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The effectiveness of disaster risk management policies in Brazilian municipalities[☆]

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ABSTRACT

This paper examines the role of disaster risk management (DRM) policies implemented by Brazilian municipalities in mitigating the social damage caused by flooding. Specifically, we analyze three commonly adopted DRM policies by local governments: flood risk mapping, supervision of flood-prone areas, and implementation of warning systems. Using an instrumental variables approach based on the spatial diffusion of DRM policies among neighbor municipalities, we show that the adoption of DRM policies is not associated with the proportion of flood-displaced individuals. This evidence indicates that these policies are insufficient in mitigating the human damage caused by floods, underscoring a need for complementary strategies or enhanced implementation measures.

1. Introduction

Due to climate variations, urbanization in high-risk areas, inadequate public infrastructure, and uncontrolled urban growth, Brazilian cities have become increasingly vulnerable to natural disasters, particularly floods, and landslides (de Loyola et al., 2016; Debortoli et al., 2017; Marengo et al., 2023). These events are particularly devastating as they are often unpredictable and occur after heavy and unexpected rainfall. Consequently, floods associated with extreme weather events have been on the rise in Brazil. Between 2004 and 2009, the recorded number of floods increased by 13%, affecting 1.1 million people across 1,433 municipalities (Veloso et al., 2022). These floods have incurred a staggering economic cost of approximately R$ 44 billion (The World Bank, 2020).

Effective disaster risk management[1] policies implemented by governments can help to mitigate the negative consequences of floods, protecting lives and reducing economic and human damage (Bakhsh et al., 2021; Fraser et al., 2021; Ji and Lee, 2021; Overly, 2021; Azadi et al., 2022). The availability of high-resolution, real-time spatial data can aid public entities in supervising, mapping, and monitoring high-risk areas, allowing for the development of efficient zoning policies and disaster risk preparation and mitigation strategies. Despite the potential benefits of these policies, data from the Brazilian Institute of Geography and Statistics (IBGE, 2020) reveals that 38.86% of municipalities have conducted mapping of their flooding risk areas, 18.54% actively supervise flood-prone areas, and only 7.84% implement flood anticipation warning systems.[2] These numbers highlight a significant gap in the country's efforts to mitigate the risks posed by flooding effectively.

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[1] According to the United Nations Office for Disaster Risk Reduction, disaster risk management encompasses the implementation of policies and strategies aimed at preventing the emergence of new disaster risks, mitigating existing risks, and effectively addressing any residual risks. This comprehensive approach bolsters resilience and minimizes adverse social and economic consequences from disasters.

[2] The implementation of flood disaster risk management varies significantly across countries, particularly in developing regions. Globally, only 52% of countries have early warning systems for natural disasters, while coverage in Least Developed Countries drops to less than half. The quality of these systems ranges from countries lacking basic equipment to those with advanced networks. Countries with limited to moderate Multi-Hazard Early Warning Systems (MHEWS) coverage experience disaster-related mortality rates nearly six times higher and five times more disaster-affected people per capita compared to those with substantial coverage (UNDRR, 2023). Early warnings issued just 24 h in advance can reduce damages by up to 30%, and an $800 million investment in such systems for developing countries could prevent annual losses of $3–16 billion (UNDRR and WMO, 2022). In Brazil, the adoption of flood early warning systems remains limited due to budgetary constraints, inadequate infrastructure, and limited awareness of their importance.

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In this context, the present paper aims to investigate whether these disaster risk management (DRM) policies implemented by local governments effectively mitigate flood-related damage. More specifically, conditioned on having experienced a flood, we will evaluate whether municipalities that adopt policies for mapping flood-prone areas, supervising risk areas, and implementing warning systems are better able to mitigate the human damage of subsequent floods when compared to municipalities that do not adopt such policies. Our primary outcome for assessing the human impact of flood events will be the proportion of flood-displaced individuals. It is important to note that the primary goal of DRM policies is to prevent or mitigate the social damage from future flood events.[3] Therefore, this study seeks to verify the achievement of this objective by evaluating the effectiveness of these public policies in the context of Brazilian municipalities.

To investigate the effects of DRM policies on the proportion of affected individuals, we employ an instrumental variables approach, as the adoption of these policies is endogenous to the municipalities and may be influenced by various socioeconomic, political, and geographic unobserved factors. We will take advantage of the geographic diffusion of DRM policies across Brazilian municipalities to construct an instrument for the adoption of DRM policies based on the adoption rates of neighboring municipalities. The rationale is that neighboring municipalities' policy adoption can exert influence through peer pressure, imitation effects, or knowledge spillovers. It is plausible to assume that this instrument satisfies the exclusion restriction since Brazilian municipalities operate with administrative and political independence, implying that local policy implementation does not directly impact flood-related human damage in other jurisdictions. Our database features a cross-sectional format, combining DRM policy adoption data from the 2020 *Pesquisa de Informações Básicas Municipais* (MUNIC) survey by the Brazilian Institute of Geography and Statistics (IBGE), flood impact statistics collected from (Veloso et al., 2022), and socioeconomic and geographic auxiliary data from various official sources.

Our findings indicate that the adoption of DRM policies by flooded municipalities is not related to a reduction in the proportion of flood-displaced individuals compared to flooded municipalities that did not adopt such policies. This conclusion applies to different estimation strategies (OLS and 2SLS/IV), alternative instrument metrics, alternative measures of flood damage, different empirical specifications, the remotion of outliers observations, and alternative inference procedures. Therefore, our results provide evidence that the overall effectiveness of DRM policies implemented by Brazilian municipalities may not meet initial expectations, highlighting the necessity for further enhancements and adjustments.

