The hidden effects of a major environmental disaster: the case of the Brumadinho dam failure.*

Flávia Chein †

Igor Vieira Procópio ‡

Cristine C. X. Pinto §

Environmental disasters are becoming increasingly frequent and affecting more people, making it a topic of great interest to researchers and public managers. Adverse events can impact the full development of a pregnancy, and the effect of environmental disasters on human health is a matter of concern. Such disasters can either be natural or artificial. In Brazil, natural disasters such as prolonged droughts in the northeast, floods, and windstorms are common, while artificial disasters include fires, oil spills, and, more recently, iron ore dam failures. The two most significant cases are the failures of the Mariana and Brumadinho dams.

This paper aims to evaluate the impact of the Brumadinho dam failure on the health of children exposed during the intrauterine period. Specifically, the study intends to verify if there was a possible selection in the uterus in favor of girls, leading to a change in the relationship between boys and girls born alive. Additionally, the researchers seek to understand whether this mechanism occurs due to increased male fetal deaths.

Key Words: Dam failure, Brumadinho, Selection in utero, Sex ratio

JEL Classification: I14, J10, J13

Area: Applied Microeconomics

---

* We are thankful to FAPEMIG, CAPES, and CNPq for financialăsupport.

† Department of Economics, Federal University of Juiz de Fora. Fellow of CNPq research productivity. Address: Rua José Lourenço Kelmer, s/n, Juiz de Fora, Brazil, 36036-900.Tel.: +55-32-2102-3554. E-mail: flavia.chein@ufjf.br.

‡ Department of Economics, Federal University of Juiz de Fora

§ Insper. Fellow of CNPq research productivity.

1 Introduction

A growing literature points to the relationship between adverse shocks occurring during pregnancy and fetal development, with consequences for individuals' neonatal and future health. Several forms of adverse shocks have been studied (Almond & Currie, 2011; Almond, Currie, & Duque, 2018). Pioneering studies evaluate the effect of maternal malnutrition during pregnancy on diseases in adulthood. Empirical evidence shows fasting during Ramadan impacts children's educational development problems, mental health, and adult wealth measures. Several studies evaluate the effect of maternal stress, providing evidence of the negative relationship between exposure to adverse shocks in the womb and fetal development.Torche (2011); Tan et al. (2009); Torche and Kleinhaus (2012); Chang, Chang, Lin, and Kuo (2002); Glynn, Wadhwa, Dunkel-Schetter, Chicz-DeMet, and Sandman (2001) study the effects of earthquakes,Currie and Rossin-Slater (2013); Hamilton, Martin, Mathews, Sutton, and Ventura (2009); Xiong et al. (2008) analyze the effects of hurricanes, Tong, Zotti, and Hsia (2011) investigate the impacts of floods and Laplante, Brunet, Schmitz, Ciampi, and King (2008); King and Laplante (2005); Laplante et al. (2004) seek to understand the impacts of snowstorms.

Specifically in Brazil, a recent concern is related to the failure and the threat of loss of ore dams.Thompson et al. (2020) and Armstrong, Petter, and Petter (2019) warn of the increase in cases of dam failure that has doubled in the last twenty years. In 2014, a dam in Itabirito, State of Minas Gerais, collapsed, with three confirmed deaths. In 2015, a dam leak in Mariana, Minas Gerais, caused nineteen confirmed deaths and is considered one of the disasters caused by ore leaks with the most significant environmental impact. In 2019, again in the State of Minas Gerais, the dam in Brumadinho collapsed. Although the damage in environmental terms was more minor about the Mariana breach, the impact on human lives was the greatest ever recorded in world history. The most recent information points to two hundred seventy-two deaths. However, the consequences of the tragedy go beyond direct deaths, impacting mental health due to fear and material losses.

Mrejen, Perelman, and Machado (2020) and Carrillo, Da Mata, Emanuel, Lopes, and Sampaio (2020) analyze the impact of exposure in utero to the rupture of the Mariana Dam on the health of exposed newborns.Mrejen et al. (2020) found that children who were exposed in utero showed a reduction in gestation time and an increase in the probability of being born preterm. The results of Carrillo et al. (2020) point to a reduction in birth weight and an increase in infant mortality.

A less explored aspect in this literature is how a natural disaster can impact the sex ratio of live births. The sex ratio of live births, the proportion of boys born alive to the total number of children born alive, is stable over time, especially in large populations. Studies show this ratio is biased toward boys, with the value slightly over 0.51. (James & Grech, 2018; Masukume, O'Neill, Khashan, Kenny, & Grech, 2017; Davis, Gottlieb, & Stampnitzky, 1998). Negative shocks during pregnancy impact the reduction of the sex ratio; that is, it decreases the proportion of boys to live-born girls. Therefore, a relative increase in the birth of girls is a sign of poor health for mothers or the general population.(James & Grech, 2018).

Male fetuses are more fragile than female fetuses. Therefore, they are more sensitive to some adverse situations during pregnancy. In addition to being more fragile, they grow more during pregnancy, thus demanding more resources from mothers. Due to these characteristics of the pregnancy of male fetuses, in adverse situations with resource restrictions or an environment with a high level of stressors, there is a greater number of spontaneous abortions of male fetuses, which causes an inversion in the sex ratio of live births. (Torche & Kleinhaus, 2012; Trivers & Willard, 1973; T. Bruckner & Catalano, 2007; Catalano & Bruckner, 2006; Catalano, Bruckner, Marks, & Eskenazi, 2006; Fukuda, Fukuda, Shimizu, & Møller, 1998; Valente, 2015).

Therefore, reductions in the sex ratio are a sign of an increase in fetal deaths, mainly male, due to an adverse situation during pregnancy. James and Grech (2018) highlight that the sex ratio of live births can be a helpful measure as an indicator of public health. Reducing the sex ratio is also essential to understand the mechanisms that act on birth and child health outcomes after a stressful event during pregnancy.

Two mechanisms can lead to a reduction in the sex ratio with distinct consequences for the health of live births. The most cited mechanism in the literature, especially in articles in economics, is related to the Theory of Fetal Origin.(Barker, 1995; Barker & Osmond, 1986; Almond & Currie, 2011). According to this theory, pregnant women and fetuses adapt to adverse situations, altering their genes' expression and producing a phenotype adapted to restrictive conditions. This adaptation would imply worse results in the baby's birth and future health problems. On the other hand, Catalano and Bruckner (2006) points to a possible positive selection in utero in adverse situations. According to this literature, there is a survival threshold for embryos and fetuses. If the health conditions of the fetus are below this threshold, a miscarriage occurs. This threshold becomes higher in adverse shocks, with a more rigorous selection process in utero. Therefore, with this threshold change, the most fragile fetuses do not survive, and live births are part of a positively selected cohort.

On January 25, 2019, an iron ore tailings dam broke in Brumadinho, State of Minas Gerais, reaching part of the municipality. In addition to the nearly 300 fatalities, mainly of employees of the mining company, the tailings flowed until the Paraopeba River drained them. The contamination of the river waters caused damage in another eighteen municipalities along the Paraopeba river bed. Studies indicate that, in addition to environmental damage, there was an increase in psychological problems in the affected population.(Noal, Braga, Leal, Vargas, & Eliazar, 2021; Miranda et al., 2021; Mayorga, 2020a; Noal, Rabelo, & Chachamovich, 2019). This paper explores the increased stress caused by an exogenous event to investigate the impact on children in the womb during the disaster.

The main objective of this article is to evaluate a possible impact on the sex ratio of the cohort of live births that suffered from the effects of the environmental disaster in Brumadinho during pregnancy. Additionally, the primary mechanism that reduces the sex ratio is investigated whether it is the adaptation of the fetus during pregnancy, which can lead to worse birth outcomes, or whether it is natural selection, generating a positively selected cohort of live births.

To achieve this goal, data from the National System of Live Births from 2011 to 2019 and a synthetic differences-in-differences strategy are used to compare the live births of the municipalities affected by the disaster with the live births of a control group.

The results point towards reducing the sex ratio of live births in those municipalities affected by the disaster caused by the dam rupture in Brumadinho. The negative effect is more substantial in the cities closest to the rupture site and manifests in the beginning and middle of pregnancy. Evidence indicates that both mechanisms act to reduce the sex ratio.

The paper seeks to contribute to the literature on the effects of in-utero exposure to adverse events and child development by presenting a possible mechanism that explains the results observed in live births. If after an adverse event, an impact analysis on birth measurements on those children exposed to the event while in utero finds no effect, but if there is a change in the ratio of live-born boys and girls, this change signals that there has been an increase in fetal deaths(Catalano & Bruckner, 2006).

The remainder of the paper is divided as follows. Section 2 presents information about the Brumadinho Disaster. Section 3 briefly discusses the mechanisms that can reduce the sex ratio of live births. Section 4 brings the database. The fifth section discusses the empirical strategy. Section 5 presents the article's results, and section 6 offers the final remarks.

2 Brumadinho disaster as a stress inducer

On January 25, 2019, the tailings dam at the Córrego do Feijão mine in Brumadinho, Minas Gerais, failed, causing its tailings to reach a large expanse of land in the municipality of Brumadinho before reaching the waters of the Paraopeba River. Nearly three hundred people died under the mud.

Satellite images released by the IBGE identified seventeen other towns located along the course of the Paraopeba River that were affected by the dam's tailings, in addition to the municipality of Brumadinho.

Figure 1 shows the area directly affected by the tailings mud until it reached the bed of the Paraopeba River. Already the figure 2 presents the municipalities affected by the tailings via pollution of the river waters.

Figura 1: Area affected by the Disaster

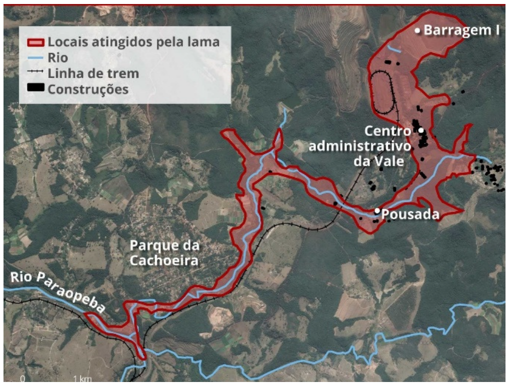
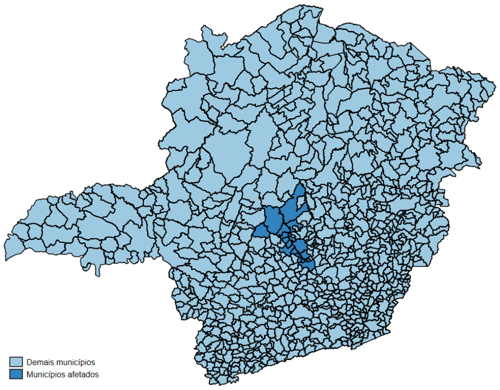


Figura 2: Municipalities Affected by the Disaster



Some studies assess the extent of the environmental tragedy, showing that of the total area affected, more than 50% was native vegetation, activities occupied 19% with a high circulation of people, and 13% by agricultural activities. (Peixoto & Asmus, 2020).

In addition to the environmental impacts and direct deaths, a disaster of such magnitude as the Brumadinho disaster has implications on the health and especially the mental health of people directly and indirectly affected. (Noal et al., 2019) highlight some factors that contributed to the Brumadinho disaster having a substantial impact on the mental health of the population, such as the magnitude of the disaster, the high number of people directly affected, destruction of private properties and the contamination of the Paraopeba River, an essential source of water for irrigation of crops, fishing and water supply for the population.

Studies after the disaster point to increased negative behaviors, such as alcoholism, domestic violence, depression, and psychotic outbreaks. These mental health problems were more concentrated in the municipality of Brumadinho but spread to the cities along the bed of the Paraopeba River. (Mayorga, 2020b) emphasizes that these adverse effects were observed with different gradations among the affected municipalities.

