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Estimating environmental damages of a tailings dam failure: The case of the Fundão Dam in Brazil

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Abstract: We present the results of a contingent valuation study aimed at estimating the monetary value of environmental and cultural/heritage injuries caused by the Fundão (tailings) Dam failure in Brazil in 2015 as perceived by the Brazilian population. While the valuation literature considering mining-related externalities is considerable, valuation studies of injuries resulting from mining incidents are scarce and most available damage assessments apply market valuation methods while rarely considering environmental and other nonmarket-valued impacts. The flooding and the release of tailings from the dam failure led to injuries to sediments, watercourse opacity, and oxygenation, changes in riparian morphology, loss of human life, mortality to fish and wildlife, changes in the food chain and more along the 675 km watercourse of the Doce River. This was arguably the greatest environmental and cultural/heritage injury ever caused by a single tailings dam collapse. The study followed state-of-the-art recommendations for the development, administration, and data analysis of stated-preference valuation methods. The survey of a representative sample of 5,195 Brazilian urban households revealed that the average lower-bound willingness-to-pay estimate to avoid a similar incident in the near future was 137 USD and the parametric-based estimate was 230 USD per household, which aggregates to 7.96 or 12.91 billion USD, respectively. This corresponds to environmental damages of 176 or 295 USD per m3 of tailings released.

Keywords: tailings dam failure, nonmarket environmental damages, contingent valuation, willingness to pay

JEL codes: Q51, Q30, Q20

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1. Introduction

Extraction of natural resources typically result in environmental and health injuries that can either occur continuously, and generate a stream of negative externalities to society (e.g., air and water pollution), or injuries that happen incidentally, when catastrophic events suddenly occur. There is a considerable body of research regarding quantification and valuation of continuous mining and nonmining-related environmental and health externalities and they are routinely being considered in economic cost-benefit analyses and policy decisions (Menegaki & Damigos 2020; Ferrini *et al.* 2021). On the other hand, the evidence for the valuation of injuries related to catastrophic events is much scarcer. While some notable examples include Carson *et al.* (2003) and Bishop *et al.* (2017), many valuation studies conducted in such cases are related to the legal process of damage-assessment and hence the results may sometimes not be published or get published with great delays (e.g., the Cosco Busan oil spill[1], Montrose chemical contamination[2], Oklahoma vs. Tyson case over water contamination from disposal of animal waste[3]).

In this paper, we focus on the valuation of the environmental and cultural injuries of a tailings dam failure. Tailings dams are used to store tailings – liquid, slurry of fine particles, and solid byproducts of mining operations after ore is separated from the gangue (co-occurring waste material). They rank among the largest engineered structures on earth (Owen *et al.* 2020). Although there is no complete inventory, there are an estimated 30,000 tailings dams around the world (WMTF 2022). Tailings dams are more likely to fail than conventional (cement and steel) dams (Martin & Davies 2000; Roche *et al.* 2017), leading to damages to downstream sediments, watercourse opacity and oxygenation, riparian morphology, fish and wildlife, food chains and more.[4] Consequently, tailings dams represent a significant environmental liability associated with mining projects. Using a case study of the Fundão Dam failure in 2015, we demonstrate a methodology and estimate the economic value of the environmental and cultural/historic injuries associated with this incident.

The Fundão Dam was used to store tailings from the nearby iron ore mine of the Samarco Mariana Mining Complex near Mariana, Minas Gerais, Brazil. On the 5th of November 2015 it suffered a catastrophic failure, resulting in the release of 44.4 million cubic meters of mine tailings. The subsequent flooding devastated the downstream villages of Bento Rodrigues and Paracatu de Baixo and killed 19 people. However, the tailings spread further, polluting 675 km of the Doce River and eventually reaching the Atlantic Ocean. This was arguably the most serious environmental damage caused by a tailings dam collapse to date (Carmo *et al.* 2017; Santamarina *et al.* 2019; LACTEC 2020a).

While the valuation literature of mining-related externalities is considerable (for a recent review see, e.g., Menegaki & Damigos 2020; Ferrini *et al.* 2021), valuation studies of injuries

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[1] The Cosco Busan assessment was carried out to assess damages caused by oil spilled from a freighter in San Francisco Bay (https://darrp.noaa.gov/oil-spills/mv-cosco-busan)

[2] The Montrose case assessed environmental injuries caused by chemical contamination of nearshore ocean habitat (https://darrp.noaa.gov/hazardous-waste/montrose)

[3] The Oklahoma vs. Tyson case assessed environmental damages caused by the use of poultry litter in the Illinois River watershed (https://www.nbcnews.com/id/wbna33010159)

[4] In addition, some tailings may be toxic or radioactive.

resulting from mining incidents are scarce and most available damage assessments apply market valuation methods while rarely considering environmental impacts. For example, Bennagen (1998) estimated the value of the injuries associated with a tailings dam incident in Philippines and included forgone income of households associated with fishing, farming and recreation, without considering nonmarket damages to the environment. A notable example of a broader, stated-preference valuation of mining externalities can be found in Mendonça and Tilton (2000). They elicit the willingness to pay of the population of the city of Brasilia, capital of Brazil, to avoid the operation of a largescale mining complex in the Serra dos Carajás area of the Amazon Basin.

As a result, the available valuation literature does not address many important risks associated with suddenly occurring, disastrous incidents related to hard rock natural resources extraction. This is potentially limiting for the socially efficient management of natural resources, because it means that some important inputs to cost-benefit analyses of various policies cannot be accounted for – such as ecological or cultural costs of a tailings dam break (Adiansyah *et al.* 2015; Adiansyah *et al.* 2017). Our study is one step toward filling this gap, outlining a methodology and practical application of a state-of-the-art stated preference-based valuation of a tailings dam failure. It provides a reference for future studies and via benefit-transfer techniques, it allows for including monetized tailings dams-related risks in policy considerations.

