**Cause of Failure of the Lagoa do Pirocáua Dam at the Aurizona Mine on March 25, 2021, Maranhão State, Northeast Brazil**

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## LIGHTNING SUMMARY

On March 25, 2021, the failure of the Lagoa do Pirocáua dam at the Equinox Gold Aurizona mine in Maranhão State, northeast Brazil, contaminated the water supply of the village of Aurizona. According to Equinox Gold and the National Mining Agency, the failure was caused by a 10,000-year precipitation event. Based on precipitation records from the surrounding weather stations, the return period of the storm was less than one year. The root cause of the dam failure was the lack of any inspection and maintenance.

## ABSTRACT

The failure of the Lagoa do Pirocáua dam at the Equinox Gold Aurizona mine on the Atlantic coast of Maranhão State, northeast Brazil, on March 25, 2021, at 4:00 am local time, contaminated the water supply of the village of Aurizona, which still has not been restored. The purpose of the 7-meter high earthen dam was to capture sediments from the open pits and to store water for use in the mining operation. According to Equinox Gold and the National Mining Agency (ANM), the failure was caused by overtopping of the dam, which resulted from 426 mm of rain over March 23-24, corresponding to a 10,000-year precipitation event, with 112.7 mm, 315 mm and 27 mm of rain on March 23, 24 and 25, respectively. However, according to precipitation maps from the National Institute of Meteorology (INMET), no location on the Atlantic coast of the state of Maranhão received more than 150 mm of rainfall over March 24-28. Moreover, precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA, which combine rainfall records from the INMET network and the network of the National Center for Natural Disaster Monitoring and Alerts (CEMADEN) show total precipitation of 400-450 mm for the entire month of March 2021 at the site of the Aurizona mine, which is well within the climatological normals. The Laboratory of Meteorology precipitation maps indicate rainfall amounts of 10-15 mm, 25-30 mm and 90-95 mm at the Aurizona mine site on March 23, 24 and 25, respectively. The surrounding INMET weather stations of Turiaçu (59 kilometers to the southeast), Tracuateua (128 kilometers to the northwest) and Capitão Poço (154 kilometers to the southwest) received 48-hour rainfall amounts of 41.9 mm, 35.2 mm, and 30.8 mm, respectively, over March 23-24, corresponding to return periods of 0.3 years, 0.2 years, and 0.5 years at each of the respective weather stations. The most extreme precipitation event at any of the surrounding weather stations was the 48-hour rainfall amount of 131.1 mm at Turiaçu over March 24-25, corresponding to a return period of 2.3 years. The closest earthquake during March 21-25 was an earthquake with magnitude 4.1 in Guyana, 1606 kilometers to the northwest, on March 24. According to information from ANM, the dam spillway had identified problems and no corrective measures were being undertaken. Moreover, the monitoring instruments were inappropriate and there were no plans to install new

instruments. In addition, there were no design documents, no manuals or formal procedures for monitoring and inspection, no emergency action plan, and no regular submission of inspection and monitoring reports. Finally, the dam had never been issued a Declaration of Condition of Stability. Prior to the failure, the existence of the dam was not mentioned in any available documents from the mining company. ANM did not provide any evidence that the dam had failed by overtopping. The proximal cause of the failure could also have been internal erosion or slope instability. However, the root cause of the failure should be regarded as systematic neglect. Since all of the problems that existed with the failed dam are still present in the reconstructed dam, which is even lower than the failed dam, it should be assumed that the risk of failure is even greater at the present time than it was when the dam initially failed.

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## INTRODUCTION

On March 25, 2021, at 4:00 am local time, a failure occurred of the Lagoa do Pirocáua dam at the Aurizona mine on the Atlantic coast of Maranhão State, northeast Brazil (Angelo, 2021; Business and Human Rights Resource Centre, 2021) (see Figs. 1-2). Equinox Gold is a Canadian mining company that operates the Aurizona mine through their wholly-owned Brazilian subsidiary Mineração Aurizona S/A (MASA). The failure contaminated Lagoa Juiz de Fora, which serves as the water supply for the 4000 inhabitants of the village of Aurizona (see Figs. 3-4). As of this writing, the community water supply has still not been restored. ("Lagoa" is the Portuguese word for "pond" or "lagoon" and will be used throughout this report when it occurs as part of a name.) Lagoa do Pirocáua is an exhausted open pit and is used to capture and store sediment from the other open pits (see Figs. 3-5). Lagoa do Pirocáua is also used to capture water from the watershed for recycling into the mining operation, but is not used for the storage of mine tailings (ANM, 2021a; Equinox Gold, 2021a). The dam had been 7 meters high and constructed out of soil (ANM, 2021b).

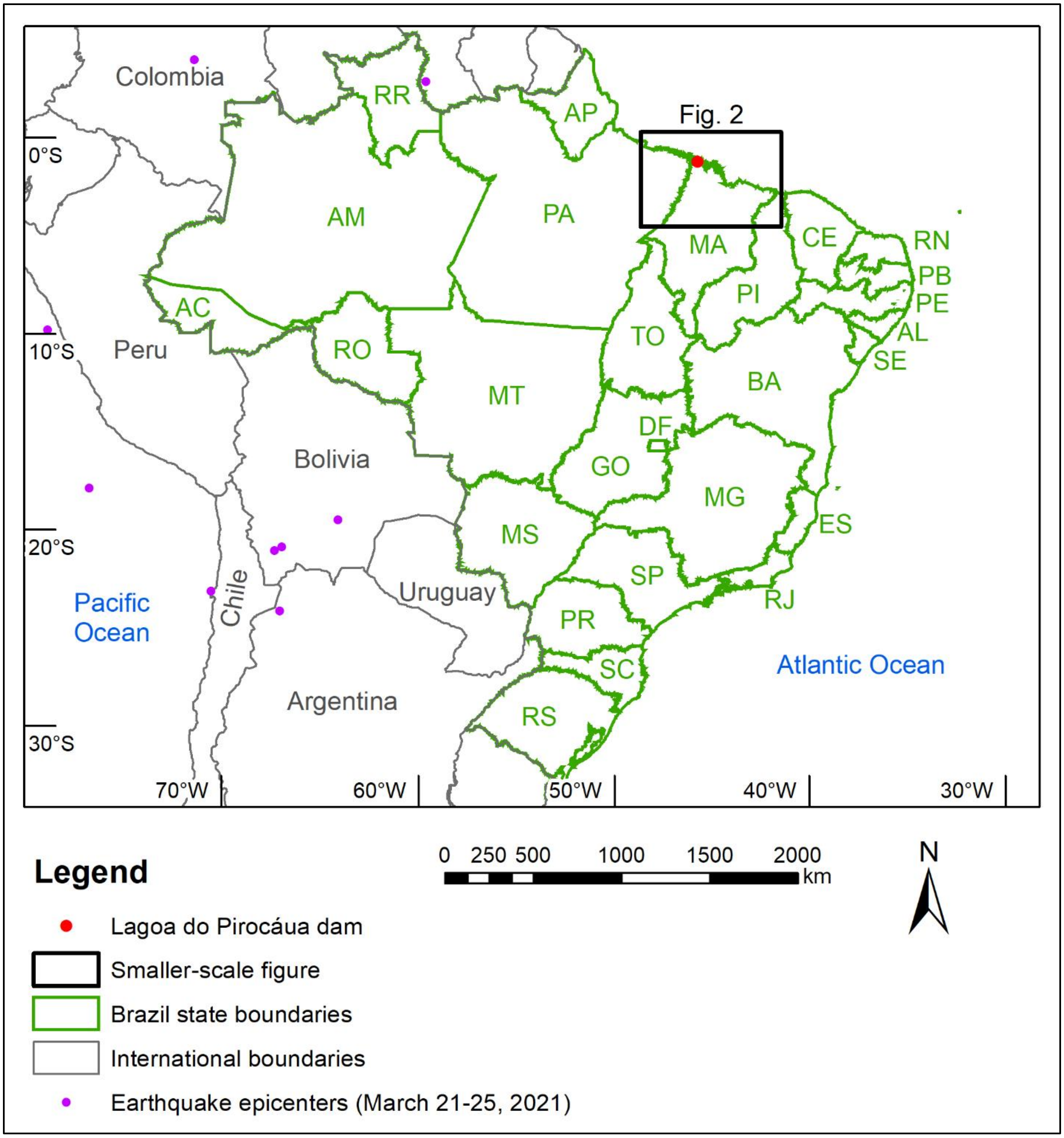


**Figure 1.** The failure of the Lagoa do Pirocáua dam at the Aurizona mine, owned by the Canadian mining company Equinox Gold, contaminated the water supply of the village of Aurizona. According to Equinox Gold and the National Mining Agency (ANM), the failure was caused by overtopping of the dam as a result of the 426 mm of rain that fell during March 23-24, 2021, which constituted a 10,000-year precipitation event (event with an annual exceedance probability of 0.01%).

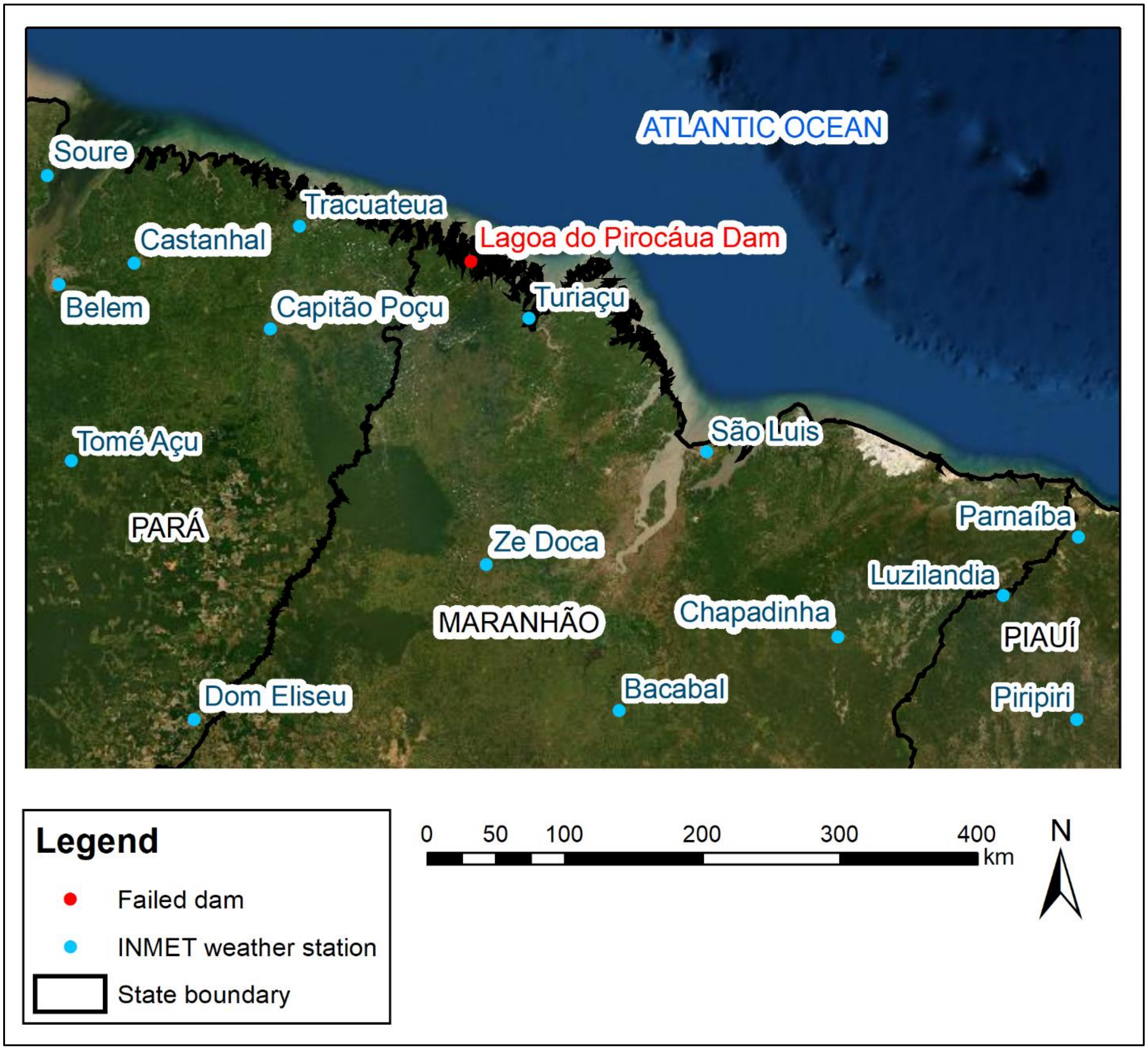


**Figure 2.** The closest National Institute of Meteorology (INMET) weather stations to the failed Lagoa do Pirocáua dam are at Turiaçu (59 kilometers to the southeast), Tracuateua (128 kilometers to the northwest), and Capitão Poço (154 kilometers to the southwest). The precipitation records at the Turiaçu weather station are most likely to be representative of conditions at the Lagoa do Pirocáua dam, due to their proximity and common location on the Atlantic coast. In addition, the elevation of the crest of the Lagoa do Pirocáua dam (30 meters above sea level) is within 5 meters of the Turiaçu weather station (34.38 meters above sea level; see Table 1). Locations of weather stations from INMET (2021b).

Equinox Gold (2021a-c) has attributed the dam failure to an extreme precipitation event with a return period of 10,000 years (corresponding to an annual exceedance probability of 0.01%). According to Equinox Gold (2021b), "From March 23-25 the northwest region of Maranhão State, Brazil received exceptionally heavy rain (more than 450 mm), described as a 1-in-10,000-years rain event." Equinox Gold (2021a) was more specific in writing, "*Conforme informações coletadas das estações pluviométricas da MASA, nos dias 23/03 e 24/03, foi registrado um acúmulo de chuva de 426mm em 48 horas. De acordo com os cálculos de quantis de chuvas, pode-se considerar que houve um evento chuvoso com tempo de recorrência de*

*10.000 anos, cientificamente definido como chuva decamilenar*” [According to information collected from the pluviometric stations of MASA, on March 23 and March 24, an accumulation of 426 mm of rain was recorded in 48 hours. According to the calculations of rainfall quantiles, it can be considered that there was a rain event with a recurrence time of 10,000 years, scientifically defined as a decamillennial rain]. Equinox Gold (2021a) further clarified that 112.7 mm, 315 mm, and 27 mm of rain fell on March 23, 24 and 25, respectively. (Rainfall amounts of 112.7 mm and 315 mm add to 427.7 mm, not 426 mm. Throughout this report, the values 112.7 mm and 315 mm will be used in referring to daily precipitation, while 426 mm will be used when referring to the 48-hour precipitation.)

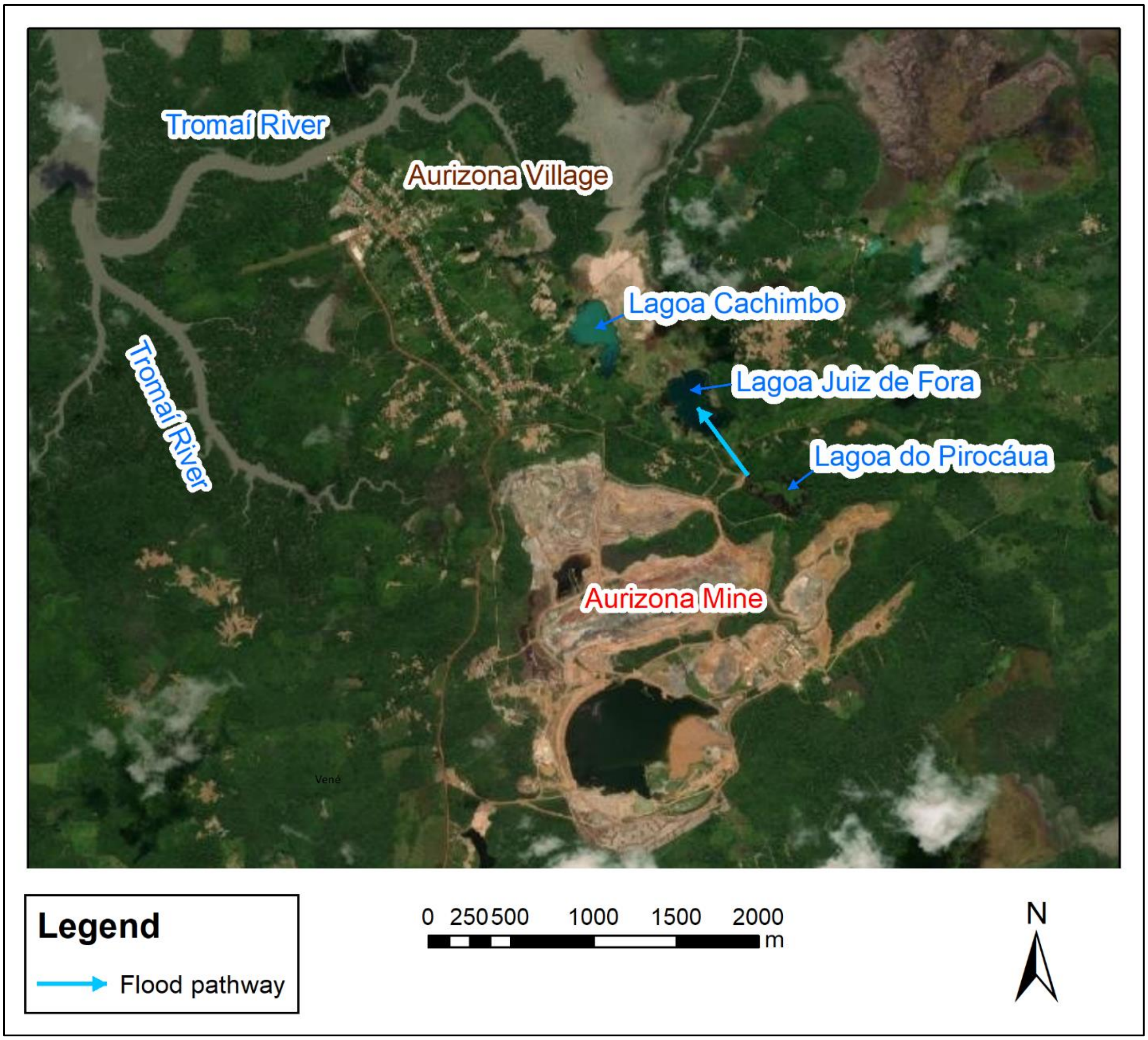


**Figure 3.** The failure of the Lagoa de Pirocáua dam resulted in contamination of Lagoa Juiz de Fora, which is the water supply for the 4000 inhabitants of the village of Aurizona.

