ~~among them~~, only two events with a maximum magnitude...

Re:The sentence was rewritten.

Lines 220-224. 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).

Line 223. However, compared to the number of reservoirs in Northeast, 17.8% of the reservoirs show RTS that although there are fewer cases in the region, the relative value is comparatively higher. (of the total number of earthquakes or number of what?)

Re:Compared to the number of RTS with number of reservoirs in the northeast region.

The sentence was rewritten.

Lines 231-233. 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.

Line 225. ….although there are fewer cases in the region, the relative ~~value~~ is comparatively higher.

Re:Value has been replaced by number.

Lines 231-233. However, compared to the number of reservoirs, 17.8% in the Northeast shows that although there are fewer cases in the region, the relative number is comparatively higher.

Correlation of RTS with geological characteristics

Line 232. Despite the laboratory ~~studies on~~ these properties, little progress has been made, especially due…

Re:The sentence was rewritten.

Lines 239-242. 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).

Line 239. ...low resistance to rupture, facilitates liquid penetration all the way to the deepest and most…

Re:The sentence was rewritten.

Lines 244-247. 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.

Line 243. characteristics, ~~I~~ was compared…

Re: Ok! We were correct.

Lines 250-251. 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):

Dimensional physical properties and their correlations

Line 265. ...more likely to trigger earthquakes, ~~corroborating~~ Simpson (1986) findings.

Re:Corroborating has been replaced by confirming.

Lines 275-278. 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.

Line 272. you are determining initial type later -maybe this is something you should mention there

Re: The type of seismicity is one of the items in Table 2. We do not understand.

Line 274. We observed that the height is not limitant, which is the height of the largest dam. (Please redraft)

Re:The sentence was rewritten.

Lines 285-286. We observe that the height does not have a limit between 20m and 209m, which is the height of the largest dam.

Response Time

Line 284-286. 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. (If you want to describe to different behaviour than please redraft the sentence.)

Re:The description was for the steady state.The sentence was rewritten.

Lines 295-297. 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.

Line 294. ~~O~~f the 30 RTS cases, only 4 were considered as a delayed response while 17 cases had only an initial response (Figure 15).

Re:Changing the suggested phrase would change the meaning.

Line 299. The delayed response cases represent 43% in total, that is, almost half of them have hydraulic behavior.

(Is this accordance with you have described in row 280-289?)

Re: We insert to the paragraph (280-289) the nomenclature hydraulic and mechanical behavior.

Lines 297-301. 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) .

Highest Magnitude

Line 303. It is known that in large reservoirs, the chances of pressure in the rock pores to affect the existing...

(As the pressure in the rock pores increases affects existing seismic structures below a dam, so the chance of RST also increases. This is what you suggested? Please redraft)

Re:We cannot say that. Our results point out the majority of cases in the initial response reservoir, that is, related to the rapid increase in elastic effort due to the reservoir load.

Line 312. ~~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

Re:The sentence was rewritten.

Lines 323-325. 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.

Lines 314-316. 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. (Is this in agreement with that you have referred from literature (row 257- Simpsons)?

Re:Yes, confirming Simpson (1986) findings.

The sentence was rewritten.

Lines 325-327. 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

Lines 318-319. Several events were either not felt or there was no micro-seismic survey defining its intensity, they were considered Intensity I ~~here~~.

Re:The sentence was rewritten.

Lines 329-330. Several events were not felt, or there was no micro-seismic survey to define its intensity, for these we consider Intensity I.

Line 323. Have such equations published previously? You might need to say that this is only applicable for dams in the investigated area.

Re:These equations have not been published previously. We will inform in the text that the equation is applicable only to the dams investigated in this study.

Conclusions

Line 331. The created web viewer, RISBRA, presents ~~as~~ an interactive platform with easy access and great potential to improve knowledge on the RTS in Brazil.

Re:Fixed.

Line 342-343. The created web viewer, RISBRA, presents an interactive platform with easy access and great potential to improve knowledge on the RTS in Brazil.

Line 338. Despite having a small number of RTS, the Northeastern region has comparatively higher relative value compared to other regions. (What Value?)

Re:Compared to the number of RTS, 17.8% in the Northeast shows that although there are fewer cases in the region, the relative value is comparatively higher. The sentence was rewritten.

Lines 351-353. Despite having a small number of RTS, 5 cases, the Northeast region has a comparatively higher relative value of RTS compared to other regions.

Line 339. 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.

Re:The sentence was rewritten.

Lines 354-356. 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.

Lines 344-346. 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. (based on data obtained from, or based on evaluated data- these are your results?

Re:Yes, these are our results. Based on the evaluated data.

Line 352. 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.

Re:The sentence was rewritten.

Lines 367-369. 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.

Line 355-357. 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.

Re:The sentence was rewritten.

Lines 370-372. 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.

Lines 360-361. 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.

Re:The sentence was rewritten.

Lines 373-375. 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

Line 363. 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).

Re:Fixed

Line 377. 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).

TABLES

Line 550. It should be more dense to fit one page.

Re:We agree. We will make the change.

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.

Line 552. This table should be cut in to more tables each containing headings to be able to process.

Re:We agree. We will make the change.

Nº	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
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.
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
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
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)

12	11	10	9	8	7	6	N°	
Furnas	Funil	Emborcação	Castanhão	Capivari- Cachoeira	Capivara	Campos Novos	**Name**	
MG	MG	GO/MG	CE	PR/SP	PR/SP	SC	**Federative unit**	
127	50	158	85	60	60	196	**Height (m)**	
22,950	0,258	17,588	6,700	0,178	10,540	1,477	**Volume ($10^{-3}km^3$)**	
-	808,0	653,0	100,0	-	-	-	**Maximum water depth in the Reservoir (m)**	
1.44	33.46	473.0	458.00	13.1	576.0	34.6	**Area of the reservoir (km2)**	
1963	2002	08/1981	2003	07/1970	01/1976	10/2005	**Start of impoundment**	
Thrust and Folding	Craton	Thrust and Folding	Thrust and Folding Range.	Thrust and Folding Range	Basin	Basin	**Geological Province**	
Initial *	Delayed	Initial	Initial - Delayed	Initial	Initial- Delayed		**Seismicity type**	
1966/11/15	2011/08/14	1982/05/20	2007/08/07	1971/05/21	1979/03/27	2005/10/12	**Date (YY/MM/DD)**	**Largest Events**
3.2	3.2	1.6	2.3	3.9	3.7	1.8	**Magnitude**	
mI	mR	ML	mD	ML	mb	ML	**Magnitude Type**	
IV-V	IV-V	I	I	VI	VI-VII	I	**Io (MMI)**	
0.03 -0.15	0.03 -0.15	-	-	0.08 - 0.15	0.08 -0.25	-	**PGA (g)**	
~1?	8	~1	1?	~1	~3	0.01	**ΔT (year)**	
-	Margin	Inside	Margin -Inside	-	Margin	Inside	**Location**	
Berrocal et al. (1984) and Barros	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)	Ribotta et al. (2010)	**References**	

										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**
13	Irapé	MG	209	5,964	470,8	137.0	12/2005	Thrust and Folding	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)
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
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.

	24		23		22	21	20
N°	24		23		22	21	20
Name	Porto Colombia e Volta Grade		Paraibuna-Paraitinga		Nova Ponte	Miranda	Marimbondo
Federative unit	MG/SP		SP		MG	MG	MG/SP
Height (m)	40	55	84 /105		142	79	90
Volume ($10^{-3}km^3$)	2,3	1,525	1,270	2,636	12,792	1,120	6,150
Maximum water depth in the Reservoir (m)	-		-		-	-	-
Area of the reservoir (km2)	19.5	143.0	47.0	177.0	443.0	70.0	438.0
Start of impoundment	09/1973	04/1973	1976	1974	10/1993	08/1981	1975
Geological Province			Thrust and Folding Range.		Basin	Basin	Basin
Seismicity type			Initial		Initial- Delayed	Initial- Delayed	Initial
Largest Events							
Date (YY/MM/DD)	1974/02/24		1977-11-16		1998/05/22	2000-05-06	1978/07/25
Magnitude	4.2		3.3		4.0	3.3	2.0
Magnitude Type	mD		mb		mR	mR	ML
Io (MMI)	VI-VII		IV		VI	V-VI	I
PGA (g)	0.08 - 0.25		0.03 and below		0.08 - 0.15	0.03 and 0.15	-
ΔT (year)	~1		~1			2.7	~3
Location	Margin?		Inside		Margin	Margin	Margin
References	Berrocal et al. (1984), Veloso (1992a) and Gomide (1999)		Mendiguren (1980) eand Ribotta (1989)		Chimpliganond (2002), Marza, Barros, Soares et	Barros e Caixeta (2003) e Assumpção et	Veloso et al. (1987)

										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**
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		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)

										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**
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)

Figures.

Line 560. Reference?

Re: (data from the www.inducedearthquakes.org. Last accessed 20 February 2020)

Line 562. Not readable blurry.