The study is based on in-person interviews with a representative sample of 5,195 Brazilian urban households. The study employed a stated preference-based valuation approach. Respondents were informed of a possible program to convert all tailing dams in the country to the alternative technology of "dry-stacking". This program was described as a way to avoid another expected dam break in Brazil in the next 10 years that would result in "damages to the environment and historical and cultural heritage similar to those that occurred in the Fundão Dam incident". The details of the environmental damages of the dam break were described and their context given. The payment vehicle was a tax increase added to household electricity bills, which was identified as one of the most inescapable ways of collecting revenues in Brazil. The elicitation format used was a single-bounded, binary choice, which under certain conditions has been shown to be incentive compatible (Carson & Groves 2007). We found that the average lower-bound willingness-to-pay (WTP) estimate was 137 USD[5] and the parametric-based estimate was 230 USD per household, which aggregates to 7.96 or 12.91 billion USD, respectively. This corresponds to environmental damages of 176 or 295 USD per m^3 of tailings released. In what follows, we discuss policy implications and conclusions of these results.

The rest of the paper is organized as follows: Section 2 describes the case study, methods and data; In section 3, we present the results, ie. the estimated value of avoiding future risks associated with tailings dams in Brazil, which were expected to cause another incident just like the Fundão Dam case; The last section summarizes the main findings.

[5] For purposes of this study, we used a conversion rate of 4.1 BRL/USD, which was the average rate between November 2019 to March 2020, when the data was collected.

2. Methods and data

While the market value of property damages or profit losses associated with catastrophic incidents are relatively easy to calculate, estimating the monetary value of environmental injuries is more difficult. This is because no well-organized market comprised of traded quantities of these goods and services with well-defined prices exists that would allow one to directly estimate the value of what was lost. In cases where the environmental injuries result in observable changes in human behavior (i.e. revealed preferences), it is possible to rely on revealed preference methods, such as the travel cost or the hedonic price method.[6] However, these approaches usually do not include all components of damages. In particular, they do not allow for estimation of non-use (or so called passive use) components of the economic value, which stem from consumers' willingness to pay for things they do not directly use/consume (e.g., nature reserves).

The only known methods capable of estimating economic values that include use and non-use components are based on stated preferences (Freeman *et al.* 2014). They use responses to survey questionnaires that construct markets to allow representative members of the public to make choices and express their preferences in a referendum-type valuation mechanism. Such a Contingent Valuation (CV) study describes the environmental injury to be valued and a new policy to eliminate the environmental injury or to prevent a similar injury from happening in the future. The policy is associated with introducing a coercive cost (e.g. a tax) and under certain additional conditions (e.g., perceived consequentiality of the study) the choices can be made incentive compatible, so that they reveal respondents' true preferences and values (Carson & Czajkowski 2014a).

The economics literature prescribes extensive guidelines regarding the design and implementation of CV studies (e.g., Mitchell & Carson 1989; Arrow *et al.* 1993; Bateman *et al.* 2004; Freeman *et al.* 2014; Champ *et al.* 2017; Johnston *et al.* 2017). Our study followed these guidelines closely to estimate the monetary value of the economic loss suffered by Brazilian households as a result of injuries to environment and heritage/cultural resources caused by the Fundão Dam failure.

2.1. Case study

Apart from the human deaths and leaving two thousand people homeless, the Fundão Dam Incident led to losses in economic activities and adverse impacts to property and municipal infrastructure. The injuries to environmental and heritage/cultural resources caused by the Fundão Dam failure within the river basin were also severe. The greatest environmental and cultural damage in the Doce River Basin occurred within the first 110 km downstream of the (collapsed) Fundão Dam, where approximately 50% of the tailings and mud severely impacted the riverbanks and riverside forest and caused a large number of animal deaths. Some 25% of the tailings and mud was stopped behind the Risoleta Neves hydro-electric dam and,

[6] Revealed preference methods are based on observations of human behavior to make inferences about value. For example, the value of lost recreation at beaches affected by an oil spill can be estimated by observing how beach visitation patterns and travel costs changed as a result of beach oiling.

consequently, reduced damage intensity downstream with no further adverse impacts to the riverside forest. The remaining tailings and mud (25%) went all the way down river reaching the sea, some 660 km away. *Figure 1* presents a map illustrating the geographical location of the damages.

Figure 1. Map illustrating geographical location and distribution of the damages.

The goal of the CV study was to estimate a monetary value for losses to the citizens of Brazil from the injuries to the environment (including losses to aquatic biota, terrestrial wildlife, birds and riparian forest) and cultural/heritage resources caused by the incident. The scope of the study did not include valuing loss of life, human health impacts, private losses to individuals and companies, or adverse impacts to municipal governments and public infrastructure. The study was commissioned by the Brazilian Federal Public Prosecutor's Office.

2.2. Survey design and implementation

In typical stated preference studies, a survey instrument presents respondents with an object of choice, describes a context in which a choice is to be made, and then asks the respondent to make a choice. For this study, the object of choice was a program that would prevent one future[7]

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[7] The prevention of a future spill/incident/contamination event is often used as a proxy for the spill/incident/contamination event being evaluated. For example, this approach was followed in the evaluation of public, passive-use losses arising from the Deepwater Horizon oil spill in the Gulf of Mexico (Bishop *et al.* 2017).

tailings dam failure that would have the exact same impacts to the environment and cultural/historic sites that occurred as a result of the Fundão Dam Incident (FDI)[8].

Making sure that respondents make their choices while being adequately informed and believing the contingent scenario required careful design of the survey instrument and extensive pretesting. Key elements of the survey included descriptions of the effects of the incident, a likelihood of another dam failure like this occurring within the specified time frame, and the new program to improve dam safety that, if carried out, would prevent that future dam failure and the associated effects/damages, while not delivering any other benefits. Each element of the questionnaire was composed of carefully tested written and graphic information shown to be understandable to respondents and which did not make them feel pushed to make a choice either for or against the program. This ensured that the choice expressed by respondents reflected their personal assessment of the cost of the dam safety program relative to the benefits that would be provided if it was carried out and how it would be paid for. We note that the design of the study satisfied the necessary conditions for incentive compatibility, which means that a single dominant strategy for rational respondents was to reveal their preferences truthfully.

The questionnaire[9] started with a section collecting sociodemographic data from the household respondent. The next section described aspects of the FDI in terms of damages and injuries that have already been addressed through judicial actions and/or restoration actions. This was important, because the FDI affected many items that go beyond environmental and cultural heritage, such as the loss of life, impacts to lifestyles, municipalities and infrastructure, corporate assets, local water supplies and commercial fishing and infrastructure, and hence they were not supposed to be included in the elicited value estimates. We helped ensure that these elements were not included as the benefits of the new safety program by making sure that respondents understood that the law already required that the responsible parties paid indemnification for all damages caused to people, municipalities and businesses. The questionnaire gave details regarding the ongoing compensation program. In addition, respondents were informed that in the wake of a more recent tailings dam break, requirements had been implemented that would effectively eliminate loss of life in any future dam failures. Overall, the intent of this section of the survey was to inform respondents that in situations like the FDI, the law requires responsible parties to compensate individuals, municipalities and businesses and that this had indeed been done. The implication for respondents was that this compensation was well established and would take place if future incidents were to occur. As a result, respondents were left with the impression that the program, if carried out, will not provide additional impacts (benefits) beyond the ones that were described to them.