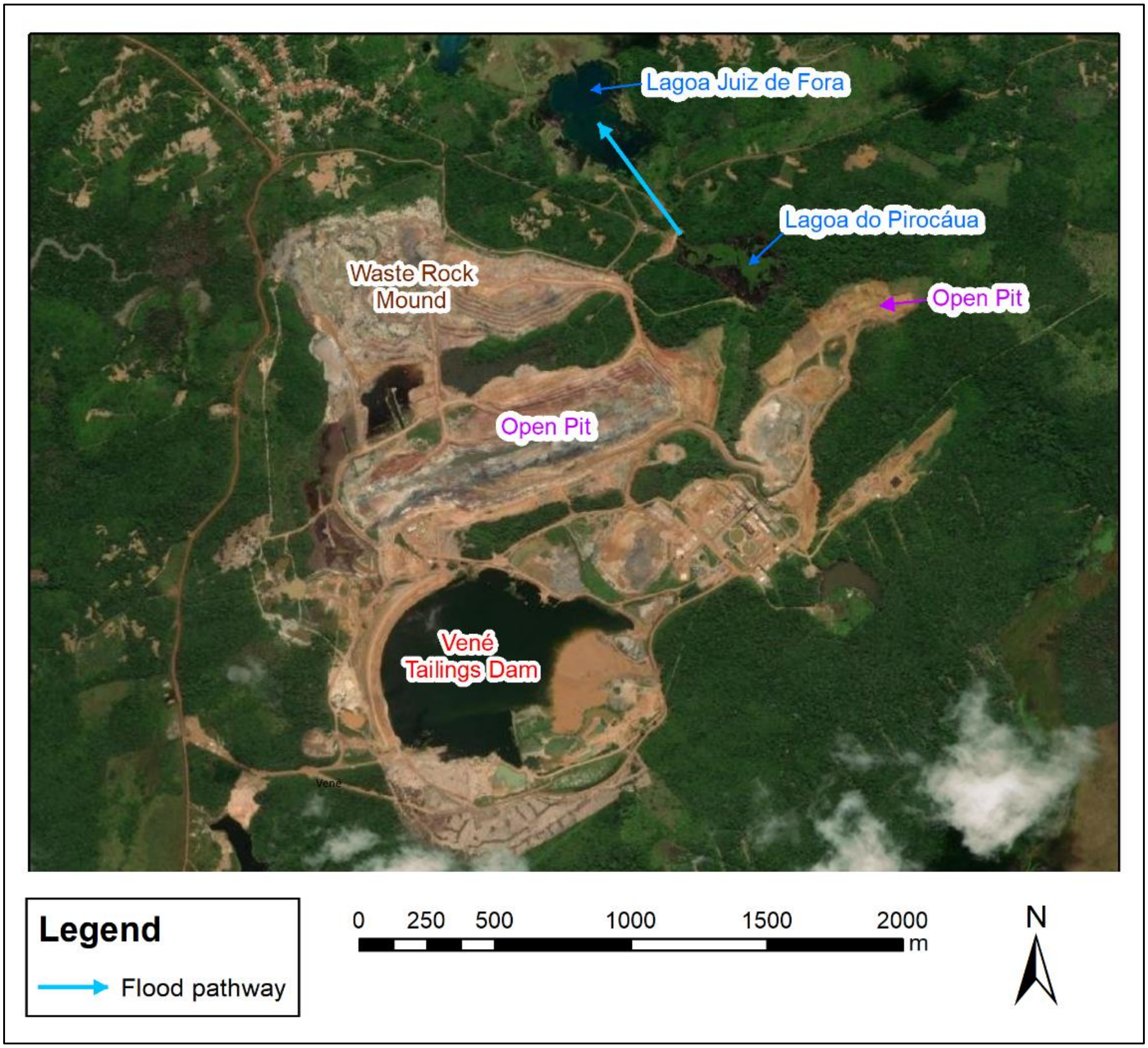


**Figure 4.** The failure of the Lagoa de Pirocáua dam resulted in contamination of Lagoa Juiz de Fora, which is the water supply for the 4000 inhabitants of the village of Aurizona. The Lagoa de Pirocáua dam was used to capture and store water for use in the mining operation and to capture sediment from the open pits. According to the State Secretariat for the Environment and Natural Resources (SEMA), the failure of the Lagoa de Pirocáua dam may been caused not only by the heavy rain of the previous two days, but also by the collapse of an open pit that is above and to the east of Lagoa de Pirocáua.

From the perspective of Equinox Gold (2021a-c), since the dam failure resulted from an extreme precipitation event, the mining company cannot be held responsible for the dam failure and nothing could have been done to prevent the failure. According to Equinox Gold (2021a), "*O que ocorreu, na realidade, foi um volume excessivo de chuvas, com registros pluviométricos anormais, em um curto intervalo de tempo, o que deu causa à inundação de vários córregos e lagos da região, dentre os quais a Lagoa do Pirocaua … Assim, embora se solidarize com a situação e esteja adotando diversas medidas para apoiar as comunidades próximas à operação e minimizar os eventuais danos à infraestrutura local,* ***a MASA reitera que não concorreu, de nenhuma forma, para a ocorrência ou agravamento do citado incidente****. Como pode ser* *constatado a partir dos registros pluviométricos indicados nos itens abaixo, o evento em questão está exclusivamente relacionado ao excesso de chuvas ocorrido na região. O transbordamento da Lagoa do Pirocaua foi um fenômeno de causa natural severa, ocasionado por condições meteorológicas totalmente anormais … Não havia qualquer medida que a MASA pudesse ter adotado para impedir ou minimizar os impactos das chuvas … Todas as consequências do acidente decorreram unicamente de um fato natural, associado a chuvas intensas, sem que exista qualquer nexo de causalidade com as atividades desempenhadas pela mineradora*” [What actually happened was an excessive volume of rain, with abnormal pluviometric records, in a short period of time, which caused the flooding of several streams and lakes in the region, including the Lagoa do Pirocaua ... Thus, although it sympathizes with the situation and is adopting several measures to support the communities close to the operation and minimize any damage to the local infrastructure, **MASA reiterates that it did not contribute, in any way, to the occurrence or aggravation of the aforementioned incident.** As can be seen from the rainfall records indicated in the items below, the event in question is exclusively related to excess rainfall in the region. The overflowing of Lagoa do Pirocaua was a phenomenon of severe natural causes, brought on by totally abnormal meteorological conditions … There was no measure that MASA could have adopted to prevent or minimize the impacts of the rains … All the consequences of the accident resulted solely from a natural fact, associated with heavy rains, without any causal link with the activities performed by the mining company] (boldface in the original).


Figure 9: Overview of the area of Lagoa do Pirocáua

**Figure 5.** According to the State Secretariat for the Environment and Natural Resources (SEMA), the failure of the Lagoa de Pirocáua dam may been caused not only by the heavy rain of the previous two days, but by the collapse of an open pit that is above and to the east of Lagoa de Pirocáua (off the photo to the right). View of aerial photo is to the northeast. Labeled photo from ANM (2021a) with overlay of English labels.

The National Mining Agency [Agência Nacional de Mineração (ANM)] inspected the site of the dam failure on March 31, 2021 (ANM, 2021a). In their monthly report, ANM (2021a) repeated the claim of Equinox Gold in writing, "*Conforme informações coletadas das estações pluviométricas da MASA, nos dias 23/03 e 24/03, foi registrado um acúmulo de chuva de 426mm em 48 horas. De acordo com os cálculos de quartis de chuvas, constantes no Relatório de Dam Break para a Barragem do Vené, também situada no empreendimento, pode-se considerar que houve um evento chuvoso com tempo de recorrência de 10.000 anos (chuva decamilenar)*" [According to information collected from the rainfall stations of MASA, on March 23 and March 24, an accumulation of 426 mm of rain was recorded in 48 hours. According to the calculations of rainfall quartiles, contained in the Dam Break Report for the Vené dam, also located in the project, it can be considered that there was a rain event with a recurrence time of 10,000 years (decamillennial rain)]. The Vené dam is the tailings dam for the Aurizona mine (ANM, 2021c; see Fig. 4). The above-mentioned Dam Break Report is not publicly available.


Figure 11: Situation of the dam after the overtopping

**Figure 6**. According to ANM (2021a), the 7-meter high Lagoa do Pirocáua dam failed by overtopping, which caused a breach in the dam. ANM (2021a) did not offer any evidence to support the overtopping hypothesis, aside from the assumption that 426 mm of rain fell over the previous two days. View of ground photo is to the southeast. Labeled photo from ANM (2021a) with overlay of English labels.

ANM (2021a) further argued that the extreme precipitation event resulted in an overtopping and failure of the embankment dam (see Fig. 6). An embankment dam is any dam constructed out of unconsolidated materials, such as soil, sand, clay, rock fill, or mine tailings. Often, the overtopping of an embankment dam results in the erosion and breach of the dam (see Fig. 7). According to ANM (2021a), "*Este evento de chuva atípico causou a rápida elevação no nível do lago e resultou no transbordamento, ou galgamento (figura 10), da estrutura, o que, por sua vez, gerou um processo de brecha do maciço, resultando em sua ruptura e liberação de parte do volume de água armazenada*" [This atypical rain event caused the rapid rise in the lake level and resulted in the overflowing, or overtopping … of the structure, which, in turn, generated a process of breach of the mass, resulting in its rupture and the release of part of the volume of stored water]. A dam failure refers to an uncontrolled release of water or other materials that were stored behind the dam without necessarily implying the collapse or loss of structural integrity of the dam itself (Fell et al., 2015). Equinox Gold (2021a-c) repeatedly refers to the failure of the Lagoa do Pirocáua dam as an "overflow," which could imply a simple loss of water with no impact on the dam. However, the explanation and photos by ANM (2021a) clarify that the dam was breached along its entire height of 7 meters (see Fig. 6).

**Figure 7.** Overtopping of an embankment dam often results in the erosion and breach of the dam. The photos above show the overtopping and breach of the Glashütte embankment dam in Germany on August 23, 2002. Photos from Association of State Dam Safety Officials (2021a).

The State Secretariat for the Environment and Natural Resources [Secretaria de Meio Ambiente e Recursos Naturais (SEMA)] inspected the dam failure on the morning of March 25 and offered an alternative cause of failure (SEMA, 2021; Governo do Maranhão—Agência de Notícias [Government of Maranhão—News Agency], 2021). According to SEMA (2021), prior to the dam failure, another open pit to the east of Lagoa do Pirocáua (see Figs. 4-5) collapsed, releasing its water into Lagoa do Pirocáua. SEMA (2021) wrote, "*Na vistoria, os fiscais da SEMA identificaram que a causa do rompimento do talude da Lagoa do Pirocaua não foi apenas o intenso volume de chuva, mas em decorrência da existência de uma outra cava de mineração que servia como reservatório de água pluvial, localizada acima da Lagoa do Pirocaua e denominada de cava leste, que se rompeu. Dessa forma, o choque mecânico e o volume de água existente na cava provocaram a desestabilização do talude da Lagoa do Pirocaua, gerando o rompimento, que atingiu duas outras lagoas: a Lagoa de Juiz de Fora e a Lagoa do Caximbo*" [In the inspection, SEMA inspectors identified that the cause of the rupture of the embankment of Lagoa do Pirocaua was not only the heavy volume of rain, but due to the existence of another mining pit that served as a rainwater reservoir, located above the Lagoa do Pirocaua and called the East Pit, which broke up. Thus, the mechanical shock and the volume of water in the pit caused the destabilization of the embankment of Lagoa do Pirocaua, generating a rupture, which affected two other lakes: Lagoa de Juiz de Fora and Lagoa do Caximbo]. Since March 2021, no other reports or investigations have been released regarding the cause of failure of the Lagoa do Pirocáua, aside from ANM (2021a), Equinox Gold (2021a-c) and SEMA (2021).

The objective of this report is to answer the following question: Do the reports by the mining company and governmental agencies provide a complete and adequate explanation for the cause of failure of the Lagoa do Pirocáua dam? Before discussing the methodology for addressing this question, I will first review the major causes of failure of embankment dams. This will be followed by a review of the known history of the Lagoa do Pirocáua dam.

## REVIEW OF CAUSES OF FAILURE OF EMBANKMENT DAMS

The most common causes of failures of embankment dams are overtopping, internal erosion, slope instability, and earthquakes (Fell et al., 2015). Although embankment dams can also fail due to failure of the foundation, this is less common in small dams, such as the Lagoa do Pirocáua dam. Although, as mentioned above, overtopping often results in the erosion and breach of the dam, dam failure does not necessarily occur after any episode of overtopping. The duration of overtopping could be too short to result in sufficient erosion to breach the dam. Erosion after overtopping can also be partially prevented (depending upon the duration of overtopping) by installing a rock cover on the downstream face of the embankment. Due to the lack of any design documents, it is not known whether the Lagoa do Pirocáua dam had a rock cover or whether any other measures had been taken to prevent erosion of the downstream face.


**Figure 8.** Internal erosion (also called piping) is the phenomenon in which seepage through an embankment dam washes solid particles out of the dam, resulting in the loss of structural integrity of the dam. Photos show an embankment dam in the process of failure by internal erosion near Tunbridge, Australia, in 2005. Photos from Fisher et al. (2017).

Internal erosion (also called piping) is the phenomenon in which seepage through an embankment dam washes solid particles out of the dam, resulting in the loss of structural integrity of the dam (see Fig. 8). Internal erosion can be prevented by increasing the width of the dam (distance from the reservoir to the downstream face) or decreasing the slope of the downstream embankment, so as to decrease the hydraulic gradient and, thus, the seepage velocity. Other preventive measures including the installation of drains, which will force seepage to exit at the toe of the dam rather than along the face, or filters that will trap fine particles and prevent their transport out of the dam. Typically, the emergence of muddy water on the downstream face of an embankment dam is a sign of the initiation of internal erosion and a signal to begin emergency repairs, such as constructing a buttress along the toe of the dam to lengthen the seepage pathway.

Slope instability occurs when the shear stress exceeds the shear strength along a surface within the dam (see Fig. 9). Slope instability can be promoted by an increase in pore pressure within the dam or by a rise in the water table. Under certain circumstances, the dam material can undergo liquefaction, in which the pore pressure rises high enough that the solid particles no longer touch other, so that the mass of solid particles and water behaves like a liquid with zero shear strength. Liquefaction and slope instability can also be promoted by the cyclic action that occurs during earthquakes.

**Figure 9.** Slope instability occurs when the shear stress exceeds the shear strength along a surface within the dam. Photo shows a failure of a levee along the Mississippi River near Darrow, Louisiana, in 1983. Photo from Association of State Dam Safety officials (2021b).

It is important to note that overtopping, internal erosion, slope instability, and earthquakes are all proximal or ultimate causes, that is, the causes that occurred more or less immediately before dam failure. However, dams fail because of a chain of events or causes, of which the proximal cause is only the final event or the trigger. The first step in the chain, which starts the events in motion, is the root cause. The root cause could also be an ongoing event that, if it had been removed, would have prevented the dam failure. The proximal cause is nearly always a physical event, such as water overtopping and eroding away a dam. The root causes, as well as many of the intervening causes, are always the actions of human beings. In this way, a dam is an anthropogenic construct, not a physical landform.

The following possible chain of events, which could apply to the Lagoa do Pirocáua dam, is presented in order to illustrate the distinction between root and proximal causes:

1) A dam is constructed with no plan for monitoring, inspection and maintenance.
2) The reservoir fills faster than expected and to a level that is higher than expected.
3) Since the dam is not monitored, inspected or maintained, no one notices the rate and level of reservoir filling, so that no corrective action is taken.
4) The deposition of sediment behind the dam causes the reservoir level to rise even higher.
5) Since the dam is not monitored, inspected or maintained, no one notices the sediment deposition or rising reservoir level, so that no corrective action is taken.
6) The growth of shrubs and other vegetation on the downstream embankment increases its potential for erosion.
7) Since the dam is not monitored, inspected or maintained, no one notices the growth of shrubs and other vegetation, so that no corrective action is taken.
8) The runoff of rainfall along the downstream embankment forms gullies, which increases the potential for further erosion on the embankment.
9) Since the dam is not monitored, inspected or maintained, no one notices the formation of gullies, so that no corrective action is taken.
10) Due to the typical high water level behind the dam, a relatively minor storm causes water to flow over the top of the embankment.
11) Since the dam is not monitored, inspected or maintained, no one notices that water is flowing over the top of the embankment, so that no corrective action is taken.
12) Due to the pre-existing erosion of the embankment, a relatively short period of overtopping results in the deep erosion and breach of the dam.

The important point is that, although the final event (deep erosion of the embankment by the flowing water) is purely physical, the root cause is the ongoing lack of monitoring, inspection and maintenance. If at any point in the chain of events, the root cause had been reversed (a program of monitoring, inspection and maintenance had been initiated), the chain of events would have been broken and failure would not have occurred.