3 Sex ratio of live births: Selection in utero or affected cohort

The sex ratio of live births is a measure that signals the health of the live birth cohort(Inoue & Mizoue, 2022; James & Grech, 2018; Davis et al., 1998). The sex ratio can be calculated as the percentage of boys born alive or the total number of boys born alive for every 100 girls born alive. It is a measure that shows stability over time and between different populations. The value found is biased towards boys, who represent approximately 51%

Several studies have analyzed the reduction in the sex ratio of live births after situations that have increased the population's stress level. Fukuda et al. (1998), Catalano, Yorifuji, and Kawachi (2013), Torche and Kleinhaus (2012), Fukuda, Fukuda, Mason, Shimizu, and Andersen (2018) andHamamatsu, Inoue, Watanabe, and Umezaki (2014) verify a reduction in the sex ratio after the occurrence of earthquakes, T. A. Bruckner, Lebreton, Perrone, Mortensen, and Blondel (2019), Grech (2015) and Masukume et al. (2017) after terrorist attacks, Valente (2015), Dagnelie, De Luca, and Maystadt (2018), Ansari-Lari and Saadat (2002) and Zorn, Šučur, Stare, and Meden-Vrtovec (2002) due to civil conflicts and wars.

The association between exposure to negative shocks during pregnancy and a reduction in the sex ratio is explained by the increase in male fetal and embryonic deaths. This increase is due to the spontaneous abortion of the most fragile male fetuses.(Catalano & Bruckner, 2006; Forchhammer, 2000). Therefore, an increase in the sex ratio of spontaneous abortions causes a reduction in the sex ratio of live births.

The literature points to two possible mechanisms that act towards the increase of male fetal deaths in adverse situations. To facilitate the exposition of the arguments of the two explanations in the literature, it is worth noting that both are based on a hypothetical distribution of fetal health. The distribution curve of male and female fetuses is believed to be separate, with the male curve being shifted to the left; male fetuses are more fragile than female fetuses. Another critical point to highlight is the high rate of spontaneous abortions, even in situations of normality and abundant resources during pregnancy. These miscarriages are not random; they occur in the lower tail of the fetal health distribution. It is a process of natural selection during pregnancy. Therefore, live births do not represent their conception cohorts; they are positively selected. There is, thus, a threshold of fetal survival; for those fetuses below a cut-off line in the health distribution, a miscarriage will occur.

With this model of fetal health distribution and the cut-off line for survival in mind, the following two possible mechanisms that reduce the sex ratio of live births in adverse situations are presented. The first is related to natural selection in the uterus, which can be defined as the process that ends pregnancy when the mother does not have enough resources to continue. (T. A. Bruckner & Catalano, 2018). The stress response during pregnancy is manifested by the change in the fetal survival line that shifts to the right, i.e., the maternal tolerance criterion for the survival of fetuses in the lower tail of the distribution becomes more stringent.(Catalano & Bruckner, 2006). Since male fetuses represent the highest density at the bottom of the distribution, this shift to the right of the survival line ends the pregnancy of more male than female fetuses, increasing the sex ratio of stillbirths and reducing the sex ratio of live births.

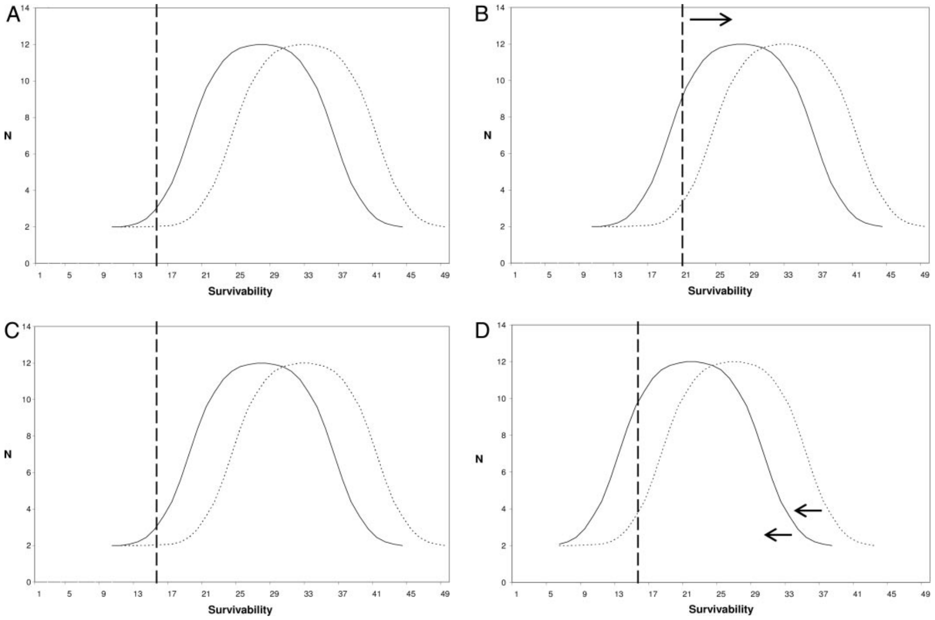
Suppose this mechanism is the main one that reduces the sex ratio. The implication is that the live birth cohort presents better birth and health outcomes throughout life, as the stressor event selected the strongest fetuses. This positive selection happens much more prominently for boys than girls, who are little affected by the change in the maternal tolerance criterion.

The theory of fetal origin presents the second explanation. According to this theory, an adverse event during pregnancy interacts with embryonic and fetal plasticity, negatively impacting intrauterine development. Unlike the previous answer, there is no shift in the fetal survival line but a change to the left of the health distribution. Even if this shift occurs for both sexes, the fraction of male fetuses below the survival line increases about the fraction of girls, leading to a proportionately more significant increase in male fetal deaths than female fetal deaths, and as a result of this process, a reduction in the sex ratio of live births.

Contrary to the natural selection explanation, the impact is a cohort of live births with worse birth outcomes and more significant health problems over the life cycle.

Figure 3 from Catalano and Bruckner (2006) summarizes this discussion. Graphs A and C represent the situation of normality. The solid curve is the health distribution for boys, and the dotted curve is for girls. The vertical line indicates the fetal survival threshold. The explanation of natural selection is represented by the passage from graph A to graph B. Note that the survival line shifted to the right while the two health curves remained unchanged. The explanation of the fetal origin is represented in the transition from graph C to graph D. The survival line stays intact, while the health distribution curves shift to the left.

Figura 3



The two mechanisms are not mutually exclusive and may co-occur. Each definition in the literature will remain the same; therefore, an empirical analysis is necessary. In summary, if, after a negative shock and a reduction in the sex ratio, there is an improvement in birth and health outcomes throughout the life cycle of the affected cohort, it is understood that natural selection in the womb was the primary mechanism. If a worsening of the health indicators of the affected cohort is observed, it is concluded that the mechanism proposed by the theory of fetal origin prevailed.

It is essential to highlight that most works analyzing adverse shocks' impact on fetal development only examine birth or health measures throughout the life cycle. The absence of significant results in this type of analysis does not mean any effect; it may be that there was an impact on the cohort affected by the shock but that the two mechanisms act simultaneously, masking the impact on the practical measures.

4 Data

Data from the Live Birth Information System (SINASC) are used to assess the impact of the Brumadinho dam failure on the sex ratio of live births and primary birth outcomes.

Information from 2011 to 2018 is used, including children born before the dam rupture and, therefore, were not affected while they were in the womb, and from the year 2019, which represents the data of children who were in the womb at the moment of the dam failure. SINASC presents information on the child's date and place of birth, which is essential for defining exposure to shock, as well as information on the child's sex, birth weight, gestational age, and some characteristics of the mother.

The combination of date of birth and time of gestation information makes it possible to infer the date of conception, which defines exposure to shock. Suppose the child was conceived before the dam failure and born after the dam was exposed to wonder during intrauterine development. To analyze the evolution of the sex ratio and the possible impact of the stress generated by the dam failure, the previous periods that serve as a basis for comparing the behavior of the sex ratio must be divided into periods equal to the exposure period. To shock. Therefore, groups of children whose birth date falls within nine-month periods counting back from the dam failure were created for those born before the dam failure.

When analyzing the effects of shocks during pregnancy, it is essential to identify the period during which the shock occurred. Two divisions of the gestation period are adopted in this study. The first divides the gestation period into two. The first half comprises the period from conception to twenty weeks, while the second half corresponds to more than twenty weeks until birth. The other division refers to the three trimesters of pregnancy. Therefore, if the shock occurred between the moment of conception and the thirteenth week of gestation, the surprise is defined as having occurred in the first trimester, in the second trimester if it happened between the thirteenth and twenty-sixth week of pregnancy, and in the third trimester. Suppose it happened after the twenty-sixth week. For each division, groups of children born before the break were created, divided into 140 days and 90 days, respectively.

Another critical point in defining the exposed children is the residence municipality at the time of the shock. As shown in the previous section, in addition to Brumadinho, another seventeen municipalities suffered from the impact of the displacement of waste through the channel of the Paraopeba River. One of these municipalities is Betim, a large municipality in which only a tiny portion was affected. As a result, this municipality is not considered a municipality affected by the dam failure in this study. Of the remaining municipalities, as highlighted by (Mayorga, 2020b), the residents perceived the intensity of the disaster differently. As a result, the analysis is carried out with two perspectives on the affected municipalities. In the first one, all the municipalities affected by the dam failure are considered, and only the municipalities closest to Brumadinho, which felt the effects more strongly, are considered.

This article's primary variable of interest is the sex ratio of live births, presented as the ratio between live births and total births. In large populations, this ratio has specific stability and is biased towards boys; more boys are born than girls, approximately 51

However, the municipalities affected by the Brumadinho dam failure are small municipalities with fewer live births per year. Table 1 presents the population in 2010 for each of the municipalities and the total number of live births from 2011 to 2019. Pará de Minas is the largest city, with a little over eighty-four thousand inhabitants and an average live births of around one thousand and one hundred per year. Fortuna de Minas is the smallest city in terms of population, with two thousand seven hundred and five inhabitants and a little more than thirty live births per year. For all municipalities, there are approximately four hundred live births per year.

Due to the low number of live births in most municipalities affected by the dam failure, it is impossible to analyze the impact separately in each city. In small populations, the sex ratio has a very high natural oscillation, making it impossible to identify whether an adverse shock caused a given change.

The following three graphs clarify the problem of analyzing changes in the sex ratio in small populations. The graphics show the distribution of the sex ratio between 2011 and 2019, considering the previously adopted

Tabela 1: Affected municipalities, population, and number of live births

Municipality	Population in 2010	Live births								
		2011	2012	2013	2014	2015	2016	2017	2018	2019
Brumadinho	33.973	462	446	435	485	508	438	438	402	465
Esmeraldas	60.271	829	829	958	1093	1119	1094	1211	1188	1146
Florestal	6.600	92	70	67	80	94	76	70	91	63
Igarapé	34.851	554	572	616	586	631	562	566	619	600
Juatuba	22.202	343	379	361	469	422	385	392	387	408
Mário Campos	13.192	199	202	238	210	242	212	208	238	203
Pará de Minas	84.215	1.109	1.076	1.122	1.201	1.196	1.118	1.138	1.161	1.115
São Joaquim de Bicas	25.537	373	388	377	415	393	371	420	371	453
Felixlândia	14.121	139	147	145	167	123	118	152	127	124
Curvelo	74.219	923	971	981	1028	1015	902	952	1021	995
Fortuna de Minas	2.705	36	31	25	35	30	35	32	40	30
Maravilhas	7.163	88	75	84	79	74	85	67	87	86
Papagaios	14.175	198	173	193	188	193	167	177	185	168
Paraopeba	22.563	276	274	341	283	327	274	305	285	343
Pequi	4.076	53	51	49	50	54	42	42	44	41
Pompéu	29.105	404	406	411	437	436	422	410	440	429
São José da Varginha	4.198	45	44	33	49	65	38	42	32	53

Source: IBGE, 2010; SINASC, 2011-2019

divisions, the entire period of pregnancy, periods of 140 days, and periods of 90 days. The distributions of all live births in Brazil are presented for the aggregate live births in the seventeen municipalities affected by the dam tailings, followed by the distribution considering only the municipalities closest to the dam. Finally, the sex ratio distributions for each city are presented.