Re: This figure was removed.

Line 584. Too big compared to other figures . Reference?

Re: This figure was removed.

Line 589 and 590. Reference? Not readable

Re: The OMT-G and Relational Model are models made in softwares for use in the application of the physical model. It is in Portuguese because the database was developed in that language. We will make it readable

Line 595. Reference?

Re: We do not put the website address because we are implementing it. I hope it will be available at the same time as the publication.

Line 601. Reference

Re: Data from the bulletin of the IAG IAG-USP and SISBRA (Brazilian bulletin cataloged by SIS-UnB.

Data from the bulletin of the IAG IAG-USP and SISBRA (Brazilian bulletin cataloged by SIS-UnB.

Line 602. Figure 9 has been compiled by the authors of this paper?

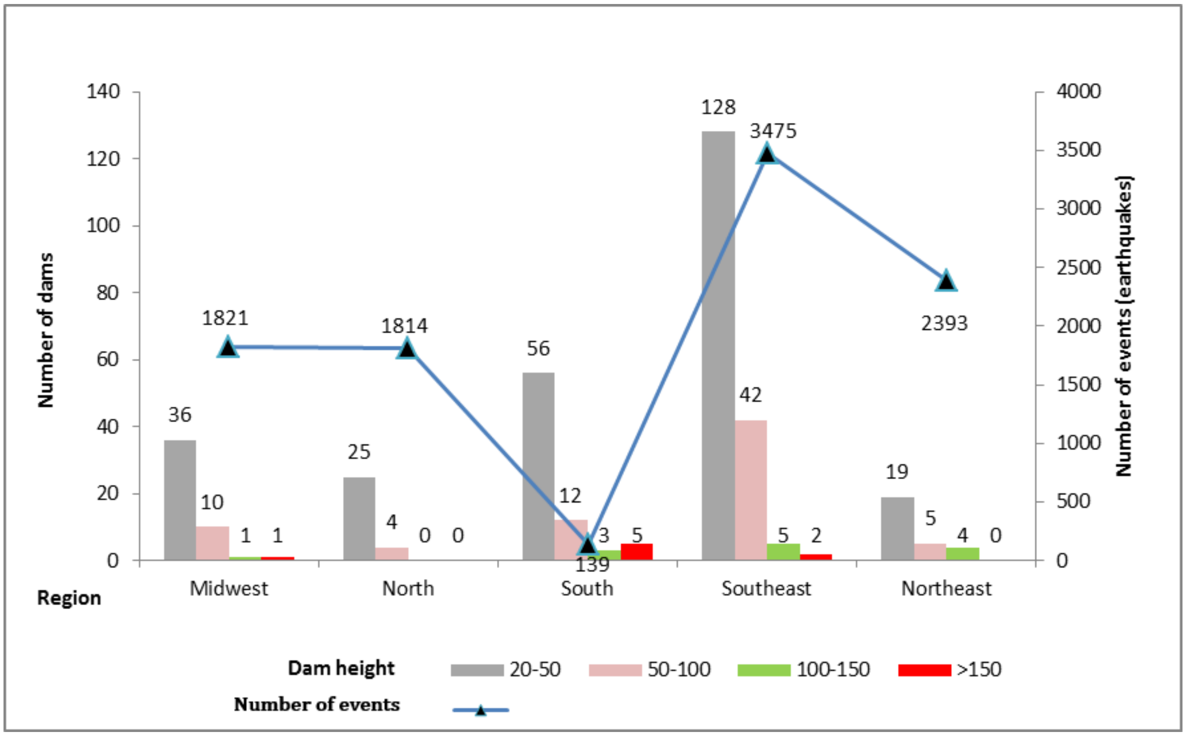
Meaning of the blue line?

Magnitude of earthquake can be represented in this figure ? It would be great to see.

Re: Figure 7 was created by the authors.

The blue line represents the number of events (earthquakes) by region.

Our proposal is not to add more information to the graph. We believe it would be too much information.



Line 608. Reference?

Re:Data from the Brazilian Committee on Dam.

Data from the Brazilian Committee on Dam. (Figure 8)

Line 615. Figure 11 has been compiled by the authors of this paper?

Re:Figure 9 was created by the authors.

Line 625. Reference?

Re:Datas from the Brazilian Committee on Dams-2018 and CPRM Mineral Resources Research Company.

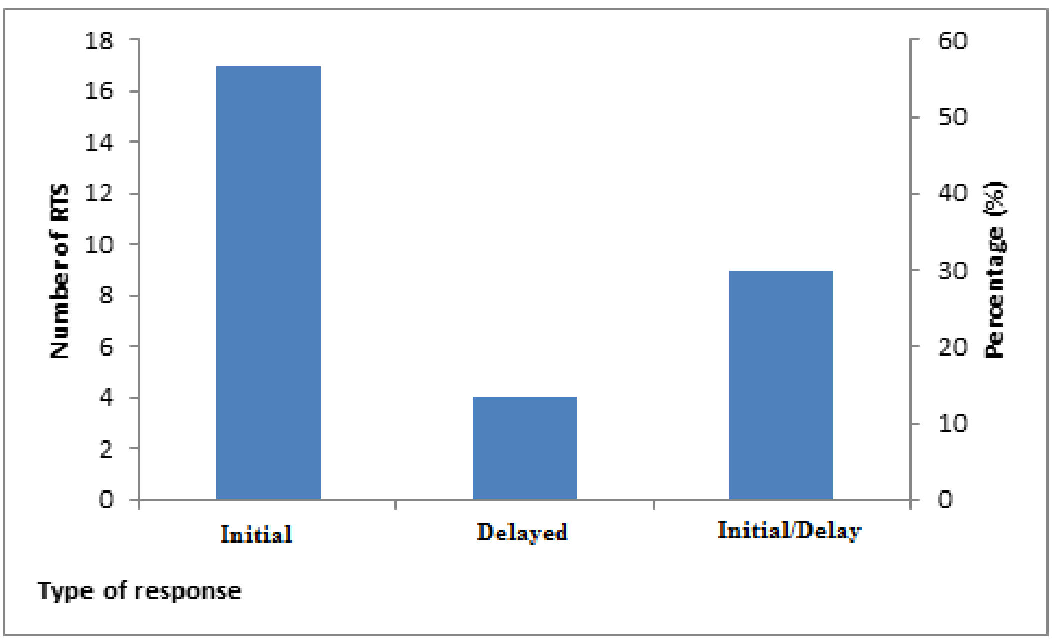
Datas from the Brazilian Committee on Dams-2018 and CPRM Mineral Resources Research Company.(Figure 10)

Line 631. Figures 13-18 has been compiled by the authors of this paper?

Re:Figures 11 to 16 are the authors' creations.

Line 641. Blurry

Re:The figure has been redone for better clarity.



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, UF, 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).

Acknowledgments

The authors thank the Comitê Brasileiro de Barragens for providing the data from the Cadastro Nacional de Barragens.

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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.

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)

	N°	5	6	7	8	9	10
	Name	Carmo do Cajuru	Campos Novos	Capivara	Capivari- Cachoeira	Castanhão	Emborcação
	Federative unit	MG	SC	PR/SP	PR/SP	CE	GO/MG
	Height (m)	22	196	60	60	85	158
	Volume ($10^{-3}km^3$)	0,192	1,477	10,540	0,178	6,700	17,588
	Maximum water depth in the Reservoir (m)	749,7	-	-	-	100,0	653,0
	Area of the reservoir (km2)	2.3	34.6	576.0	13.1	458.00	473.0
	Start of impoundment	1954	10/2005	01/1976	07/1970	2003	08/1981
	Geological Province	Craton	Basin	Basin	Thrust and Folding Range	Thrust and Folding Range.	Thrust and Folding Range.
	Seismicity type	Delayed		Initial- Delayed	Initial	Initial - Delayed	Initial
Largest Events	**Date (YY/MM/DD)**	1972/01/23	2005/10/12	1979/03/27	1971/05/21	2007/08/07	1982/05/20
	Magnitude	3.7	1.8	3.7	3.9	2.3	1.6
	Magnitude Type	mb	ML	mb	ML	mD	ML
	Io (MMI)	VI	I	VI-VII	VI	I	I
	PGA (g)	0.08 - 0.15	-	0.08 -0.25	0.08 - 0.15	-	-
	ΔT (year)	18	0.01	~3	~1	1?	~1
	Location	Margin	Inside	Margin	-	Margin -Inside	Inside
	References	Veloso et al. (1987) and Viotti et al. (1995,1997)	Ribotta et al. (2010)	Assumpção et.al (1995)	Berrocal et. al.(1984) eand Mioto et.al. (1991)	Ferreira et. al. (2008)	Viotti et al. (1997,1995)

										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**
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)
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 Range	Delayed	1985/12/17	3.0	ML	V-VI	0.03 -0.15	16	Margin	Veloso et al. (1987)

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
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)
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°	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
22	Nova Ponte	MG	142	12,792	-	443.0	10/1993	Basin	Initial- Delayed	1998/05/22	4.0	mR	VI	0.08 - 0.15		Margin	Chimpliganond (2002), Marza, Barros, Soares et al. (1999)
23	Paraibuna-Paraitinga	SP	84 /105	1,270 / 2,636	-	47.0 / 177.0	1976 / 1974	Thrust and Folding Range.	Initial	1977-11-16	3.3	mb	IV	0.03 and below	~1	Inside	Mendiguren (1980) eand Ribotta (1989)
24	Porto Colombia e Volta Grade	MG/SP	40 / 55	2,3 / 1,525	-	19.5 / 143.0	09/1973 / 04/1973			1974/02/24	4.2	mD	VI-VII	0.08 - 0.25	~1	Margin?	Berrocal et al. (1984), Veloso (1992a) and Gomide (1999)
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		1979/07/05	1.9	ML	I	-	~2	Inside	Berrocal eand Fernandes (1996)

										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**
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)

ΔT, Time interval (years) since the beginning of filling;MMI, Modified Mercalli Scale; Doubtful cases; PGA(g), Peak Ground Acceleration; Adapted by Marza et al. (1999).