## HISTORY OF LAGOA DO PIROCÁUA DAM

There is no publicly available information about the Lagoa do Pirocáua dam aside from what is found in the ANM (2021b) mining dam database called the Integrated Management System for Mining Dams [Sistema Integrado de Gestão de Barragens de Mineração (SIGBM)]. In fact, there is no mention of the existence of this dam in any publicly available technical documents from the mining company (Lycopodium Minerals Canada Ltd., 2017; AGP Mining Consultants Inc., 2020). Moreover, the information about the Lagoa do Pirocáua dam and even its existence was not entered into the SIGBM database until after the dam had failed. According to ANM (2021a), "*A referida estrutura, apesar de possuir um barramento, desta forma a caracterizando como barragem de mineração, não estava cadastrada no SIGBM … Questionada sobre as características construtivas do barramento a empresa afirmou não possuir nenhum histórico construtivo em seus arquivos, afirmando inclusive, a dificuldade de entender quais* *foram os métodos de construção e os controles tecnológicos utilizados … No que tange às obrigações legais da empresa, em razão de a estrutura "Lagoa do Pirocaua" se enquadrar no Art. 2º, I da Portaria 70.389/2017, determinou-se o seu imediato cadastro no Sistema Integrado de Gestão em Segurança de Barragens de Mineração – SIGBM …*" [The aforementioned structure, despite having a dam, thus characterizing it as a mining dam, was not registered in the SIGBM … Asked about the constructive characteristics of the dam, the company stated that it has no construction history in its files, even stating the difficulty of understanding what were the construction methods and technological controls used … With regard to the company's legal obligations, due to the fact that the "Lagoa do Pirocaua" structure falls under Art. 2º, I of Ordinance 70.389/2017, its immediate registration in the Integrated Management System for Safety of Mining Dams – SIGBM was determined …]

All of the following information about the Lagoa do Pirocáua dam is taken from ANM (2021b) and is the information that was provided by Equinox Gold. The dam is described as "*cava com barramento construído*" [open pit with constructed dam] that stores sediments and not tailings. The dam is described as "*desativada*" [deactivated], presumably because the dam had already failed at the time of registration. The web site also reports that the "*vida útil prevista"* [expected useful life] of the dam is 4.00 years, although it is not clear how a "deactivated" dam can have any "expected useful life." The dam was constructed from "*terra homogênea*" [homogenous earth] on a foundation of saprolite or weathered rock. The maximum height of the dam is 7.00 meters, the length of the crest is 30.00 meters, and the surface area of the reservoir is 71,500.00 square meters. According to ANM (2021b), the "*Volume de projeto licenciado do Reservatório"* [Licensed Reservoir Design Volume] is 160,000.00 cubic meters, while the "*Volume atual do Reservatório"* [Current Reservoir Volume] is 20,000.00 cubic meters. The above probably means that 140,000 cubic meters (87.5% of the stored volume) was released due to dam failure, although this is not specified. Based on a comparison of the current surface area and volume, the average current depth of the pond (or the depth subsequent to dam failure) is only 28 centimeters. With regard to the design flood, the web site indicates "*TR [Tempo de Retorno] inferior a 500 anos ou Desconhecida / Estudo não confiável*" [Return period less than 500 years or Unknown / Unreliable study] (AMN, 2021b), which could simply mean that has never been any study of the flood that the dam should be able to accommodate.

A disturbing aspect of the information provided by Equinox Gold (AMN, 2021b) is the implicit admission that there was virtually no care or maintenance of the dam prior to failure. Although ANM (2021b) lists the maximum spillway discharge as 0.50 cubic meters per second, it also states under the category "*Confiabilidade das estruturas extravasora*" [Reliability of overflow structures], "*Estruturas com problemas identificados, com redução de capacidade vertente e sem medidas corretivas*" [Structures with identified problems, with reduced capacity and without corrective measures]. Under the category "*Tipo de auscultação*" [Type of monitoring], the web site states "*Existe instrumentação em desacordo com o projeto sem processo de instalação de novos instrumentos*" [There is instrumentation that is inappropriate for the project with no process for installing new instruments]. The web site confirms that there is no backup dam, there are no design documents, there are no manuals or formal procedures for monitoring and inspection, there is no emergency action plan, and there has been no regular submission of inspection and monitoring reports or safety analyses. It is most important that the Lagoa do Pirocáua dam never received a Declaration of Condition of Stability, which is required for all mining dams (ANM, 2021b). Equinox Gold has not provided any information as to how they reconcile their admission of lack of maintenance of the dam on the ANM (2021b) web site with their assertion that ***"A MASA reitera que não concorreu, de nenhuma forma, para a ocorrência ou agravamento do citado incidente"***[**MASA reiterates that it did not contribute, in any way, to the occurrence or aggravation of the aforementioned incident]** (boldface in the original) (Equinox Gold, 2021a).

Much of the information on the ANM (2021b) web site is a choice among alternatives with no space for free responses. These choices assume a minimum level of care and maintenance, so that the reality could potentially be much worse than what is indicated on the web site. For example, under the category "*Confiabilidade das estruturas extravasora*" [Reliability of overflow structures], there are only four options:

1) *"Estruturas civis bem mantidas e em operação normal / barragem sem necessidade de estruturas extravasora"* [Civil engineering structures well maintained and in normal operation / dam without the need for overflow structures]
2) *"Estruturas com problemas identificados e medidas corretivas em implantação"* [Structures with identified problems and corrective measures in implementation]
3) *"Estruturas com problemas identificados e sem implantação das medidas corretivas necessárias"* [Structures with identified problems and without implementation of necessary corrective measures]
4) *"Estruturas com problemas identificados, com redução de capacidade vertente e sem medidas corretivas"* [Structures with identified problems, with reduced capacity and without corrective measures]

(The web site uses a different numbering system.) In other words, there is no way to indicate that a dam needs a spillway and does not have a spillway. There is also no way to indicate that it is not known whether a dam does or does not have a spillway, or whether a dam does or does not need a spillway, any of which would be consistent with the lack of any design documents.

As another example, under the category "*Relatórios de inspeção e monitoramento da instrumentação e de Análise de Segurança*" [Reports on instrumentation inspection and monitoring and Safety Analysis], the web site (ANM, 2021b) lists five options:

1) *"Emite regularmente relatórios de inspeção e monitoramento com base na instrumentação e de Análise de Segurança"* [Regularly submits inspection and monitoring reports based on the instrumentation and Safety Analysis reports]
2) *"Emite regularmente APENAS relatórios de Análise de Segurança"* [Regularly submits ONLY Safety Analysis reports] (emphasis in the original)
3) *"Emite regularmente APENAS relatórios de inspeção e monitoramento"* [Regularly submits ONLY inspection and monitoring reports] (emphasis in the original)
4) *"Emite regularmente APENAS relatórios de inspeção visual*" [Regularly submits ONLY visual inspection reports] (emphasis in the original)
5) *"Não emite regularmente relatórios de inspeção e monitoramento e de Análise de Segurança"* [Does not regularly submit inspection and monitoring reports and Safety Analysis reports]

(The web site uses a different numbering system.) In other words, there would be no way to clarify that a mining company had never submitted either an inspection and monitoring report or a Safety Analysis report. The lack of submission of any reports is quite likely, considering that the dam had never received a Declaration of Condition of Stability and was not even registered on the SIGBM prior to dam failure (ANM, 2021a-b). Further information about the Lagoa do Pirocáua dam will be provided in the Results section.

## METHODOLOGY

Based on the preceding sections, the objective of this report can be subdivided into the following questions:

1) Was the failure of the Lagoa do Pirocáua dam preceded by a 10,000-year or similar rare precipitation event?
2) Was the failure of the Lagoa do Pirocáua dam preceded by an earthquake?
3) Is there convincing evidence for overtopping as the cause of failure of the Lagoa do Pirocáua dam?
4) Have appropriate steps be taken to prevent further failure of the Lagoa do Pirocáua dam?

The first question was addressed by comparison of the available precipitation records from the Aurizona mine with the daily precipitation records of the National Institute of Meteorology [Instituto Nacional de Meteorologia (INMET)] (INMET, 2021a-c) and the Laboratory of Meteorology, State University of Maranhão – UEMA [Laboratório de Meteorologia, Universidade Estadual do Maranhão – UEMA] (Núcleo Geoambiental, 2021a-d). The closest INMET weather stations to the failed Lagoa do Pirocáua dam are at Turiaçu (59 kilometers to the southeast), Tracuateua (128 kilometers to the northwest), and Capitão Poço (154 kilometers to the southwest) (see Fig. 2 and Table 1). The precipitation records at the Turiaçu weather station are most likely to be representative of conditions at the Lagoa do Pirocáua dam, due to their proximity and common location on the Atlantic coast. Based on Google Earth, the elevation of the failed dam site is 23 meters above sea level. Adding an additional 7 meters for the dam height (ANM, 2021a-b) yields a crest elevation of 30 meters above sea level, or within about 5 meters of either the Turiaçu weather station (34.38 meters above sea level; see Table 1) or the Tracuateua weather station (24.68 meters above sea level; see Table 1). Due to its greater distance, more inland location (see Fig. 2) and greater elevation (79.10 meters above sea level; see Table 1), the Capitão Poço weather station should be less representative of conditions at the Lagoa do Pirocáua dam than either the Turiaçu or Tracuateua weather stations. Although the Capitão Poço weather station is automatic and the Turiaçu and Tracuateua weather stations are conventional (or manual), the Capitão Poço weather station has been less consistently operational (84% of the time) than either the Turiaçu (99% of the time) or Tracuateua (98% of the time) weather stations (see Table 1). The precipitation maps of the Laboratory of Meteorology – UEMA combine the records from the INMET network and the network of the National Center for Natural Disaster Monitoring and Alerts [Centro Nacional de Monitoramento e Alertas de Desastres Naturais (CEMADEN)].

**Table 1. INMET weather stations in vicinity of Lagoa do Pirocáua dam[1]**

| Name | Type | Initial Date (m/d/y) | Coverage[2] (%) | Latitude (°N) | Longitude (°E) | Elevation (m) |
|---|---|---|---|---|---|---|
| Capitão Poço | Automatic | 04/17/2011 | 84 | -1.7335 | -47.0575 | 79.10 |
| Tracuateua | Manual | 09/07/1972 | 98 | -1.0636 | -46.8653 | 24.68 |
| Turiaçu | Manual | 07/28/1976 | 99 | -1.6614 | -45.3719 | 34.48 |

[1]INMET (2021b)
[2]Coverage based on percentage of operational days between initial date and June 20, 2021

The return periods for extreme precipitation events with durations of 24, 48 and 72 hours were calculated for Turiaçu, Tracuateua and Capitão Poço using standard methods described by

Watson and Burkett (1995). As above, the Turiaçu and Tracuateua weather stations are more reliable in this respect, since they have nearly continuous daily precipitation records beginning in 1976 and 1972, respectively, while the Capitão Poço weather station has been operational only since 2011 (see Table 1). For each weather station, each year was assigned a ranking number $M$ with the years ranked in order from the full year with the highest daily precipitation ($M = 1$) to the lowest daily precipitation ($M = 44$ for Turiaçu, $M = 48$ for Tracuateua, $M = 9$ for Capitão Poço; see Tables A1-A3 in Appendix). The return period for each precipitation event was then calculated as

$$T = \frac{n+1}{M} \tag{1}$$

where $T$ is the return period in years and $n$ is the number of years ($n = 44$ for Turiaçu, $n = 48$ for Tracuateua, $n = 9$ for Capitão Poço). In all cases, the best fit to rainfall amount as a function of return period was a logarithmic function. The return periods were converted into annual exceedance probabilities using

$$AEP = \frac{100}{T} \tag{2}$$

where $AEP$ is the annual probability as a percentage that a precipitation event with a particular duration will be equaled or exceeded during any given year.

The possibility of an earthquake that preceded the failure of the Lagoa do Pirocáua dam was investigated by comparison with the records of the Brazilian Seismographic Network [Rede Sismográfica Brasileira (RSBR)], which is composed of 84 stations and sponsored by the Geological Survey of Brazil [Serviço Geológico do Brasil] (Bianchi et al., 2018; Centro de Sismologia da Universidade de São Paulo [Seismology Center of the University of Sao Paulo], 2021). Earthquakes were considered anywhere in Latin America for the five days including and preceding the dam failure (March 21-25, 2021). All magnitudes were based on body waves ($m_b$ scale), for which the RSBR has a detection threshold of $m_b = 3.5$ for earthquakes in Brazil as a whole and $m_b = 3.0$ for earthquakes in northeast Brazil, including the vicinity of the of the Lagoa do Pirocáua dam (Bianchi et al., 2018; Centro de Sismologia da Universidade de São Paulo, 2021).

In the absence of any other evidence for proximal causes of dam failure, such as ground photos or eyewitness accounts, the consideration of the evidence for overtopping was based solely upon the report by ANM (2021a). Although drone videos were provided to the author by the National Council on Human Rights [Conselho Nacional de Direitos Humanos (CNDH)], they did not provide any useful information, mostly because the coverage was too far to the north. In the same way, the consideration of the possibility of further dam failure was based solely upon the report by ANM (2021a) and information about the Lagoa do Pirocáua dam on the ANM (2021b) web site.

## RESULTS

### *Comparison with Precipitation Records*

The claim of Equinox Gold (2021a-c) is that 426 mm of rain fell on the mine site during March 23-24, 2021, constituting a 10,000-year event, with 112.77 mm on March 23, 315 mm on March 24, and another 27 mm on March 25 (see Table 2). (Note the contradiction between the claimed total for March 23-24 and the daily totals for March 23 and March 24.) The purpose of this subsection is to determine whether the claims are realistic and consistent with precipitation records from governmental agencies. As a first step, the claims were compared with the INMET precipitation map for March 24-28, 2021 (see Fig. 10). (There is no comparable map that includes March 23, 2021. The previous newsletter (INMET, 2021d) includes a precipitation map for March 17-21, 2021). According to INMET (2021c), no part of the Atlantic coast of the state of Maranhão (including the Aurizona mine) received more than 150 mm of rain during the five days between March 24 and 28, 2021 (compare Fig. 10 with Fig. 2 for mine location). This observation could be reconciled with the claim that 426 mm of rain fell on the mine site during March 23-24, 2021, only if at least 276 mm of rain fell on March 23 and no more than 150 mm of rain fell on March 24 with no rain during March 25-28, which is inconsistent with the daily totals claimed by Equinox Gold (2021a) (see Table 2).

**Table 2. Comparison of precipitation at Lagoa do Pirocáua dam and neighboring INMET weather stations, March 23-25, 2021**

| Weather Station | Daily Precipitation (mm) | | |
|---|---|---|---|
| | March 23 | March 24 | March 25 |
| Lagoa do Pirocáua dam[1] | 112.7 | 315 | 27 |
| Capitão Poço[2] | 28.6 | 2.2 | 4.2 |
| Tracuateua[2] | 3.0 | 32.2 | 47.9 |
| Turiaçu[2] | 10.4 | 31.5 | 99.6 |

[1]Equinox Gold (2021)
[2]INMET (2021b)

As a second step, the precipitation records of Equinox Gold can be compared with monthly precipitation maps for the state of Maranhão by the Laboratory of Meteorology – UEMA (Núcleo Geoambiental, 2021a). Fig. 11a shows total precipitation of 400-450 mm for the entire month of March 2021 at the site of the Aurizona mine, near the northernmost point of Maranhão (compare Fig. 11a with Fig. 2). This observation cannot be reconciled with the precipitation records by Equinox Gold (see Table 2) even if no rain at all fell during the entire month of March outside of March 23-25. Fig. 11b shows the deviation in total precipitation for the month of March 2021 in comparison with climatological normals. The monthly rainfall at the site of the Aurizona mine (compare Fig. 11b with Fig. 2) was well within the normal range (in the range between 25% below and 35% above the average monthly rainfall). This last observation is certainly inconsistent with the occurrence of a 48-hour, 10-000-year storm during the same month.

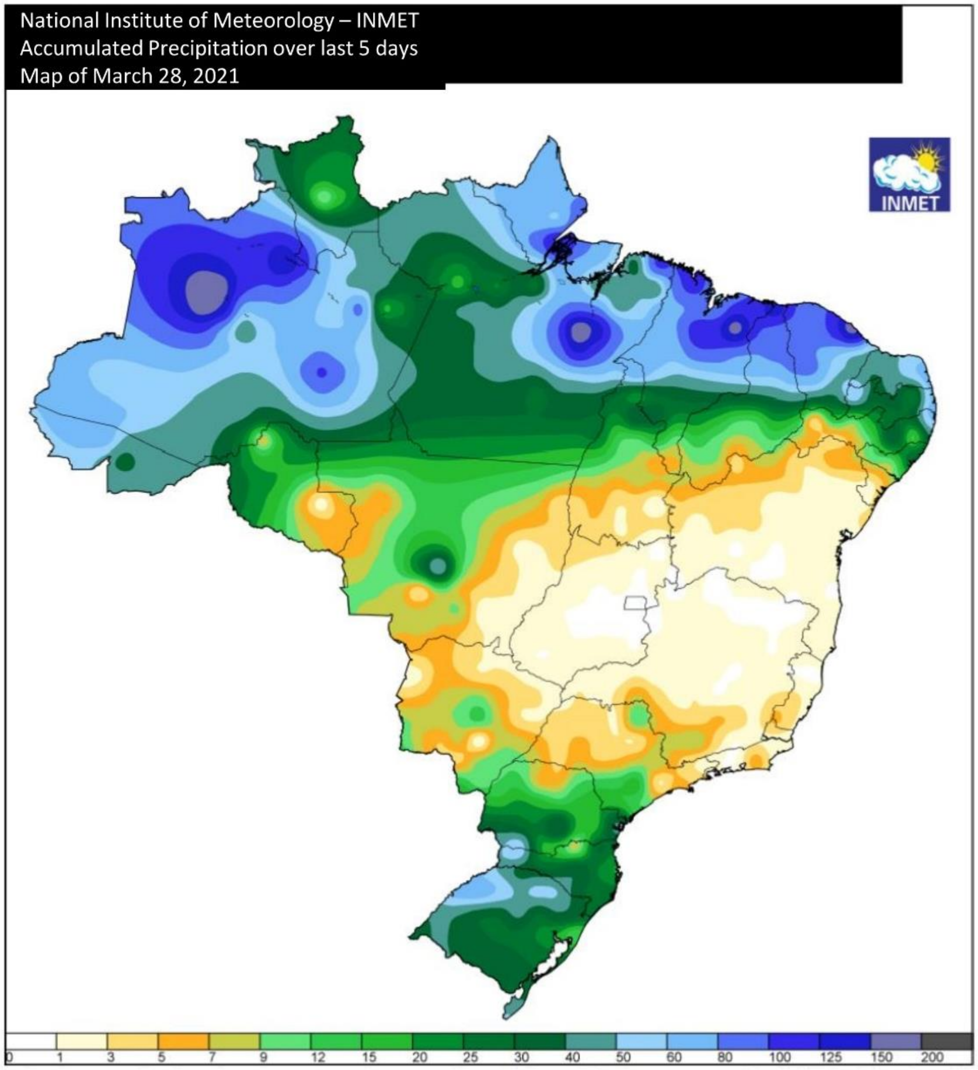


Figure 1: Accumulation of rain between March 24 and 28, 2021. Source: INMET

**Figure 10.** According to INMET (2021c), no part of the Atlantic coast of the state of Maranhão (including the Aurizona mine) received more than 150 mm of rain during the five days between March 24 and 28, 2021 (compare with Fig. 2). This observation could be reconciled with the claim of Equinox Gold (2021a-c) that 426 mm of rain fell on the mine site during March 23-24, 2021, only if at least 276 mm of rain fell on March 23 and no more than 150 mm of rain fell on March 24 with no rain during March 25-28. On the other hand, Equinox Gold (2021c) claims that rainfall amounts were 112.7 mm, 315 mm and 27 mm on March 23, 24, and 25, respectively (see Table 2). (Note that 112.7 mm and 315 mm add to 427.7 mm, not 426 mm.) Map from INMET (2021c) with overlay of English labels.