This paper is closely related to the literature examining the consequences of disaster prevention policies on both the incidence of natural disasters and the susceptibility of populations to their effects. Overall, studies evaluating the impact of local preemptive investments and specific DRM policies show that these actions can effectively reduce the number of affected individuals, the risk of new disasters, and the property damage associated with such events (Ji and Lee, 2021; Davlasheridze et al., 2017; Ostriker and Russo, 2022; Ayala-García and Dall'Erba, 2022; Sales, 2023). However, qualitative papers also indicate that some DRM policies may be ineffective or insufficient due to poor implementation, insufficient integration into political systems, challenges in defining and measuring results, and a lack of alignment with broader governance frameworks (Aerts et al., 2018; Jamieson, 2016; Rivera et al., 2015; Ogra et al., 2021). Additionally, despite the overall benefits of disaster prevention policies, Healy and Malhotra (2009) found that voters often reward incumbent politicians who allocate more funds to disaster relief rather than prevention. This behavior can discourage local governments from effectively implementing DRM policies and spending with preventive measures, resulting in a suboptimal allocation of resources and ultimately leaving populations more vulnerable to natural disasters.

More generally, our paper also relates to the empirical literature that investigates the role of government actions and institutional factors in reducing economic damage caused by disasters. Several studies demonstrate that the quality of governance, the fiscal capacity, and the political system significantly influence both the degree of vulnerability to disasters and the recovery trajectory following catastrophic events (Tol, 2022; Di Marcoberardino and Cucculelli, 2024; Barone and Mocetti, 2014; Anbarci et al., 2005; Kellenberg and Mobarak, 2008). The central idea is that places with robust institutions, higher development levels, stronger fiscal capacity, and effective democratic systems are better positioned to make significant and effective investments in disaster prevention policies and are more engaged with collective actions, which not only potentially reduce the severity of events but also can mitigate the associated socioeconomic damages, promoting sustained recovery aftershocks. In line with this general evidence, studies specific to Brazil suggest that municipalities with better urban infrastructure (including a sewage system and garbage collection), higher fiscal capacity, and a larger area of natural forest cover are less susceptible to natural disasters and experience less damage as a result (Sant'Anna, 2018; De Oliveira et al., 2020).

This paper contributes to the literature that evaluates the consequences of disaster prevention policies by providing unprecedented evidence for Brazil regarding the effectiveness of three disaster risk management policies (the supervision of flood-prone areas, mapping of flooding risk areas, and adoption of warning systems) in mitigating human flood damage. Through this comparative analysis, policymakers can gain valuable insights into the real efficacy of each specific policy, allowing for better monitoring, improvement, and implementation of new disaster management strategies. This contribution is particularly relevant in a developing country that is increasingly vulnerable to disasters due to global warming and rapid urbanization in high-risk areas. Previous studies investigating the impact of local policies on disasters in Brazil have focused primarily on the quality of urban infrastructure and local development outcomes (Sant'Anna, 2018; De Oliveira et al., 2020), with little emphasis on the role of different disaster risk management policies.

The remainder of the paper is organized as follows. Section 2 describes an overview of disaster risk management policies in Brazil. Section 3 describes our empirical approach and Section 4 presents the data sources, variable definitions, and descriptive statistics. Section 5 presents the main results and robustness checks. Finally, Section 6 presents the conclusion and discusses some policy implications.

2. Disaster risk management policies in Brazil

Brazil is a federal country consisting of the central government, 26 states plus the Federal District, and 5,570 municipalities. Disaster risk management policies are shared among these three levels of government under the supervision and coordination of the central government.[4] Although the first structure of the National Civil Defense

[3] Additional flood prevention measures highlighted in the literature include spatial planning, such as zoning restrictions to limit development in high-risk areas, infrastructure upgrades like levees and drainage systems, and nature-based solutions such as conserving wetlands and restoring riverbanks (Wilby and Keenan, 2012; Tyler et al., 2019; Khan et al., 2023). Effective governance, requiring coordination across levels and sectors, and public awareness of flood risks also play crucial roles in preparedness and prevention (Dieperink et al., 2016; Driessen et al., 2016; Siegrist and Gutscher, 2006). Moreover, understanding the dynamic interactions between hazard, exposure, and vulnerability is essential for tailoring effective strategies (Di Baldassarre et al., 2014). These strategies can complement the policies analyzed in this study, providing a more integrated framework for flood risk management.

[4] According to the 1988 Brazilian constitution, it is the central government's competence to plan and promote permanent defense against public calamities, especially droughts, and floods.

in Brazil was created in 1942 as a response to the Second World War, it was not until 1988 that the Brazilian National Civil Defense System (SINDEC) was effectively institutionalized to operate throughout the entire national territory (IFRC, 2012). The SINDEC enables the establishment of consistent national guidelines for civil defense policies by the central government, provides suggestions and recommendations to local disaster risk management policies, coordinates rescue teams and assists in the evacuation of risk areas, and allocates financial resources to subnational governments affected by extreme weather events.

The structure of civil defense in Brazil underwent significant institutional changes in the early 2010s, prompted by a series of major disasters[5] that led to social mobilization movements advocating for changes in laws and regulations to enhance the prevention, mitigation, and combat of natural disasters. This mobilization ultimately resulted in the introduction of Federal Law N° 12,608/2012, the first legal framework for civil defense originating from the federal legislative branch.[6] This new regulatory framework brought about important advances, including the standardization of the management cycle and disaster prevention in line with global guidelines, a clearer definition of the responsibilities of each federal entity, greater integration with other public policies, improvement of governance processes, and a shift in priority towards prevention and mitigation policies, as opposed to actions focused solely on relief efforts (The Brazilian Ministry of Regional Development, 2022). Another important change was the creation of the Brazilian Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), a federal research institute dedicated to the advancement of natural disaster forecasting systems.