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

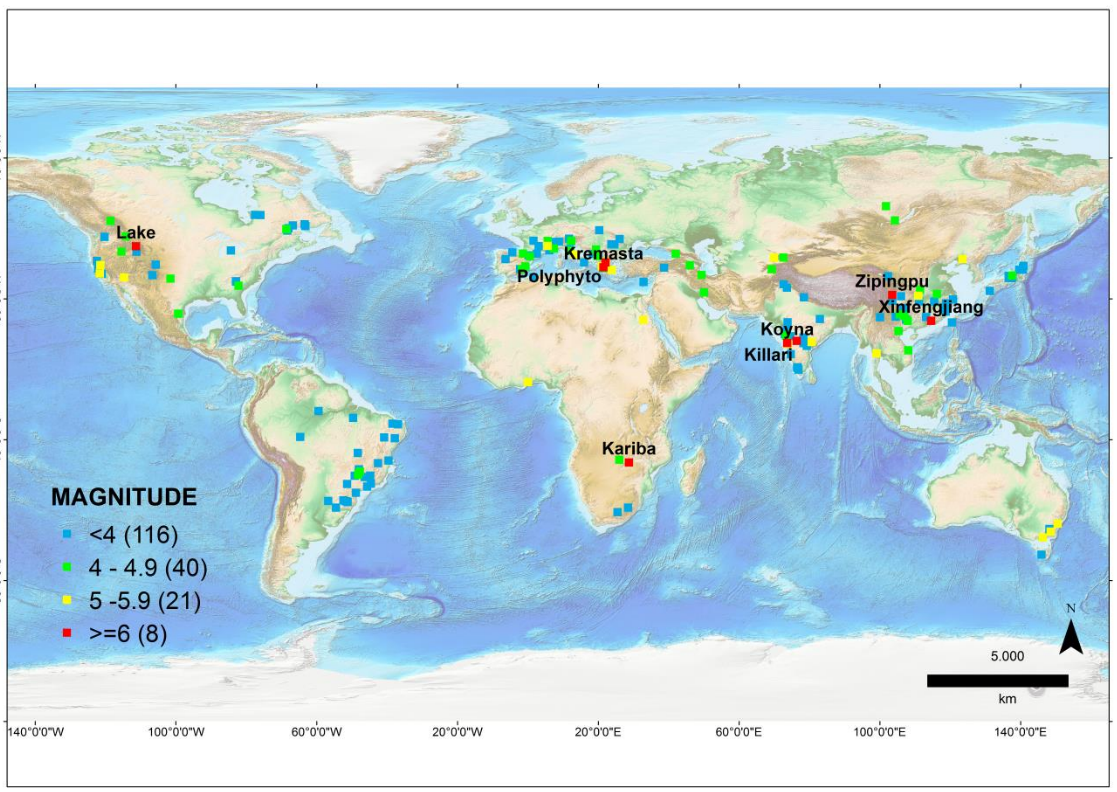


Fig 1 - World map of events triggered by reservoirs. (Data from the

www.inducedearthquakes.org. Last accessed 10 May 2020)

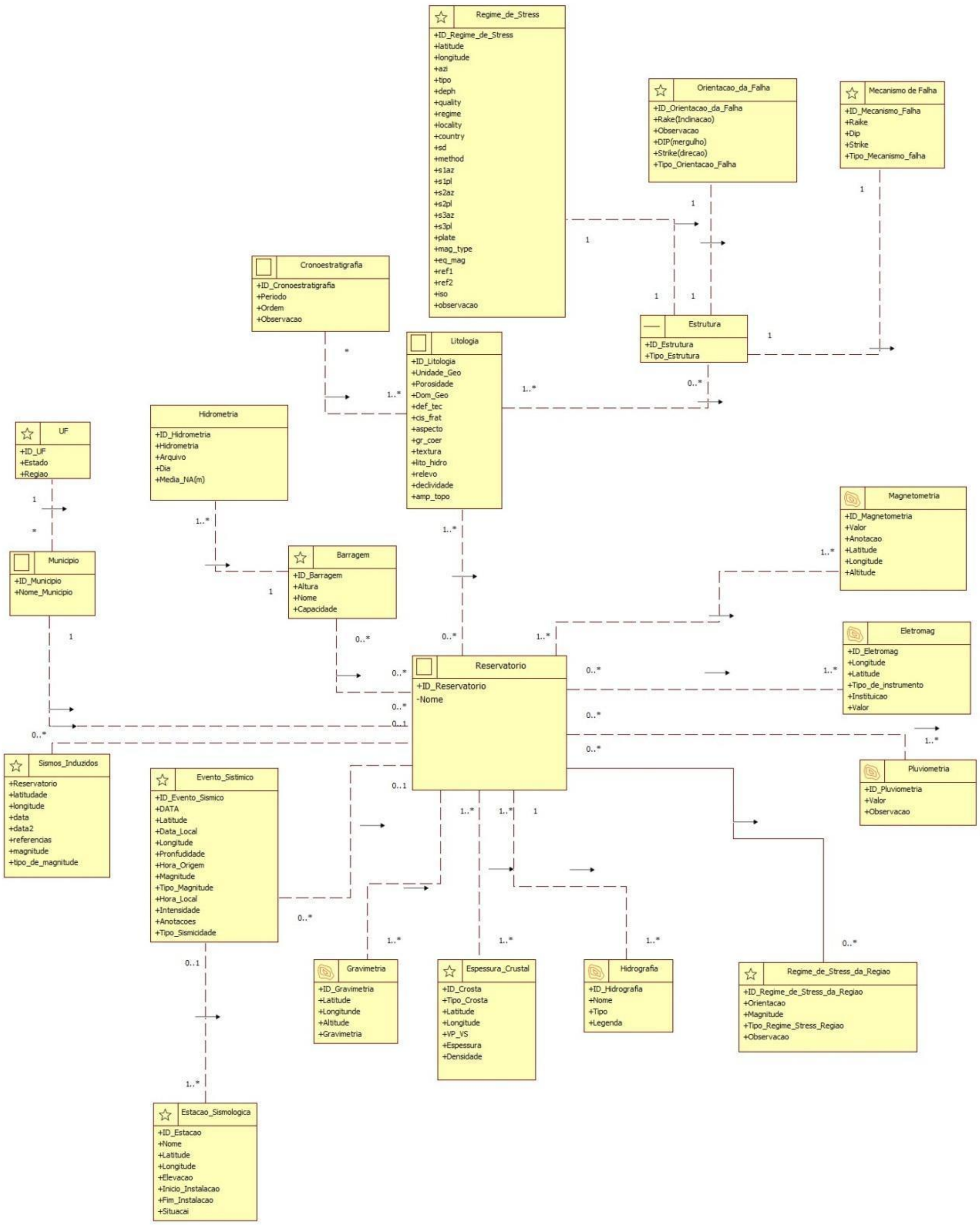


Fig 2- OMT-G Model of Reservoir-triggered Seismicity Database.