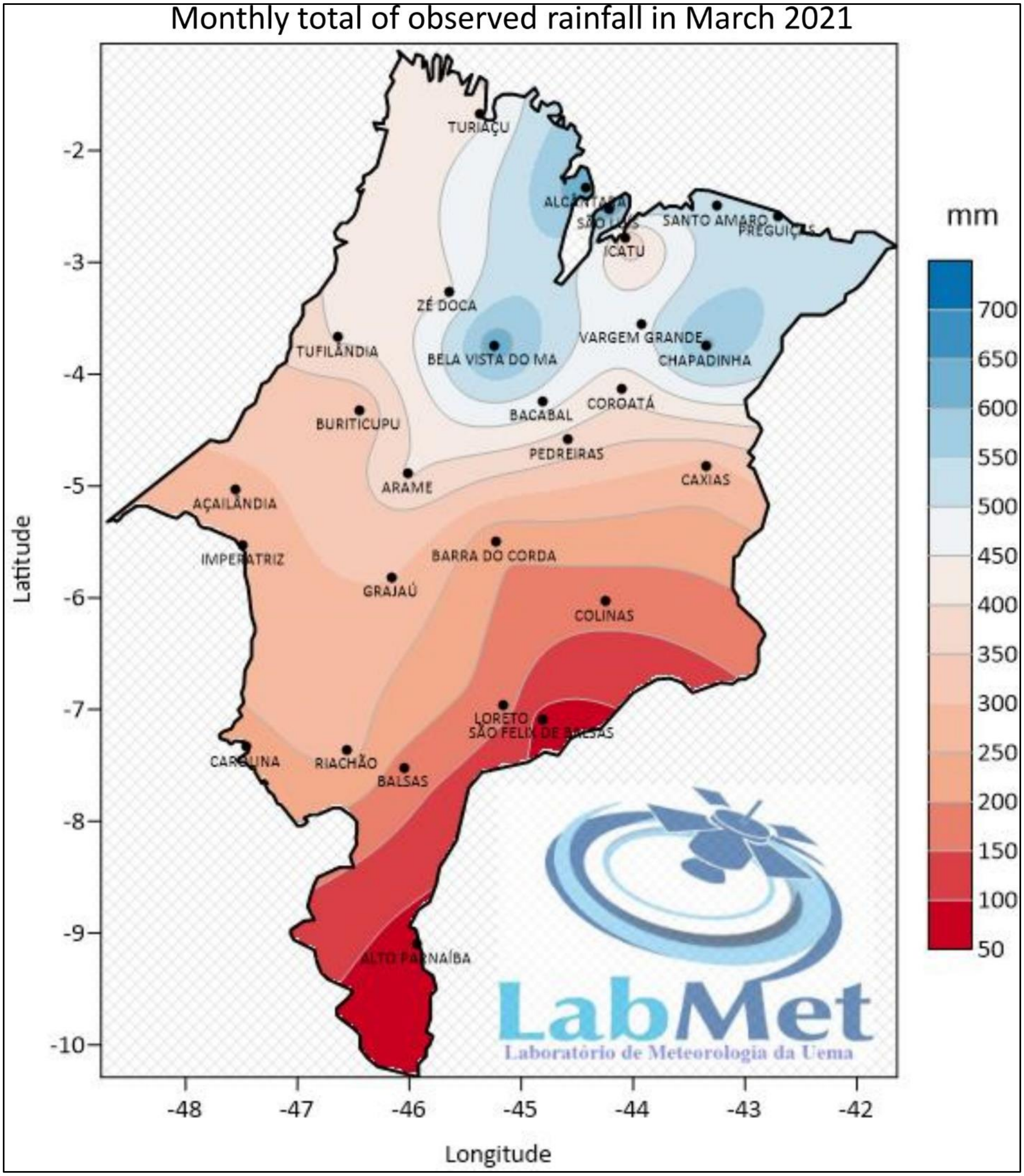

**Figure 11a.** Precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA combine rainfall records from the INMET network (see Fig. 2) and the network of the National Center for Natural Disaster Monitoring and Alerts (CEMADEN). The above map shows total precipitation of 400-450 mm for the entire month of March 2021 at the site of the Aurizona mine, near the northernmost point of Maranhão (compare with Fig. 2). By contrast, Equinox Gold and ANM claim that 426 mm of rain fell at the mine site during March 23-24, 2021, corresponding to a 10,000-year event, with another 27 mm of rain on March 25, 2021. Map from Núcleo Geoambiental (2021a) with overlay of English labels.

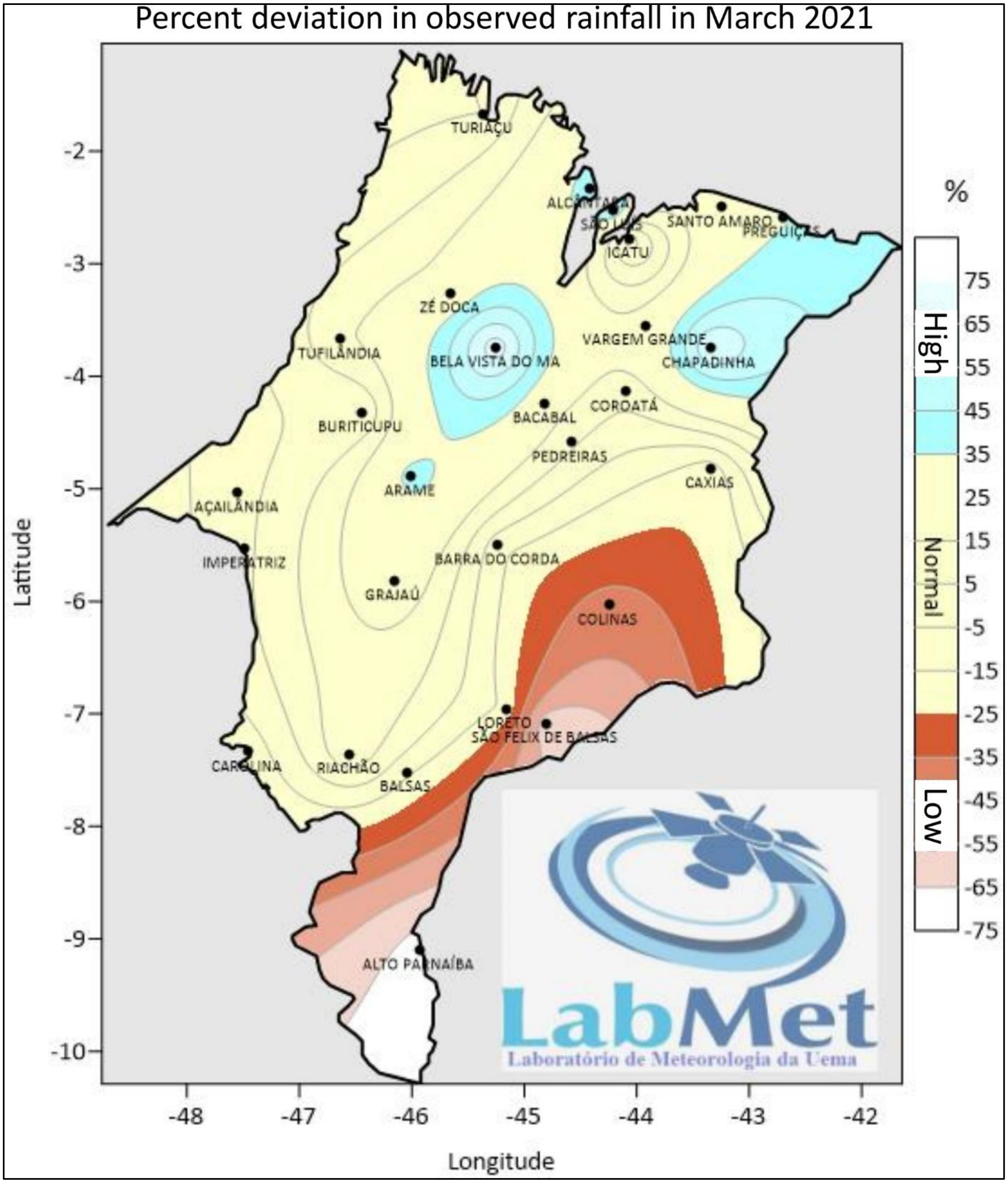


**Figure 11b.** Precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA combine rainfall records from the INMET network (see Fig. 2) and the network of the National Center for Natural Disaster Monitoring and Alerts (CEMADEN). The above map shows the deviation in total precipitation for the month of March 2021 in comparison with climatological normals. The monthly rainfall at the site of the Aurizona mine, near the northernmost point of Maranhão (compare with Fig. 2), was well within the normal range. By contrast, Equinox Gold and ANM claim that 426 mm of rain fell at the mine site during March 23-24, 2021, corresponding to a 10,000-year event. Map from Núcleo Geoambiental (2021a) with overlay of English labels.

As a third step, the precipitation records of Equinox Gold can be compared with daily precipitation maps for the state of Maranhão by the Laboratory of Meteorology – UEMA (Núcleo Geoambiental, 2021b-d). The March 23 map shows 10-15 mm of rain at the site of the Aurizona mine (compare Fig. 2 with Fig. 12a). The March 24 map shows 25-30 mm of rain at the site of the Aurizona mine (compare Fig. 2 with Fig. 12b). The March 25 map shows 90-95 mm of rain at the site of the Aurizona mine (compare Fig. 2 with Fig. 12c). The daily precipitation maps cannot be reconciled with the precipitation records of Equinox Gold (see Table 2). In fact, the precipitation record of Equinox Gold does not even reproduce the temporal pattern of the daily precipitation maps for the state of Maranhão, which consists of steadily increasing rainfall amounts from March 23-25 with the maximum rainfall on March 25, or after the dam failure.

The fourth and most important step is to compare the precipitation records of Equinox Gold directly with the precipitation records of the three closest INMET weather stations (see Table 2). The claimed rainfall amounts at the Aurizona mine are far less than the rainfall amounts at the INMET weather stations, with the maximum daily rainfall at a neighboring INMET weather station being 99.6 mm at Turiaçu on March 25 (after the dam failure). The precipitation records at the Atlantic coastal stations of Turiaçu and Tracuateua reproduce the temporal pattern of the daily precipitation maps by the Laboratory of Meteorology – UEMA (see Figs. 12a-c) with steadily increasing daily rainfall from March 23-25. The Capitão Poço weather station, which is farther inland (see Fig. 2), received very little rainfall after March 23.

Logarithmic curves are excellent fits to the relation between rainfall amount and return period for all three INMET weather stations (Turiaçu, Tracuateua, Capitão Poço) for storm durations of 24, 48 and 72 hours (see Figs. 13a-c, 14a-c and 15a-c). This means the rainfall amounts for storms with return periods less than 100 years can be reliably determined for all three weather stations, with somewhat less certainty for Capitão Poço, due to its shorter operational period, as discussed above. Thus, the claim of a storm with a 10,000-year return period on March 23-24, 2021, at the site of the Aurizona mine can be compared with the return periods of the corresponding precipitation events at the three INMET weather stations. For completeness, at each INMET weather station, the return periods were considered for the following intervals:

1) 24-hour storms on March 23, 24 and 25
2) 48-hour storms on March 23-24 and March 24-25
3) 72-hour storms during March 23-25

It should be noted that return periods less than one year are not really meaningful since a storm with a return period of one year already has a 100% probability of exceedance in any given year. However, these very short return periods are still stated in order to emphasize the normality of the rainfalls that occurred at the three INMET weather stations during March 23-25, 2021.

At the INMET Turiaçu weather station, 24-hour rainfall amounts were 10.4 mm, 31.5 mm, and 99.6 mm for March 23, 24 and 25, 2021, corresponding to return periods of 0.2 years, 0.3 years, and 1.8 years, respectively, with the 24-hour precipitation on March 25 corresponding to an annual exceedance probability of 56% (see Table 2 and Fig. 13a). The 48-hour rainfall amounts were 41.9 mm and 131.1 mm for March 23-24 and 24-25, 2021, corresponding to return periods of 0.3 years and 2.3 years (annual exceedance probability of 44%), respectively (see Table 2 and Fig. 13b). The 72-hour rainfall amount was 141.5 mm for March 23-25, 2021, corresponding to a return period of 1.8 years (annual exceedance probability of 55%) (see Table 2 and Fig. 13c).

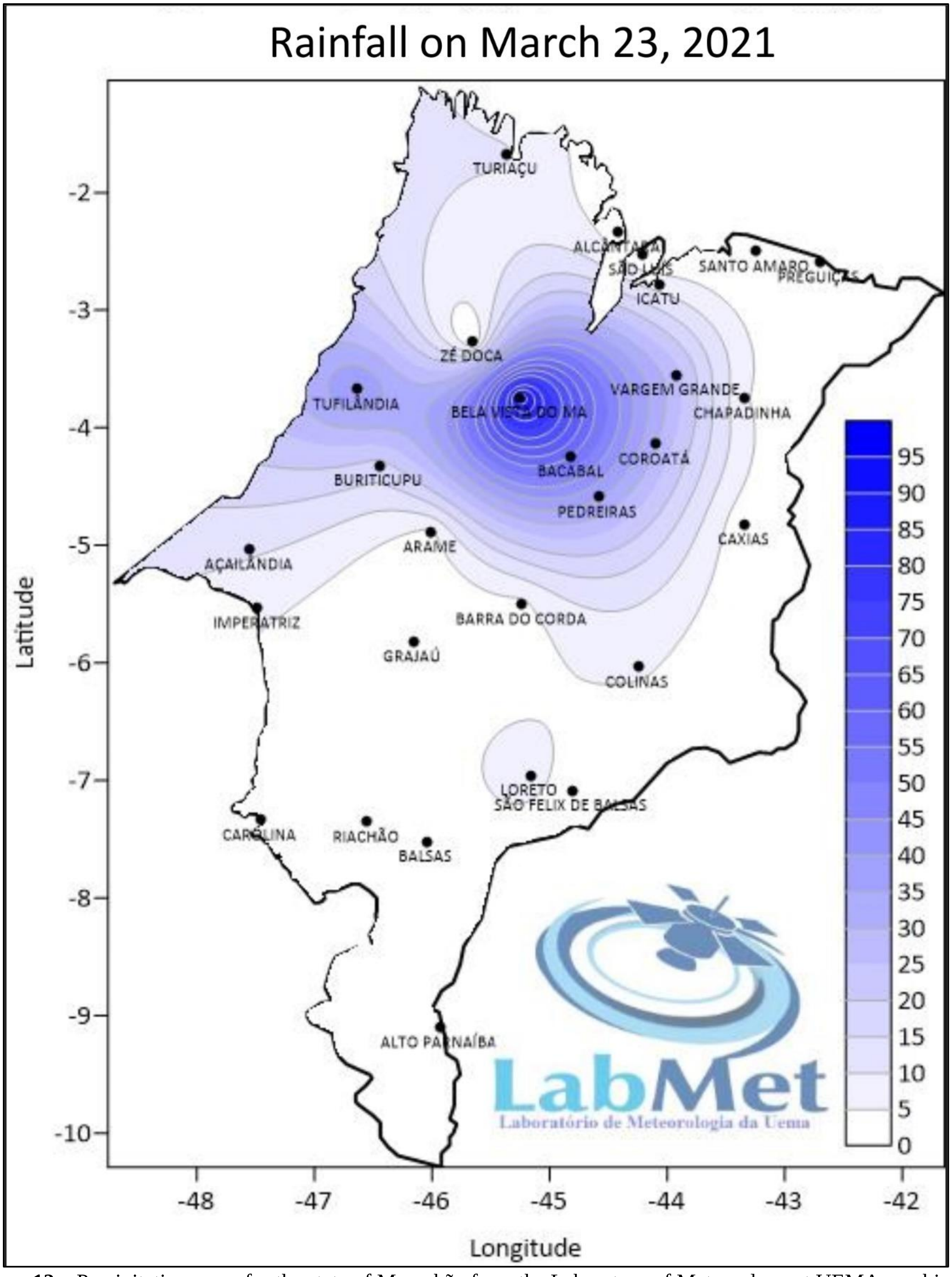


**Figure 12a.** Precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA combine rainfall records from the INMET and CEMADEN networks (see Fig. 2). The above map shows 10-15 mm of rainfall for March 23, 2021, at the site of the Aurizona mine, near the northernmost point of Maranhão (compare with Fig. 2). By contrast, Equinox Gold claims that the mine site received 112.7 mm of rainfall on March 23, 2021. Map from Núcleo Geoambiental (2021b) with overlay of English labels.