Under the new regulatory framework, Brazilian municipalities have been delegated the task of organizing and implementing national disaster risk management policies at the local level. This includes mapping and supervising risk areas, informing the public about potential natural hazards, and promoting land-use management to prevent construction in flood-prone or landslide-prone areas. In the event of a natural disaster, municipalities must declare a state of emergency or public calamity and provide temporary housing and supplies to affected residents. Although Federal Law n° 12,608/2012 defines these responsibilities, only 43.34% of Brazilian municipalities have adopted at least one public policy for disaster management, according to a survey of *Pesquisa de Informação Básicas Municipais* (MUNIC) conducted by the Brazilian Institute of Geography and Statistics (IBGE) in 2020.

The primary objective of our paper is to analyze the effectiveness of a set of disaster risk management (DRM) policies that are currently being implemented by Brazilian municipalities. Specifically, we will analyze if the human impact of subsequent floods is mitigated when the local governments adopt three different local public policies: flood risk area mapping, supervision of flood-prone areas, and flood warning systems. The process of flood risk area mapping involves a comprehensive classification of the municipality's territory based on its geomorphology, taking into account factors such as elevation, proximity to water bodies, and soil characteristics. This DRM policy enables the determination of areas with varying degrees of susceptibility to flooding, aiding in the identification of high-risk zones. Simultaneously, the supervision of flood-prone areas is implemented to deter human settlements and construction activities in areas that have been identified as having a high flood risk. By preventing new constructions in these high-risk areas, the aim is to reduce the potential damage and loss of life caused by future flooding events. Furthermore, the flood warning system is established as a proactive mechanism to efficiently inform residents about potential disaster risks. This system integrates real-time data from weather monitoring stations, river gauges, and meteorological forecasts to provide timely and accurate warnings. Through various communication channels such as mobile alerts, sirens, and public announcements, residents receive vital information about imminent flood threats, enabling them to take precautionary measures, evacuate if necessary, and safeguard their lives and property. Fig. 1 shows the spatial distribution of municipalities that have implemented each DRM policy.

Table 1
Adoption rate (%) of DRM policies in Brazilian municipalities by regions.

	Flood risky mapping	Supervision of risky areas	Warning system
North region	41.77%	17.94%	5.16%
Northeast region	26.00%	12.69%	4.82%
Southeast region	47.72%	22.60%	11.57%
South region	53.96%	23.48%	11.11%
Midwest region	22.81%	17.98%	1.32%
Brazil	39.63%	18.90%	7.98%

Note: The adoption rates are based on data from the 2020 MUNIC Survey.

Fig. 1 illustrates that flood risk area mapping is the most widely adopted DRM policy among Brazilian municipalities, with an adoption rate of 39.63%. Following closely is the supervision of flood-prone areas, which holds an adoption rate of 18.9%, while the implementation of warning systems lags behind at 7.98%. Table 1 details the adoption rates of DRM policies across the five Brazilian macro-regions. Particularly notable are the South and Southeast regions, recognized as the country's most developed areas, which show the highest proportion of municipalities implementing DRM policies, whereas the Midwest Region exhibits the lowest adoption rate among these regions.

In Table A.1 of the Appendix, we present a simple linear probability model to examine the climatic and socioeconomic factors[7] that affect the adoption of DRM policies across Brazilian municipalities. The results from this exercise indicate a significant positive correlation between the adoption of Disaster Risk Management (DRM) policies and the past occurrence of flooding and extreme rainfall events. Additionally, the results also suggest that these DRM policies are more likely to be implemented in municipalities characterized by higher levels of development, greater degrees of urbanization, and larger populations. This trend highlights the tendency for more developed, urbanized regions with higher population densities to prioritize adopting preventive measures in response to recurring climate-related hazards.

3. Empirical strategy

Initially, to investigate whether disaster risk management (DRM) policies are effective in mitigating flood damage, we estimated the following ordinary least squares (OLS) regression to evaluate the association between the adoption of DRM policies and the proportion of flood-displaced individuals:

$$\%FloodDisplaced_i = \beta_0 + \beta_1 DRM_i + \mu X_i' + \varepsilon_i \quad (1)$$

where $\%FloodDisplaced_i$ is the outcome variable and measures the proportion of homeless or displaced people because of a flood event in relation to the local population of the municipality i and DRM_i is our variable of interest and has a dichotomous format, assuming the value of 1 if the municipality adopts a specific DRM policy (mapping,

[5] In the late 2010s, Brazil experienced three major national catastrophes that caused a significant social commotion. These included the 2008 flash floods in Santa Catarina, which resulted in 135 deaths, the 2010 floods in Pernambuco and Alagoas that claimed 25 lives, and the 2011 landslides in the mountainous region of Rio de Janeiro, which resulted in a staggering 1192 fatalities.

[6] Until then, civil defense policies were created exclusively by actions of the federal executive branch through decrees, federal ordinances, or provisional measures.

[7] We detail the definitions and the sources of each variable used in this exercise in Section 4.