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[8] The wording “incident” instead of “accident” or “disaster” was used throughout the survey, in line with the conservative approach to prevent any perception that might anticipate the injury levels before their detailed presentation.

[9] The final version of the questionnaire is available in the supplementary materials available online at xxx (blinded for review, included as a regular appendix).

2.2.1. Environmental and cultural heritage damages

The next section of the questionnaire informed respondents about the environmental and cultural/heritage injuries caused by the FDI. An understanding of the ecosystem and habitat functions needed to be stressed before the injury scenario was presented to respondents so that they could understand the context from a scientific perspective. Therefore, the injury scenario began by presenting the baseline ecological functions and interactions among forest, watershed and fauna and how the mud flow from the incident affected them. This helped the interview narrative transition to detailed descriptions of the environmental and heritage/cultural injuries with minimal confusion or misunderstanding. Due to the scientific uncertainty concerning recovery from the injuries, it was decided to adopt the most conservative (i.e. shortest) recovery times that were deemed feasible by physical and biological scientists.

Table 1 and Table 2 summarize the pre-FDI baseline conditions and injuries to environmental and heritage/cultural resources, respectively, that are described in the questionnaire. Each injury was described in the questionnaire using available scientifically-based quantitative indicators for losses and expected recovery times based in the cited references. It was also made clear that no species had become extinct or disappeared due to the FDI. For example, respondents were told that birds could fly to other nearby areas with unaffected habitats and would return later after the injured riparian forest along the Doce River recovered. Estimated recovery times for each injury were usually specified in ranges spanning several years, as provided by natural scientists involved in the project.

Table 1: Classification of environmental damages of the FDI

	Before the incident (LACTEC 2019a, b)	The injury (LACTEC 2020b, c)	Recovery time
Aquatic Life	Habitat of 100 species, 38 of which are rare and 15 endemic	The habitats of 90 species suffered injuries	60 to 70 years
Riparian Forest	Present at 660 km on the banks of the river	The forest was impaired, on average, 30 m on either side of the river along the first 110 km	25 to 30 years
Wildlife	Habitat of 440 species	Alligator, otter, turtles	60 to 70 years
		Other wildlife species	25 to 30 years
Birds	125 species were observed	25 species were no longer seen in the region	25 to 30 years

Table 2: Classification of heritage damages of the FDI

Category	Total existing in the region	Totally destroyed	Partially destroyed
Archaeological sites (LACTEC 2020d) Indigenous cemeteries, ruins of gold mines and very old paintings	450	15	55
Cultural Goods (LACTEC 2020f) Old mansions, chapels, churches and religious images	4,300	1,500	1,100
Cultural manifestations (LACTEC 2020e) Celebrations, processions, festivities and traditional events	1,200	5	55

For aquatic life, apart from showing the number of collected dead fish, the narrative pointed out that the increase of heavy metals in the water from the mine tailings had caused tumors, difficulty breathing and reproduction problems in some of the fish. As a consequence, the recovery pathway for the fish would be adversely affected. The recovery time of 60 to 70 years was based on the simplified estimate of the natural removal time by river erosion of the volume of tailings released into the environment (LACTEC 2020b).

The extent of injuries to the riparian forest was provided in the narrative with an emphasis on its connection to animals living along the river and the possibility of reforestation/recovery from the injuries caused by the FDI. The destruction of the forest in the first 110 km of the affected river was described as occurring, on an average, to the first 30 meters of forest on each bank. The estimated recovery time of 25 years was based on Liebsch *et al.* (2008), who show that after that time there is substantially less variation in species richness of a damaged forest fragment, compared to an undamaged forest fragment.

In the case of wildlife, it is believed that most individual animals died from suffocation under the mud and it was not possible to find and count them. Therefore, emphasis was placed on a description of the habitat recovery times for species living in the Doce River Basin. Longer recovery times were given for animals that are highly dependent on water quality for food and habitat. Injuries to birds were described by presenting the number of species which fled to nearby regions after the dam rupture and the time that would be required for them to return and recover to pre-FDI baseline.

The injury descriptions included images of the affected resources presented on cards to the respondents.

For heritage/cultural losses, it was possible to present information on some of the quantities of assets totally or partially destroyed, such as archaeological sites and cultural sites (e.g. mansions, chapels, churches, altars and religious images). For adversely affected cultural events, such as holiday celebrations, processions, festivities and traditional cultural events that took place in various communities located in the Doce River Basin, the number of assets existing before the incident and how much was totally or partially destroyed was also shown. In the case of heritage/cultural losses, there was no mention of recovery time, due to the unique nature of each asset and the diversity among them, leading to potentially irreparable damage to that heritage.

2.2.2. Contingent scenario

The questionnaire next presented current safety measures that are required of all mining companies and said that another incident similar to FDI would occur in the next ten years, with impacts to environment and heritage resources equivalent to those experienced as a result of the FDI. The questionnaire then described a new technology, dry tailings, that would eliminate all mining dams and prevent an incident like FDI from occurring in the future. The technology allows for removing the water from the tailings, leaving only the dry sediments that could be compressed into blocks that could be stacked and prevented from collapsing. The proposed program included compulsory adoption of the new technology in all future mining operations, as well as drying up and doing away with all mud dams that already existed in Brazil.[10]

Respondents were informed that, if left to the 90 mining companies, the implementation of the dry tailings regulations for the 280 tailings dams in Brazil would take more than 10 years. Respondents were told that a possibly quicker resolution could be accomplished if the government paid the capital costs of the program and mining companies paid all operational expenses. As a result, the dry tailing technology could be deployed in 2, instead of 10 years, thereby virtually eliminating the possibility of another incident like the FDI.[11]

The payment mechanism used in the study was designed to be believable to respondents and binding upon them if the program was implemented. Participants in focus groups and interviews readily understood that the national budget was fully allocated, and that the national government was perceived to be constrained in its ability to quickly enact new laws that might be used to pay for a dry tailings program. To address these issues, respondents were told that it was possible, without enacting new laws, to temporarily increase an existing tax. In this case the respondents were told that the dry tailings program would be funded by a temporary increase in the federal tax on their households' electricity bill. The selection of this payment vehicle minimized, to the extent possible, the problems associated with other taxes in Brazil not always being paid by every household (Adams *et al.* 2008; Seroa da Motta & Ortiz 2018).