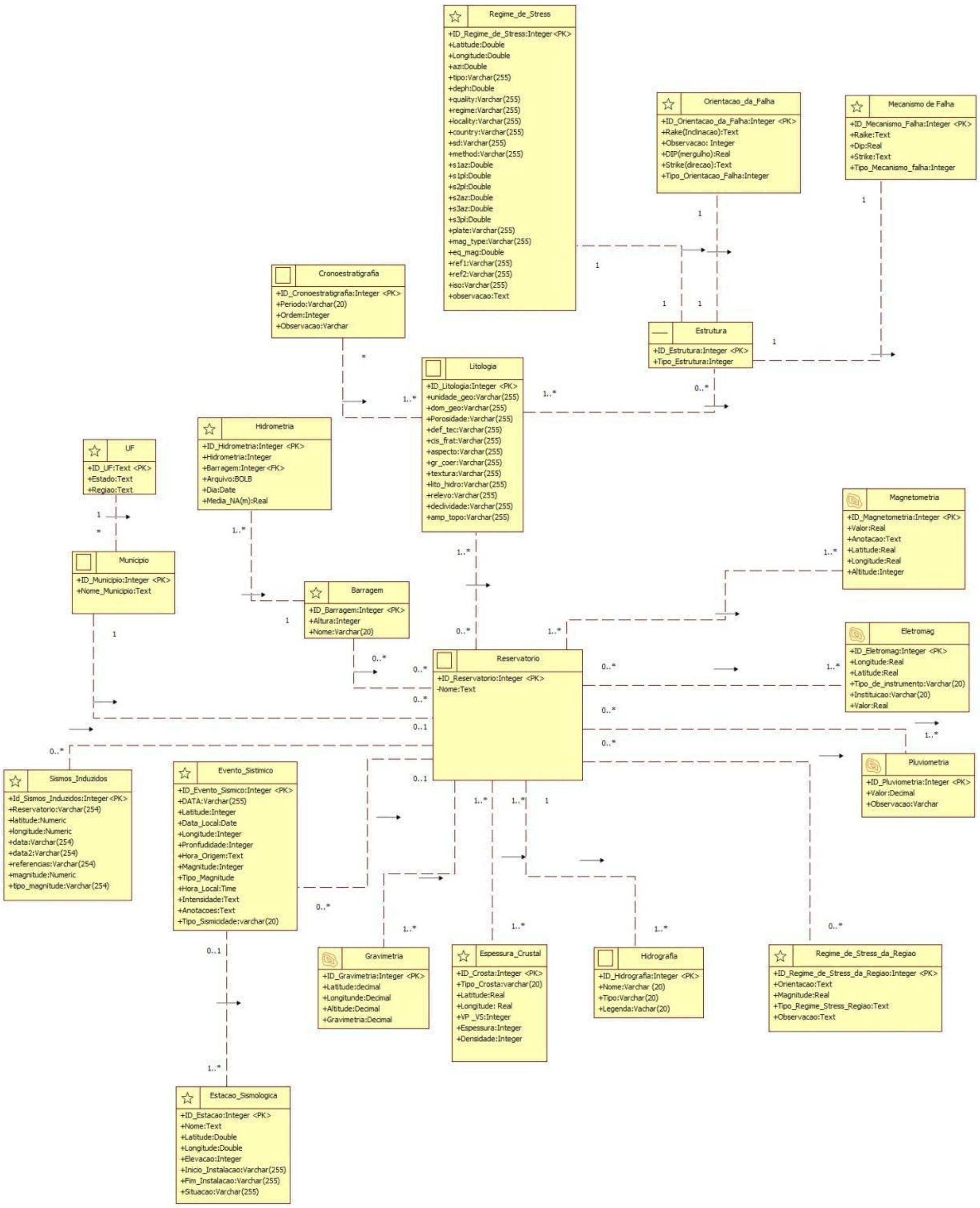


Fig 3- Relational model of Reservoir-triggered Seismicity Database.

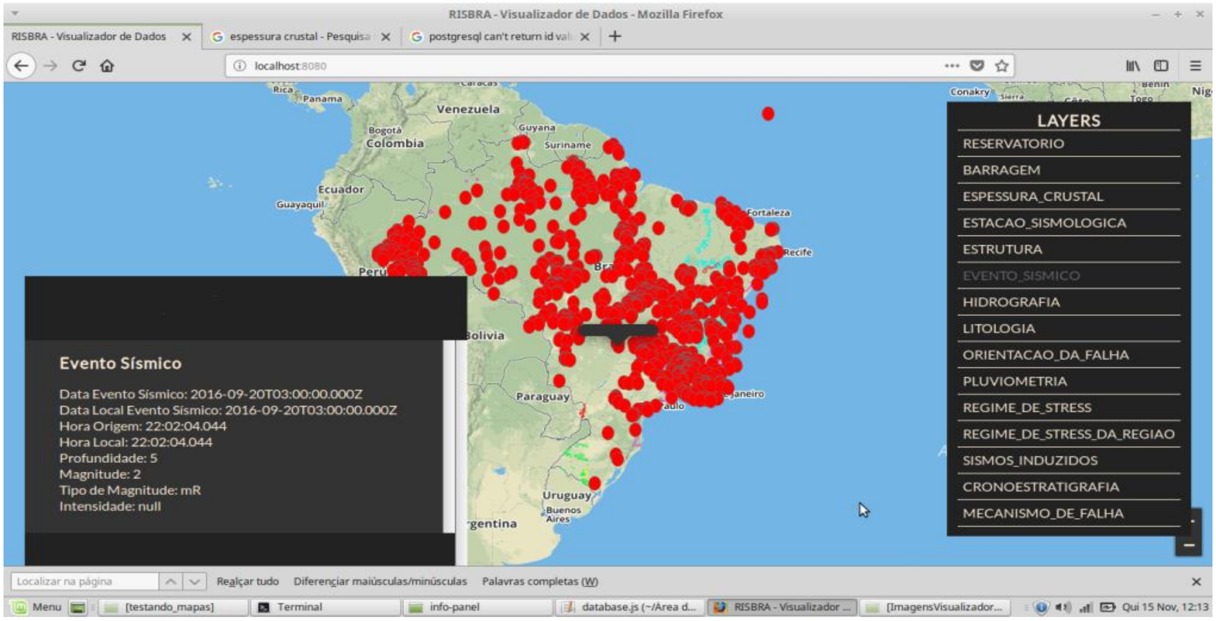


Fig 4- Example of researching Brazilian seismicity in RISBRA. The seismic events are represented by red ball and table to the left with information regarding this seismic event layer.

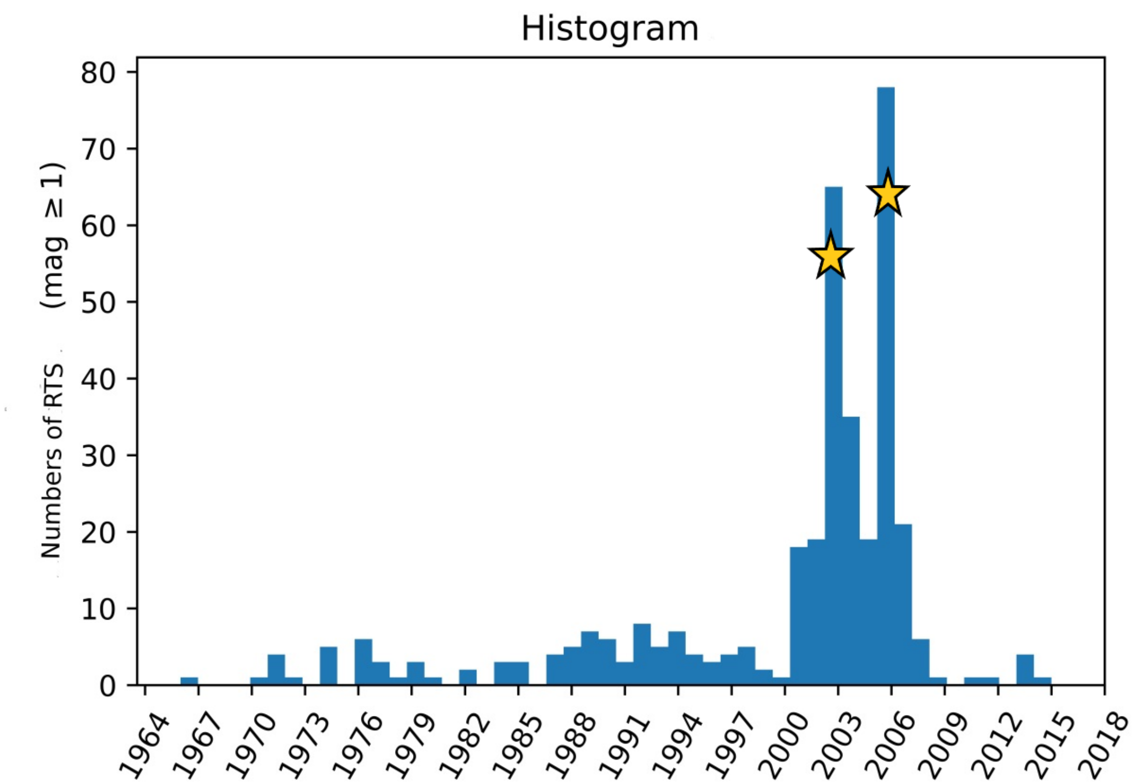


Fig 5- Histogram of the RTS numbers with a magnitude greater 1, per year. The yellow stars highlight the seismic swarms at the Itapebi and Carmo Cajuru dams in 2003 and Lajeado and Nova Ponte in 2006.