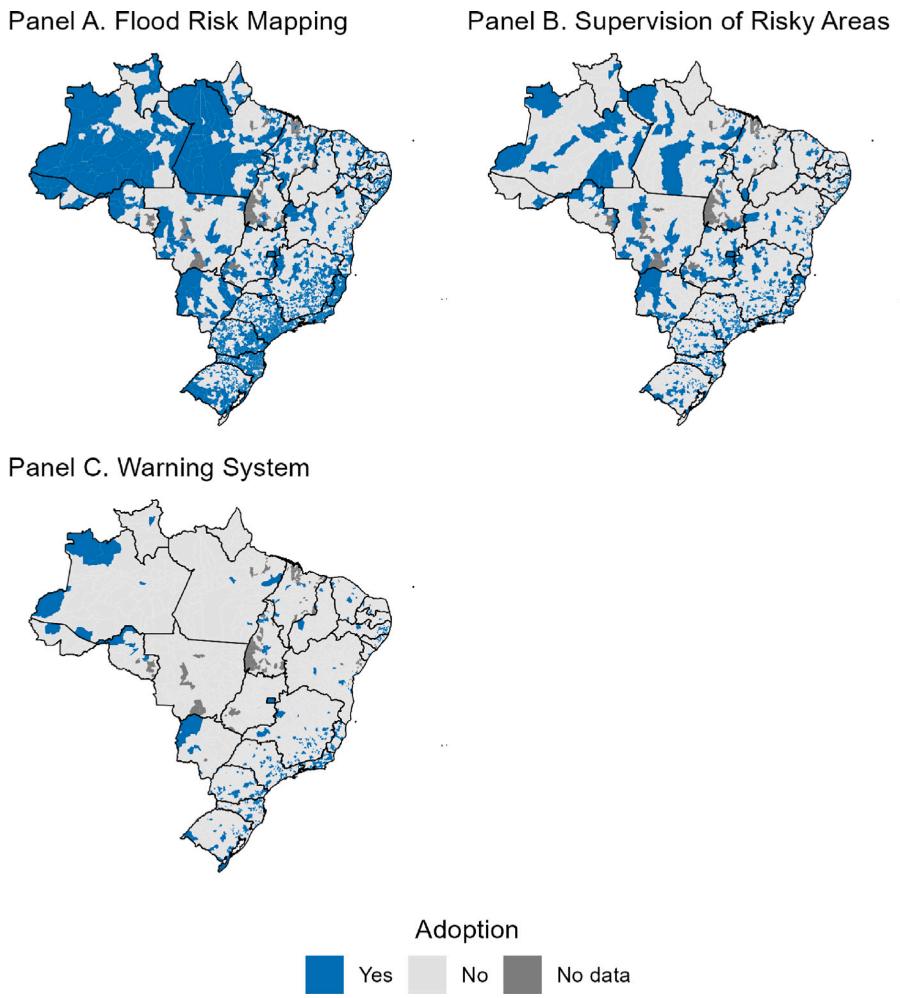

Fig. 1. Spatial distribution of municipalities by adopted DRM policy.
Note: The municipalities marked in blue are those that adopt mitigation policies. The other municipalities include non-adopters or those that do not have information.

supervision of flood risk areas or warning system) and assuming 0 otherwise. X_i' is a vector of socioeconomic and geographic control variables with the potential to affect both the human damage associated with the flood and the adoption of DRM policies. Lastly, ε_i is the idiosyncratic error term and represents all unobserved variables that affect the outcome variable. Our parameter of interest is given by β_1, which measures the association between DRM policies and flood damages conditional on the control set and the fact that municipalities have experienced a flood. To avoid the problem of reverse causality between the adoption of the DRM policy and the flood human damage, we will use data from flood-displaced individuals associated with floods that occurred in 2020 and information on policy adoption collected in the previous year, in 2019.

The main concern when estimating Eq. (1) by OLS is that the adoption of the DRM policy is not random, but rather determined by the local government decisions, which can generate correlations between the variable of interest and unobserved variables that are not included in the model. For example, municipal administrators who are more concerned about environmental and climate change issues may be more likely to implement DRM policies in their municipalities. Furthermore, given that implementing these public policies requires a significant level of resources and continuous regulation, only larger and more developed municipalities may be able to adopt them effectively. These potential confounding factors may be associated with the variable of interest, leading to endogeneity, which results in biased and inconsistent coefficients.

We will use an instrumental variable approach to deal with this potential endogeneity problem. More specifically, we take advantage of the spatial diffusion of DRM policies across Brazilian municipalities (Fig. 1) and adopt the proportion of neighboring municipalities that implement a DRM policy as an instrument for local adoption of the DRM policy. This instrument is commonly used in literature that investigates the economic impacts of fiscal rules and government reforms between different jurisdictions (Caselli and Reynaud, 2020; Giuliano et al., 2013). The rationale behind this instrument is that neighboring governments can influence the adoption of public policies in a specific location. For example, Dobbin et al. (2007) identified five possible channels for the diffusion of public policies across different locations: coercion, imitation, socialization, competition, and learning.

In DRM policy adoption, local municipalities often rely on three key channels: imitation, learning, and coercion, drawing from neighboring experiences. Imitation occurs as local governments replicate successful practices, like establishing anticipation warning systems observed in nearby cities that effectively reduce flood damage. Learning involves sharing information, technologies, and strategies among jurisdictions; for instance, a municipality can enhance flood risk mapping by adopting successful measures from its neighbors. Coercion, driven by external pressures such as federal standards or regional competition, compels municipalities to implement DRM policies to maintain parity with peers and meet regulatory expectations for climate resilience. Therefore, to estimate the instrumental variable regression, we adopt the two-stage least squares (2SLS) method. The first-stage regression is given by the following specification:

$$DRM_i = \alpha_0 + \alpha_1 NeighbourDRM_i + \mu X_i' + u_i \quad (2)$$

where $NeighbourDRM_i$ is the proportion of municipalities neighboring municipality i that implement the DRM policies (mapping, supervision of flood risk areas or warning system). The other variables in Eq. (2) are the same as explained previously. After estimating the first-stage equation by OLS, we obtain the predicted values of the dependent variable (denoted by $\widehat{DRM_i}$) and substitute them into the second-stage regression which is similar to Eq. (1). By adopting this procedure using a 2SLS estimation, we can address the endogeneity problem and obtain more accurate coefficients to evaluate the effectiveness of DRM policies in reducing human damages associated with floods.