Graph 4 shows the sex ratio distribution considering the period of two hundred and seventy days (the entire period of pregnancy). Note that the distribution in Brazil is very concentrated, around 51%. The dispersion increases a little for the aggregate of municipalities affected by the disaster, and the same occurs for the total of closer municipalities. On the other hand, the distributions of each city individually show behavior with a significant variation over time.

Graphs 5 and 6 present the same type of analysis as the graph 4, changing only the length of the analyzed period.

The exciting thing about focusing on these graphs is that the sex ratio varies very little in large populations and fluctuates significantly in small populations. The conclusion is that it is impossible to analyze the impact of a negative shock during pregnancy on the sex ratio of tiny people, as it is impossible to isolate the effect of the wonder of natural variation in these small populations. Based on these results, the analysis is carried out for the set of affected municipalities and the collection of cities closest to the dam failure.

Figure 7 presents the evolution of the sex ratio considering periods of 270 days, which corresponds approximately to the pregnancy period. There is a variation in the balance around the historical value of the sex ratio $(\tilde{0}.51)$. The dotted vertical line represents the last period before the dam burst. Subfigure 7a presents the evolution for the set of all affected municipalities, while figure 7b presents the change to the nearest cities. It is possible to notice that even with a natural oscillation of the sex ratio and a low value of this ratio four periods before the dam rupture, the lowest value of the series is precisely the period in which live births were affected by the dam rupture during the intrauterine period.

The graphs in figure 8 present the evolution of the sex ratio considering periods of 140 days. In shorter periods, the population of live births is also smaller, which reflects a more significant oscillation in the sex ratio compared to the previous graphs. Again, even with this more significant oscillation, the smallest value

Figura 4: Sex Ratio Distribution - 270 days

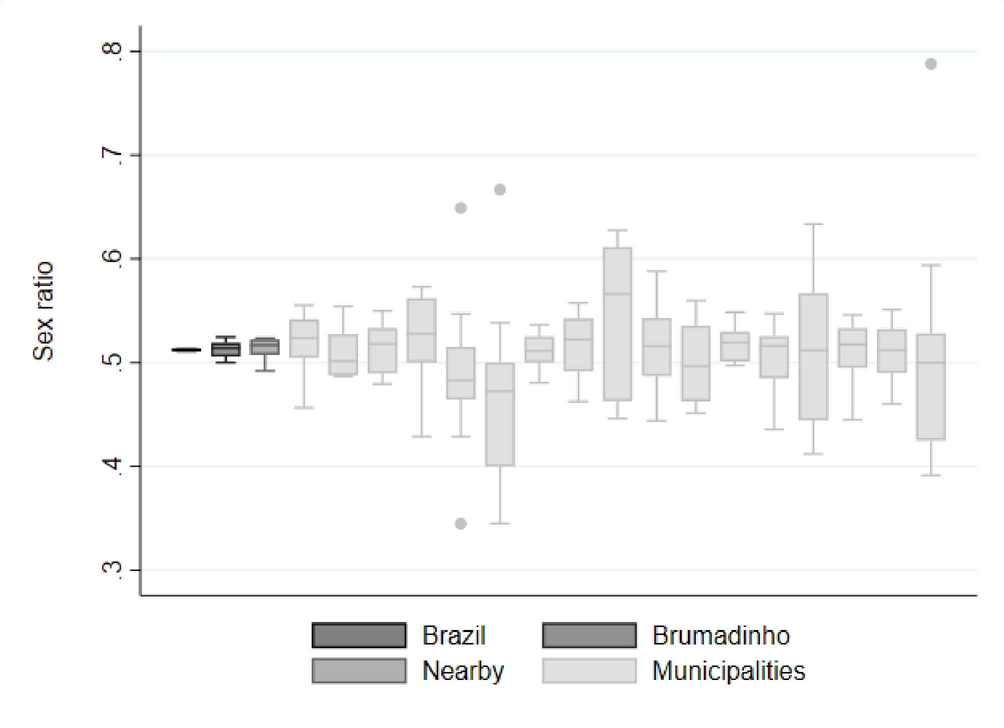
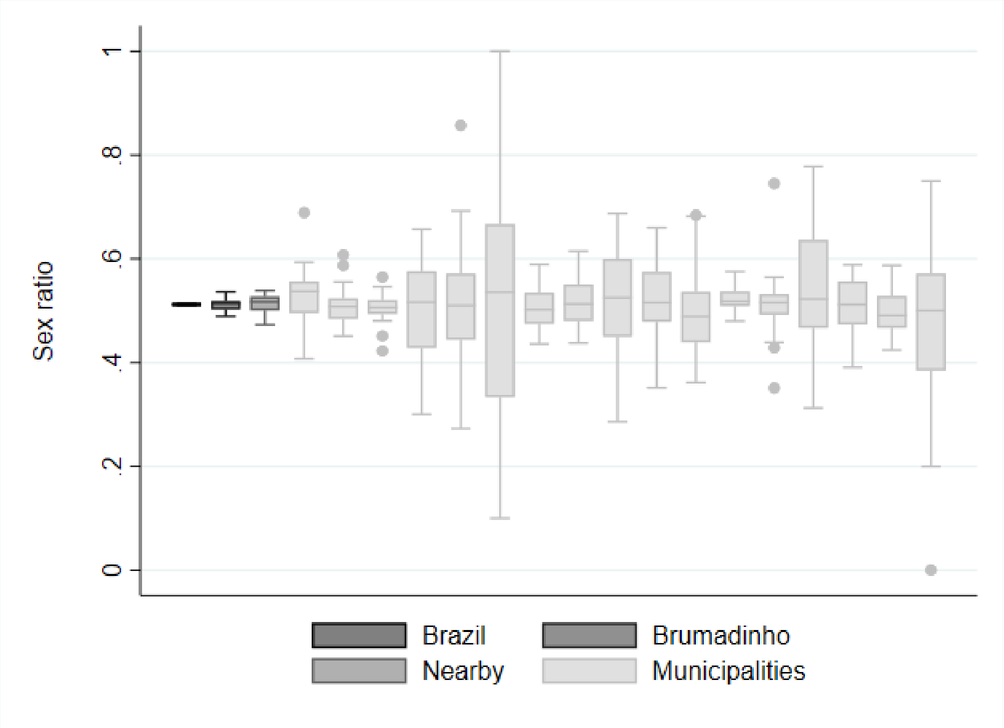


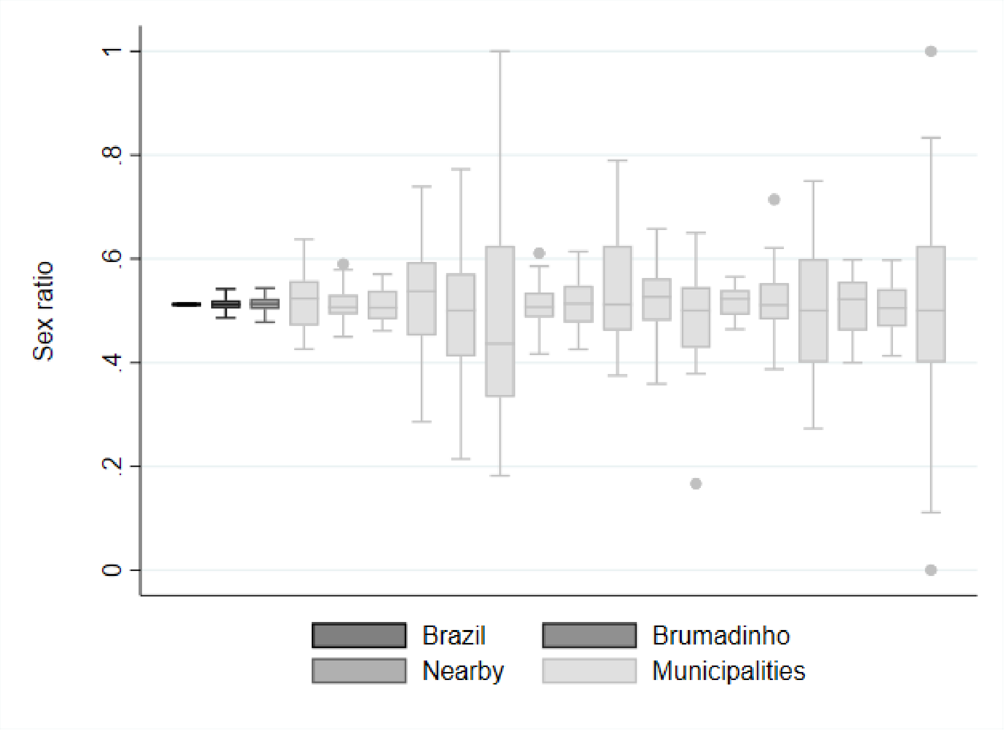
Figura 5: Sex Ratio Distribution - 140-day period



of the series is observed for the cohort affected by the dam failure during pregnancy.

Finally, the graphics 9a and 9b show the evolution of the sex ratio for the ninety-day periods. In addition

Figura 6: Sex Ratio Distribution - 90-day period



to the more significant oscillation, two points should be highlighted. First, on the graph 9a, the lowest value of the sex ratio series occurs before the dam rupture, warning that the value found for those exposed during the second trimester of pregnancy may be an oscillation of the sex ratio. Second, in graph 9b, it is possible to notice that the first two trimesters of pregnancy show a lower value of sex ratio than the rest of the series.

5 Empirical Strategy

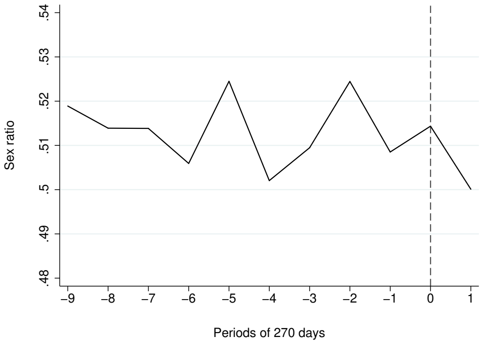
The graphs presented in the previous section point to the main challenges of identifying the causal relationship between the Brumadinho dam failure and the effect on the sex ratio. The natural oscillation of the sex ratio over time, mainly when a low number of live births is observed due to the population size of the area to be analyzed or the short period, or even a combination of the two factors, is the main challenge. Even though the observed value of the sex ratio after the dam failure is the lowest in the analyzed time series, it is not possible to say that this reduction was caused by the problems resulting from the dam failure.

The ideal in this scenario would be to observe the behavior of the sex ratio for the set of municipalities affected by the Brumadinho disaster if they had not been involved. As this situation is not possible, the alternative is to find municipalities with similar behavior to the municipalities affected in the periods before the dam rupture and to verify if the reduction in the sex ratio observed in the cities affected by the tailings of the dam mud was also observed in the others counties.