(

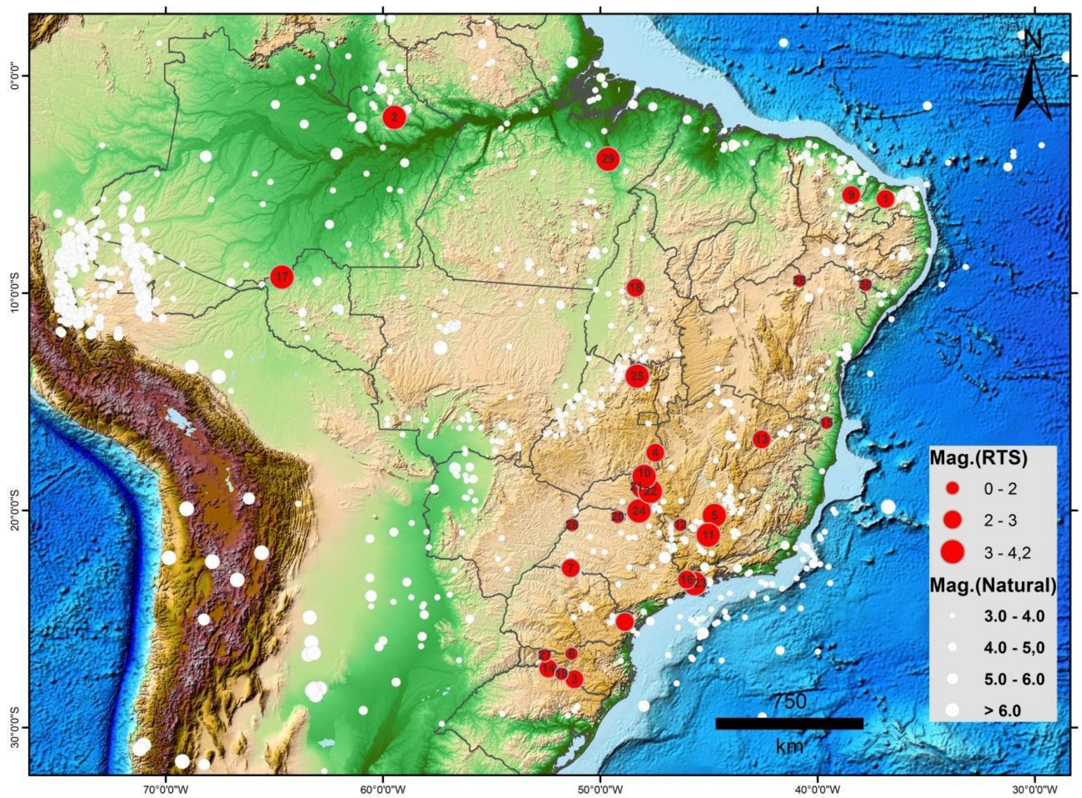


Fig 6 – Map of Brazil showing natural earthquakes (white circles, with magnitude) and RTS in Brazil (red circles, with magnitude, numbered as stated by Table 2). Data from the bulletin of the IAG-USP and SISBRA-UnB.

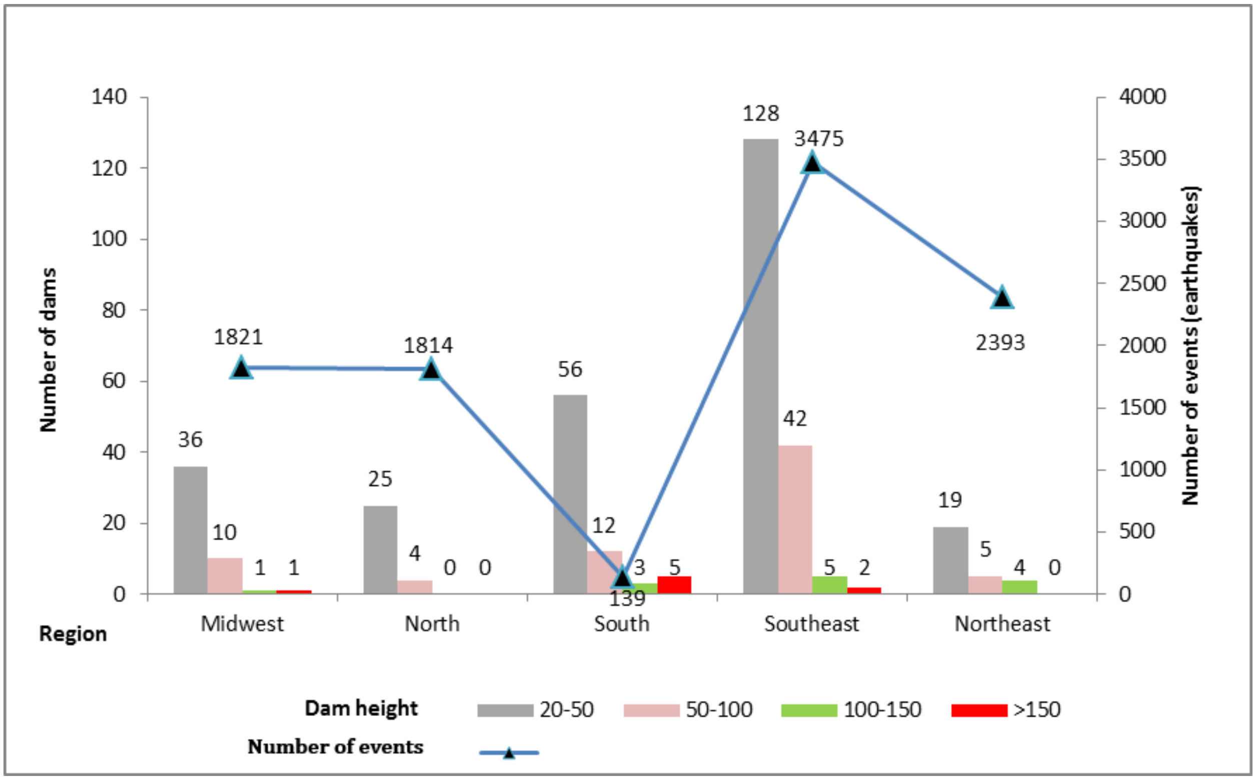


Fig 7- Graph showing the earthquakes, dams, and regions of the country. The southeastern region concentrates the highest and the most dams in the country.

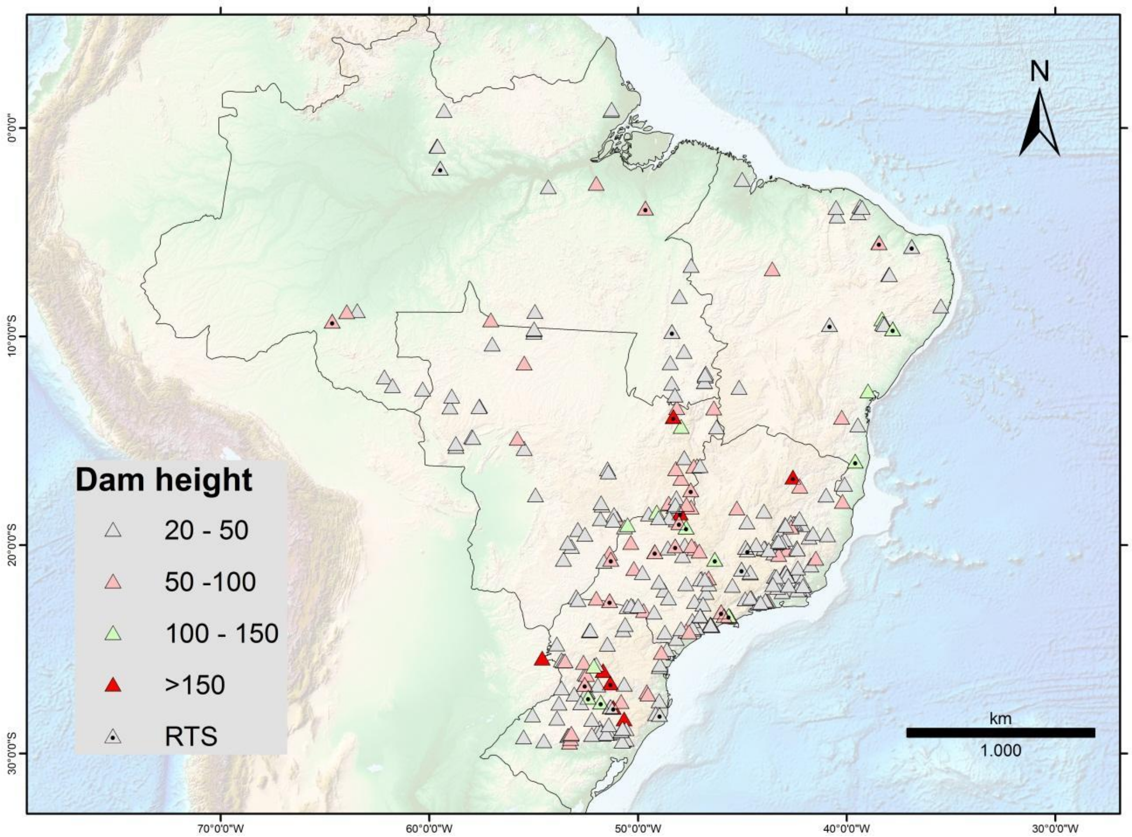
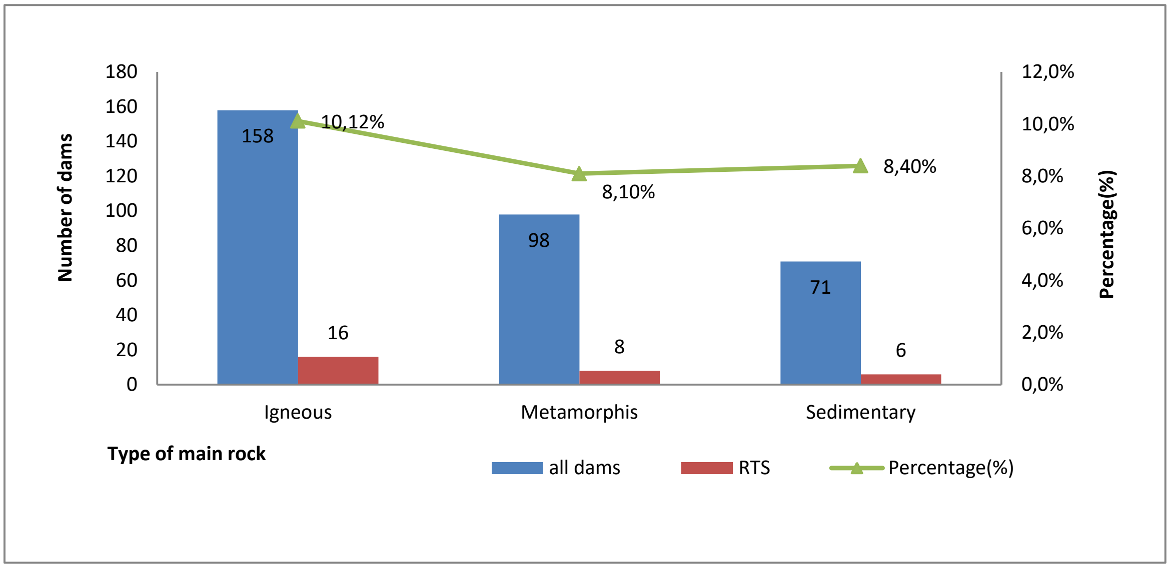