For the 2SLS estimation to result in consistent and unbiased coefficients, the instrumental variable must satisfy two conditions: relevance and exogeneity. The relevance condition establishes that the instrumental variable must be correlated with the endogenous variable conditioned on controls. This condition can be easily evaluated by checking whether the coefficient α_1 of Eq. (2) is statistically different from zero. The exogeneity condition establishes that the instrumental variable is uncorrelated with the error term (ε_i in Eq. (1)) conditioned on the other controls so that the only way the instrument affects the outcome is through its effect on the endogenous variable.

While the exogeneity condition cannot be empirically tested, we believe it is likely to hold in our setting. Firstly, our instrument does not directly influence the outcome variable. In Brazil, municipalities operate as autonomous and horizontally independent entities, meaning that local policies are designed to regulate only their jurisdictions. Accordingly, local DRM policies focus on mitigating risks within the municipality territory and do not directly influence external areas. For instance, when a local administration maps or inspects flood-prone areas, legal frameworks mandate that these actions remain confined within its jurisdictional boundaries.

Secondly, while unobserved factors from surrounding municipalities may be correlated with our instrument, it is unclear how these would drive the number of flood-displaced individuals of a different jurisdiction. Although this possibility exists, we believe the exogeneity condition would only be violated under strict and unlikely circumstances. For instance, one might argue that neighboring municipalities' adoption of DRM policies correlates with aspects of their local governance quality, which is unobserved. However, to violate the instrument's exogeneity assumption, governance quality must generate spillover effects that hypothetically enhance the governance of municipalities exposed to floods. Subsequently, this improved governance would have to effectively influence the share of flood-displaced individuals.

In practice, such a large chain of influence appears improbable and difficult to observe, especially given that the number of flood-displaced individuals is primarily driven by the inherent characteristics of the flood event itself, such as its intensity, geographic extent, and overlap of the shock on populated areas. Nevertheless, we acknowledge that our instrument is not random, and the exogeneity condition could be violated in specific circumstances. For this reason, we will perform a set of robustness tests using alternative instrument and outcome variable definitions and avoid making any causal claims throughout the paper.

4. Data and summary statistics

We combine different databases to evaluate the effectiveness of disaster risk management policies in Brazilian municipalities. This includes data on the adoption of public policies from the *Pesquisa de Informações Básicas Municipais* (MUNIC); records of the occurrence of natural disasters and their respective human damages collected by Veloso et al. (2022) and, finally, auxiliary land use data from the MapBiomas platform, socioeconomic data from the Brazilian Demographic Census and rainfall data collected by Xavier et al. (2022). Our database uses a cross-sectional format because DRM policy information was only collected consistently in one year. Since our interest is to evaluate the effectiveness of DRM in reducing the subsequent flood damage, it only makes sense to consider municipalities that experienced floods in time after the adoption of DRM policies. Thus, our analysis will be restricted to the 302 Brazilian municipalities affected by floods in 2020. In the following paragraphs, we will present a comprehensive overview of the different data sets used and the construction and definition of each variable of interest.

Data on DRM policies. We obtained the DRM policy data from the *Pesquisa de Informações Básicas Municipais* (MUNIC), a survey conducted almost annually by the Brazilian Institute of Geography and Statistics (IBGE). The objective of this survey is to collect information on the structure, dynamics, and functioning of local governments, including the adoption of various local public policies. Although the MUNIC survey has been conducted since 1999, it was only in 2020 that a dedicated and consistent[8] questionnaire was introduced to collect information about the adoption of DRM policies across Brazilian municipalities. As detailed in Section 2, our analysis will check the effectiveness of three different DRM policies[9]: mapping flood-risk areas, supervision of flood-prone areas, and implementing a warning system. These variables will be binary, with a value of 1 indicating adoption by municipalities and 0 indicating non-adoption. The MUNIC data, publicly released in 2020, were collected in 2019, but lack specific dates indicating when municipalities start adopting their policies. Lastly, it is important to note that the DRM policy data will also be useful in constructing our instrumental variable discussed in the previous subsection, which is defined by the proportion of neighboring municipalities adopting each DRM policy.

Data on Flooding Damage. We employ the dataset constructed by Veloso et al. (2022) as the source of our dependent variable. This comprehensive dataset encompasses information on natural disasters occurring in Brazil from January 2003 to February 2021, georeferenced at the municipal level and updated every month. The primary data sources utilized by Veloso et al. (2022) are government and institutional reports, ensuring the reliability of the data. Within this dataset, nine types of natural disasters are identified: floods, droughts, flash floods, inundations, landslides, frosts, storms, windstorms, and barrier collapses. Each type includes details on the number of affected individuals categorized by injuries, displacement, homelessness, sickness, or fatalities. To summarize the human damage of floods, our main analysis will focus on the number of individuals displaced and rendered homeless by 2020 flooding events, divided by the local population (share of flood-displaced individuals).