The difference-in-differences method deals with this type of situation by comparing the difference in the value of the outcome variable between the affected units and a control group before the occurrence of the shock or policy to be analyzed with the differences in that same variable after the shock or procedure. However, two problems emerge when using the method in the scenario described in this article. First, as

Figura 7: Evolution of the Sex Ratio - Period of Pregnancy

(a) Brumadinho



(b) Nearby municipalities

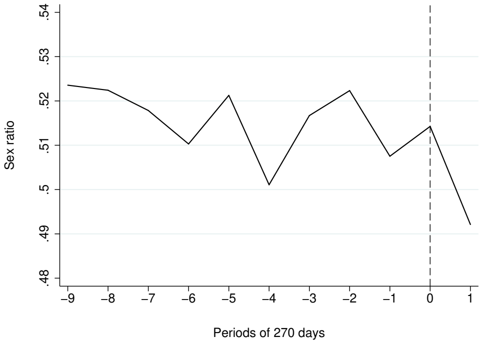
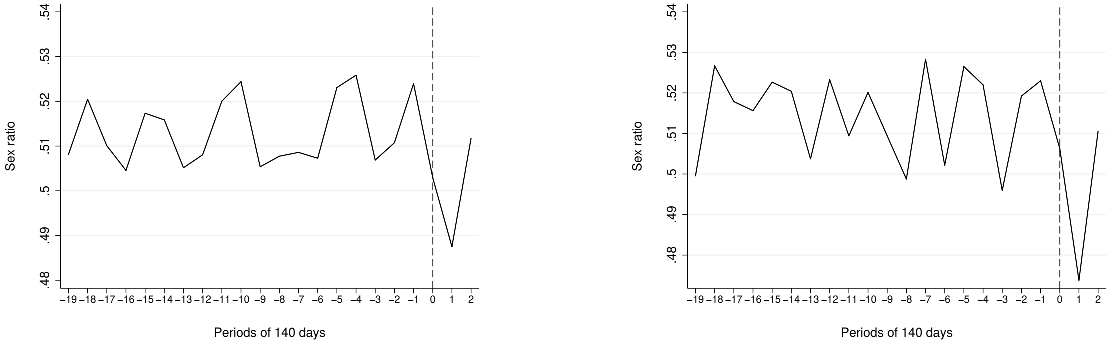


Figura 8: Evolution of Sex Ratio - Half of the Pregnancy



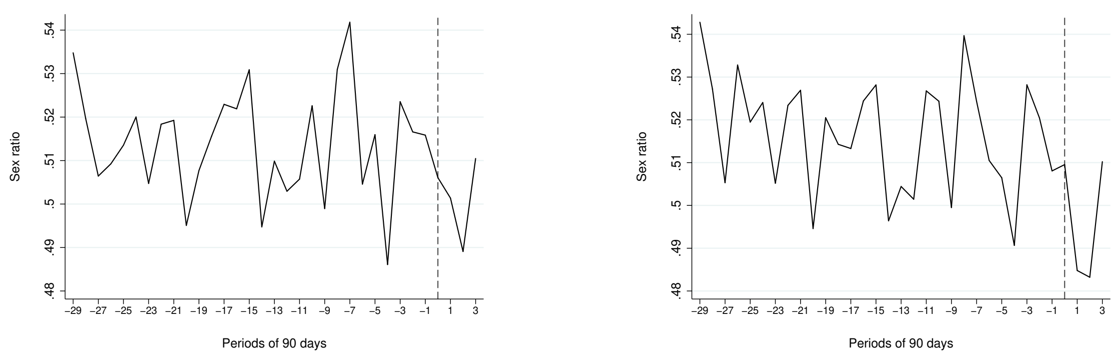
(a) Brumadinho

(b) Nearby municipalities

discussed in the database section, the behavior of the sex ratio in units with a low number of live births is volatile, with a very high oscillation. As a result, it is necessary to aggregate all affected municipalities into a single unit. However, the different methods only present good properties for analyzing one treated unit.

The other problem lies in the difficulty of meeting the central hypothesis of the differences-in-differences method, the idea of parallel trends. For the difference observed between the control group and the treated unit in the post-shock period, the behavior of the outcome variable in the periods before the shock must present a parallel evolution. Due to the sex ratio's natural oscillation over time, finding municipalities that

Figura 9: Evolution of Sex Ratio - Trimesters of Pregnancy


(a) Brumadinho

(b) Nearby Municipalities

offer a similar change is challenging.

Both problems can be tackled using the construction of a synthetic unit. Abadie and Gardeazabal (2003) proposes a synthetic control method to deal with cases in which only one team is affected by the phenomenon to be analyzed and by a small number of possible control units. The authors propose using a weighted average of the control units to construct the treatment team's potential outcome without treatment. Suppose such a synthetic unit can be found. In that case, the difference in yield between the treated unit and the synthetic unit in the post-treatment period is interpreted as the causal effect of the treatment.

A series of articles appeared that applied and improved the synthetic control method. More recently,Arkhangelsky, Athey, Hirshberg, Imbens, and Wager (2021) proposed using the artificial control framework and developed the synthetic differences-in-differences method.

Therefore, the synthetic differences-in-differences method is used in this article to estimate the causal relationship between the stress caused by pregnant women due to the Brumadinho dam failure and the observed reduction in the sex ratio.

The estimations are applied in six different specifications formed by combining the elements of two groups. One group refers to the definition of affected municipalities, where two purposes are used. In the first definition, all municipalities affected by the dam's tailings are considered, while in the second, only the nine closest municipalities are considered. The other refers to the three possibilities of dividing the gestational period. The entire pregnancy period is used, then the pregnancy is divided into two halves and finally into three trimesters.

An important point in applying methods that seek to build a synthetic unit is the definition of candidate control units.(*donor pool*). In the specific case of this article, as presented in the section on the database, it is known that the sex ratio has a high variability in municipalities with a low number of live births. This high variability over time makes it difficult to identify the effect. Therefore, municipalities with small live births are not considered possible candidates for control. The number of live births in the affected unit depends on the definition of the affected area, all the municipalities, or only the closest ones, and the adopted division of the gestational period. The choice of cut-off criterion for the municipalities that make up the control group is, therefore, based on the number of live births. For each specification mentioned above, it was defined that every municipality with several live births equal to or greater than 80% of the number of live births of the treated unit in the first period analyzed is considered in the group of municipalities that are candidates for control.

Another critical point in the method is the definition of which variables will be used to construct the weights of the synthetic unit. Using the lagged result variable and considering some relevant covariates to explain the result variable is possible. In the case of this article, the sex ratio, the primary variable of interest, is poorly explained by variables related to the mothers' characteristics. Therefore, a specification with only lagged variables is adopted. As the sex ratio for the treated unit fluctuates over the analyzed time, the specification will use lags for each period.

Several estimations with different cutoff criteria were performed to verify whether the results were sensitive to the cutoff criterion and to give them more robustness.

6 Results

6.1 Effects on the sex ratio

This section presents the main results of the article and the analysis of the possible effects of the Brumadinho dam failure on the sex ratio of live births. Table 2 presents the results for the six estimations, as presented in the empirical strategy section. The results are displayed as follows. Columns (1) and (2) analyze the effect of the dam failure considering the pregnancy period as a whole. In column (1), the live births in all seventeen municipalities affected by the dam tailings are deemed affected by the disaster. In contrast, in column (2), only the municipalities closest to the dam failure site are considered. In columns (3) and (4), the results of the estimations are presented with the division of the gestational period in two for all the affected municipalities and the closest ones, respectively. Finally, the division into gestational trimesters is used in columns (5) and (6).

The result of column (1), despite presenting a negative coefficient, has no statistical significance. Analyzing the effect only in the most intensely affected municipalities, column (2), there is a reduction in the sex ratio of almost two percentage points. This result corroborates the idea that in stressful situations during pregnancy, the probability of a live birth being a girl increases due to the more significant number of spontaneous abortions in boys. Therefore, comparing the two results, it is highlighted that the intensity of stress matters for the most significant increase in male fetal deaths.

The next two columns of the table 2, columns (3) and (4), analyze the effect by dividing the gestational period in two. Although there is no consensus on the most sensitive period, some studies find that the first half of pregnancy is more sensitive.(Torche, 2011; Catalano et al., 2006).The results found in this article are in the same direction, showing evidence of a reduction in the sex ratio for the affected cohort during the first half of pregnancy. This result occurs even when all municipalities affected by the dam failure are considered. The effect is greater than the magnitude found in the specification considering the entire gestational period, with two and a half percentage points in the specification for all municipalities and almost five percentage points for the closest municipalities. This greater magnitude is expected, as this specification better identifies the shock-sensitive period. As there is no result for the second half of pregnancy, the effect was diluted when analyzing the entire pregnancy period. It is important to highlight again the increase in the effect of the specification with all municipalities for the specification with only the closest municipalities.

In columns (5) and (6), the analysis results of dividing the gestational period into three trimesters are presented. In column (5), where all municipalities are considered, only during the second trimester of pregnancy is there a significant effect of the stress caused by the dam failure. The result indicates a reduction of almost two percentage points in the sex ratio. The results in column (6) show a decrease in the sex ratio in the first two quarters of more than two percentage points. The results of these two specifications corroborate

Tabela 2: Sex Ratio

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,0088	-0,0184*				
	(0,0075)	(0,0098)				
1st half			-0,0250**	-0,0471***		
			(0,0120)	(0,0152)		
2nd half			-0,0002	-0,0064		
			(0,0116)	(0,0119)		
1st trimester					-0,0077	-0,0377**
					(0,0132)	(0,0148)
2nd trimester					-0,0198*	-0,0243*
					(0,0114)	(0,0146)
3rd trimester					-0,0052	0,0008
					(0,0140)	(0,0160)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

the results presented in columns (3) and (4) that the effects are more felt in the beginning and middle of pregnancy.

It is essential to compare the results found in this article with the literature results. It is necessary to emphasize that studies focus on shocks that occur continuously or over a certain period, and others concentrate on single-event wonders, as in this article. Among studies analyzing prolonged shocks,Kemkes (2006) finds a reduction of almost four percentage points due to the French Revolutionary War (1792-1802), Valente (2015) reports a decrease of nearly two percentage points when analyzing civil conflicts in Nepal andSanders and Stoecker (2011)estimates a reduction of minus half a percentage point caused by air pollution in the United States. Considering shocks caused by single events,Peterka, Peterková, and Likovskỳ (2004) finds a reduction of approximately four percentage points in the sex ratio after the Chornobyl disaster, and Torche (2011) reports a decrease of almost six percentage points.

6.2 Selection in utero or fetal origin?

The previous section presented evidence of a reduction in the sex ratio due to the stress caused by the Brumadinho dam failure. The decline was concentrated in the beginning and middle of pregnancy, with greater intensity in those municipalities closest to the dam failure site. This section seeks to understand the primary mechanism that explains this reduction. Negative impacts on birth outcomes indicate that the main transmission channel was via the fetal origin theory; that is, the plasticity of fetal development causes the fetus to adapt to the adverse condition, worsening some birth outcomes. If positive impacts on birth outcomes are observed, the primary mechanism that acted in the inversion of the sex ratio was a selection in utero. It is important to remember that these two possible mechanisms are not mutually exclusive; they can act concomitantly, even causing no effect in live births, especially when looking at the mean birth measurements.

Therefore, the results of the impact of the dam failure on birth weight, probability of being born with low weight, gestation time, the likelihood of being born prematurely, and intrauterine growth are presented below. For each of these birth measures, three sets of results are presented. Analyzing the impact on live births without separation by sex of live births, and analyzing boys and girls separately

The first birth outcome analyzed is birth weight, the leading birth characteristic studied in the literature. Table **??** presents estimates for all live births without distinguishing the child's sex. No statistically significant results were found. This first result indicates that both phenomena affected the live birth cohort simultaneously. It is interesting to note that despite the estimated coefficients not showing statistical significance, it is clear that the sign is positive in the estimations considering all municipalities and becomes negative in almost all estimates for the group of closest cities. This inversion of the signal alerts to a possible influence of the shock intensity on the results and mechanisms involved.

Tabela 3: Birth weight

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	10,3558	-11,4833				
	(12,5916)	(18,9669)				
1st half			6,4833	3,7458		
			(25,5558)	(19,2389)		
2nd half			5,7658	-16,4129		
			(18,7911)	(18,2552)		
1st trimester					14,1598	-2,6812
					(23,6537)	(19,5988)
2nd trimester					0,6305	-13,2884
					(19,4857)	(19,1594)
3rd trimester					22,4683	-0,4491
					(17,1436)	(20,3402)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

The following two tables present the results separated by sex of live births. Again, no results are found analyzing the effect only in boys. However, it is interesting that almost all the coefficients presented have negative values, except for the two coefficients related to the third trimester, indicating a possible greater sensitivity of boys. Already in table 5, which presents the results for girls, there is a positive effect on birth weight when looking at the set of all affected municipalities and the entire period of pregnancy (column 1). This result is the first evidence that girls may be more impacted by selection in utero than by shifting the health curve to the left, representing a worsening in the cohort's health.