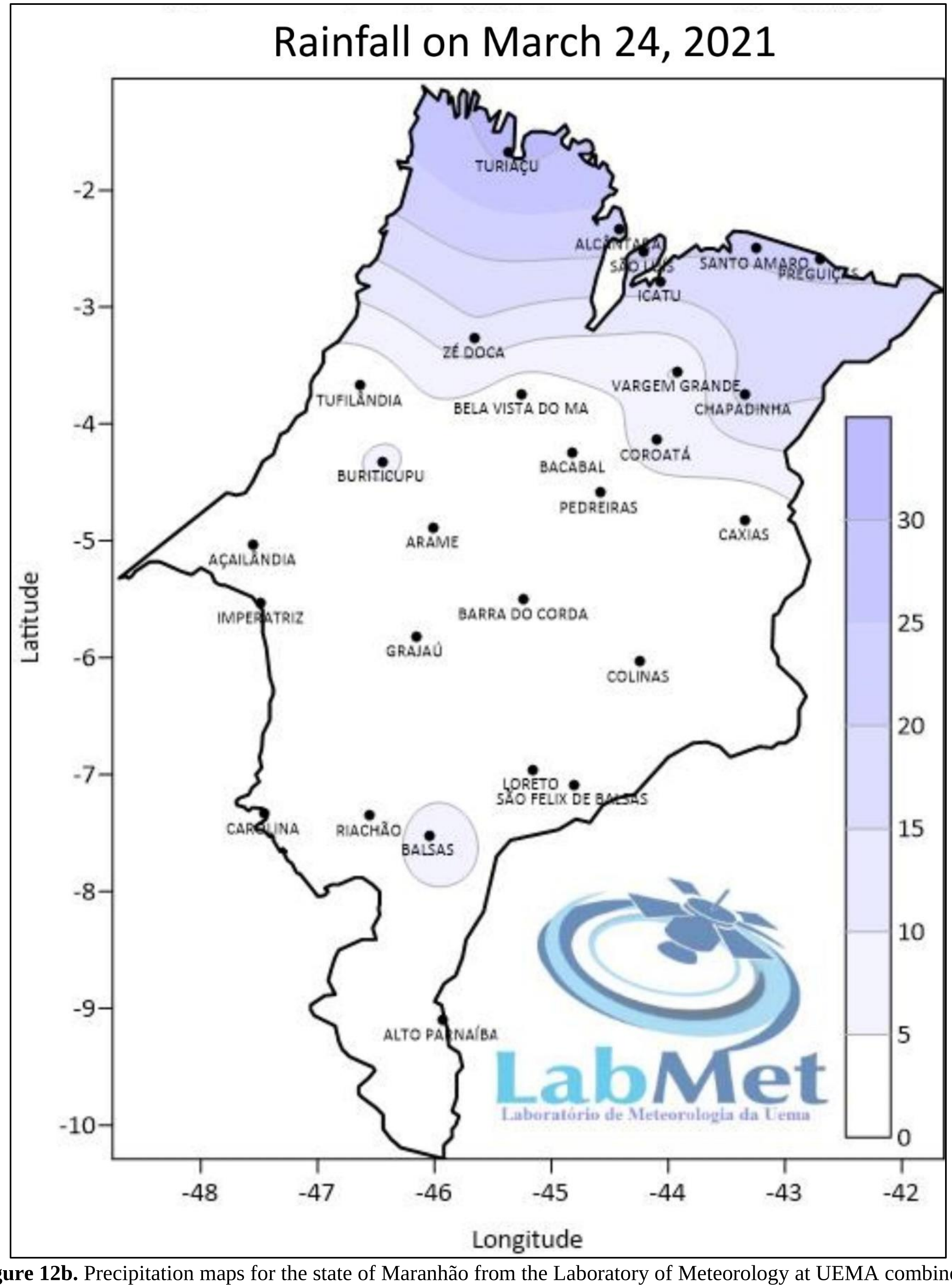


**Figure 12b.** Precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA combine rainfall records from the INMET and CEMADEN networks (see Fig. 2). The above map shows 25-30 mm of rainfall for March 24, 2021, at the site of the Aurizona mine, near the northernmost point of Maranhão (compare with Fig. 2). By contrast, Equinox Gold claims that the mine site received 315 mm of rainfall on March 24, 2021. Map from Núcleo Geoambiental (2021c) with overlay of English labels.

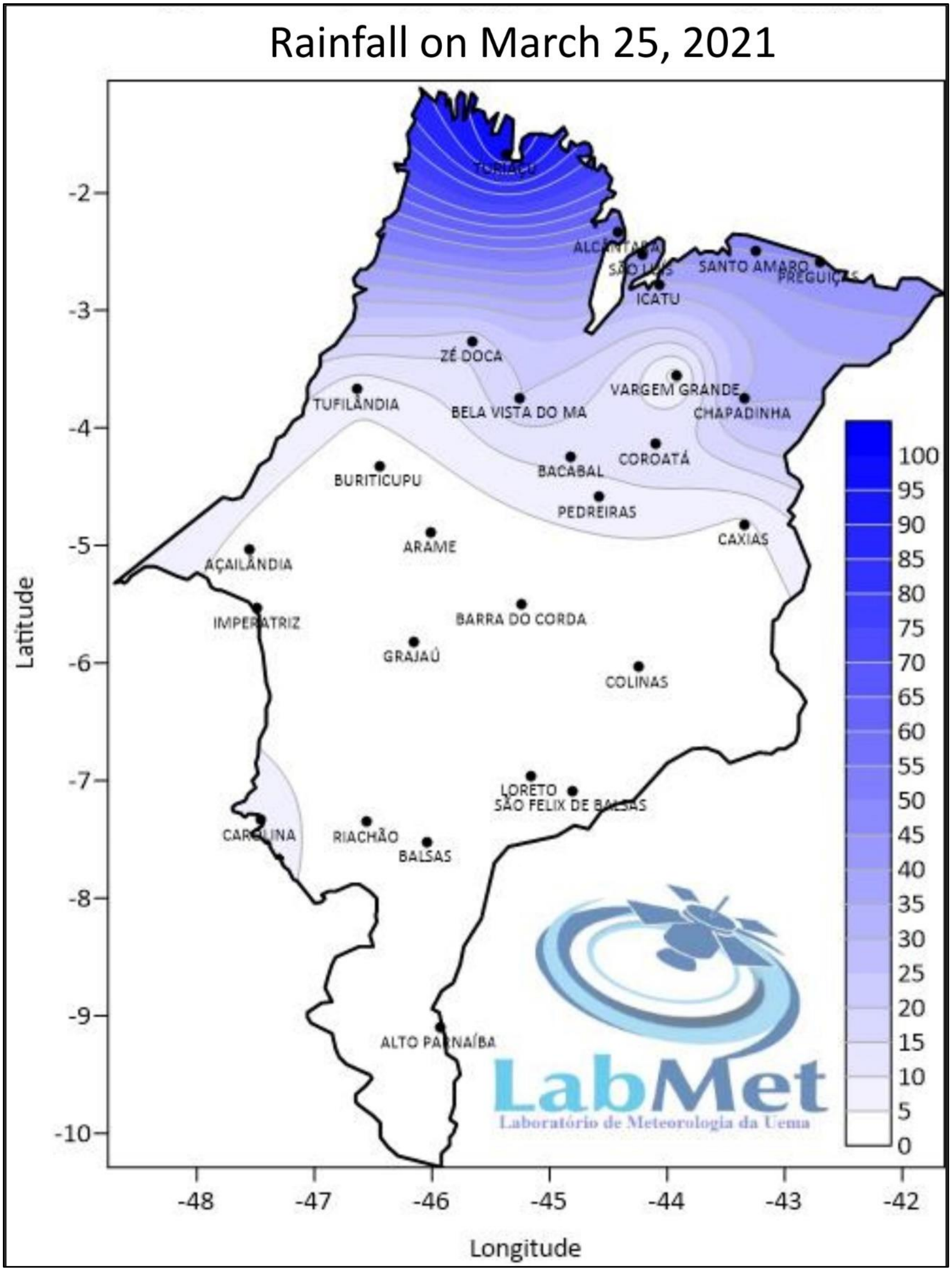


**Figure 12c.** Precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA combine rainfall records from the INMET and CEMADEN networks (see Fig. 2). The above map shows 90-95 mm of rainfall for March 25, 2021, at the site of the Aurizona mine, near the northernmost point of Maranhão (compare with Fig. 2). By contrast, Equinox Gold claims that the mine site received 27 mm of rainfall on March 25, 2021. Map from Núcleo Geoambiental (2021d) with overlay of English labels.

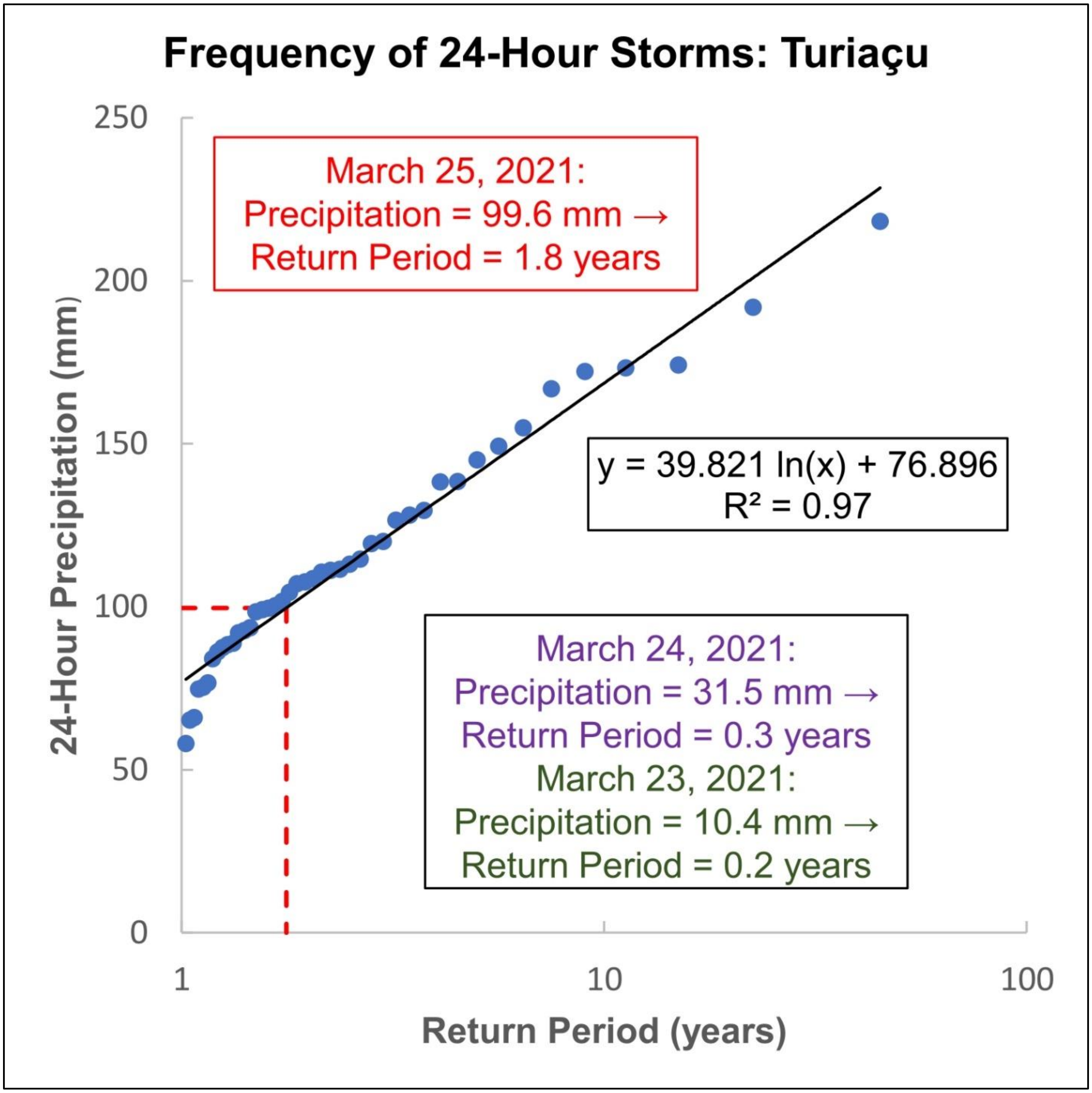


**Figure 13a.** At the INMET Turiaçu weather station (see Fig. 2 and Table 1), 24-hour rainfall amounts were 10.4 mm, 31.5 mm, and 99.6 mm for March 23, 24 and 25, 2021, corresponding to return periods of 0.2 years, 0.3 years, and 1.8 years, respectively. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Turiaçu were calculated from data in INMET (2021b).

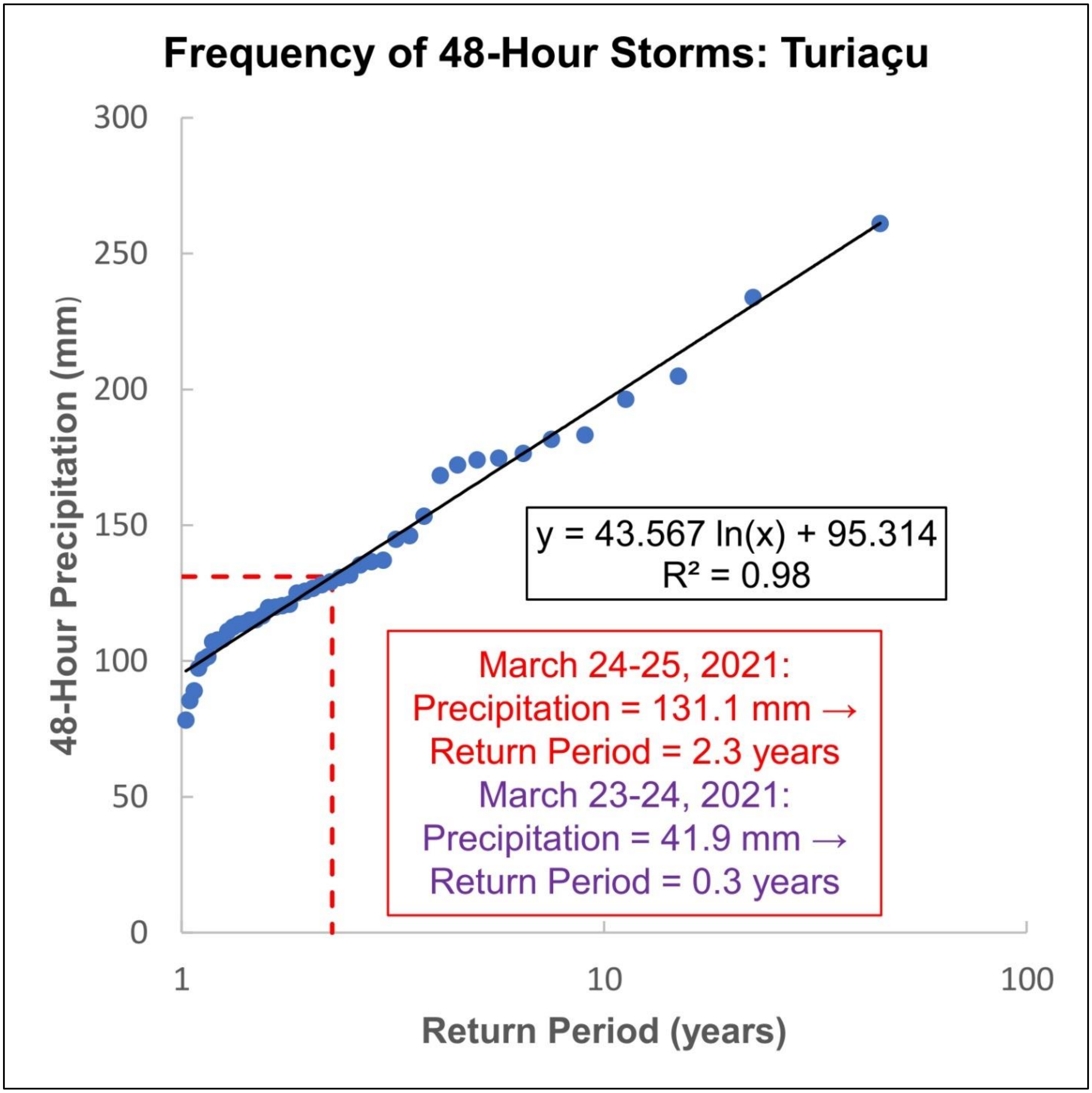


**Figure 13b.** At the INMET Turiaçu weather station (see Fig. 2 and Table 1), 48-hour rainfall amounts were 41.9 mm and 131.1 mm for March 23-24 and 24-25, 2021, corresponding to return periods of 0.3 years and 2.3 years, respectively. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Turiaçu were calculated from data in INMET (2021b).

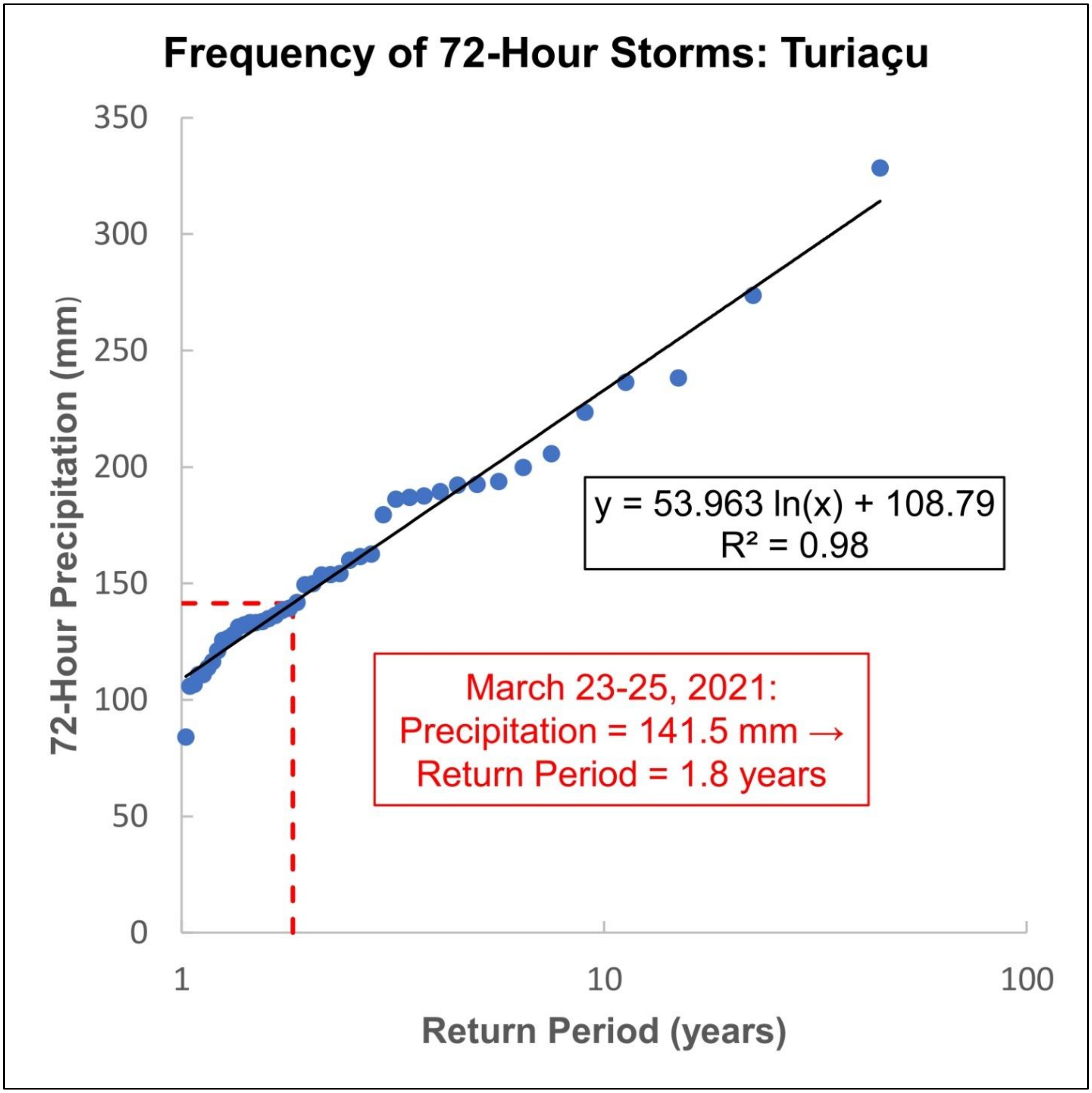


**Figure 13c.** At the INMET Turiaçu weather station (see Fig. 2 and Table 1), the 72-hour rainfall amount was 141.5 mm for March 23-25, 2021, corresponding to a return period of 1.8 years. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Turiaçu were calculated from data in INMET (2021b).