Next, respondents were reminded of reasons they might vote for or against implementing the dry tailings project. The questionnaire then asked each respondent if he/she would vote for or against the dry tailings project if its implementation would cost them a specified amount in terms of an increased tax on their electric bills. The specific question was formulated as follows:

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[10] While the narrative describing the dry tailings program was hypothetical, it was designed in such a way as to create incentive compatibility and consequentiality in the minds of the respondents.

[11] Framing the dry tailings project in this way accomplished two goals. First, testing of this description revealed that it addressed the desire of survey respondents to have mining companies pay for the program. Second, it established the rationale that the government would pay for part of the program, thus motivating the need for taxes to be raised for this project.

Now I will ask you to vote for or against the tax increase, taking into account all that I have just said and that the purpose of this tax increase is to implement the dry tailings and to end all mud dams in 2 years, and avoid damages to the environment and historical and cultural heritage, as happened in Mariana.

The amount of the tax increase in the electricity bill is related to your family's income. For a house like yours, the TOTAL cost for you and your family that lives with you would be R$._____, paid in 10 FIXED monthly instalments of R$ ____ during next year.

Do you vote for or against this tax increase on the electricity bill?

Those voting against the project were asked to explain their vote by choosing from among a list of reasons, which included economic and protest motivations. The rest of the questionnaire included de-briefing questions to verify preferences, attitudinal characteristics and comprehension.

2.2.3. Development of the survey instrument and the administration of the study

The questionnaire design followed several experimental steps with focus groups and in-depth and pilot surveys to motivate respondents to focus only on non-market values of environmental and cultural/heritage damages.

The language of the questionnaire was developed in close cooperation with physical and biological scientists to convey a clear and accurate understanding of the environmental and cultural services injuries resulting from the FDI. The survey included textual and graphic information describing the injury to environmental/heritage resources, including maps and diagrams, presenting the spatial features of the incident, infographics, with recovery actions and information from official sites, and images and photos of the impacted species and heritage assets. This information, along with a description of a program that could prevent one future tailings dam failure, and the flow and wording of the survey instrument was extensively tested in focus groups, in-depth personal interviews, and pilot surveys which took place from January to November 2019.

The design of the survey instrument included consultations with physical, biological, survey and valuation experts. The development of the questionnaire was facilitated by conducting 35 focus groups and 38 personal in-depth interviews with representatives of different social groups. Focus groups and personal interviews were scheduled in 9 different locations across Brazil, including São Paulo (central Eastern region), Recife (Northeast region), Belo Horizonte (Southeast region), Curitiba (South region), Goiânia (Center-West region) and Belém (North region), as well as cities in the incident area (Governador Valadares and Linhares). At each stage of the pretesting, research team members evaluated the materials in terms of comprehension and plausibility by the participants and adjusted survey materials as needed. Finally, three pilot tests were conducted. Each one included approximately 400 respondents each. These pilot tests allowed evaluation of survey implementation procedures and tax amounts to be used in the referendum question and provided the assessment of preliminary results for small samples in various locations around Brazil.

The final survey was initiated in November 2019 and concluded in March 2020. Our sampling targeted the population of urban, income-earning, households located in 10 representative metropolitan regions and municipalities across Brazil[12], with the goal of obtaining 5,200 completed in-person, survey interviews. Survey data collection was undertaken following standard, high-quality, survey research protocols. Completed in-person interviews were carefully verified. Quality control measures for each completed interview employed consistency checks, such as the time respondents took to answer each question and the total interview time, the declared income compared to other household characteristics and the number of people contributing to household income.

2.3. Econometric framework

Inferring WTP values from the binary choice data representing respondents' votes is grounded in economic theory (Freeman *et al.* 2014). Original models of WTP are based on the random utility framework (McFadden 1974; Hanemann 1984) and infer the values indirectly (using the estimated utility function).[13] However, when the goal of a study is to provide a single estimate of WTP, a direct estimation of WTP may be preferred (Cameron 1988). Even though not all were directly modelled, WTP functions have straightforward representations as utility function differentials, they are more flexible and allow for avoiding complicated, and in some cases implausible, distributional consequences of indirect estimation of WTP based on preference functions. In what follows, we apply two approaches to estimating mean WTP, a non-parametric and a parametric approach, each with different strengths and weaknesses.

Our non-parametric estimator of mean WTP was based on the work of Lewbel (2000) and Watanabe (2010). For the parametric estimates, we considered a large number of candidate parametric distributions including the zero-inflated model (Gurmu & Trivedi 1996). The non-parametric approach estimates a lower bound of mean willingness to pay. It does not rely upon ad hoc assumptions about the cumulative density function of WTP between the observed tax amounts; rather it simply assumes it stays the same between the observed tax amounts. The parametric approach, on the other hand, assumes a specific distribution of WTP in the population, particularly with respect to vote probabilities between the tax amounts used in the experimental design (i.e. the specified tax amounts).

Overall, the non-parametric approach has the advantage of being conservative, ie. the true mean WTP is definitely not lower than the non-parametric estimate. On the other hand, the parametric estimate has the advantage of minimizing error in the estimate of the true (but unknown) mean WTP. However, the true mean WTP can be either somewhat lower or higher than the parametric estimate. Choosing between the use of a parametric or a non-parametric estimate ultimately depends on the purpose to which the estimate will be used.

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[12] The rural population of Brazil, which accounts for 14% of the country's total, was not surveyed due to logistical reasons arising from its spatial dispersion.

[13] We refer the reader to excellent seminal textbooks such as Bateman *et al.* (2004), Champ *et al.* (2017), and Haab and McConnell (2003) for a detailed presentation of welfare theory and the utility-maximization-based framework for non-market valuation.