Other Data. In some alternative specifications, we also incorporate geographic and socioeconomic variables as controls, as they could be associated with both the share of flood-displaced individuals and the adoption of DRM policies. Municipalities may be more inclined to implement DRM policies when they possess geographic and climatic features that increase the flood risk. To consider this, we utilize two control variables: the proportion of the municipality's territorial area covered by water bodies (including lakes, rivers, and ocean), sourced

[8] The 2013 MUNIC also presents information about the adoption of DRM policies in Brazilian municipalities. However, this survey is quite limited because this data was only collected for 32.97% of Brazilian municipalities. On the other hand, DRM policy adoption information is available for all municipalities in the 2020 MUNIC.

[9] It is important to note that the MUNIC survey also provides information on other initiatives implemented by local governments to mitigate or prevent flooding. These initiatives are categorized into two groups: engineering actions (such as constructing macro-dredging channels, river dredging, and building dams) and risk management policies (including those considered in this study). In this paper, we focus on the latter, as these policies aim to mitigate the damage caused by floods rather than prevent the flooding itself.

Table 2
Summary statistics.

A. Main variables	Mean	SD	Min	Max
Share of flood-displaced individuals	0.02	0.04	0	0.37
Flood risk mapping (0/1)	0.74	0.44	0	1
Supervision of risky areas (0/1)	0.31	0.46	0	1
Warning system (0/1)	0.23	0.42	0	1
B. Control variables	**Mean**	**SD**	**Min**	**Max**
Share of area covered by water bodies	0.02	0.05	0	0.53
Days with heavy rainfalls	0.26	0.58	0	4
Urbanization rate	0.67	0.23	0.15	1
Informality rate	0.05	0.07	0	0.46
Log(GDP Per capita)	2.3	0.3	0.91	5.08
Log(Population)	10.12	1.22	7.42	14.15
C. Instrumental variables	**Mean**	**SD**	**Min**	**Max**
% of Neighboring adoption (Mapping)	0.59	0.31	0	1
% of Neighboring adoption (Supervision)	0.29	0.24	0	1
% of Neighboring adoption (Warning System)	0.16	0.21	0	1

Notes: The table displays the mean, standard deviation (S.D.), and minimum and maximum values for each variable.

from the MapBiomas platform, and the occurrences of heavy rainfall, quantified by the number of days with precipitation exceeding 100 mm. This latter variable is derived from rainfall data collected by the National Water Agency and processed by Xavier et al. (2022). Additionally, vulnerability to climate disasters also varies with the type of urbanization and the socioeconomic characteristics of municipalities. To account for this, we include four variables extracted from the 2020 Brazilian Demographic Census: the log of GDP per capita, the log of the population size, the urbanization rate, and the informality rate (defined as the proportion of local households with inadequate infrastructure). Table 2 presents the descriptive statistics for the variables described above.

5. Results

5.1. Main results

We begin by presenting the results of the estimation of Eq. (1) using OLS for each DRM policy investigated. The odd-numbered columns of Table 3 show results from a simple linear regression that includes only the DRM policy variable, while the even-numbered columns include results controlling for a set of geographic and socioeconomic covariates at the municipality level. Columns 1–2 present point estimates for the flood risk mapping, columns 3–4 for the monitoring and supervision of flood-prone areas, and columns 5–6 for the warning system policy. In all our estimations, we will use heteroskedasticity-robust standard errors.

Table 3 shows positive point estimates for all DRM policies. In columns (1) and (2), for example, the coefficients of interest are positive and statistically significant at a 1% level, suggesting a positive relationship between the adoption of flood mapping policy and the share of flood-displaced residents. The estimate in Column (2) indicates that adopting this policy increased the share of displaced individuals by 1.2%. For flood supervision, point estimates are also positive but

Table 3
The effect of DRM policies on flood-displaced individuals: OLS estimates.

Dependent variable: Share of flood-displaced						
	(1)	(2)	(3)	(4)	(5)	(6)
	Flood mapping		Flood supervision		Warning system	
DRM policy	0.012***	0.018***	0.003	0.008	0.01	0.014**
	(0.004)	(0.005)	(0.005)	(0.006)	(0.007)	(0.007)
Controls	No	Yes	No	Yes	No	Yes
Number of observations	301	301	301	301	301	301

Notes: This table shows estimates of Eq. (1) by OLS using the share of flood-displaced Individuals as the outcome. The control set considers the following variables: log population, log GDP per capita, urbanization rate, informality rate, % of the area covered by water, and the number of days with heavy rainfall. The heteroscedasticity-robust standard errors are presented in parentheses. Significance: *** represents p < 0.01,** represents p < 0.05,* represents p < 0.1.

Table 4
The effect of DRM policies on flood-displaced individuals: 2SLS estimates.

Panel A. Second-stage IV	Dependent variable: Share of flood-displaced					
	(1)	(2)	(3)	(4)	(5)	(6)
	Flood mapping		Flood supervision		Warning system	
Fit DRM policy	0.025	0.027	0.035	0.063	0.005	0.01
	(0.02)	(0.03)	(0.03)	(0.06)	(0.02)	(0.02)
Panel B. First-stage IV	**Dependent variable: DRM policy**					
	(1)	(2)	(3)	(4)	(5)	(6)
	Flood mapping		Flood supervision		Warning system	
Neighboring DRM	0.28***	0.27***	0.268**	0.186	0.642***	0.575***
	(0.08)	(0.08)	(0.11)	(0.11)	(0.13)	(0.13)
Controls	No	Yes	No	Yes	No	Yes
KP F-statistic - First stage	12.12	11.08	6.19	2.89	33.09	25.41
Wu-Hausman	0.24	0.10	0.76	1.00	0.07	0.04
Number of observations	301	301	301	301	301	301