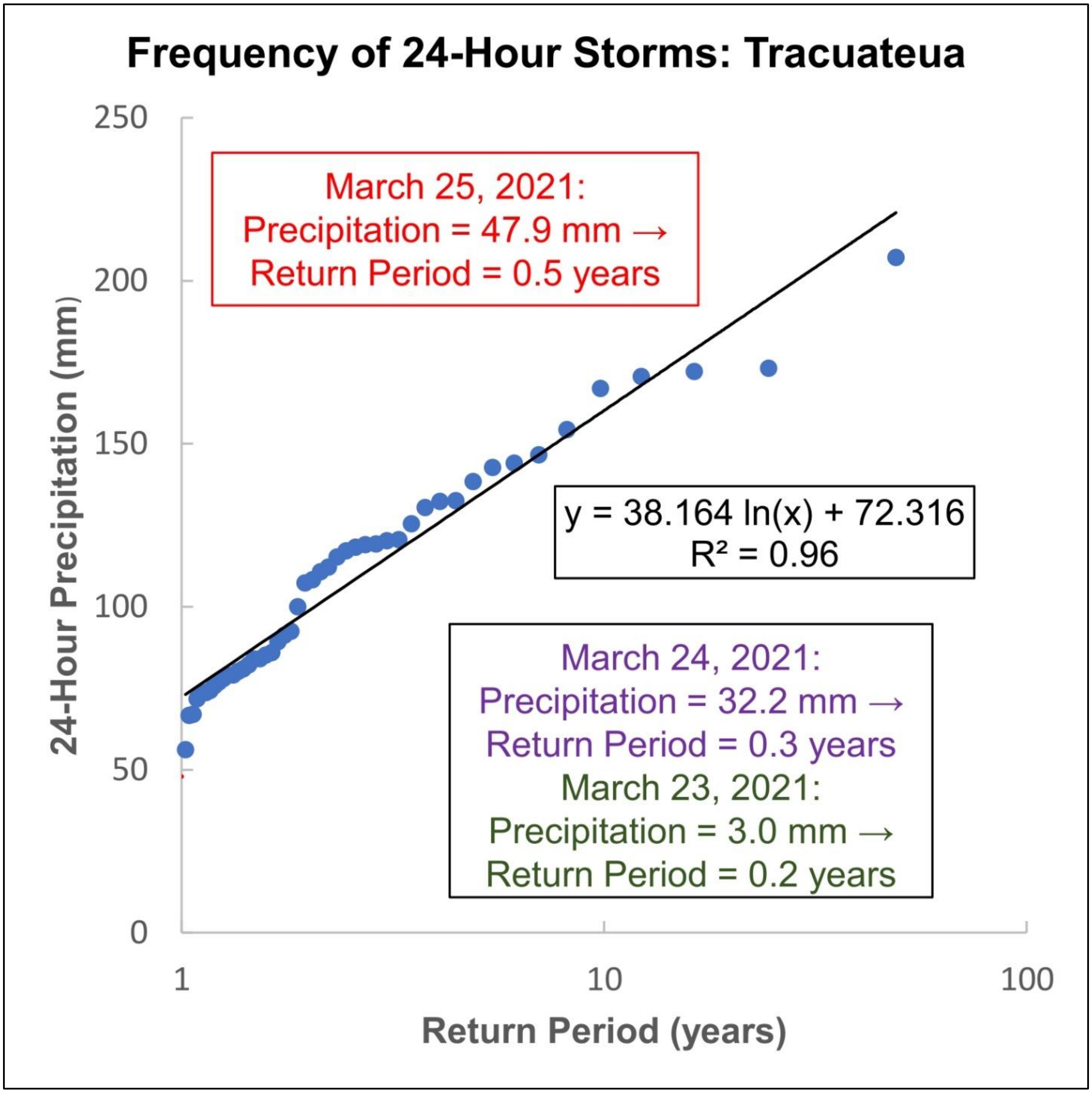


**Figure 14a.** At the INMET Tracuateua weather station (see Fig. 2 and Table 1), 24-hour rainfall amounts were 3.0 mm, 32.2 mm, and 47.9 mm for March 23, 24 and 25, 2021, corresponding to return periods of 0.2 years, 0.3 years, and 0.5 years, respectively. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Tracuateua were calculated from data in INMET (2021b).

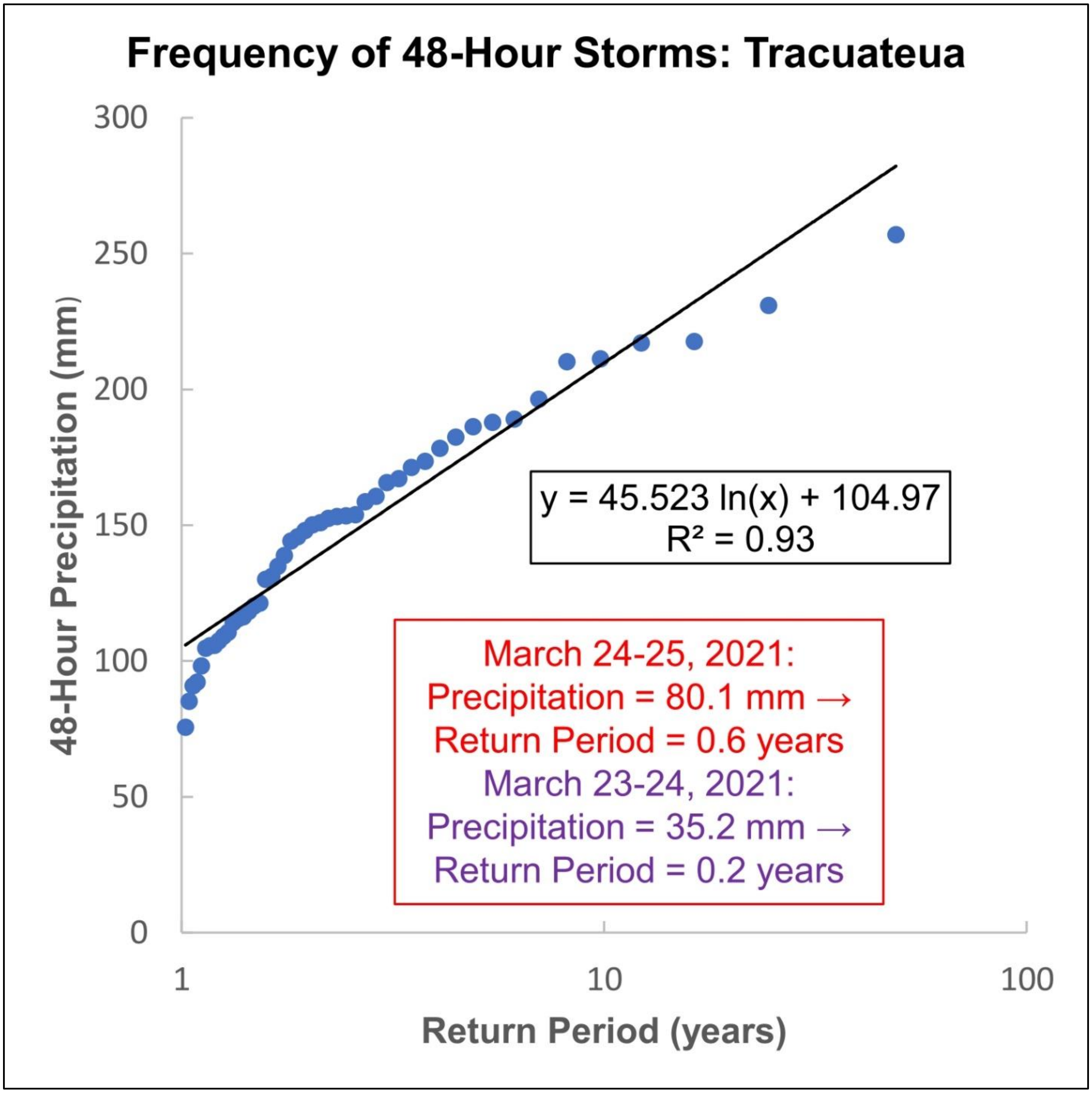


**Figure 14b.** At the INMET Tracuateua weather station (see Fig. 2 and Table 1), 48-hour rainfall amounts were 35.2 mm and 80.1 mm for March 23-24 and 24-25, 2021, corresponding to return periods of 0.2 years and 0.6 years, respectively. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Tracuateua were calculated from data in INMET (2021b).

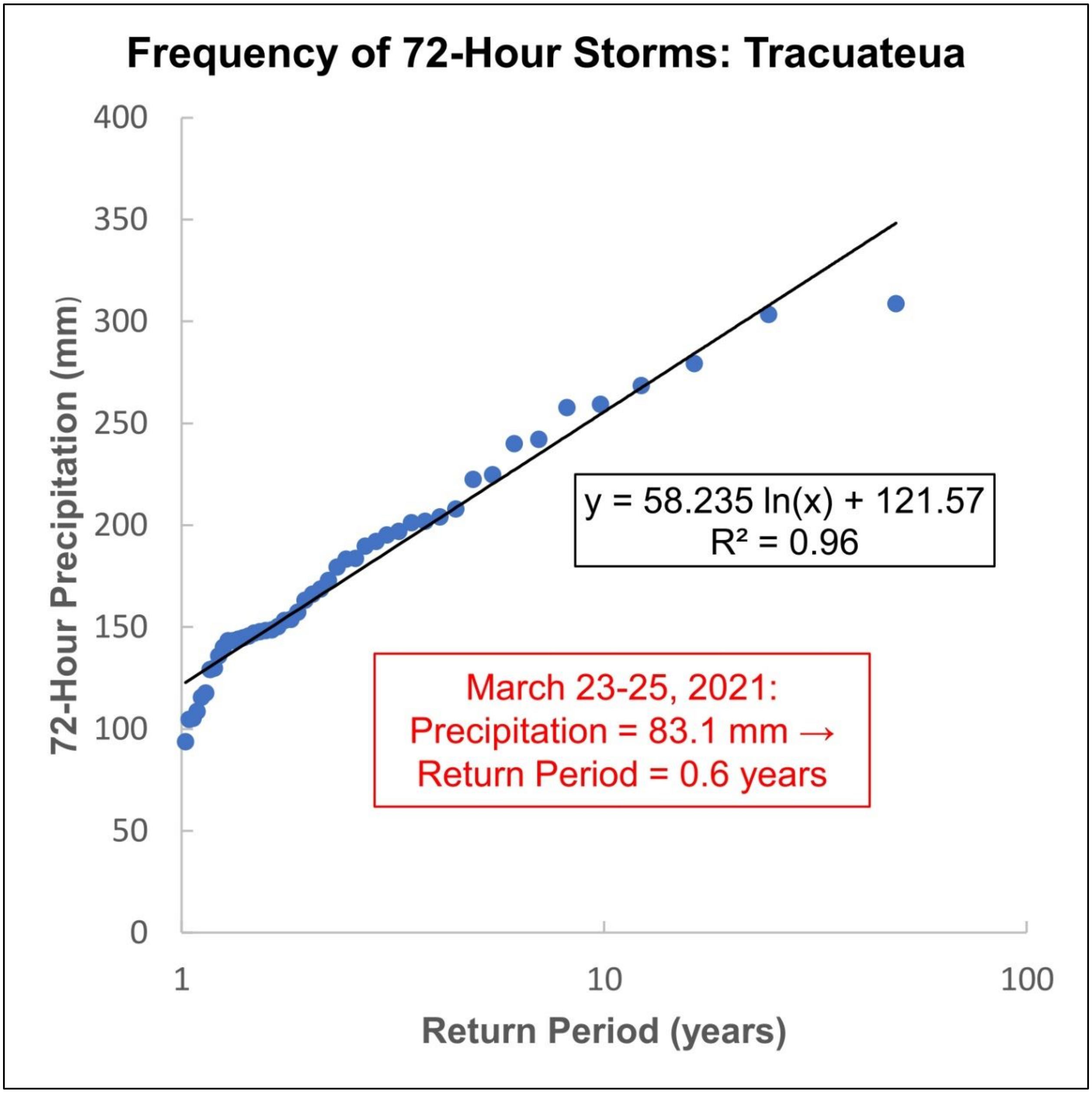


**Figure 14c.** At the INMET Tracuateua weather station (see Fig. 2 and Table 1), the 72-hour rainfall amount was 83.1 mm for March 23-25, 2021, corresponding to a return period of 0.6 years. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Tracuateua were calculated from data in INMET (2021b).

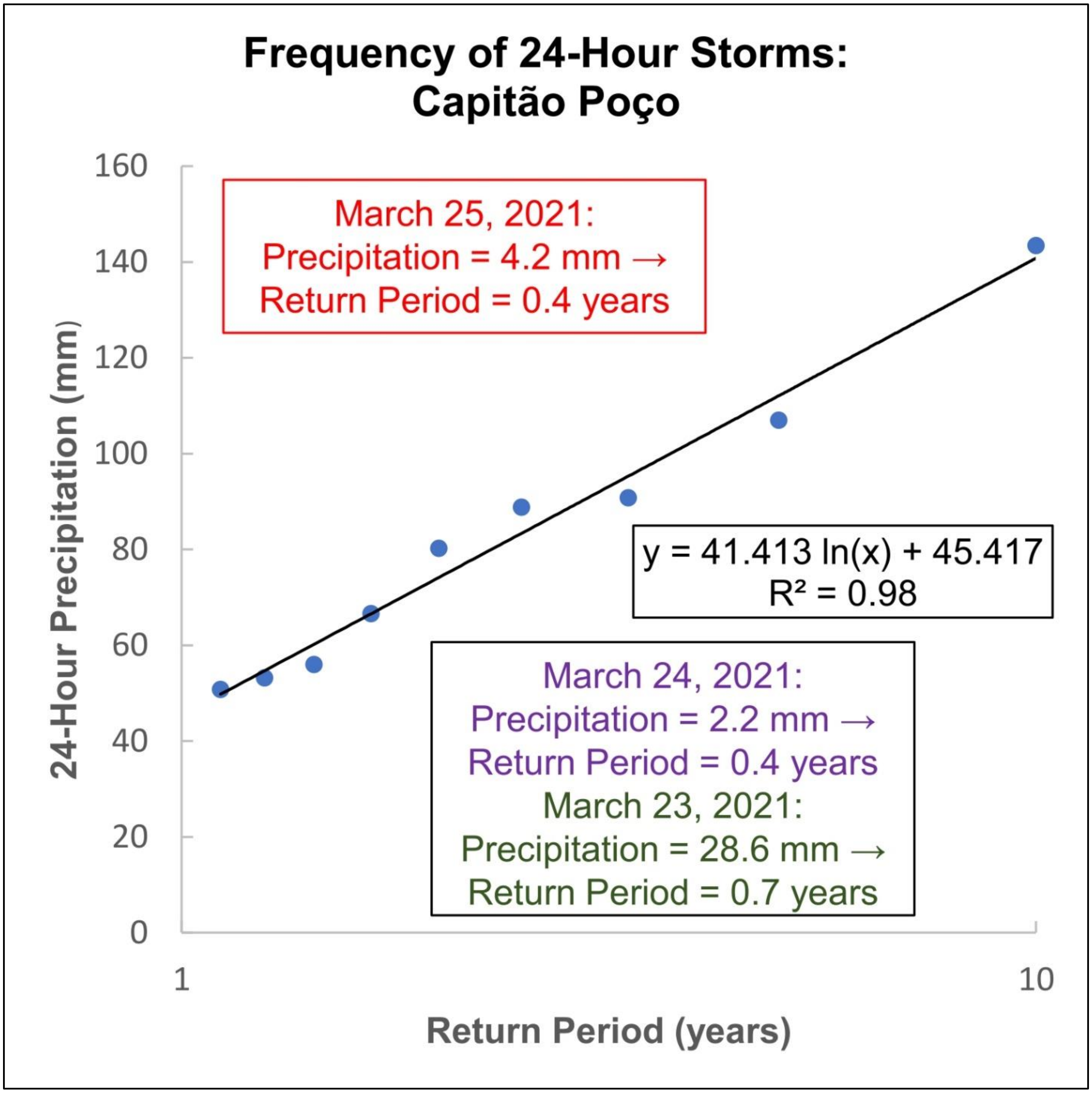


**Figure 15a.** At the INMET Capitão Poço weather station (see Fig. 2 and Table 1), 24-hour rainfall amounts were 28.6 mm, 2.2 mm, and 4.2 mm for March 23, 24 and 25, 2021, corresponding to return periods of 0.7 years, 0.4 years, and 0.4 years, respectively. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Capitão Poço were calculated from data in INMET (2021b).