2.3.1. Non-parametric estimator of mean WTP

In our case, the Lewbel-Watanabe non-parametric estimator of mean WTP is equivalent to the ABERS (Ayer *et al.* 1955) and Turnbull (1976) estimator.[14] For a random sample of N individuals who are offered different tax amounts (b) let individual i's true WTP be WTP_i. Respondent's votes on the program provided at the cost of b_i reveal if their WTP is higher or lower than b_i. The probability of observing a 'no' vote can therefore be mathematically represented using a cumulative distribution function (CDF):

$$P\left(\{no\}_i\right) = P\left(WTP_i < b_i\right) = CDF\left(b_i\right).$$

With random assignment of the tax amount, the non-parametric estimate of $CDF\left(b_i\right)$ becomes (Haab & McConnell 2003):

$$CDF\left(b_j\right) = \frac{N_j}{T_j},$$

where N_j represents the number of 'no' votes to a given tax amount $\left(b_i\right)$ and T_j indicated the total number[15] of individuals in the sample who were given the tax amount $\left(b_i\right)$, and the variance of the estimator becomes:

$$V\left(CDF\left(b_j\right)\right) = \frac{CDF\left(b_j\right)\left(1 - CDF\left(b_j\right)\right)}{T_j} = \frac{N_j\left(T_j - N_j\right)}{T_j^3}.$$

In the case of continuous design for the tax amounts (and a maximum tax amount exceeding the maximum WTP in the population), the Lewbel-Watanabe estimator of mean WTP is unbiased and consistent. Unfortunately, these assumptions rarely can be met in practice. For practical reasons, valuation studies rather usually use a discrete design for the tax amounts (a few discrete tax amounts randomly assigned to respondents). It is also infeasible to use the highest tax amount that is larger than the highest possible WTP in the population, as there is no a priori information on the maximum WTP, and it could be very large requiring that the continuous taxes span a very large range. As a result, the Lewbel-Watanabe estimate of mean

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[14] We use a finite set of tax amounts and observe no monotonicity violations for the increased probability of voting 'no' with increasing tax amounts.

[15] In the case of weighting the sample observations, the sum of individual weights can be used instead of the number of votes/individuals.

WTP becomes a conservative (lower-bound) estimate of WTP, and in the case of no monotonicity violations it becomes equal to the traditional ABERS (Ayer *et al.* 1955) and Turnbull (1976) estimator.

For the case of using a discrete tax amount design, the CDF can only be evaluated at these tax amounts. Suppose there are M tax amounts $\{b_1,...,b_M\}$. We can obtain an unbiased and consistent estimator of the CDF of a 'no' vote at these M levels. For the other levels, our estimator conservatively extrapolates to the next highest observed probability of voting 'no'. For example, if we observe that the probability of a 'no' vote to be p_1, p_2, p_3 for tax amounts b_1, b_2, b_3, respectively, we conservatively assume that the probability of voting 'no' for tax amounts between b_1 and b_2 is p_2 (the same as for the highest observed tax amount in this range), and the probability of voting 'no' for tax amounts between b_2 and b_3 is p_3. In reality, the probability of voting 'no' is likely to continuously increase between tax amounts, rather than experience a jump to the next higher observed level as soon as the tax amount rises above the observed level. For this reason, our non-parametric estimator of WTP can be considered a lower-bound for the actual (true) WTP. It is conservative in a sense of not relying on any assumptions for extrapolating to the probability of 'no' votes between the levels observed for tax amounts – instead it assumes the highest possible probability of voting 'no', conditional on satisfying monotonicity of probability levels for increasing tax amounts.

Under these assumptions, the non-parametric estimate of mean WTP can be calculated as:

$$WTP \geq WTP_{NP} = \sum_{j=0}^{M} b_j \left(CDF\left(b_{j+1}\right) - CDF\left(b_j\right) \right),$$

where $b_0 = 0$, $b_{M+1} = +\infty$, $CDF(b_0) = 0$, and $CDF(b_{M+1}) = 1$. The corresponding variance of the estimator is given by:

$$V\left(WTP_{NP}\right) = \sum_{j=0}^{M} V\left(CDF\left(b_j\right)\right)\left(b_j - b_{j-1}\right)^2.$$

2.3.2. Parametric estimator of mean WTP

The parametric approach also produces an estimate of mean WTP, but it relies on additional statistical structure imposed by the use of a parametric model, particularly the necessary assumptions about vote probabilities between the different tax amounts used in the experimental design (i.e. the specified tax amounts). We considered a large number of candidate parametric distributions of WTP, including their zero-inflated variants (Gurmu & Trivedi 1996). Since in our case respondents were asked to indicate whether they would vote yes or no for a program of implementing the new policy at a given cost to them (tax amount), a response to a binary choice question reveals if one's true maximum WTP is lower or higher than the tax amount.

This information can be used to fit an assumed parametric distribution describing people's WTP.

Assuming the WTP distribution is of a particular form (e.g., normal) with unknown parameters describing its mean and standard deviation, the probability of observing a particular choice is equal to the cumulative distribution function (CDF) of the assumed distribution evaluated at the upper bound (i.e., the probability that WTP is lower than the upper bound) less the CDF of this distribution evaluated at the lower bound (i.e., the probability that WTP is lower than the lower bound).[16] The parameters of the selected parametric distribution can be found by maximizing the product of these probabilities for the observed choices of all respondents.

Formally, the probability that individual i's WTP lies between the accepted tax amount $b_{i,s}$ (lower bound) and the next higher tax amount $b_{i,s+1}$ (upper bound) can be expressed as:

$$P\left(b_{i,s} \leq WTP_i < b_{i,s+1}\right) = CDF\left(b_{i,s+1}, \boldsymbol{\beta}_i\right) - CDF\left(b_{i,s}, \boldsymbol{\beta}_i\right),$$ [17]

where CDF denotes a cumulative distribution function of the considered WTP distribution and $\boldsymbol{\beta}_i$ is a vector of the distribution parameters (for example, for a normal distribution, $\boldsymbol{\beta}_i$ consists of a mean and a standard deviation).

The parameters of the distribution can be estimated using the maximum likelihood method. The probability specified in (1) expresses individual i's contribution to the likelihood function, while the log-likelihood function for a sample of N individuals can be formulated as:

$$\log L = \sum_{i=1}^{N} w_i \log\left[CDF\left(b_{i,s+1}, \boldsymbol{\beta}_i\right) - CDF\left(b_{i,s}, \boldsymbol{\beta}_i\right)\right],$$

where w_i represent weights that account for the possible over- or underrepresentation of specific individuals in the sample relative to the target population.