Tabela 5: Birth weight - Girls

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	25,0332*	-17,3648				
	(13,4929)	(23,9579)				
1st half			25,1943	20,1524		
			(27,9764)	(24,6650)		
2nd half			21,9364	-9,2030		
			(23,7469)	(22,0156)		
1st trimester					36,7373	11,8873
					(26,4958)	(24,6901)
2nd trimester					14,9658	5,3288
					(25,1279)	(31,7848)
3rd trimester					20,8245	-11,1127
					(21,7865)	(32,2428)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 4: Birth weight - boys

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-8,2867	-16,9520				
	(19,8377)	(21,8327)				
1st half			-14,5309	-14,4971		
			(37,4340)	(26,3599)		
2nd half			-15,2881	-7,5783		
			(21,0864)	(23,1188)		
1st trimester					-19,0278	-21,4657
					(32,4648)	(29,0980)
2nd trimester					-11,3454	-29,6962
					(24,5260)	(22,2610)
3rd trimester					5,3140	6,0515
					(20,6977)	(26,7736)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

In addition to looking at the average birth weight, it is also essential to analyze the probability of the child being born with a low birth weight. Exploring the impact on the bass is necessary as it is possible that, on average, the effect is not very noticeable or that the product is concentrated in the lower tail of the distribution. Therefore, the following three tables present the estimates for the impact on birth weight. Appendix 1 shows birth weight density graphs comparing pre-shock and post-shock weights. Although the curves are very similar, it is possible to notice that the lower tail of children affected by the dam failure is a little denser, indicating that the negative effect is more concentrated in this part of the distribution.

In table 6, there was an increase in the probability of being born with low weight for children in the third trimester of intrauterine formation and living in the municipalities closest to the dam failure. Despite being a relevant result, this result does not help to understand the mechanism that led to a reduction in the sex

Tabela 6: Low birth weight

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	0,0031	0,0103				
	(0,0069)	(0,0076)				
1st half			0,0028	0,0080		
			(0,0105)	(0,0094)		
2nd half			-0,0005	0,0115		
			(0,0067)	(0,0079)		
1st trimester					-0,0043	0,0084
					(0,0086)	(0,0112)
2nd trimester					-0,0032	0,0078
					(0,0088)	(0,0099)
3rd trimester					0,0070	0,0182*
					(0,0075)	(0,0099)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

ratio presented in the previous section, as there is no effect on the sex ratio for those affected during the third trimester of pregnancy.

When analyzing boys in isolation, the results contribute to a better understanding of the primary mechanism that acts to reduce the sex ratio. In table 7, there is an increase in the probability of being born with low birth weight for affected boys during the second trimester of intrauterine development. The increase in likelihood was almost two percentage points considering all municipalities, column (5) and a little more than two and a half points for the closest cities, column (6). The results indicate a more significant effect of the negative shift in the health distribution for boys compared to selection in utero. This result is most clearly shown in the lower tail of the distribution. Therefore, there was not necessarily a shift of the entire distribution; it is more likely that the distribution has become less concentrated, with only the lower tail shifting to the left.

Tabela 7: Low birth weight - boys

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	0,0115	0,0113				
	(0,0076)	(0,0084)				
1st half			0,0202	0,0177		
			(0,0129)	(0,0112)		
2nd half			0,0096	0,0081		
			(0,0082)	(0,0095)		
1st trimester					0,0051	0,0076
					(0,0118)	(0,0147)
2nd trimester					0,0175*	0,0241**
					(0,0096)	(0,0113)
3rd trimester					0,0012	0,0077
					(0,0091)	(0,0116)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

The results of the isolated analysis for girls are presented in the table 8. The result is similar to that found in table 6, with an increase in the probability of birth with low manifesting in the affected girls in the third trimester. It is interesting to note that when comparing the results of the table 7 and 8, it is said that the effects are manifested at different times of the pregnancy period. While for boys, the beginning and middle of pregnancy is a more sensitive period, for girls, it occurs in the final stage of pregnancy.

Tabela 8: Low birth weight - girls

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,0033 (0,0079)	0,0097 (0,0101)				
1st half			-0,0110 (0,0132)	-0,0087 (0,0131)		
2nd half			0,0001 (0,0103)	0,0110 (0,0112)		
1st trimester					-0,0071 (0,0108)	-0,0067 (0,0151)
2nd trimester					-0,0150 (0,0102)	-0,0147 (0,0136)
3rd trimester					0,0113 (0,0112)	0,0341** (0,0141)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

In addition to the analysis of birth weight, it was also verified whether the dam rupture impacted gestation time, the probability of premature birth, and intrauterine growth. No significant results were found for these measures. This reinforces the idea that the two mechanisms work in reducing the sex ratio. The tables with these results are presented in Appendix 2.

In general, the only result with significant estimates that help to understand the mechanism that acts to reduce the sex ratio is the probability of low birth weight in boys. Therefore, it is clear that both agencies work to reduce the sex ratio. However, there is evidence of an aspect little highlighted in the literature; a negative shock does not necessarily displace the entire health distribution. A more pronounced shift may occur in the lower tail, causing an increase in the dispersion of the health distribution.

7 Robustness Analysis

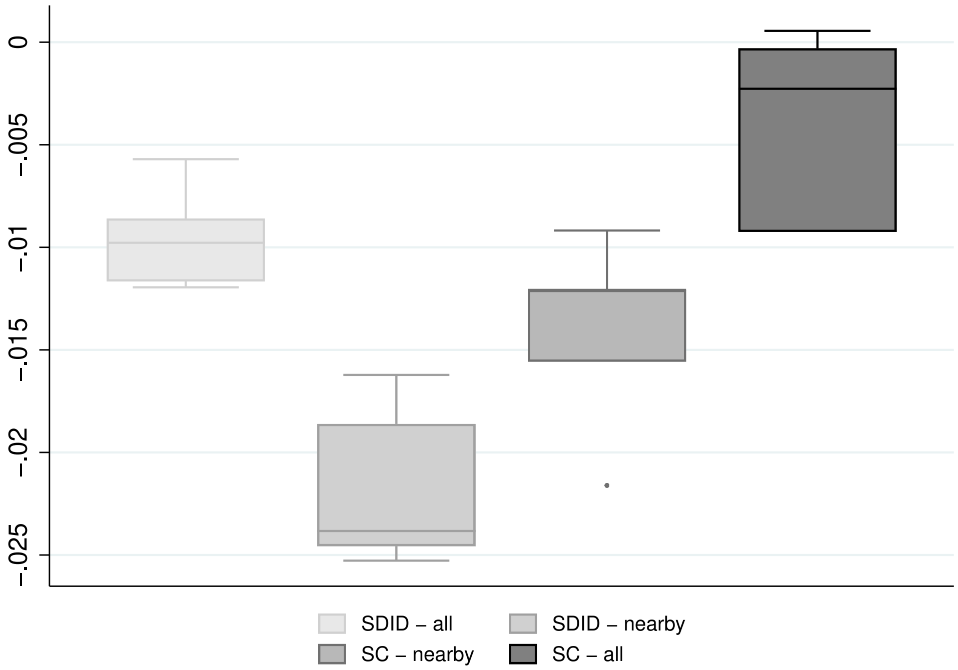
The results indicate that the dam failure impacted the sex ratio, reducing the proportion of live-born boys. The criterion for selecting the municipalities to compose the control group was based on the number of live births. However, the cut-off limit is an arbitrary decision by the researcher. It is essential to verify the sensitivity of the results to this choice. Therefore, in this section, a series of estimations are carried out, altering this set to get an idea of the results' sensitivity. Still, the synthetic control method was also used to seek greater robustness of the results. For each specification and cutoff using the synthetic differences-in-differences method, the results estimated by the synthetic control method are presented.

Another way to obtain more excellent reliability of the results is to carry out placebo tests, creating a fictitious date for the shock. Specifically, in this article, the biggest challenge is to mimic the natural oscillation of the sex ratio, by analyzing the graphs 7, 8 and 9, it is noted that, in a period close to the dam failure, the sex ratio reached values very close to the values observed after the shock, mainly for the specifications that consider the entire gestational period and for those that use the trimesters of gestation.

To obtain greater confidence that the result found was caused by the stress caused by the dam failure and not just a coincidence of the sex ratio having fluctuated down at the same time, a series of placebo tests were estimated, reducing the shock date.

First, the results for robustness are presented by changing the cut-off limit based on the number of live births and using the synthetic control method. In the figure 10, the results for the robustness analysis considering the entire gestational period are presented. To summarize the results, we offer the distribution of estimates for each specification, the synthetic differences-in-differences method for all municipalities and only the closest ones, and the synthetic control method for all cities and only the closest ones. It is possible to notice that all the estimates present negative coefficients for the two specifications using the method of differences in differences. The same occurs for the synthetic control method applied only to the closest municipalities. The synthetic control method for all cities presents estimates with values relative to zero, including estimates in the upper tail showing positive values. In general, the results show that the forecast for the municipalities most comparable to the dam failure is robust to changes in the cutoff limit of cities by the number of live births.

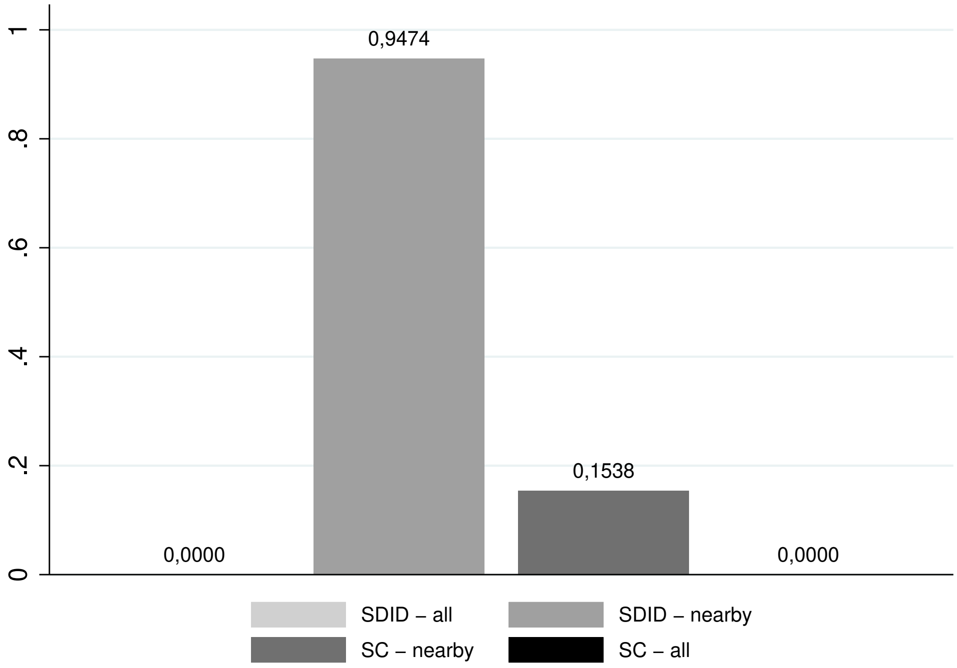
Figura 10: Pregnancy robustness



However, in addition to looking at the variability of the estimates, it is necessary to analyze the statistical significance of these estimates. In the figure 11, the percentage of assessments presented significant coefficients at 10%. The estimates considering all municipalities were not substantial. When looking only at the closest cities, it is observed that almost all the calculations using the synthetic differences-in-differences method have significant coefficients. In contrast, only 15% of the estimates use the synthetic control method.