Notes: This table shows estimates of 2SLS using the share of neighboring municipalities adopting a DRM policy as an instrumental variable. The control set considers the following variables: log population, log GDP per capita, urbanization rate, informality rate, % of the area covered by water, and the number of days with heavy rainfall. The heteroscedasticity-robust standard errors are presented in parentheses. Significance: *** represents p < 0.01,** represents p < 0.05,* represents p < 0.1.

not statistically significant. Finally, the point estimates for warning systems, while positive, do not provide clear evidence of a significant association with the share of flood-displaced individuals. Although we have included a comprehensive set of covariates in our OLS specification, the relationships suggested in Table 3 can be biased due to the likely presence of other unobserved confounding factors at the municipal level. The main threat to the validity of our estimates is the existence of unobserved factors that could affect both the adoption of DRM policies and the proportion of flood-displaced individuals. In other words, our results in Table 3 may reflect spurious regression due to the influence of unobservable confounders. To address this issue, we adopted the instrumental variables approach discussed in Section 3.

Table 4 reports the results of the 2SLS estimations using the proportion of neighboring municipalities that implement a DRM policy as an instrument for the adoption of DRM. Columns (1), (3), and (5) present the estimates without controlling for other variables, while Columns (2), (4), and (6) include controls for municipality characteristics. Panel A presents the second-stage results, while Panel B shows the corresponding first-stage results.

The second-stage estimations of Panel A in Table 4 indicate a non-statistically significant relationship between DRM policies and the proportion of flood-displaced individuals across all 2SLS specifications.

This relationship remains non-significant even after including municipal characteristics as additional controls, suggesting that DRM policies are ineffective in reducing the human damages of floods. It is possible to notice that the 2SLS coefficients are higher than those obtained by OLS for most point estimates, except for the estimate in column 6. A comparison of OLS and 2SLS results, however, is not as straightforward as one might think. Using OLS, we estimate the average treatment effect of the DRM policy for all cities affected by flooding (average treatment effect). In contrast, the IV/2SLS estimate captures the average effect of the DRM policy for the subset of cities in which the spatial diffusion of DRM policies among neighboring municipalities effectively shifts the probability of local DRM adoption (local average treatment effect). Additionally, the OLS coefficient may be biased upward due to unobserved variables.

The first-stage estimates of Panel B in Table 4 show a positive and statistically significant correlation between the spatial diffusion of DRM policies among neighboring municipalities and DRM policy adoption in all specifications (except for column 4), suggesting that the relevance condition of the IV holds for flood risk area mapping and flood warning systems. This evidence indicates that cities with a larger proportion of neighboring municipalities that have adopted the DRM policy are more likely to adopt it as well, implying that imitation might be a prevailing behavior in Brazilian cities. Finally, the first-stage Kleibergen–Paap F statistic is lower than the usual rule of thumb (equal to 10, as shown by Stock and Yogo (2002) only for the Flood Supervision policy in the specifications of columns (3) and (4), suggesting a possible weak instrument in this specific estimation.

The absence of effectiveness of DRM policies in reducing the human damage of floods evidenced in Table 4 can be explained by different factors. Firstly, limited financial resources can constrain the ability of local authorities to implement truly effective policies. The Brazilian National Treasure Secretary (STN) reports that municipalities allocate around 85% of their total budgets to current expenditures, leaving little funding for infrastructure, equipment, and personnel training to mitigate disaster risks. Additionally, Damacena et al. (2022) found that 72% of Brazilian municipalities do not have a dedicated budget for civil defense actions. These factors combined can affect the quality and performance of DRM policies.

Another factor that may contribute to the ineffectiveness of DRM policies is the potential lack of coordination and cooperation among different agencies and sectors involved in disaster risk management, leading to fragmented, overlapping, and non-integrated policies. Additionally, the short implementation period of some policies may affect their effectiveness. The new regulatory framework for disaster risk management in Brazil was established in 2012, and some policies may not have had sufficient time to become fully effective. For example, the local policies may have been approved but not yet implemented or are still in the testing phase. In this sense, the timing of adoption in each municipality might differ, affecting the maturation of these policies and, consequently, their average effect on disaster prevention and damage reduction. Given our cross-sectional analysis and the lack of data on the year of policy implementation across municipalities, we cannot investigate this particular issue. Therefore, continuous monitoring is necessary to assess the performance of DRM policies over time and identify potential gaps for future improvements.

5.2. Robustness checks

In the previous subsection, we showed that local DRM policies are not associated with the share of flood-displaced individuals, suggesting that these policies are ineffective in their intended purpose. In this subsection, we conduct a comprehensive set of robustness tests to ensure that this finding is robust and not simply driven by our initial methodological choices. More specifically, we evaluate if our main results shown in Table 4 are sensitive to alternative metrics for the instrumental variable, different measures of flood-related human damages, the inclusion of additional controls, the removal of outlier cities from the sample, and alternative inference procedures. Table 5 provides the second-stage coefficients associated with each robustness test, presented alongside the baseline results for easy comparison.

Alternative Definition of the Instrument. To further ensure the robustness of our IV/2SLS estimates, we explored alternative definitions for the instrumental variable. The consistency and validity of these estimates can be significantly influenced by the choice of the instrument, making it crucial to test whether different formulations yield consistent results. In our primary analysis, we used the average (or proportion) of neighboring municipalities adopting DRM policies. To evaluate the robustness of our findings to this specific choice, we tested two alternative metrics: the count of neighboring municipalities adopting each DRM policy, which is presented in Estimation A.1 of Table 5, and the proportion of neighboring adoption weighted by the population size presented in the Estimation A.2 of Table 5. Column (1) of Table 5 presents the second-stage 2SLS coefficients for the flood mapping, column (2) for the flood supervision policy, and column (3) for the warning system. It is noted that regardless of the instrument definition, the coefficients are very similar to the baseline estimate and remain non-statistically significant.