The above formulas are conditional on selecting a parametric distribution, whose CDFs are calculated. However, a researcher does not usually know which parametric distribution is best for approximating the distribution of WTP in the population. Instead, it is common practice that many parametric distributions are tried to select the one that best fits the data. Because the

[16] In the case of a binary choice, if an individual voted 'yes' for a program at a particular tax amount – the lower bound of his or her true WTP is the tax amount, and the upper bound is unknown, limited by individual income. A 'no' vote reveals that this respondent's WTP is between zero (lower bound) and the presented tax amount (upper bound). The remainder of this subtraction is the probability that respondents' WTP lies between the lower and the upper bound.

[17] We operationalize the numerical estimation by using the value of the PDF evaluated at the lower bound instead of the difference of CDFs, whenever the calculated difference in the values of the CDF is numerically equal to zero.

distributions can vary with respect to the number of parameters, and distributions with more parameters can lead to better fit, one can use the Akaike information criterion (AIC) or the Bayesian information criterion (BIC), rather than simply the value of the log-likelihood function as a means for comparisons, to account for the cost of additional parameters (and penalize overfitting).

There is no theory guiding the choice of a parametric distribution – which parametric distribution best fits the WTP distribution in the population is an empirical question. In what follows, we considered a large number of candidate parametric distributions. The specifications that best performed, according to the Bayesian Information Criterion, were: Exponential, Gamma, Negative Binomial, Nakagami, Birnbaum-Saunders, Uniform, Lognormal, Rayleigh, Loglogistic, Normal, Logistic, Extreme Value and Weibull (with or without zero-inflation).[18]

It is usually found that there is a large share of respondents whose WTP is equal to zero coupled with observing relatively few very small WTP amounts.[19] There are a few econometric approaches to account for such a spike in the PDF, either by censoring the parametric distribution (Kriström 1997), truncating it or adopting a hurdle model (Cragg 1971) or using a zero-inflation/mixture model (Greene 2018).[20] We adopt the most flexible (zero-inflation) approach, in which respondents' WTP is modelled as a mixture of a Bernoulli distribution (a point mass at zero) and a given parametric distribution, allowing for an over-proportional share of zero responses (Gurmu & Trivedi 1996). As a result, the log-likelihood function becomes:

$$\log L = w_i \sum_{i=1}^{N} \left\{ (1-q_i) \cdot \log\left[CDF(b_{i,s+1}, \boldsymbol{\beta}_i) - CDF(b_{i,s}, \boldsymbol{\beta}_i) \right] + q_i \cdot \log\left[CDF(0, \boldsymbol{\beta}_i) \right] \right\},$$

where q represents the probability that individual i is a non-participant (meaning that his WTP for the program is zero).[21]

The estimated parameters of the best-fitting parametric distribution may not readily be interpretable as mean WTP. In this case, the required characteristics of the WTP distribution (mean) and its standard error can be simulated, following parametric bootstrapping method adapted from Krinsky and Robb (1986); Krinsky and Robb (1991):

[18] For the distributions with support in negative numbers, censoring negative values to zero has been used when simulating mean WTP in the sample.

[19] This is particularly expected for payment card and open-ended elicitation formats (Carson & Czajkowski 2014b).

[20] The difference between the hurdle models and the zero-inflated models is that in zero-inflated models the zeros are modelled using a two-component mixture model. With a mixture model, the probability of the variable being zero is determined by both the main distribution and the mixture weight. For notable examples of CV studies accounting for zero responses see Werner (1999), and Strazzera *et al.* (2003).

[21] q is usually assumed to be a CDF of normal or logistic distribution, leading to using the probit or logit model to account for zero-inflation.

(1) To account for the uncertainty with which the estimates are known, we use parameter estimates and the inverted Hessian at convergence[22] to define a multivariate normal distribution[23] and use it to draw a large number (10^4) of new sets of parameters.

(2) For each set of parameters simulated in step 1 we draw 10^4 values from the implied WTP distribution, including the possible zero inflation component.

(3) Observing variation in required characteristics (mean) of the WTP distributions simulated in step 2, driven by each set of parameters generated in step 1, allows estimating the uncertainty associated with the required WTP distribution characteristics.

3. Results

The responses to the vote question by 5,200 respondents who participated in the survey allow for estimation of WTP, as described in section 2.3. For both the parametric and non-parametric models, it was found that the percent of respondents voting "against" the program increased significantly as the tax amount increased. This is consistent with economic theory. To further demonstrate the validity of our study, we also tested the sensitivity of the votes to (i) income levels, (ii) socio-demographic characteristics, (iii) attitudinal characteristics; (iv) quality-related variables resulting from the survey; and (v) for the parametric estimates of WTP, sensitivity to econometric treatment of the data (model uncertainty).[24] Overall, our analysis confirmed that data collected using our survey was well-behaved from an economic theory perspective.

3.1. Non-parametric estimate of population WTP

The respondents' votes for each tax amount make it possible to estimate the CDF, as explained in section 2.3.1. This is equivalent to Lewbel-Watanabe non-parametric estimator of the population WTP. The empirical CDF is presented in Figure 2.

These results allow for calculating the non-parametric estimate of mean WTP as the area above the CDF plotted in Figure 2. The lower-bound (non-parametric-based) estimate of mean WTP, along with its standard error and 95% confidence interval is presented in Table 3.

Table 3: The lower-bound (non-parametric-based) estimate of WTP [BRL]

WTP (mean)	**WTP (s.e.)**	**WTP 95% c.i.**
56.34	2.81	50.84 - 61.84

[22] To approximate an asymptotic variance-covariance matrix.

[23] Maximum likelihood estimates are asymptotically normal.

[24] The results of these validity tests are available in the full study report available in online supplementary materials, along with data and software codes necessary to reproduce the analyses presented in this paper.

Considering that the program was associated with 10 fixed monthly instalments, the non-parametric analysis implies that lower bound estimate of total WTP is 563.38 BRL with a 95% confidence interval of 508.39 - 618.37 BRL.