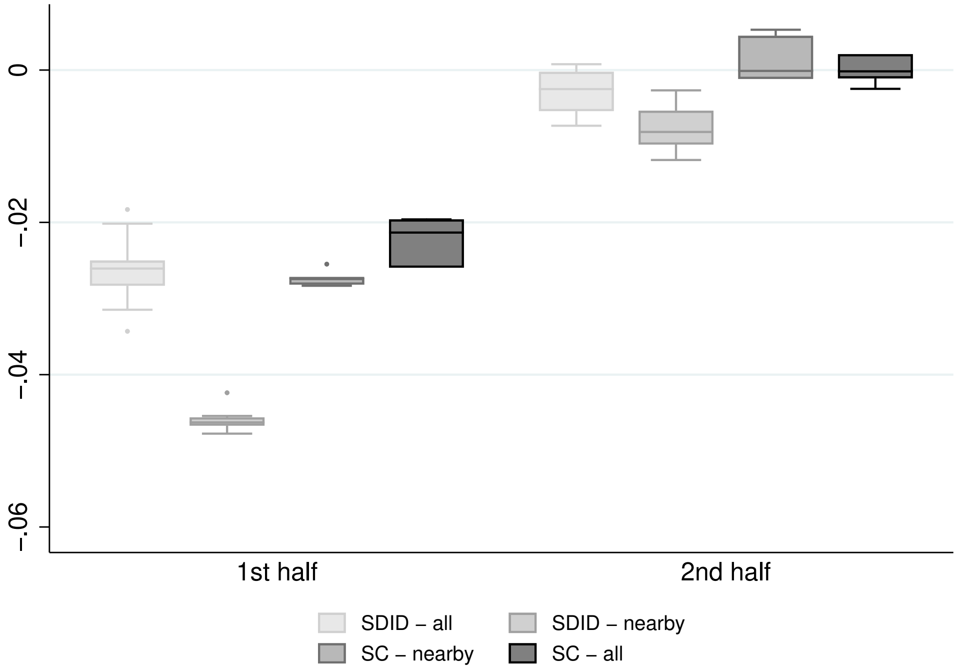
The following two graphs present the robustness analysis for the specifications considering the two halves of gestation. For the first half, all estimates have negative values. The forecast for the municipalities closest to the dam site shows less variability, indicating that they are less sensitive to the definition of control

Figura 11: Pregnancy robustness - significance level



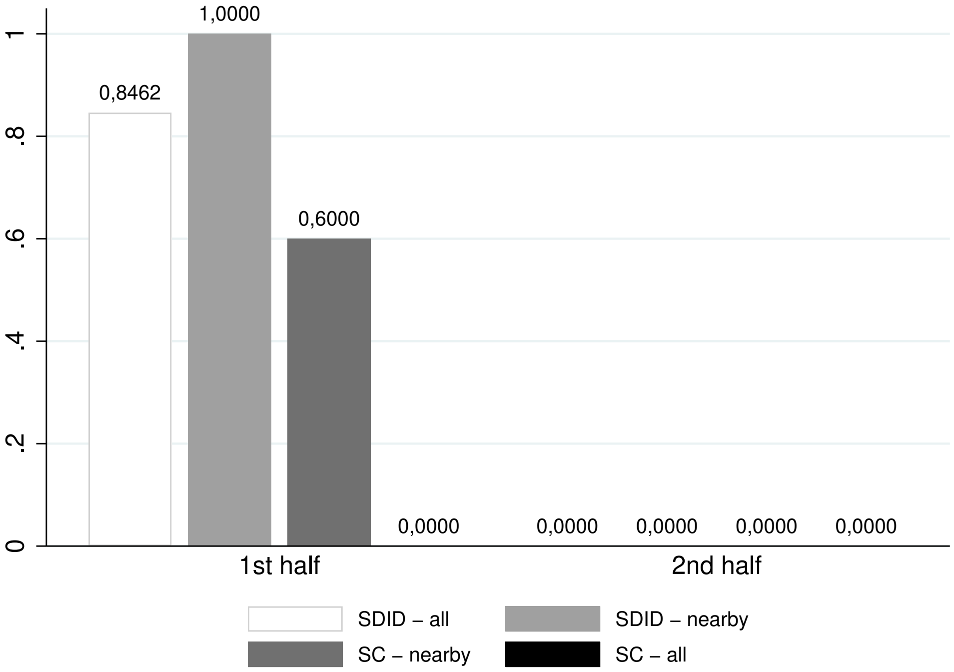
municipalities.

Figura 12: Robustness - 2 gestational periods



Considering the significance level, the results show that for the municipalities close to each other, the percentage of estimates with a significance of 10% reaches almost 85%

Figura 13: Robustness - 2 gestational periods- significance level



The next two graphs show the results of the robustness tests for dividing the gestational period into quarters. the graph 14 shows the distribution of estimated coefficients. The first quarter results show a large difference between the estimates' magnitudes for the closest municipalities group compared to all affected municipalities. For the second quarter estimates, the results show a lower sensitivity to variations in the selection criteria for control municipalities. As for the third quarter, the estimates are all close to zero.

The significance level of the estimates in the previous graph indicates that the results found for the first trimester of pregnancy, when considering only the closest municipalities, have a significance of 100%

The following exercises refer to the estimation of placebos to verify if the observed reduction in the sex ratio in the post-shock period can be interpreted as a causal effect of the dam failure or a reduction due to the natural oscillation of the balance that coincided with the dam failure. Therefore, tests are estimated by changing the shock date to dates before the shock, creating placebo shocks. Suppose the results of these estimates are not significant. In that case, it is understood that the results found in this article point to a causal relationship between the dam failure and the reduction in the sex ratio.

A series of placebos were estimated as follows. For each of the six specifications, time was regressed to half the number of pre-shock periods. For example, when considering pregnancy as a whole, there are ten pre-shock periods. Therefore, five placebo shocks were created, considering a placebo shock in the period before the real surprise, then with two previous periods, and so on until the fifth period before the shock. Regressions were estimated for each placebo with all the cutoff criteria used in the robustness presented above.

The graph in Fig. 16 indicates that the estimated placebo values are nearly zero for all six specifications.

Figura 14: Robustness quarters

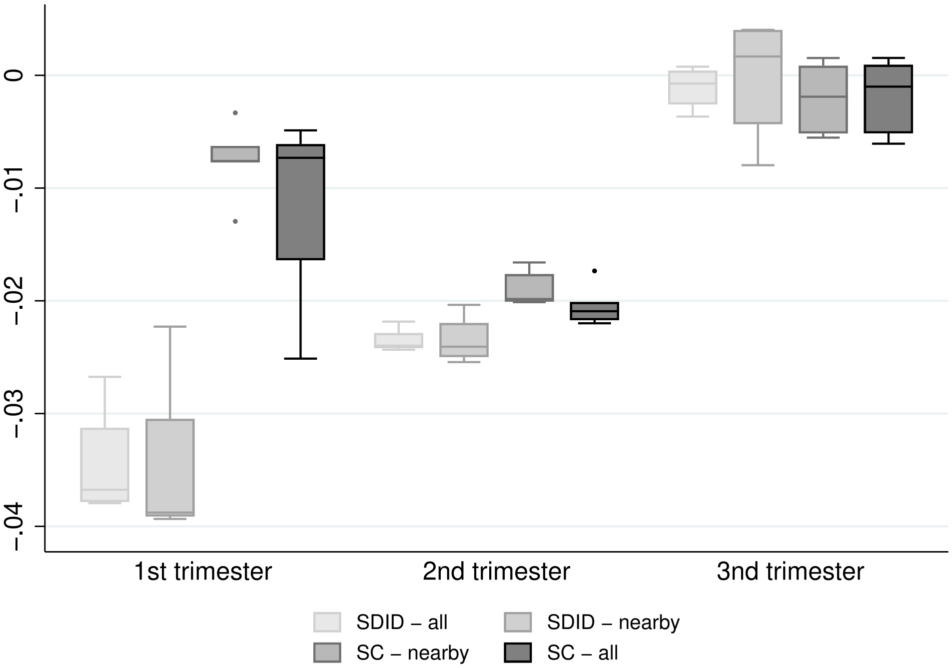
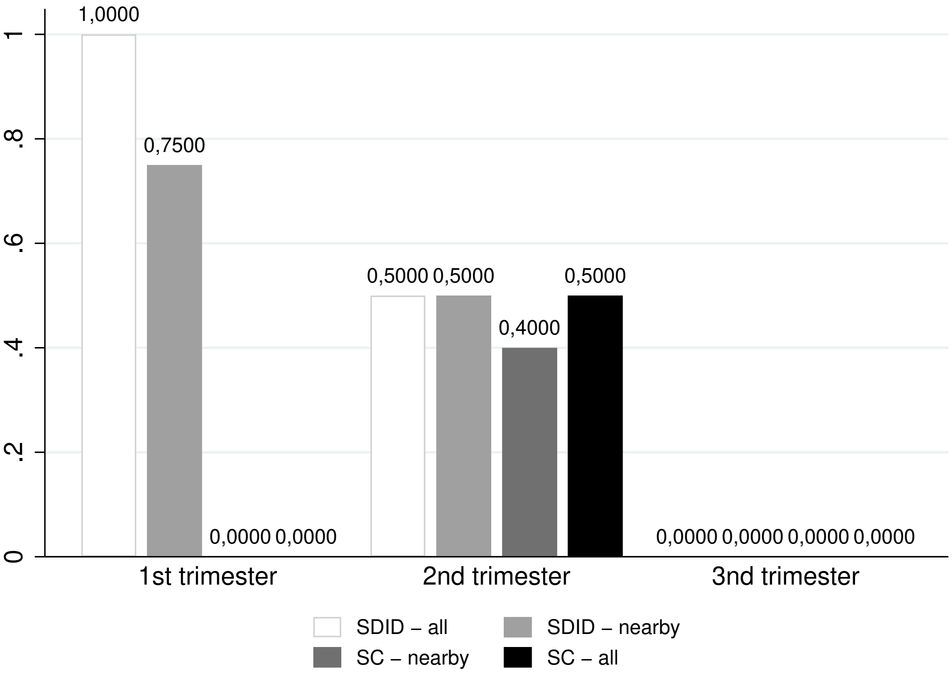
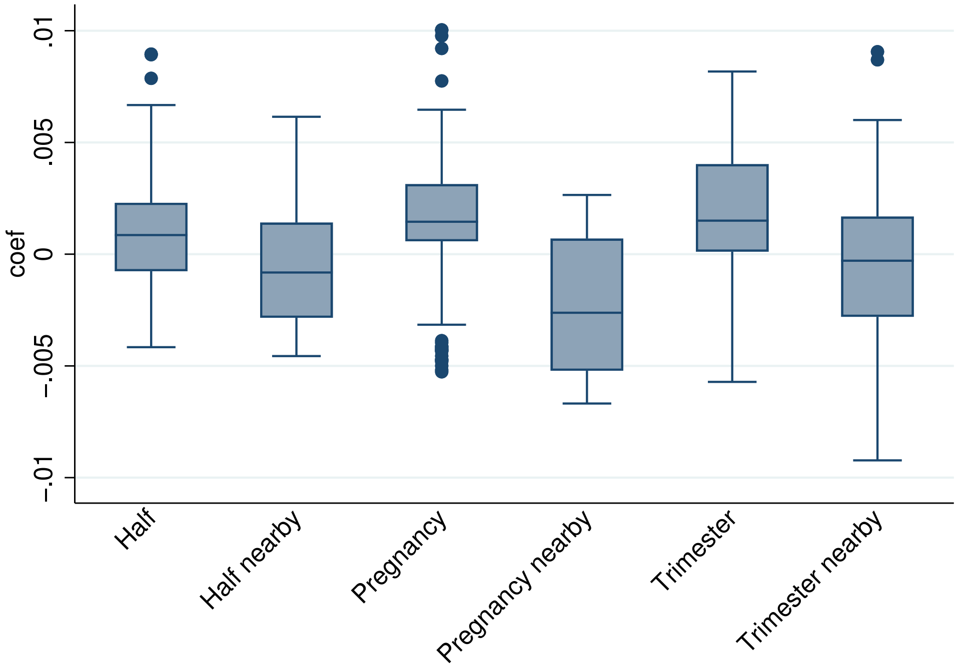