Fig 8- Map showing the location and classification by the dam height. Data by Brazilian Committee on Dam.

a)



b)

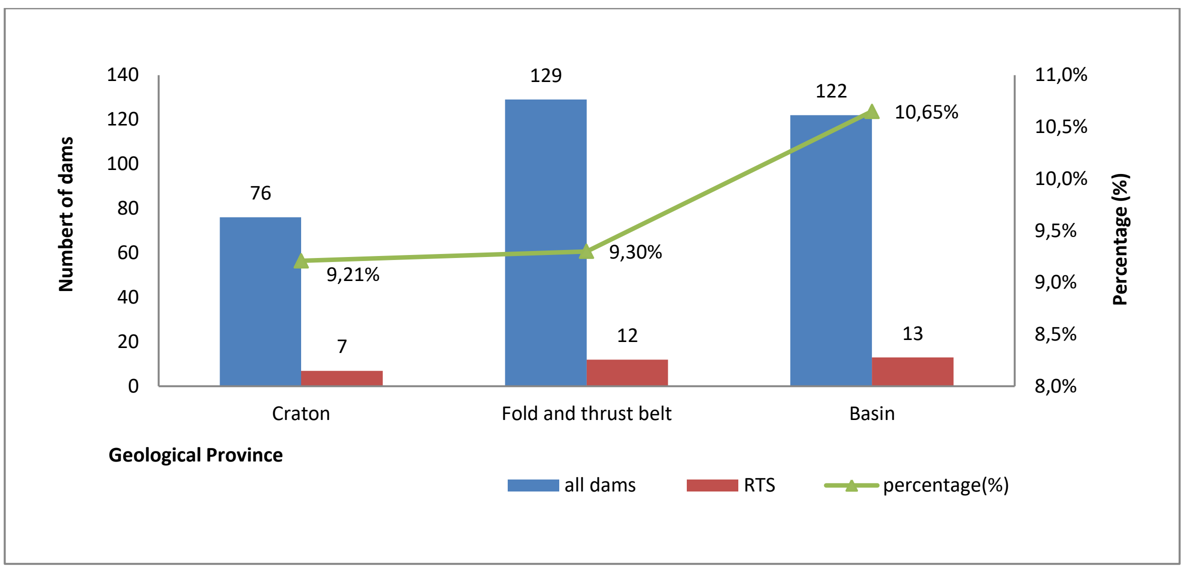


Fig 9- a) Percentage of cases of Reservoir-triggered Seismicity in Brazil as stated by main rock types (sedimentary, metamorphic and igneous) in the dam area. b) classification as stated by the main geological provinces.

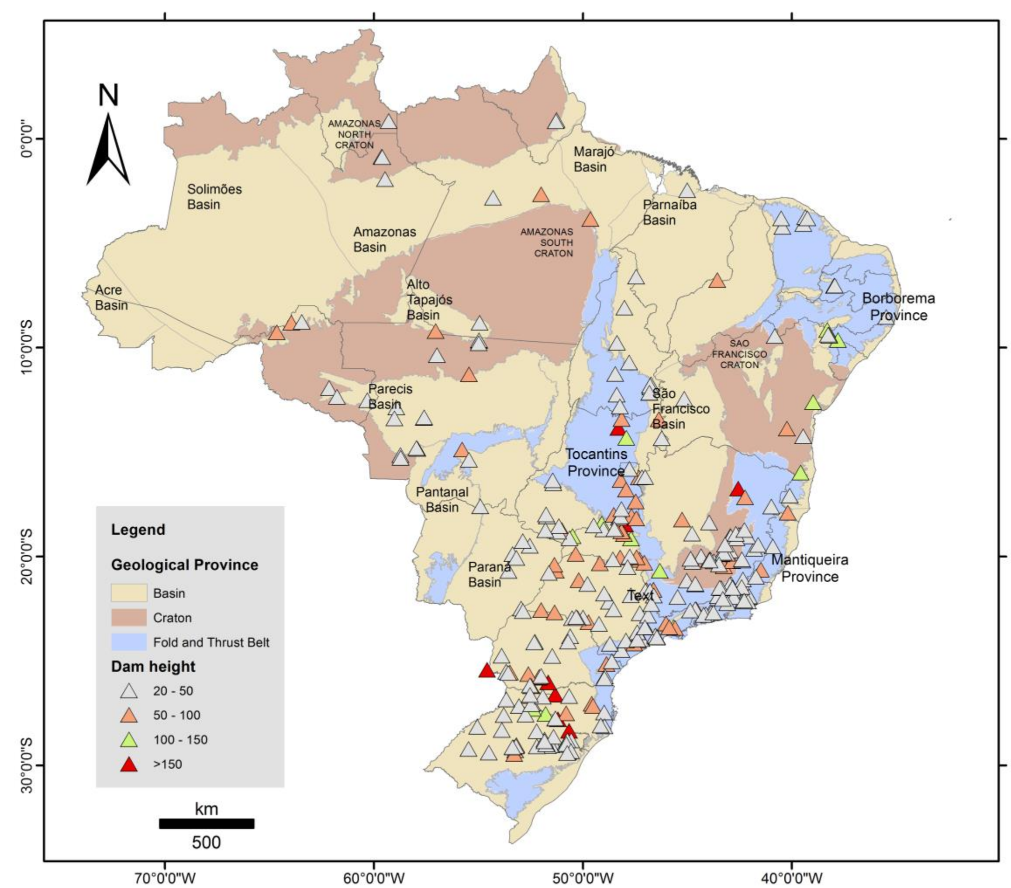
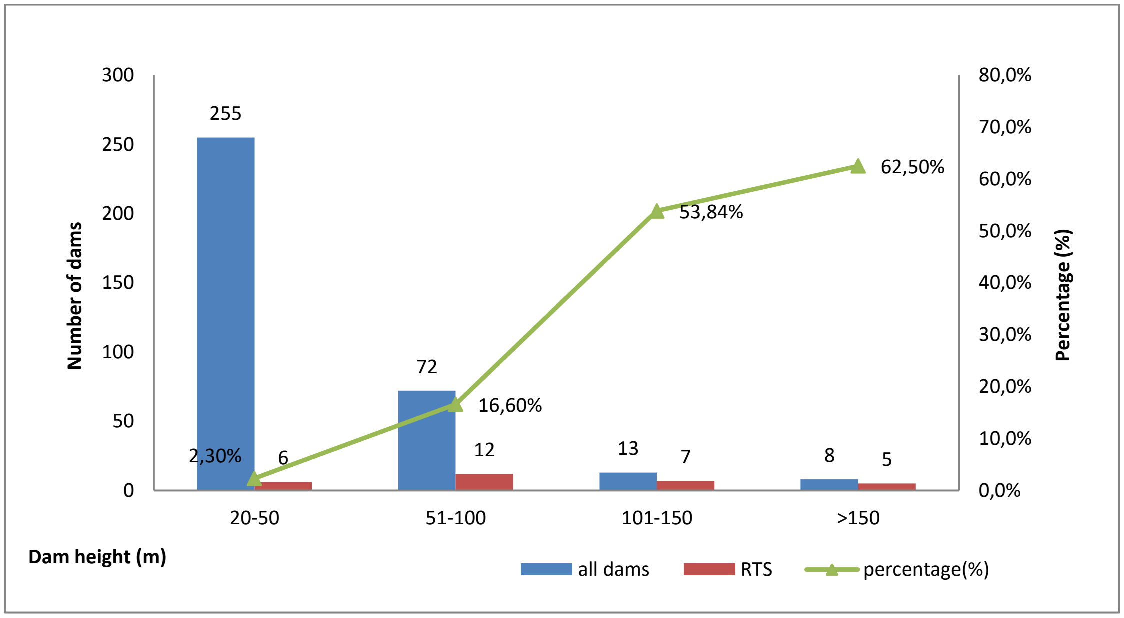