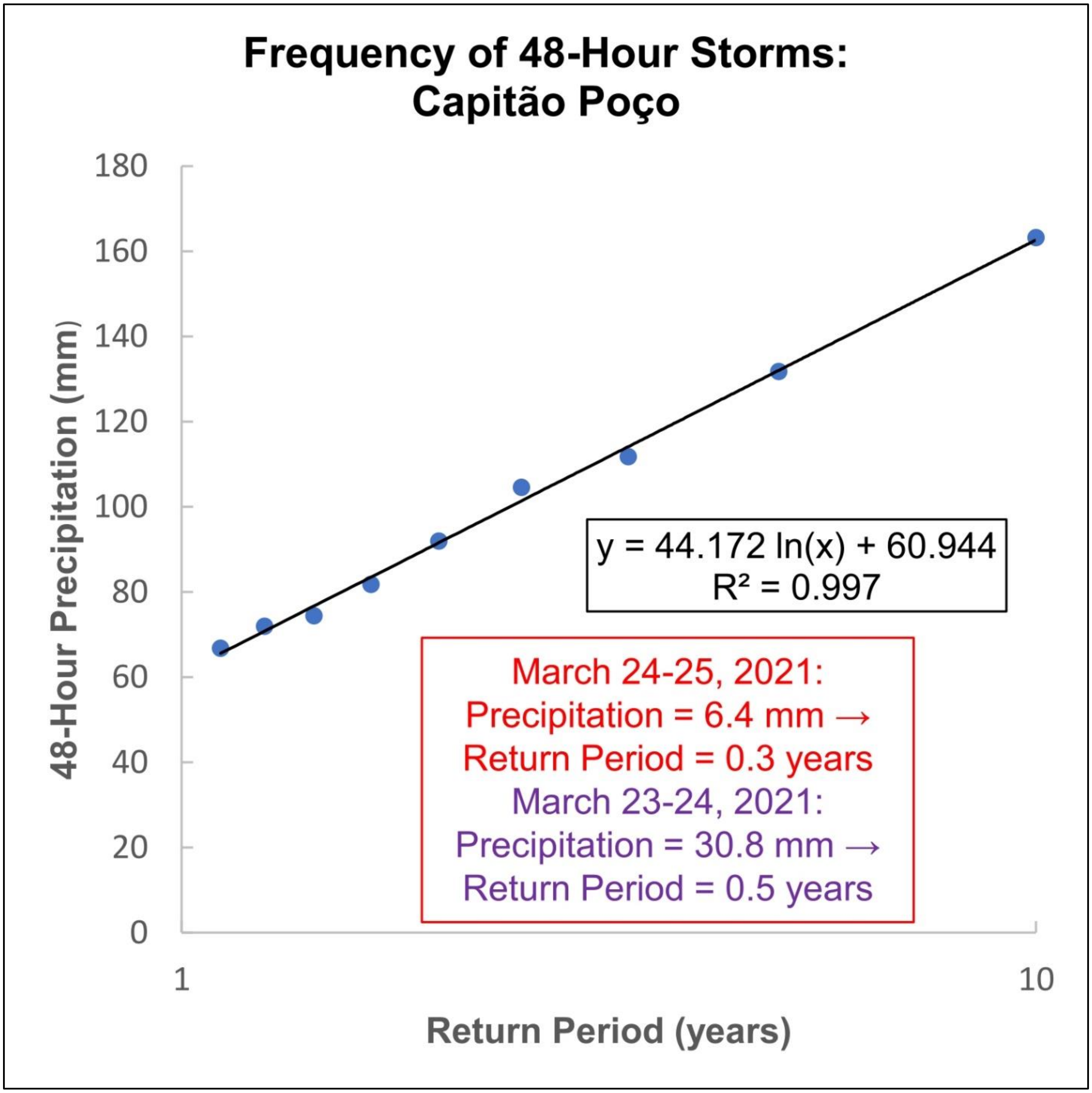


**Figure 15b.** At the INMET Capitão Poço weather station (see Fig. 2 and Table 1), 48-hour rainfall amounts were 30.8 mm and 6.4 mm for March 23-24 and 24-25, 2021, corresponding to return periods of 0.5 years and 0.3 years, respectively. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Capitão Poço were calculated from data in INMET (2021b).

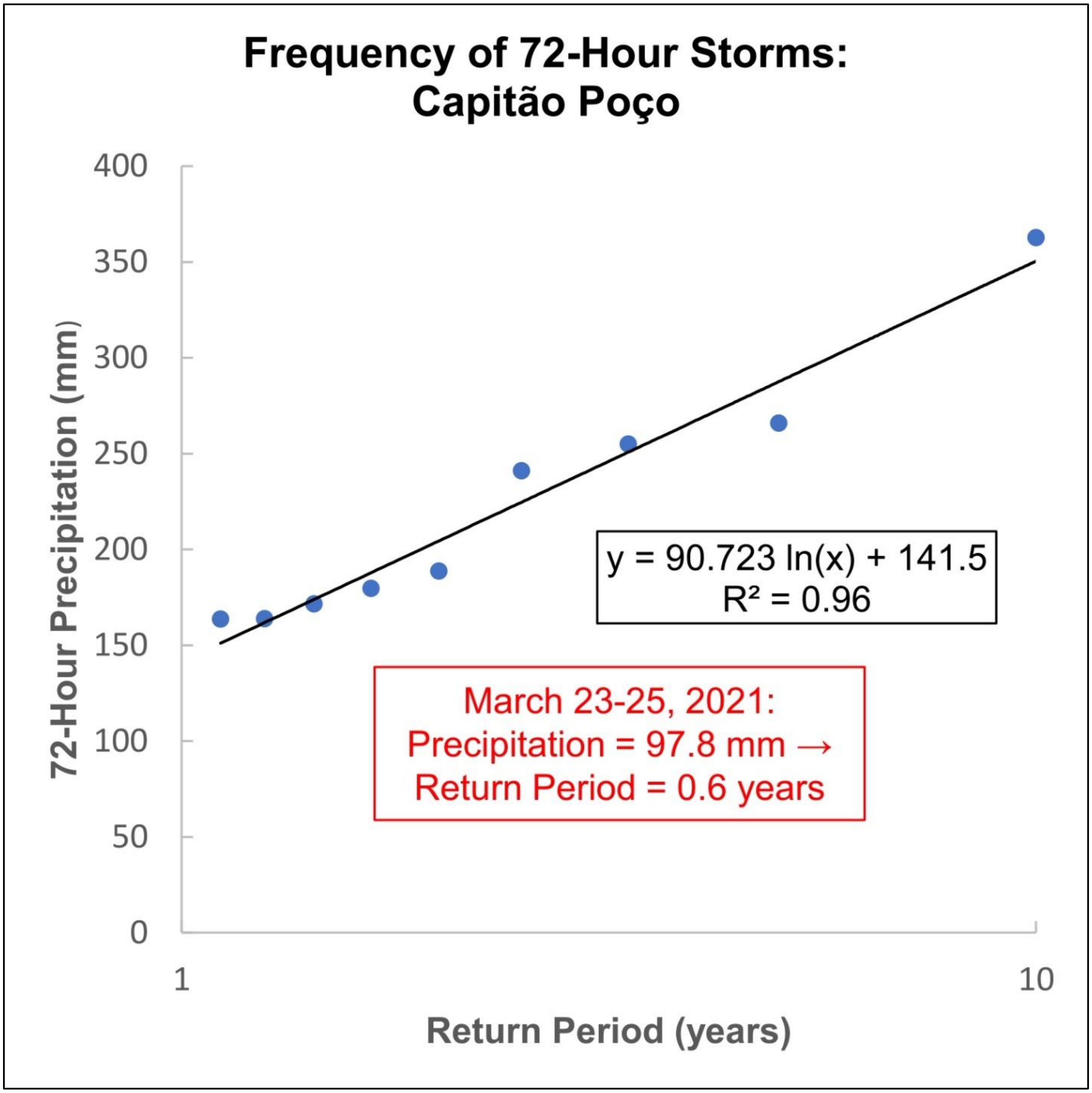


**Figure 15c.** At the INMET Capitão Poço weather station (see Fig. 2 and Table 1), the 72-hour rainfall amount was 97.8 mm for March 23-25, 2021, corresponding to a return period of 0.6 years. Note that return periods shorter than one year are not meaningful, since a one-year return period already corresponds to events with a 100% probability of exceedance in any given year. By contrast, Equinox Gold (2021a-c) and ANM (2021a) claim that 426 mm of rain fell on the Aurizona mine site during March 23-24, 2021, corresponding to a 10,000-year event. Return periods for Capitão Poço were calculated from data in INMET (2021b).

At the INMET Tracuateua weather station, 24-hour rainfall amounts were 3.0 mm, 32.2 mm, and 47.9 mm for March 23, 24 and 25, 2021, corresponding to return periods of 0.2 years, 0.3 years, and 0.5 years, respectively (see Table 2 and Fig. 14a). The 48-hour rainfall amounts were 35.2 mm and 80.1 mm for March 23-24 and 24-25, 2021, corresponding to return periods of 0.2 years and 0.6 years, respectively (see Table 2 and Fig. 14b). The 72-hour rainfall amount was 83.1 mm for March 23-25, 2021, corresponding to a return period of 0.6 years (see Table 2 and Fig. 14c).

At the INMET Capitão Poço weather station, 24-hour rainfall amounts were 28.6 mm, 2.2 mm, and 4.2 mm for March 23, 24 and 25, 2021, corresponding to return periods of 0.7 years, 0.4 years, and 0.4 years, respectively (see Table 2 and Fig. 15a). The 48-hour rainfall amounts were 30.8 mm and 6.4 mm for March 23-24 and 24-25, 2021, corresponding to return periods of 0.5 years and 0.3 years, respectively (see Table 2 and Fig. 15b). The 72-hour rainfall amount was 97.8 mm for March 23-25, 2021, corresponding to a return period of 0.6 years (see Table 2 and Fig. 15c).

In summary, according to the weather stations in both the INMET and CEMADEN networks, the days between March 23 and 25, 2021, were simply typical rainy days in the month of March on the Atlantic coast of northern Maranhão. The possibility still remains that there could have been a very localized 48-hour storm with a 10,000-year return period only at the site of the Aurizona mine that did not affect any of the surrounding weather stations. Short-duration thunderstorms and tornadoes can be highly localized, but day-long and multi-day storms tend to have larger spatial scales. In general, there is a correlation between the temporal and spatial scale of a storm, as well as between the total precipitation and the spatial scale of a storm. However, these correlations have not been well-quantified in Brazil.

A recent study quantified the spatial scales of extreme 24-hour precipitation events (return periods greater than or equal to 10 years, corresponding to annual exceedance probabilities ≤10%) for the United States during 1965-2014 (Touma et al., 2018). The study found that, for the eastern United States, the spatial scales for extreme 24-hour precipitation events reached 400 kilometers during the winter months, but were closer to 200 kilometers during the summer months. For the northwest region of the United States, spatial scales were approximately 150 kilometers with no seasonal variation (Touma et al., 2018). The spatial scales of more extreme precipitation events, such as 10,000-year events, should be considerably larger, although this has not yet been quantified. On that basis, it is highly unlikely that a 48-hour 10,000-year storm occurred at the site of the Aurizona mine and was not recorded at any of the surrounding weather stations.

### *Comparison with Seismic Records*

The Brazilian Seismographic Network recorded 13 earthquakes in Latin America during March 21-25, 2021 (see Fig. 1 and Table 3). However, none of those earthquakes occurred anywhere in Brazil. The closest earthquake during March 21-25 was an earthquake with magnitude 4.1 in Guyana, 1606 kilometers to the northwest, on March 24 (see Fig. 1 and Table 3). In summary, it is highly unlikely that the proximal cause of dam failure was an earthquake. However, it is possible that an earthquake could have occurred much earlier and that the damage from the earthquake was never repaired, contributing to the chain of events that finally culminated in dam failure. This possibility will be further explored in the Discussion section.

### *Evidence for Overtopping*

ANM (2021a) did not actually advance any evidence that the cause of failure of the Lagoa do Pirocáua dam failure was overtopping. ANM (2021a) essentially assumed that, because a 10,000-year storm occurred prior to dam failure, the dam must have failed due to overtopping.

It should be noted that, although ANM (2021a) attributed the source of knowledge of the 10,000-year storm solely to the weather station at the Aurizona mine, ANM (2021a) repeated the information from Equinox Gold without any questioning or comparison with precipitation records from other weather stations.

**Table 3. Earthquakes in Latin America during March 21-25, 2021[1]**

| Date (m/d) | Time (UTC) | Latitude (°N) | Longitude (°E) | Magnitude | Description |
|---|---|---|---|---|---|
| 3/25 | 08:13 | 13.4535 | -89.5701 | 5.0 | El Salvador |
| 3/25 | 06:48 | 10.4349 | -62.8614 | 4.2 | near coast of Venezuela |
| 3/24 | 13:27 | -17.9274 | -76.7830 | 4.8 | off coast of Peru |
| 3/24 | 02:12 | 2.8055 | -59.6170 | 4.1 | Guyana |
| 3/23 | 06:43 | -9.8418 | -78.9126 | 4.6 | near coast of northern Peru |
| 3/23 | 02:49 | 7.1149 | -71.2649 | 4.6 | Venezuela |
| 3/22 | 08:11 | -20.9310 | -66.9629 | 4.2 | southern Bolivia |
| 3/22 | 07:00 | -24.1927 | -67.0663 | 4.3 | Chile-Argentina border region |
| 3/22 | 06:39 | -23.1904 | -70.5756 | 4.0 | near coast of northern Chile |
| 3/22 | 04:38 | 3.93309 | -71.4195 | 5.2 | Colombia |
| 3/21 | 14:17 | -19.5347 | -64.0919 | 5.4 | southern Bolivia |
| 3/21 | 10:55 | -21.1070 | -67.3400 | 4.8 | Chile-Bolivia border region |
| 3/21 | 05:02 | 14.1155 | -92.4658 | 5.0 | near coast of Chiapas, Mexico |

[1]Centro de Sismologia da Universidade de São Paulo (2021)

The problem with determining the proximal cause of dam failure from only a post-failure ground photo (see Fig. 6) with no monitoring or inspection records, no ground photos during the failure, and no eyewitness accounts, is that the dam failure was so complete. A dam breach due to overtopping tends to initiate at the top of the dam, so that the breach might have a triangular or trapezoidal shape with the wider side at the top. A dam breach due to internal erosion tends to initiate at the site of emergence of the seepage and then propagate upwards, so that a partial breach might leave intact portions of the dam crest. A dam failure due to slope instability will initiate at the point on the failure surface with the lowest ratio of shear strength to shear stress and then propagate both up and down the failure surface. However, when the dam breach is total, with the dam rent from top to bottom (see Fig. 6), there is no remaining evidence of the process of dam breaching. In summary, the proximal cause of dam failure is unknown. The root cause of dam failure is known and will be addressed in the Discussion section.

### *Prospects for Further Dam Failure*

Following the dam failure, an emergency dam was constructed at the site of the failed dam (ANM, 2021a; see Fig. 16). Based on the 7-meter height of the failed dam (see Fig. 6) and the person in the photo (see Fig. 16), the reconstructed dam is about two meters high, thus, considerably lower than the failed dam. According to the ANM (2021b) web site, all of the problems that led to the failure of the initial dam still remain as of this writing. In particular, the following problems still remain with respect to the reconstructed dam:

1) The return period of the design flood for the dam is either less than 500 years or unknown.

2) There are identified problems with the overflow structures and no corrective measures are being carried out.
3) The instrumentation is inappropriate and there is no plan to install new instruments.
4) There is no backup dam.
5) There are no design documents.
6) There are no manuals or formal procedures for monitoring and inspection.
7) There is no emergency action plan,
8) There has been no submission of inspection and monitoring reports or safety analyses.
9) There has been no submission of a Declaration of Condition of Stability.

Figure 12: Emergency reconstruction of the ruptured dam.

**Figure 16.** Following the dam failure, an emergency dam was constructed at the site of the failed dam (compare with Fig. 6). According to information on the ANM web site, all of the problems that existed with the failed dam are still present in the reconstructed dam. Since the reconstructed dam is considerably lower than the failed dam, it should be assumed that the risk of failure is even greater at the present time than it was when the dam initially failed.

The above remaining problems are not simply a matter of not updating the web site because the web site clarifies that the "*Data da última Vistoria de Inspeção Regular*" [Date of Last Regular Inspection Survey] was June 11, 2021 (ANM, 2021b). Since the reconstructed dam retains the same problems as the initial dam, and since the reconstructed dam is significantly lower than the initial dam, and since the precipitation of March 23-24, 2021, was probably not rare or extreme at all, it should be assumed that the probability of failure is even greater now than it was on March 25, 2021. In this respect, it should be noted that, even if the reservoir (Lagoa do Pirocáua) mostly emptied on the morning of March 25, the reservoir is not intentionally filled by the mining operation, but fills naturally by runoff from the watershed and the flow of water and sediment from the other open pits. The reservoir could be partially or completely full at the present time, but that information is not available. It is not clear whether the "*Volume atual do Reservatório"* [Current Reservoir Volume] is still 20,000 cubic meters, but that value has not been updated (ANM, 2021b).

In fact, of this writing, ANM (2021d) classifies the reconstructed dam as Emergency Level 1. According to ANM (2017), a dam is placed into Emergency Level 1 "*quando detectada anomalia que resulte na pontuação máxima de 10 (dez) pontos em qualquer coluna do Quadro 3 - Matriz de Classificação Quanto à Categoria de Risco (1.2 - Estado de Conservação), do Anexo V, ou seja, quando iniciada uma ISE [Inspeção de Segurança Especial] e para qualquer outra situação com potencial comprometimento de segurança da estrutura*" [when an anomaly is detected that results in a maximum score of 10 points in any column of Table 3 - Classification Matrix for Risk Category (1.2 - Conservation Status) of Appendix V, that is, when an ISE [Special Safety Inspection] is initiated and for any other situation with potential compromise of the safety of the structure]. Based on the above methodology, the reconstructed Lagoa do Pirocáua dam should have a score of at least 13 points by summing 10 points for "*Estruturas com problemas identificados, com redução de capacidade vertente e sem medidas corretivas*" [Structures with identified problems, with reduced capacity and without corrective measures] (ANM, 2021b) and 3 points for "*Umidade ou surgência nas áreas de jusante, paramentos, taludes e ombreiras estáveis e monitorados*" [Moisture or springs in downstream areas, facades, slopes and shoulders are stable and monitored] (ANM, 2021b). Although the later problem sounds positive, zero points would require "*Percolação totalmente controlada pelo sistema de drenagem*" [Seepage totally controlled through the drainage system] (ANM, 2017; 2021b).

## DISCUSSION

At this point, it should be clear that the root cause of failure of the Lagoa do Pirocáua dam was systematic neglect. As discussed earlier, the history of failure of a dam or any engineering structure is not simply a sequence of physical events, but is accompanied by a sequence of concurrent human events that involve a failure to detect and/or mitigate the effects of the physical events. In the case of the Lagoa do Pirocáua dam, there was a lack of essentially any inspection, maintenance and safety analysis. There was also a lack of monitoring, in that, according to the information provided by Equinox Gold to the National Mining Agency, the monitoring instruments were inappropriate, which gives no indication as to what was being monitored. In fact, the systematic neglect was so thorough, and the failure of the dam was so complete, that it is impossible to unravel the sequence of physical events that led to the dam failure.