Figura 15: Robustness quarters - significance level



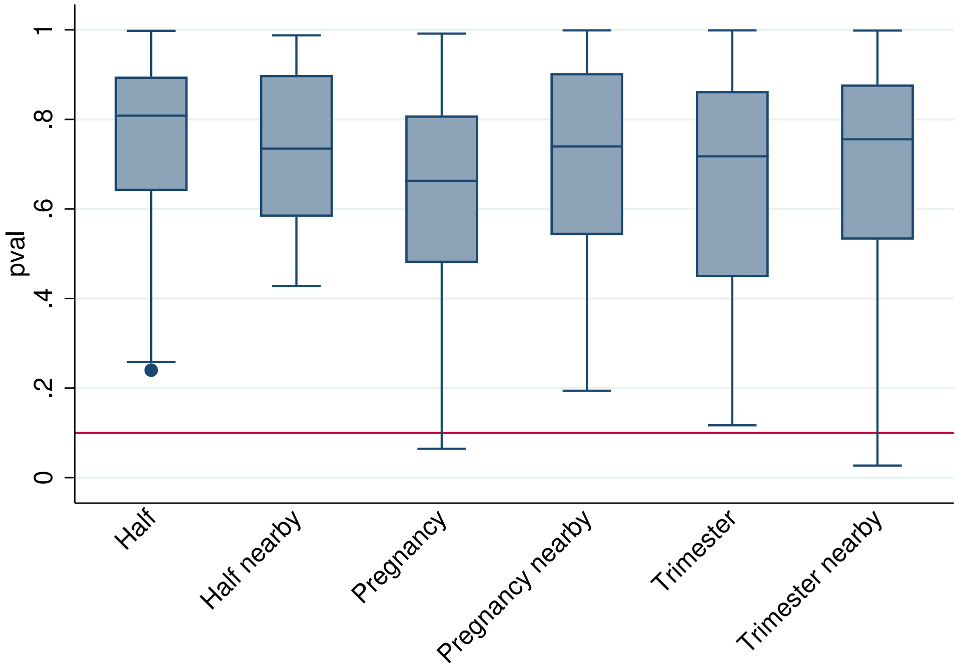
This result suggests that the reduction observed in the sex ratio in the period after the adverse effects of the disaster caused the dam failure.

Figura 16: Robustness quarters - significance level



To confirm the absence of effects in the placebo tests, the plot 17 shows the distribution of p-values of the estimates for each specification. The horizontal line drawn on the graph represents the 10% limit of the p-value. It is only for the specification of the entire pregnancy period and all municipalities, and for the specification considering pregnancy trimesters and nearby cities, there are p-values below the limit. For the specification of the pregnancy period, three estimates were found with p-values below 0.10, which represents 2.38% of all assessments for this specification. As for the specification of quarters, only one estimate had a p-value lower than 0.10, meaning 1.56%

Figura 17: Robustness quarters - significance level



8 Final Remarks

Recent cases of dam failure in Brazil raise concerns beyond the environmental effects. The affected population's health suffers negative consequences regarding physical and mental health.

The article's results provide evidence of a negative impact on the sex ratio of the cohort of live births affected by the rupture of the Brumadinho dam during pregnancy. Reductions in the sex ratio are a sign of maternal health problems during pregnancy and are caused by an increase in male fetal deaths. Two possible mechanisms act in the rise of male fetal deaths. On the one hand, there may be a shift in the health conditions of the fetuses, with a more significant number of male fetuses being below the survival line. As a result, there is an increase in male deaths and a worsening in the health of live births. On the other hand, it is argued that the health distribution of fetuses remains constant, and the line of survival is shifting. Thus, the weakest male fetuses do not survive, but the surviving cohort is positively selected. The article's results indicate that both mechanisms act to reduce the sex ratio.

It is essential to highlight that most studies investigating adverse shocks' impact on fetal development only analyze birth or health measures throughout the life cycle. The absence of significant results in this type of analysis does not mean any effect; it may be that there was an impact on the cohort affected by the shock but that the two mechanisms act simultaneously, masking the effect on the observed measures. Therefore, the importance of analyzing the impact of negative surprises on the sex ratio is highlighted.

Referências

Abadie, A., & Gardeazabal, J. (2003). The economic costs of conflict: A case study of the basque country.

American economic review, *93*(1), 113–132.

Almond, D., & Currie, J. (2011). Killing me softly: The fetal origins hypothesis. *Journal of economic perspectives*, *25*(3), 153–72.

Almond, D., Currie, J., & Duque, V. (2018). Childhood circumstances and adult outcomes: Act ii. *Journal of Economic Literature*, *56*(4), 1360–1446.

Ansari-Lari, M., & Saadat, M. (2002). Changing sex ratio in iran, 1976–2000. *Journal of Epidemiology & Community Health*, *56*(8), 622–623.

Arkhangelsky, D., Athey, S., Hirshberg, D. A., Imbens, G. W., & Wager, S. (2021). Synthetic difference-in-differences. *American Economic Review*, *111*(12), 4088–4118.

Armstrong, M., Petter, R., & Petter, C. (2019). Why have so many tailings dams failed in recent years? *Resources Policy*, *63*, 101412.

Barker, D. J. (1995). Fetal origins of coronary heart disease. *Bmj*, *311*(6998), 171–174.

Barker, D. J., & Osmond, C. (1986). Infant mortality, childhood nutrition, and ischaemic heart disease in england and wales. *The Lancet*, *327*(8489), 1077–1081.

Bruckner, T., & Catalano, R. (2007). The sex ratio and age-specific male mortality: evidence for culling in utero. *American Journal of Human Biology: The Official Journal of the Human Biology Association*, *19*(6), 763–773.

Bruckner, T. A., & Catalano, R. (2018). Selection in utero and population health: theory and typology of research. *SSM-population health*, *5*, 101–113.

Bruckner, T. A., Lebreton, É., Perrone, N., Mortensen, L. H., & Blondel, B. (2019). Preterm birth and selection in utero among males following the november 2015 paris attacks. *International journal of epidemiology*, *48*(5), 1614–1622.

Carrillo, B., Da Mata, D., Emanuel, L., Lopes, D., & Sampaio, B. (2020). Avoidable environmental disasters and infant health: Evidence from a mining dam collapse in brazil. *Health economics*, *29*(12), 1786–1794.

Catalano, R., & Bruckner, T. (2006). Secondary sex ratios and male lifespan: damaged or culled cohorts. *Proceedings of the National Academy of Sciences*, *103*(5), 1639–1643.

Catalano, R., Bruckner, T., Marks, A. R., & Eskenazi, B. (2006). Exogenous shocks to the human sex ratio: the case of september 11, 2001 in new york city. *Human reproduction*, *21*(12), 3127–3131.

Catalano, R., Yorifuji, T., & Kawachi, I. (2013). Natural selection in utero: evidence from the great east japan earthquake. *American Journal of Human Biology*, *25*(4), 555–559.

Chang, H.-L., Chang, T.-C., Lin, T.-Y., & Kuo, S.-S. (2002). Psychiatric morbidity and pregnancy outcome in a disaster area of taiwan 921 earthquake. *Psychiatry and clinical neurosciences*, *56*(2), 139–144.

Currie, J., & Rossin-Slater, M. (2013). Weathering the storm: Hurricanes and birth outcomes. *Journal of health economics*, *32*(3), 487–503.

Dagnelie, O., De Luca, G. D., & Maystadt, J.-F. (2018). Violence, selection and infant mortality in congo. *Journal of health economics*, *59*, 153–177.

Davis, D. L., Gottlieb, M. B., & Stampnitzky, J. R. (1998). Reduced ratio of male to female births in several industrial countries: a sentinel health indicator? *Jama*, *279*(13), 1018–1023.

Forchhammer, M. (2000). Timing of foetal growth spurts can explain sex ratio variation in polygynous mammals. *Ecology Letters*, *3*(1), 1–4.

Fukuda, M., Fukuda, K., Mason, S., Shimizu, T., & Andersen, C. Y. (2018). The sex ratio at birth after recent major earthquakes in japan. *Early human development*, *123*, 30–31.

Fukuda, M., Fukuda, K., Shimizu, T., & Møller, H. (1998). Decline in sex ratio at birth after kobe earthquake.

Human Reproduction (Oxford, England), *13*(8), 2321–2322.

Glynn, L. M., Wadhwa, P. D., Dunkel-Schetter, C., Chicz-DeMet, A., & Sandman, C. A. (2001). When stress happens matters: effects of earthquake timing on stress responsivity in pregnancy. *American journal of obstetrics and gynecology*, *184*(4), 637–642.

Grech, V. (2015). Terrorist attacks and the male-to-female ratio at birth: The troubles in northern ireland, the rodney king riots, and the breivik and sandy hook shootings. *Early human development*, *91*(12), 837–840.

Hamamatsu, Y., Inoue, Y., Watanabe, C., & Umezaki, M. (2014). Impact of the 2011 earthquake on marriages, births and the secondary sex ratio in japan. *Journal of biosocial science*, *46*(6), 830–841.

Hamilton, B. E., Martin, J. A., Mathews, T., Sutton, P. D., & Ventura, S. J. (2009). The effect of hurricane katrina: births in the us gulf coast region, before and after the storm.

Inoue, Y., & Mizoue, T. (2022). A preliminary analysis of the secondary sex ratio decline after the covid-19 pandemic in japan. *American Journal of Human Biology*, eajhb.

James, W. H., & Grech, V. (2018). Can sex ratios at birth be used in the assessment of public health, and in the identification of causes of selected pathologies? *Early human development*, *118*, 15–21.

Kemkes, A. (2006). Secondary sex ratio variation during stressful times: the impact of the french revolutionary wars on a german parish (1787–1802). *American Journal of Human Biology: The Official Journal of the Human Biology Association*, *18*(6), 806–821.

King, S., & Laplante, D. P. (2005). The effects of prenatal maternal stress on children's cognitive development: Project ice storm. *Stress*, *8*(1), 35–45.

Laplante, D. P., Barr, R. G., Brunet, A., Du Fort, G. G., Meaney, M. L., Saucier, J.-F., . . . King, S. (2004). Stress during pregnancy affects general intellectual and language functioning in human toddlers. *Pediatric research*, *56*(3), 400–410.

Laplante, D. P., Brunet, A., Schmitz, N., Ciampi, A., & King, S. (2008). Project ice storm: Prenatal maternal stress affects cognitive and linguistic functioning in 51/2-year-old children. *Journal of the American Academy of Child & Adolescent Psychiatry*, *47*(9), 1063–1072.

Masukume, G., O'Neill, S. M., Khashan, A. S., Kenny, L. C., & Grech, V. (2017). The terrorist attacks and the human live birth sex ratio: a systematic review and meta-analysis. *Acta Medica (Hradec Kralove)*, *60*(2), 59–65.

Mayorga, C. (2020a). Desastre de brumadinho e os impactos na saúde mental. *Ciência e Cultura*, *72*(2), 06–08.

Mayorga, C. (2020b, 04). Desastre de brumadinho e os impactos na saúde mental. *Ciência e Cultura*, *72*, 06 - 08. Retrieved from `http://cienciaecultura.bvs.br/scielo.php?script=sci_arttext&pid=S0009-67252020000200003&nrm=iso`

Miranda, D. M., Coelho, B. A. d. O., Benites, L. P., Parreira, G. d. O., Carvalho, A. J. P., & Fernandes, P. N. F. (2021). Impactos físicos e psicológicos na população de brumadinho após rompimento da barragem de rejeitos. *Rev. méd. Minas Gerais*, 31212–31212.