Fig 10- Map of Brazil with 348 dams with a height of 20m or more (data from the Brazilian Committee on Dams-2018). The colors refer to the main geological provinces (data from CPRM-Mineral Resources Research Company).

a)



b)

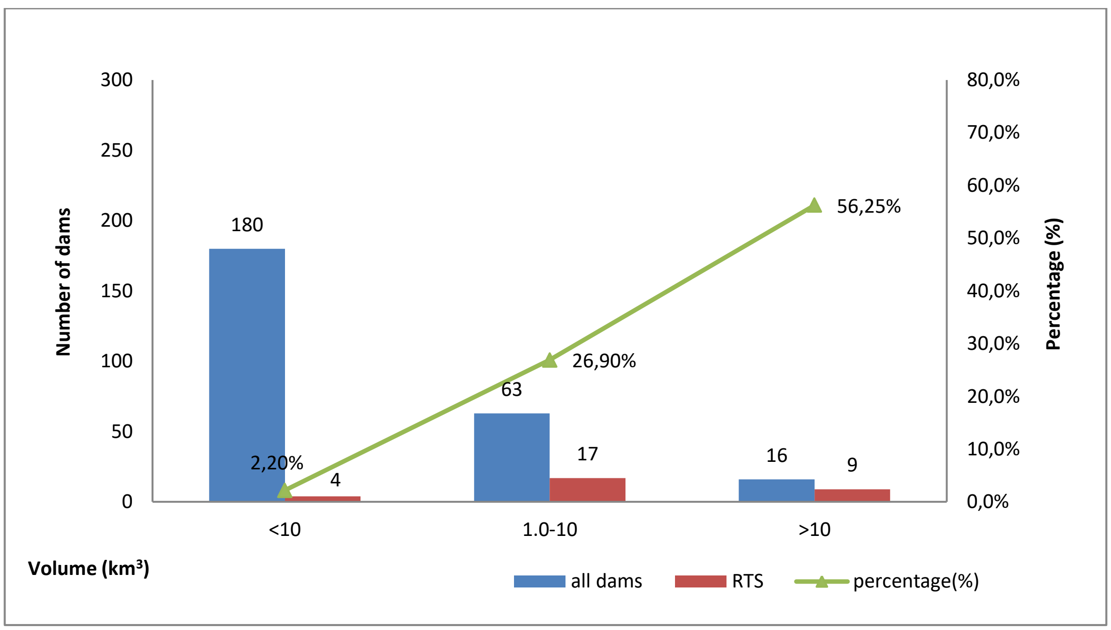


Fig 11- Percentage of cases of Reservoir-triggered Seismicity as stated by (a) dam height and (b) reservoir volume. 54% of dams taller than 100 m trigger earthquakes and 32% of reservoirs larger than $1x10^{-3}$ km^3 trigger earthquakes.

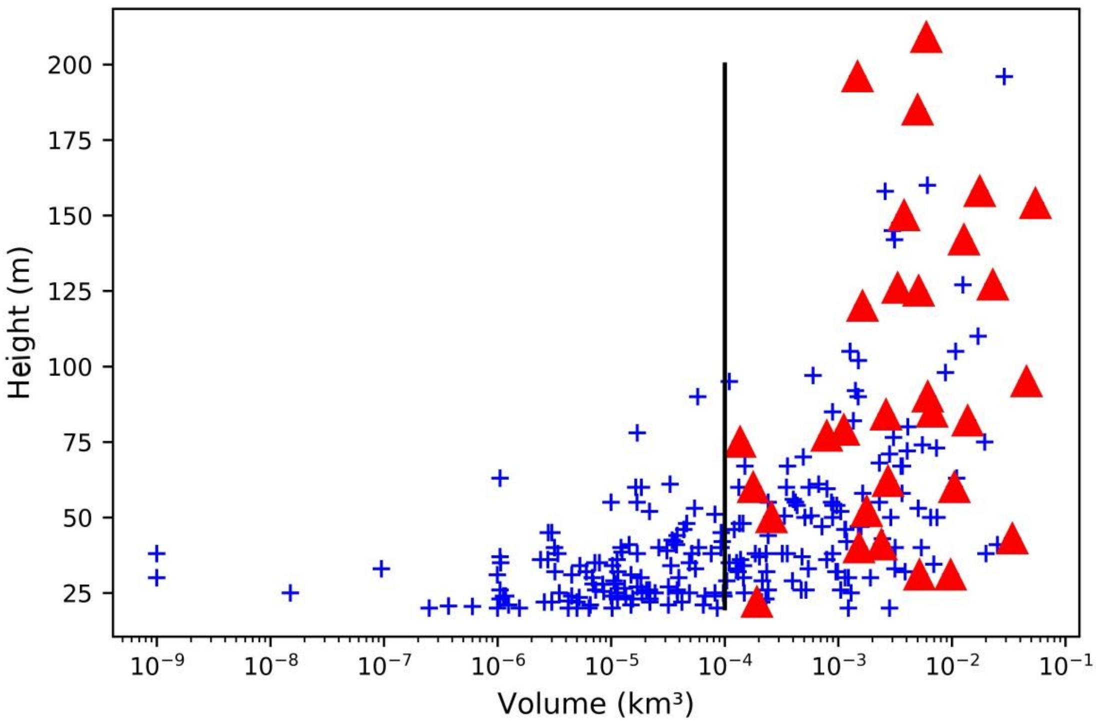


Fig 12- Graph of reservoir volume and dam height for all dams in Brazil. The triangles indicate the RTS cases and the crosses, other reservoirs. The black bar is the limit of RTS cases.

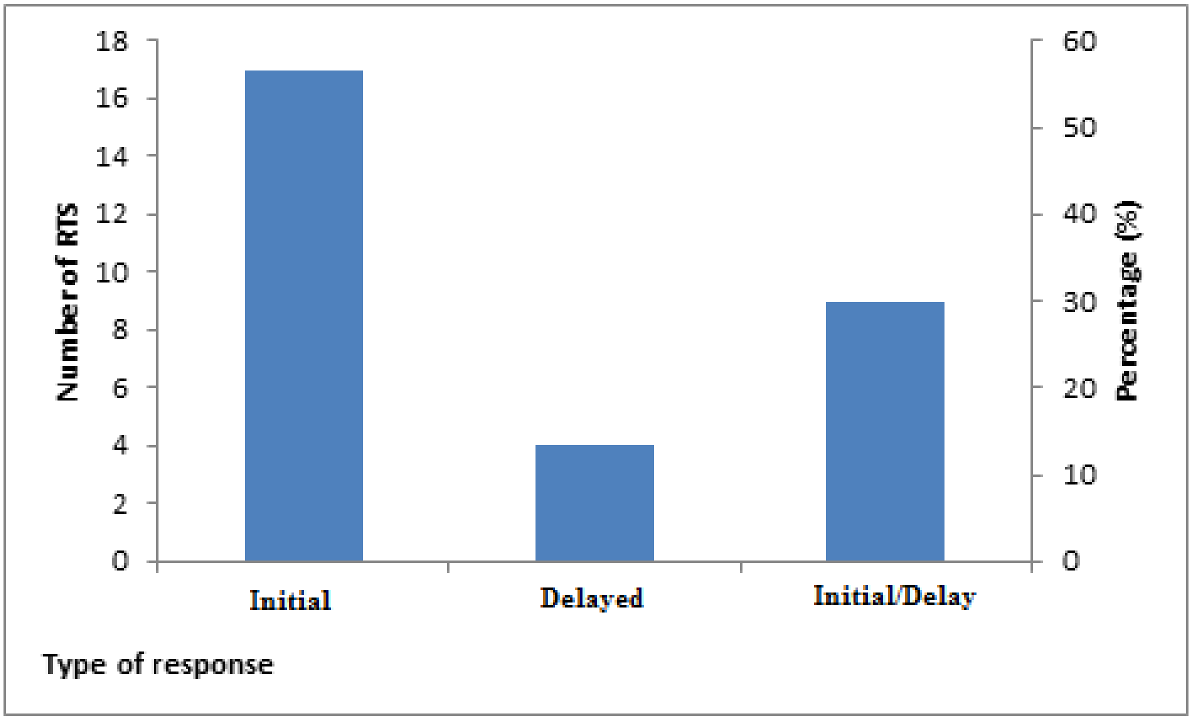


Fig 13- Graph of the type of response for RTS cases.