3.2. Parametric estimate of WTP

Following the procedure described in section 2.3.2, we fitted many typical parametric distributions to the voting data. The results are presented in Table 4. Each distribution was tried with and without a zero-inflation component. The fit of each distribution is indicated by the value of the log-likelihood function (the higher the better). However, it is expected that distributions using more parameters will generally fit the data better. In order to avoid over-parameterization of the data, we based our comparisons on the Bayesian Information Criterion (BIC), which penalizes specifications for additional parameters they require. A lower BIC implies a better fit. The specifications in Table 4 are sorted in terms of fit from best to worst. For each specification, the last two columns of Table 4 present the implied (simulated) mean WTP along with its standard error.

The results presented in Table 4 indicate that in the case of our data, the best-fitting parametric distribution was exponential with a zero-inflation component. However, it is worth noting that in terms of fit indicators, the results (and irrespective of whether BIC or AIC is used as the fit indicator) are very close for the top 19 specifications and result in similar WTP measures in the range of approximately 87-118 BRL. The CDF of the best fitting parametric distribution is presented in Figure 2, along with the non-parametric weighted (Lewbel-Watanabe) estimator.

Table 4: The results of the parametric estimation of respondents' WTP

Distribution	**Log-likelihood**	**Zero inflation**	**AIC**	**BIC**	**Param.**	**WTP (mean)**	**WTP (s.e.)**
Exponential	-2909.53	1	1.1209	1.1234	2	94.58	7.53
Gamma	-2905.35	1	1.1197	1.1235	3	94.30	10.03
Negative_Binomial	-2905.52	1	1.1197	1.1235	3	94.54	9.85
Weibull	-2908.17	1	1.1208	1.1245	3	86.63	7.99
Nakagami	-2912.64	1	1.1225	1.1263	3	98.42	6.61
BirnbaumSaunders	-2914.25	1	1.1231	1.1269	3	94.81	9.39
Uniform	-2916.98	1	1.1241	1.1279	3	87.89	4.61
Inverse_Gaussian	-2926.36	1	1.1278	1.1315	3	95.09	8.70
Lognormal	-2928.09	1	1.1284	1.1322	3	96.37	9.11
Rayleigh	-2934.62	1	1.1306	1.1331	2	101.36	5.18
Negative_Binomial	-2900.98	0	1.1322	1.1348	2	94.41	10.22
Gamma	-2902.98	0	1.1330	1.1355	2	94.31	10.51
Loglogistic	-2942.52	1	1.1340	1.1378	3	113.30	17.87
Poisson	-2950.07	1	1.1365	1.1390	2	118.18	0.64
Generalized_Extreme_Value	-2943.88	1	1.1349	1.1399	4	111.34	7.70
Normal	-2948.53	1	1.1363	1.1401	3	101.79	3.49
Logistic	-2949.92	1	1.1368	1.1406	3	107.42	3.19
Extreme_Value	-2949.98	1	1.1369	1.1406	3	117.01	3.85
Weibull	-2974.93	0	1.1610	1.1636	2	115.77	23.10
Inverse_Gaussian	-3147.04	0	1.2282	1.2307	2	86.90	21.16
Exponential	-4980.09	0	1.9427	1.9440	1	46.13	1.69
Nakagami	-6425.17	0	2.5067	2.5092	2	77.54	1.89
Logistic	-7904.43	0	3.0836	3.0862	2	46.16	1.62
Uniform	-8510.86	0	3.3202	3.3227	2	193.89	3.72
Normal	-8684.97	0	3.3881	3.3906	2	75.05	2.45
Extreme_Value	-10185.68	0	3.9734	3.9759	2	105.01	3.40
Rayleigh	-10806.60	0	4.2151	4.2164	1	82.89	1.61
Poisson	-100179.41	0	39.0719	39.0732	1	44.09	0.21

Figure 2 shows the empirical CDF of the best-fitting parametric distribution for our data, along with the non-parametric weighted Lewbel-Watanabe estimator. For the tax amounts used in our study (3, 12, 109, 375 BRL) both estimators are very close, resulting in similar expected probability of voting 'against'.

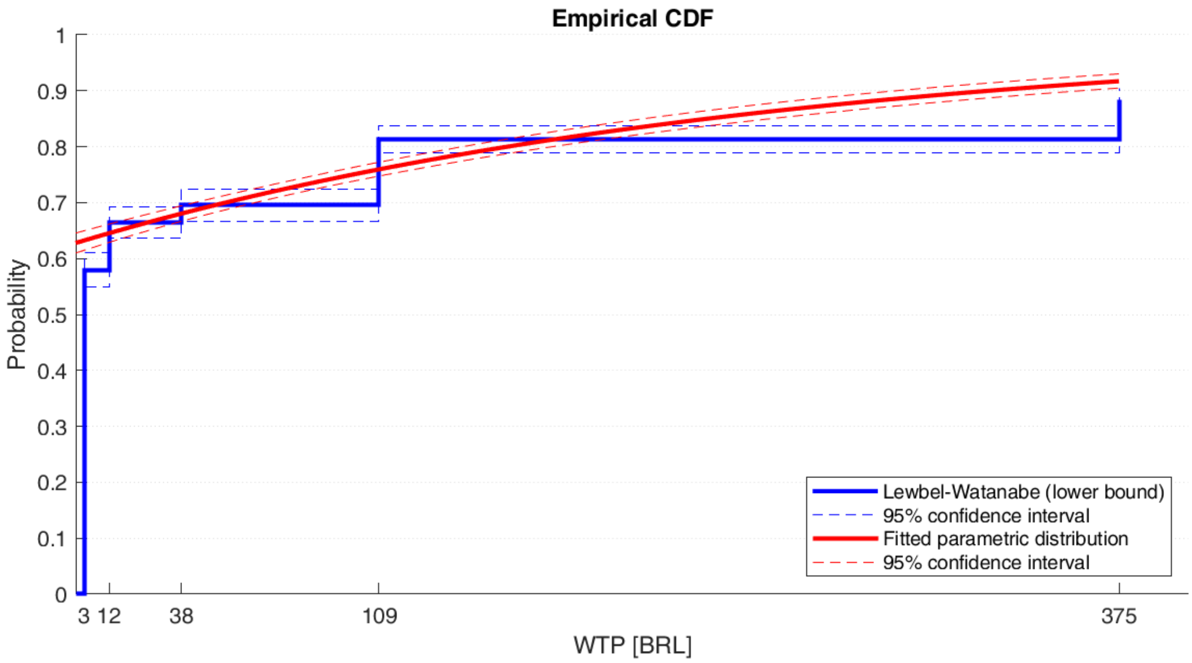

Figure 2. The Lewbel-Watanabe non-parametric and the parametric estimators of the population WTP

Our parametric estimate of the population mean WTP, along with its standard error and 95% confidence interval is presented in Table 5.