Mrejen, M., Perelman, J., & Machado, D. C. (2020). Environmental disasters and birth outcomes: Impact of a tailings dam breakage in brazil. *Social Science & Medicine*, *250*, 112868.

Noal, D. d. S., Braga, V. M. R., Leal, M. B., Vargas, A. R., & Eliazar, P. (2021). Desastre da vale: o desafio do cuidado em saúde mental e atenção psicossocial no sus. *Saúde em Debate*, *44*, 353–363.

Noal, D. d. S., Rabelo, I. V. M., & Chachamovich, E. (2019). O impacto na saúde mental dos afetados após o rompimento da barragem da vale. *Cadernos de Saúde Pública*, *35*.

Peixoto, S. V., & Asmus, C. I. R. F. (2020). O desastre de brumadinho e os possíveis impactos na saúde. *Ciência e Cultura*, *72*(2), 43–46.

Peterka, M., Peterková, R., & Likovskỳ, Z. (2004). Chernobyl: prenatal loss of four hundred male fetuses in the czech republic. *Reproductive Toxicology*, *18*(1), 75–79.

Sanders, N. J., & Stoecker, C. F. (2011). *Where have all the young men gone? using gender ratios to measure fetal death rates* (Tech. Rep.). National Bureau of Economic Research.

Tan, C. E., Li, H. J., Zhang, X. G., Zhang, H., Han, P. Y., An, Q., ... Wang, M. Q. (2009). The impact of the wenchuan earthquake on birth outcomes. *PLoS One*, *4*(12), e8200.

Thompson, F., de Oliveira, B. C., Cordeiro, M. C., Masi, B. P., Rangel, T. P., Paz, P., ... others (2020). Severe impacts of the brumadinho dam failure (minas gerais, brazil) on the water quality of the paraopeba river. *Science of the Total Environment*, *705*, 135914.

Tong, V. T., Zotti, M. E., & Hsia, J. (2011). Impact of the red river catastrophic flood on women giving birth in north dakota, 1994–2000. *Maternal and child health journal*, *15*(3), 281–288.

Torche, F. (2011). The effect of maternal stress on birth outcomes: exploiting a natural experiment. *Demography*, *48*(4), 1473–1491.

Torche, F., & Kleinhaus, K. (2012). Prenatal stress, gestational age and secondary sex ratio: the sex-specific effects of exposure to a natural disaster in early pregnancy. *Human reproduction*, *27*(2), 558–567.

Trivers, R. L., & Willard, D. E. (1973). Natural selection of parental ability to vary the sex ratio of offspring. *Science*, *179*(4068), 90–92.

Valente, C. (2015). Civil conflict, gender-specific fetal loss, and selection: a new test of the trivers–willard hypothesis. *Journal of health economics*, *39*, 31–50.

Xiong, X., Harville, E. W., Buekens, P., Mattison, D. R., Elkind-Hirsch, K., & Pridjian, G. (2008). Exposure to hurricane katrina, post-traumatic stress disorder and birth outcomes. *The American journal of the medical sciences*, *336*(2), 111–115.

Zorn, B., Šučur, V., Stare, J., & Meden-Vrtovec, H. (2002). Decline in sex ratio at birth after 10-day war in slovenia: brief communication. *Human Reproduction*, *17*(12), 3173–3177.

9 Appendix 1

Figura 18: Birth weight

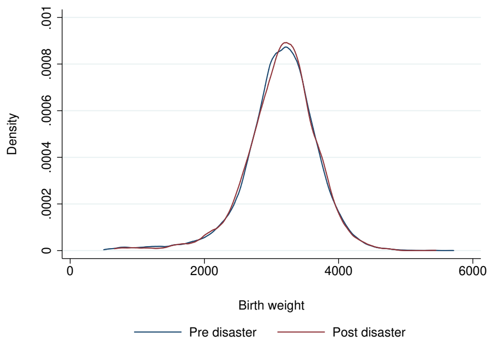


Figura 19: Birth weight -Nearby municipalities

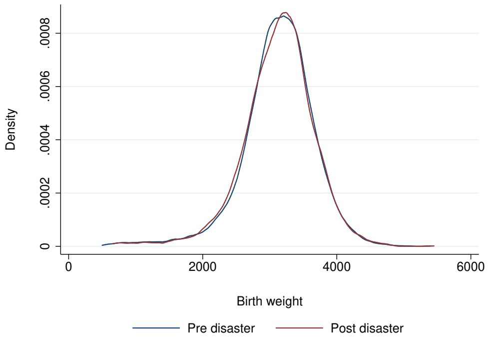


Figura 20: Birth Weight

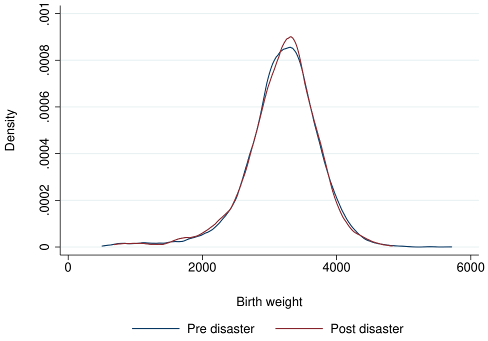


Figura 21: Birth weight - Nearby municipalities

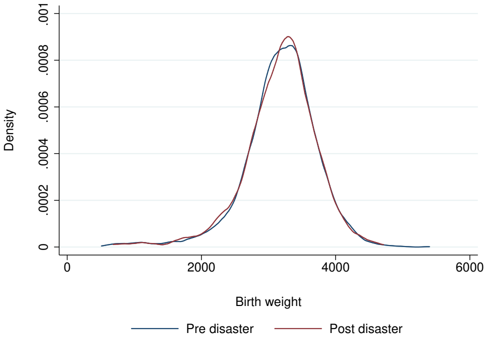


Figura 22: Birth Weight

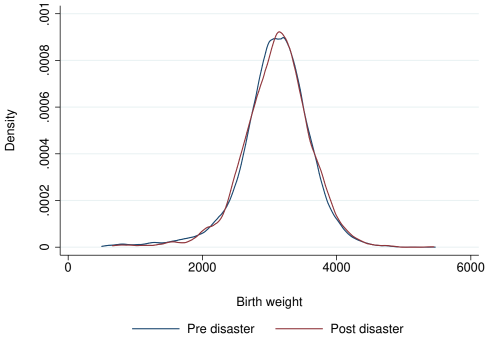
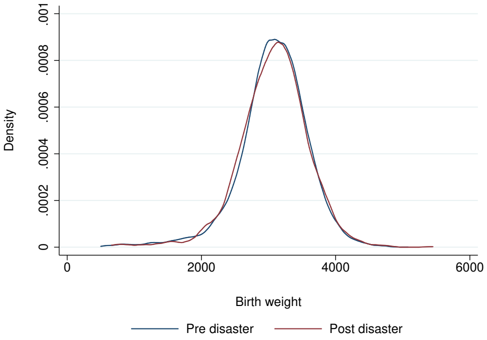


Figura 23: Birth Weight - Nearby Municipalities



10 Appendix 2

Tabela 9: Gestation time

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	0,0170	0,0055				
	(0,1133)	(0,1756)				
1st half			0,0825	-0,0358		
			(0,1025)	(0,2264)		
2nd half			0,0337	-0,0279		
			(0,0940)	(0,1335)		
1st trimester					0,0735	0,0311
					(0,1540)	(0,2080)
2nd trimester					0,0447	0,1357
					(0,1247)	(0,1834)
3rd trimester					-0,0043	0,0323
					(0,1031)	(0,1757)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 10: Gestation time boys

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,0303	0,0623				
	(0,1301)	(0,1913)				
1st half			0,0152	-0,0358		
			(0,1180)	(0,2406)		
2nd half			-0,0027	0,0024		
			(0,0942)	(0,1401)		
1st trimester					-0,0017	0,0629
					(0,1576)	(0,2120)
2nd trimester					-0,1064	0,0877
					(0,1396)	(0,2227)
3rd trimester					-0,0550	0,0745
					(0,1125)	(0,1844)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 11: Gestation time girls

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	0,0292	-0,0639				
	(0,1084)	(0,1737)				
1st half			0,0866	-0,0118		
			(0,1115)	(0,2252)		
2nd half			0,0445	-0,0567		
			(0,1128)	(0,1549)		
1st trimester					0,0366	-0,0083
					(0,1740)	(0,2339)
2nd trimester					0,1014	0,1349
					(0,1503)	(0,2282)
3rd trimester					0,0594	-0,0135
					(0,1172)	(0,1923)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 12: Premature

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,0082	0,0058				
	(0,0217)	(0,0159)				
1^{st} half			-0,0087	0,0010		
			(0,0213)	(0,0178)		
2^{nd} half			-0,0014	0,0099		
			(0,0191)	(0,0140)		
1^{st} trimester					-0,0130	-0,0074
					(0,0283)	(0,0247)
2^{nd} trimester					-0,0066	-0,0056
					(0,0251)	(0,0245)
3^{rd} trimester					0,0078	0,0130
					(0,0185)	(0,0159)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 13: Premature boys

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,0093	-0,0019				
	(0,0241)	(0,0178)				
1^{st} half			-0,0149	-0,0059		
			(0,0239)	(0,0207)		
2^{nd} half			0,0001	0,0017		
			(0,0188)	(0,0164)		
1^{st} trimester					-0,0185	-0,0189
					(0,0298)	(0,0285)
2^{nd} trimester					0,0013	0,0000
					(0,0263)	(0,0270)
3^{rd} trimester					0,0115	0,0091
					(0,0182)	(0,0180)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 14: Premature girls

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,0079	0,0115				
	(0,0212)	(0,0165)				
1st half			-0,0176	0,0006		
			(0,0226)	(0,0201)		
2nd half			-0,0106	0,0143		
			(0,0208)	(0,0173)		
1st trimester					-0,0143	-0,0069
					(0,0288)	(0,0268)
2nd trimester					-0,0221	-0,0120
					(0,0264)	(0,0273)
3rd trimester					-0,0020	0,0199
					(0,0202)	(0,0198)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 15: Intrauterine growth

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	0,0925	-0,2819				
	(0,3593)	(0,6226)				
1st half			-0,0445	0,0820		
			(0,6349)	(0,6127)		
2nd half			0,0424	-0,1037		
			(0,5109)	(0,4950)		
1st trimester					-0,0728	-0,0119
					(0,5578)	(0,6237)
2nd trimester					-0,3356	-0,4854
					(0,5700)	(0,5985)
3rd trimester					0,2761	0,1687
					(0,4052)	(0,6308)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 16: Intrauterine growth boys

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	-0,5201	-0,5408				
	(0,4752)	(0,6961)				
1st half			-0,5382	-0,1008		
			(0,9253)	(0,7568)		
2nd half			-0,5576	-0,1671		
			(0,5527)	(0,6020)		
1st trimester					-1,0531	-0,4759
					(0,8218)	(0,8726)
2nd trimester					-0,9395	-1,0439
					(0,6303)	(0,7872)
3rd trimester					-0,1151	0,1921
					(0,4810)	(0,7144)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29

Tabela 17: Intrauterine growth girls

	(1)	(2)	(3)	(4)	(5)	(6)
Pregnancy	0,4583	-0,3532				
	(0,3849)	(0,6938)				
1st half			0,4862	0,2589		
			(0,6996)	(0,6552)		
2nd half			0,5115	-0,0927		
			(0,6070)	(0,5696)		
1st trimester					0,8179	0,1844
					(0,6699)	(0,7624)
2nd trimester					0,3143	-0,0658
					(0,7055)	(0,8401)
3rd trimester					0,3674	-0,1879
					(0,5225)	(0,9221)
Controls	76	134	63	105	90	168
Pre disaster periods	10	10	20	20	29	29