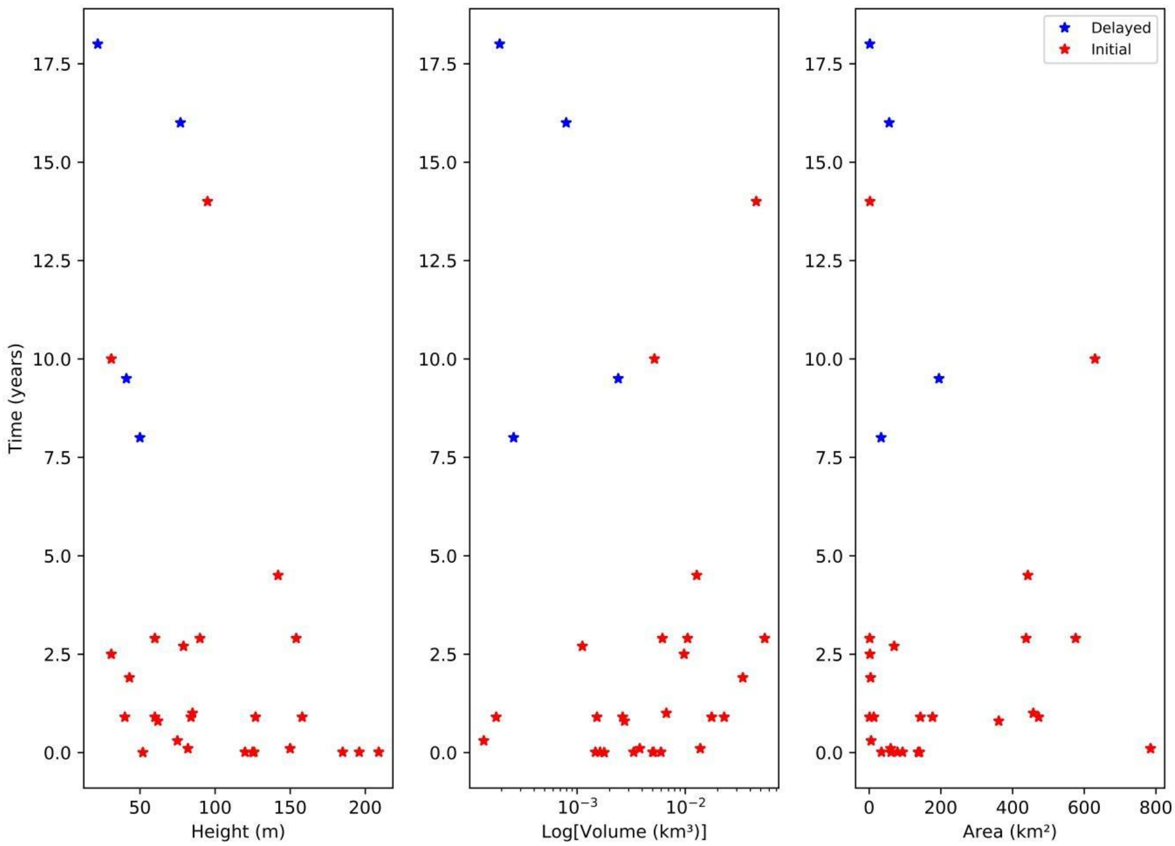


Fig 14- Graph of delay time/response versus dam height, volume, and area.

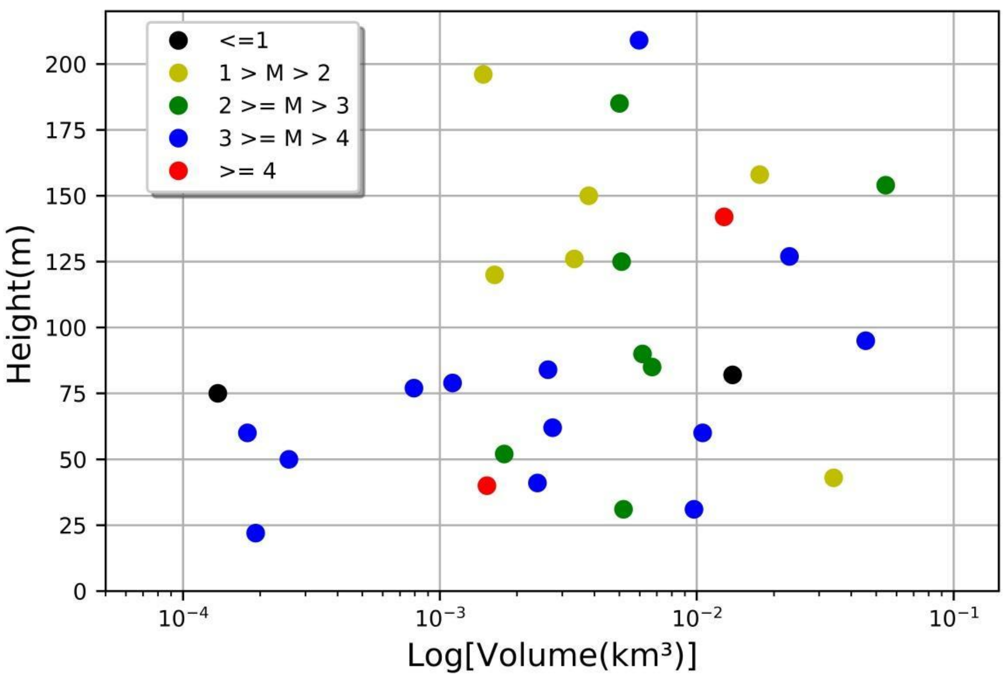


Fig 15- Distribution of reservoir volume and dam height versus the Reservoir-triggered Seismicity maximum magnitude cases.

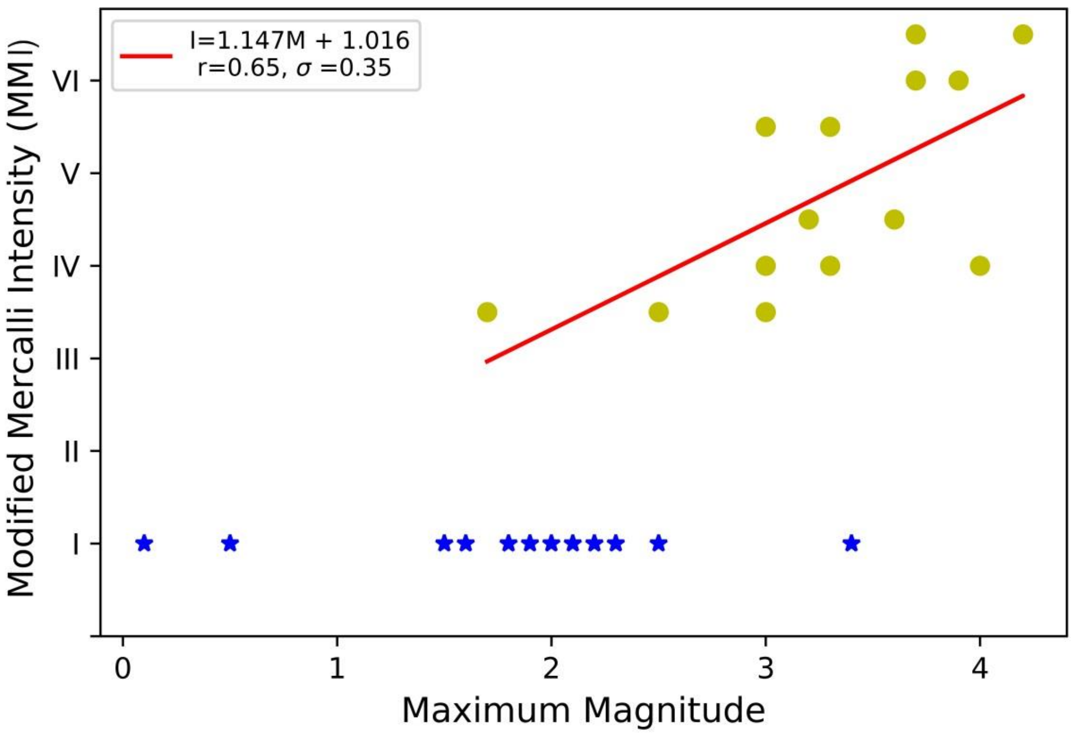


Fig 16- Graph showing maximum magnitude and intensity. The linear adjustment (bar) was performed only with data represented by circles. The blue stars indicate cases of Intensity I.