Besides the systematic neglect of the dam, which led to its ultimate failure, there was a failure to provide relevant information to the entities who could have insisted upon proper oversight of the dam. These entities were the National Mining Agency and the investors in Equinox Gold. Equinox Gold must have known that they were required to register mining dams with the National Mining Agency, to provide relevant data to the Integrated Management System for Mining Dams (SIGBM), and to obtain a Declaration of Condition of Stability, because they did all of the above for the Vené dam at the same mine (ANM, 2021c). In the same way, the Lagoa do Pirocáua dam was not even mentioned in the <u>Technical Report on the Aurizona Gold</u>

Mine—Maranhão, Brazil (AGP Consultants, 2020), which was provided to investors, nor does not the dam appear on any of the maps that include the location of the dam.

Based on the documented systematic neglect of the Lagoa do Pirocáua dam, the condition of the Vené dam at the Aurizona mine should be a matter of grave concern. A review of the Vené dam is beyond the scope of this report. However, a preliminary examination of the information on the ANM (2021c) web site shows that the Vené dam stores gold mine tailings and is 35 meters high. Although the "*Comprimento da crista do projeto*" [Design crest length] is 3045 meters, the "*Comprimento atual da crista*" [Current crest length] is 3144 meters (ANM, 2021c). Although the "*Volume de projeto licenciado do Reservatório*" [Licensed Design Reservoir Volume] is 11,600,000.00 cubic meters, the "*Volume atual do Reservatório*" [Current Reservoir Volume] is 13,461,480.31 cubic meters. The web site confirms that "*Existem pessoas ocupando permanentemente a área afetada a jusante da barragem, portanto, vidas humanas poderão ser atingidas*" [There are people permanently occupying the affected area downstream of the dam, therefore, human lives could be harmed] (ANM, 201c). The "*número de pessoas possivelmente afetadas a jusante em caso de rompimento da barragem*" [number of people possibly affected downstream in the event of a dam failure] is in the range 1 to 100 (ANM, 2021c).

Equinox Gold has repeatedly stated that, although the 10,000-year storm caused the failure of the Lagoa do Pirocáua dam, it had no impact on the Vené tailings dam or on any other aspect of the mining operation. According to Equinox Gold (2021b-c), "There was no tailings dam failure. The heavy rain event and resulting regional flooding had no impact on the operational structures at the mine, including our pits, tailings storage facility and waste rock facilities, which remain intact and operating normally." According to Equinox Gold (2021a), "*Portanto, a Barragem de Rejeitos do Vené e todas as outras instalações utilizadas para deposição de rejeitos pela empresa, permanecem com todas as suas estruturas operacionais intactas e em regular operação … Como se observa a partir das informações e dos mapas aqui apresentados, a Barragem do Vené, em que pese as intensas chuvas,* ***não sofreu qualquer tipo de extravasamento, rompimento, vazamento ou mau funcionamento"*** [The Vené Tailings Dam and all other facilities used for the disposal of tailings by the company, remain with all their operational structures intact and in regular operation … As can be seen from the information and maps presented here, the Vené Dam, despite the intense rains, **did not suffer any type of overflow, rupture, leakage or malfunction**] (boldface in the original). It is difficult to understand how a 10,000-year storm could completely destroy the Lagoa do Pirocáua dam, while having no effect on the neighboring Vené dam or on any other component of the mining infrastructure. Although the author hopes that the team that manages the Vené dam has a completely different culture and set of values than the team that managed the Lagoa do Pirocáua dam, the author cannot be optimistic about this.

## CONCLUSIONS

The conclusions of this report can be summarized as follows:

1) The claim by Equinox Gold that failure of the Lagoa do Pirocáua dam on March 25, 2021, was caused by 426 mm of rain over March 23-24, corresponding to a 10,000-year precipitation event, with 112.7 mm, 315 mm and 27 mm of rain on March 23, 24 and 25, respectively, is inconsistent with the precipitation records of Brazilian governmental agencies.

2) According to precipitation maps from the National Institute of Meteorology (INMET), no location on the Atlantic coast of the state of Maranhão received more than 150 mm of rainfall over March 24-28.
3) Precipitation maps for the state of Maranhão from the Laboratory of Meteorology at UEMA, which combine rainfall records from the INMET network and the network of the National Center for Natural Disaster Monitoring and Alerts (CEMADEN) show total precipitation of 400-450 mm for the entire month of March 2021 at the site of the Aurizona mine, which is well within the climatological normals.
4) The Laboratory of Meteorology precipitation maps indicate rainfall amounts of 10-15 mm, 25-30 mm and 90-95 mm at the Aurizona mine site on March 23, 24 and 25, respectively.
5) The surrounding INMET weather stations of Turiaçu (59 kilometers to the southeast), Tracuateua (128 kilometers to the northwest) and Capitão Poço (154 kilometers to the southwest) received 48-hour rainfall amounts of 41.9 mm, 35.2 mm, and 30.8 mm, respectively, over March 23-24, corresponding to return periods of 0.3 years, 0.2 years, and 0.5 years at each of the respective weather stations.
6) The most extreme precipitation event at any of the surrounding INMET weather stations was the 48-hour rainfall amount of 131.1 mm at Turiaçu over March 24-25, corresponding to a return period of 2.3 years.
7) The closest earthquake during March 21-25 was an earthquake with magnitude 4.1 in Guyana, 1606 kilometers to the northwest, on March 24, so that it is unlikely that the dam failure was caused by seismic activity.
8) There is no evidence that the dam failure was caused by overtopping, as claimed by the National Mining Agency (ANM).
9) According to information provided to ANM by Equinox Gold, the dam spillway had identified problems and no corrective measures were being undertaken.
10) According to information provided to ANM by Equinox Gold, the monitoring instruments were inappropriate and there were no plans to install new instruments.
11) According to information provided to ANM by Equinox Gold, there were no design documents, no manuals or formal procedures for monitoring and inspection, no emergency action plan, and no regular submission of inspection and monitoring reports.
12) The Lagoa do Pirocáua dam had never been issued a Declaration of Condition of Stability, which is required of all mining dams in Brazil.
13) Prior to the failure, the existence of the dam was not mentioned in any available documents from the mining company, including documents provided to investors.
14) The root cause of failure of the Lagoa do Pirocáua was systematic neglect.
15) Since all of the problems that existed with the failed dam are still present in the reconstructed dam, which is even lower than the failed dam, it should be assumed that the risk of failure is even greater at the present time than it was when the dam initially failed.

## RECOMMENDATIONS

The recommendations of this report can be stated as follows:

1) Equinox Gold should acknowledge its responsibility for the failure of the Lagoa do Pirocáua dam.

2) Equinox Gold should provide full compensation to the inhabitants of the village of Aurizona for all damages resulting from the failure of the Lagoa do Pirocáua dam, including the provision of alternative water supply, if necessary.
3) Equinox Gold should take all steps necessary to prevent failure of the reconstructed Lagoa do Pirocáua dam.

## ABOUT THE AUTHOR

Dr. Steven H. Emerman has a B.S. in Mathematics from The Ohio State University, M.A. in Geophysics from Princeton University, and Ph.D. in Geophysics from Cornell University. Dr. Emerman has 31 years of experience teaching hydrology and geophysics, including teaching as a Fulbright Professor in Ecuador and Nepal, and has 70 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining for mining companies, as well as governmental and non-governmental organizations. Dr. Emerman has evaluated proposed and existing mining dams in North America, South America, Europe, Africa, Asia and Oceania, and has testified on mining dams before the U.S. House of Representatives Subcommittee on Indigenous Peoples of the United States and the United Nations Permanent Forum on Indigenous Issues. Dr. Emerman is the Chair of the Body of Knowledge Subcommittee of the U.S. Society on Dams and one of the authors of Safety First: Guidelines for Responsible Mine Tailings Management.

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## APPENDIX

**Table A1. Yearly maximum precipitation over 24, 48 and 72 hours: Turiaçu[1]**

| Rank | 24-Hour | | 48-Hour | | 72-Hour | |
|---|---|---|---|---|---|---|
| | Year | Precipitation (mm) | Year | Precipitation (mm) | Year | Precipitation (mm) |
| 1 | 2008 | 218.2 | 2009 | 261.1 | 2009 | 328.5 |
| 2 | 1985 | 191.9 | 2008 | 233.8 | 2016 | 273.8 |
| 3 | 2009 | 174.2 | 1985 | 204.9 | 2002 | 238.2 |
| 4 | 2002 | 173.3 | 1977 | 196.4 | 2008 | 236.4 |
| 5 | 1979 | 172.2 | 1987 | 183.2 | 1977 | 223.5 |
| 6 | 2006 | 166.9 | 2005 | 181.6 | 1985 | 205.7 |
| 7 | 2011 | 154.9 | 2002 | 176.5 | 1980 | 199.8 |
| 8 | 1977 | 149.2 | 2016 | 174.7 | 2011 | 193.8 |
| 9 | 2016 | 145.0 | 2006 | 174.0 | 2001 | 192.5 |
| 10 | 1987 | 138.4 | 1979 | 172.2 | 1987 | 192.2 |
| 11 | 1991 | 138.3 | 2011 | 168.3 | 2005 | 189.4 |
| 12 | 1996 | 129.6 | 1991 | 153.3 | 1979 | 187.5 |
| 13 | 2018 | 128.1 | 1996 | 146.1 | 2019 | 186.9 |
| 14 | 2005 | 126.6 | 2018 | 144.8 | 2006 | 186.2 |
| 15 | 1990 | 120.0 | 1990 | 137.1 | 1991 | 179.5 |
| 16 | 1986 | 119.4 | 2001 | 136.6 | 1998 | 162.6 |
| 17 | 1989 | 114.6 | 1980 | 135.4 | 2007 | 161.6 |
| 18 | 1997 | 113.0 | 1982 | 131.7 | 1986 | 159.9 |
| 19 | 2010 | 111.5 | 1989 | 130.8 | 1990 | 154.2 |
| 20 | 2001 | 111.2 | 1986 | 129.2 | 2018 | 153.8 |
| 21 | 2000 | 110.6 | 2010 | 128.1 | 2004 | 153.6 |
| 22 | 1981 | 108.6 | 2015 | 126.7 | 1996 | 149.9 |
| 23 | 1992 | 107.6 | 1998 | 125.7 | 1982 | 149.5 |
| 24 | 2003 | 107.1 | 2019 | 125.0 | 1981 | 141.9 |
| 25 | 1980 | 104.4 | 1994 | 120.9 | 1989 | 139.4 |
| 26 | 2014 | 101.6 | 2004 | 120.4 | 2010 | 138.5 |
| 27 | 1982 | 100.3 | 1981 | 119.8 | 1992 | 136.2 |
| 28 | 2015 | 99.5 | 2020 | 119.7 | 2014 | 134.9 |
| 29 | 2020 | 99.1 | 1997 | 116.7 | 2017 | 133.7 |
| 30 | 1978 | 98.4 | 2003 | 115.2 | 2003 | 133.2 |
| 31 | 1993 | 93.6 | 2013 | 115.1 | 1994 | 133.1 |
| 32 | 1998 | 92.7 | 2007 | 113.9 | 1995 | 132.2 |
| 33 | 1995 | 92.0 | 2014 | 113.6 | 2020 | 131.3 |
| 34 | 2012 | 88.8 | 1995 | 112.5 | 2015 | 127.9 |
| 35 | 2019 | 88.4 | 2000 | 110.9 | 1988 | 126.3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 36 | 1994 | 87.5 | 1992 | 108.0 | 1997 | 125.5 |
| 37 | 2017 | 86.2 | 1999 | 107.8 | 1978 | 121.1 |
| 38 | 2013 | 84.1 | 1993 | 107.1 | 2013 | 116.5 |
| 39 | 2004 | 76.6 | 2017 | 101.6 | 1999 | 113.8 |
| 40 | 1983 | 75.3 | 1978 | 100.6 | 1993 | 110.9 |
| 41 | 1999 | 74.8 | 1988 | 97.4 | 2000 | 110.9 |
| 42 | 1988 | 66.0 | 2012 | 89.1 | 2012 | 106.7 |
| 43 | 1984 | 65.2 | 1984 | 85.5 | 1984 | 105.9 |
| 44 | 2007 | 58.0 | 1983 | 78.3 | 1983 | 84.0 |

[1]Based on daily precipitation data from INMET (2021b)

**Table A2. Yearly maximum precipitation over 24, 48 and 72 hours: Tracuateua[1]**

| Rank | 24-Hour | | 48-Hour | | 72-Hour | |
|---|---|---|---|---|---|---|
| | Year | Precipitation (mm) | Year | Precipitation (mm) | Year | Precipitation (mm) |
| 1 | 2008 | 207.2 | 2019 | 257.0 | 2019 | 308.8 |
| 2 | 1995 | 173.2 | 2008 | 230.9 | 1974 | 303.4 |
| 3 | 1983 | 172.2 | 2004 | 217.6 | 1992 | 279.4 |
| 4 | 2019 | 170.6 | 1974 | 217.1 | 2004 | 268.6 |
| 5 | 2018 | 167.0 | 1992 | 211.2 | 1995 | 259.3 |
| 6 | 1986 | 154.3 | 2018 | 210.2 | 2018 | 257.8 |
| 7 | 2011 | 146.6 | 2007 | 196.4 | 1986 | 242.1 |
| 8 | 1984 | 144.1 | 2011 | 189.0 | 2008 | 240.1 |
| 9 | 2007 | 142.7 | 2009 | 187.9 | 2003 | 224.8 |
| 10 | 2003 | 138.4 | 1995 | 186.3 | 2007 | 222.5 |
| 11 | 1992 | 132.5 | 1983 | 182.4 | 1980 | 208.0 |
| 12 | 1975 | 132.3 | 2016 | 178.3 | 1985 | 204.0 |
| 13 | 1999 | 130.4 | 1988 | 173.5 | 1991 | 201.9 |
| 14 | 2004 | 125.4 | 1986 | 171.3 | 2009 | 201.3 |
| 15 | 1988 | 120.6 | 2003 | 167.2 | 1983 | 197.0 |
| 16 | 2015 | 120.2 | 1975 | 165.7 | 2011 | 195.2 |
| 17 | 2002 | 119.2 | 1977 | 160.7 | 2016 | 192.0 |
| 18 | 1985 | 119.0 | 1985 | 158.6 | 1988 | 189.8 |
| 19 | 2009 | 118.2 | 1980 | 153.9 | 1990 | 183.8 |
| 20 | 1974 | 117.2 | 2000 | 153.4 | 1977 | 183.3 |
| 21 | 1997 | 115.3 | 1990 | 153.2 | 1975 | 179.5 |
| 22 | 1987 | 112.2 | 1987 | 152.5 | 2000 | 172.9 |
| 23 | 1994 | 110.7 | 1997 | 150.9 | 1987 | 168.6 |
| 24 | 1991 | 108.3 | 1978 | 150.1 | 1997 | 166.2 |
| 25 | 2016 | 107.3 | 1994 | 148.0 | 1979 | 163.2 |
| 26 | 1973 | 100.0 | 1991 | 145.7 | 1994 | 157.3 |
| 27 | 1978 | 92.5 | 1984 | 144.1 | 2001 | 153.7 |
| 28 | 2006 | 91.2 | 1999 | 138.8 | 1999 | 153.2 |
| 29 | 2020 | 89.2 | 2001 | 134.9 | 1978 | 150.3 |
| 30 | 1998 | 85.9 | 2015 | 131.1 | 1998 | 148.7 |
| 31 | 1981 | 85.1 | 1982 | 130.1 | 1993 | 148.3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 32 | 1977 | 84.0 | 2002 | 121.3 | 1982 | 147.7 |
| 33 | 1980 | 83.9 | 1996 | 120.2 | 2002 | 147.1 |
| 34 | 1982 | 82.2 | 1979 | 118.2 | 2015 | 145.6 |
| 35 | 2001 | 81.0 | 2017 | 116.3 | 1981 | 144.8 |
| 36 | 2017 | 80.2 | 2020 | 115.6 | 1984 | 144.1 |
| 37 | 2000 | 79.1 | 1998 | 114.1 | 2006 | 143.4 |
| 38 | 1996 | 78.9 | 1993 | 110.6 | 1976 | 143.3 |
| 39 | 1990 | 78.0 | 2006 | 109.1 | 2020 | 140.1 |
| 40 | 1979 | 76.8 | 1976 | 107.3 | 1996 | 135.9 |
| 41 | 2013 | 75.8 | 1981 | 105.8 | 2017 | 129.9 |
| 42 | 1976 | 74.3 | 2005 | 105.6 | 2005 | 129.2 |
| 43 | 2005 | 73.6 | 1973 | 104.7 | 1989 | 117.7 |
| 44 | 1993 | 73.4 | 2010 | 98.2 | 2014 | 115.5 |
| 45 | 1989 | 71.8 | 2014 | 92.2 | 2010 | 108.7 |
| 46 | 2010 | 67.0 | 2013 | 90.9 | 2013 | 105.3 |
| 47 | 2014 | 66.7 | 1989 | 85.2 | 1973 | 104.7 |
| 48 | 2012 | 56.1 | 2012 | 75.6 | 2012 | 93.8 |

[1]Based on daily precipitation data from INMET (2021b)

**Table A3. Yearly maximum precipitation over 24, 48 and 72 hours: Capitão Poço[1]**

| Rank | 24-Hour | | 48-Hour | | 72-Hour | |
|---|---|---|---|---|---|---|
| | Year | Precipitation (mm) | Year | Precipitation (mm) | Year | Precipitation (mm) |
| 1 | 2018 | 143.4 | 2018 | 163.2 | 2018 | 362.8 |
| 2 | 2019 | 107.0 | 2019 | 131.8 | 2019 | 266.0 |
| 3 | 2013 | 90.8 | 2013 | 111.8 | 2020 | 255.0 |
| 4 | 2015 | 88.8 | 2020 | 104.6 | 2013 | 241.0 |
| 5 | 2020 | 80.2 | 2015 | 92.0 | 2015 | 188.8 |
| 6 | 2014 | 66.6 | 2012 | 81.8 | 2012 | 179.6 |
| 7 | 2017 | 56.0 | 2014 | 74.4 | 2016 | 171.6 |
| 8 | 2012 | 53.2 | 2016 | 72.0 | 2014 | 163.8 |
| 9 | 2016 | 50.8 | 2017 | 66.8 | 2017 | 163.6 |

[1]Based on daily precipitation data from INMET (2021b)