Table 5: The parametric-based estimate of WTP [BRL]

WTP (mean)	WTP (s.e.)	WTP 95% c.i.
94.58	7.53	79.81 - 109.35

Considering that the program was associated with 10 fixed monthly installments, the parametric analysis implies that mean WTP is 945.78 BRL with a 95% confidence interval of 798.11 – 1,093.45 BRL.

3.3. Aggregate Lost Value

The average estimates permit determination of the value of environmental and historical/cultural heritage damages calculated with an aggregated measure for Brazilian society over the entire recovery period.

The WTP inferred from our CV approach represents mean WTP of an average urban Brazilian household. Calculating the aggregate value of damages therefore requires multiplying the mean WTP by the number of total urban households in Brazil. Considering the 55,949,131 urban households in Brazil (IBGE 2020), our conservative (lower-bound) estimate of environmental, cultural/heritage damages caused by the FDI to the Brazilian society, in terms of loss of services and resources to the end of the recovery period, is 31.52 billion BRL (13.36 billion USD, with a 95% confidence interval of 7.18 - 8.74 billion USD)[25]. The parametric estimate, based on choosing the best-fitting probability distribution to observed votes of survey participants, implies the aggregate value of damages equal to 52.92 billion BRL (13.36 billion USD, with a 95% confidence interval of 11.28 - 15.45 billion USD).[26]

4. Summary and conclusions

While the valuation literature considering mining-related externalities is considerable, valuation studies of damages resulting from sudden, catastrophic mining accidents are scarce and most available damage assessments apply market valuation methods while rarely considering nonmarket environmental impacts. The results presented in this paper use the case of Fundão Dam incident in Brazil in 2015 to estimate the economic value of the environmental and cultural/heritage damages associated with a tailings dam failure. We designed and administered a stated preference CV study following the state-of-the-art recommendations for stated preference-based valuation studies to make the results as reliable and valid as practicable (Johnston *et al.* 2017; Bishop & Boyle 2019). The questionnaire design followed several experimental steps with focus groups and in-depth and pilot surveys to motivate respondents to focus only on non-market values of environmental and cultural/heritage damages.

For the full valuation survey, we interviewed a representative sample of 5,195 Brazilians living in urban areas to gauge their WTP for introducing a new technology that would allow for the avoidance of another dam break similar to the Fundão Dam incident in the next 10 years, and hence avoid losses to the citizens of Brazil from the injuries to the environment (including losses to aquatic biota, terrestrial wildlife, birds and riparian forest) and heritage resources. We found that the average lower-bound willingness-to-pay (WTP) estimate was 137 USD and the parametric-based estimate was 230 USD per household, which aggregates to 7.96 or 12.91 billion USD, respectively.

The Fundão Dam incident illustrates that, apart from lives lost and property damages, the injury to the natural environment and heritage/cultural losses can be substantial. Considering that the dam break released 43.7 million cubic meters of mine tailings, the environmental and heritage/cultural damages can be estimated at 176 or 295 USD per m^3 of tailings released. To put our estimates in perspective, there are tens of thousands of tailings

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[25] The assumptions behind our conservative (Lewbel-Watanabe-approach-based) estimate make model-driven overestimation impossible. On the other hand, this approach results in an estimate that is likely lower than the true extent of the damages and therefore can be considered a lower-bound estimate.

[26] While the parametric approach has the advantage of minimizing the error of the estimate (relative to the true, unknown mean WTP), it is possible it underestimates or overestimates the true value by some unknown amount.

dams around the world[27] with hundreds of billions of m^3 of tailings deposited and an annual generation of new tailings of nearly 20 billion m^3 (WMTF 2022). It is estimated that since 1949 an average annual release of tailings due to dam breaks was approximately 30 billion m^3, and this number has been growing, as the cumulative tailings depositions and the number and size of active dams increase (WMTF 2022).

The expected value of environmental and heritage/cultural damages arising from catastrophic tailings dams failures constitute a substantial externality associated with storing mining tailings in dams. While the risk of tailings dam failure is relatively high (Martin & Davies 2000; Roche *et al.* 2017), our study shows that the damages associated with a catastrophic event are substantial. Meanwhile, despite considerable research dealing with mining-related externalities (Menegaki & Damigos 2020; Ferrini *et al.* 2021), the estimates of risks and damages resulting from mining incidents are scarce and are typically not included in cost-benefit analyses (Adiansyah *et al.* 2015; Adiansyah *et al.* 2017). Our study is a step towards filling this important gap in the literature.

There are several limitations of our study that need to be acknowledged. First, our sampling targeted the population of urban, income-earning, households located in 10 major metropolitan regions and municipalities across Brazil, with the goal of obtaining 5,200 completed survey interviews. The rural population of Brazil, which accounts for 14% of the country's total, was not surveyed (and were thereby not included in the estimates of damages), due to logistical reasons arising from its spatial dispersion. Second, we encountered some issues related to local cultural conditions and had to adapt our methodology, accordingly. For example, we used a temporary increase in the tax on respondent households' electricity bills as a payment mechanism, as this was found to be believable to respondents and binding upon them, since this was the most commonly paid type of tax , ie. most difficult to avoid (Adams *et al.* 2008; Seroa da Motta & Ortiz 2018). Third, the contingent scenario, which introduced a dry-stacking program and would have resulted in the drying up of all tailings dams in Brazil could have been associated with additional benefits to households. Thus, our study included extensive testing procedures that made it possible to minimize non-economic motivations or considerations, such as the creation of additional employment opportunities, when survey respondents voted for or against the program.

Overall, our study provides an estimate of environmental and heritage/cultural damages for the Fundão Dam incident. Furthermore, it provides an important reference for future studies and can serve as a source for benefit transfer valuation of risks associated with mining-related natural resource extraction technologies. We argue that tailings dams represent a significant environmental liability associated with mining projects that should not be ignored when comparing available hard rock natural resources extraction technologies.

[27] Approximately half (16,000) of the tailings dams are currently active, with an estimated 85% of catastrophic failures historically arising from active tailings dams.

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