Alternative Measures of Flood Damage. In the main estimates, we use the share of flood-displaced individuals as the outcome variable to measure and summarize the human impact of floods. The results indicate that the adoption of DRM policies is not associated with the proportion of flood-displaced people. However, it is possible that this evidence does not reflect the full impact of DRM policies, especially concerning more severe types of human damage caused by floods, such as the number of missing persons or deaths resulting from disasters. To check whether this is the case, estimation B.1 in Table 5 uses as the outcome variable the proportion of the sum of individuals killed, missing, sickened, or injured related to flood events in relation to the size of the local population. It is noted that the 2SLS results are not statistically significant for all local policies, reinforcing the idea that the adoption of DRM policies is not associated with lower human damage from floods. Furthermore, we also checked whether our main result changes when we use the absolute number of flood-displaced individuals (estimation B.2 in Table 5) and the log of the number of flood-displaced individuals (estimation B.3 in Table 5), but the results are also not sensitive to these changes.

Including Additional Controls. In our main estimates, we only include the control variables presented in Table 2. To check the robustness of the results to the inclusion of a larger number of controls, we also include variables identified in previous literature as potentially influential in disaster damage. Thus, estimation B.4 in Table 5 shows the results with the inclusion of the following controls: the share of municipal territory with forest cover, the proportion of households with piped water, the proportion of households with sewage systems, and the log of the volume of local public expenditure.

Evaluating Outlier Influence. Considering that our sample has a limited number of 302 municipalities, our results may be partially influenced by outlier observations. To assess the robustness of our main result to this particular issue, we re-estimated our IV/2SLS result by eliminating from our sample the municipalities that had a large proportion of flood-displaced individuals (Removal of observations above the 90th decile in Estimation C.1 of Table 5 and above the 75th decile in Estimation C.2 of Table 5) and also the set of cities that suffered floods but had no people affected (Estimation C.3 of Table 5). As can be seen, the main results are not sensitive to the existence of outlier municipalities associated with the distribution of the flood-displaced variable.

Alternative Inference Procedures. Finally, the lack of statistical significance in the relationship between DRM policies and the proportion of flood-displaced individuals may have been potentially explained by an upwardly biased standard error. In our main analysis,

Table 5
Robustness checks.

	2SLS (1) Flood mapping	2SLS (2) Flood supervision	2SLS (3) Warning system
Baseline DRM coefficient	0.027	0.063	0.01
	(0.03)	(0.06)	(0.02)
A. Robustness to different IV metrics			
A.1 - Sum of neighboring DRM adoption	0.052	0.079	0.016
	(0.04)	(0.06)	(0.02)
A.2 - Weighted share of neighboring DRM adoption	0.036	0.065	0.021
	(0.02)	(0.06)	(0.03)
B. Robustness to different outcomes and controls			
B.1 - Share of severely flood-affected individuals	0.001	−0.002	0.001
	(0.002)	(0.003)	(0.001)
B.2 - Number of flood-displaced individuals	593.28	1114.279	−433.919
	(813.952)	(1825.565)	(624.105)
B.3 - Log of flood-displaced individuals	2.07	1.61	1.746
	(1.931)	(3.698)	(1.388)
B.4 - Including more controls	0.009	0.045	0.005
	(0.03)	(0.05)	(0.02)
C. Robustness to outlier influence			
C.1 - Dropping top 10% of flood-displaced distribution	0.01	0.011	0.002
	(0.02)	(0.01)	(0.01)
C.2 - Dropping top 25% of flood-displaced distribution	0.007	0.0001	−0.00002
	(0.01)	(0.01)	(0.004)
C.3 - Dropping zeros of flood-displaced distribution	0.019	0.109	0.009
	(0.04)	(0.15)	(0.02)
D. Alternative inference procedures			
D.1 - Standard errors without correction	0.027	0.063	0.01
	(0.031)	(0.068)	(0.021)
D.2 - Clustered standard errors by municipality	0.027	0.063	0.01
	(0.025)	(0.057)	(0.018)
D.3 - Conley (1999) standard errors - 50 km	0.027	0.063	0.01
	(0.028)	(0.066)	(0.017)
D.4 - Conley (1999) standard errors - 100 km	0.027	0.063	0.01
	(0.03)	(0.068)	(0.018)

Notes: Only the coefficients associated with the second-stage regression of our IV/2SLS estimation are shown. All estimations include the following covariates: log population, log GDP per capita, urbanization rate, informality rate, % of the area covered by water, and the number of days with heavy rainfall. Except for Panel D, the heteroscedasticity-robust standard errors are presented in parentheses. Significance: *** represents $p < 0.01$,** represents $p < 0.05$,* represents $p < 0.1$.

we used heteroskedasticity-robust standard errors. To check whether this methodological choice affects our conclusions, we re-estimated the IV/2SLS regression using the following alternative inference methods, presented in Table 5: conventional standard errors (estimation D.1), standard errors clustered by municipality-level (estimation D.2), and, to adjust for a possible spatial autocorrelation of the residuals, we applied the (Conley, 1999) method with cut-off distances of 50 km (estimation C.3) and 100 km (estimation C.4). It can be seen that, although the standard errors vary between the specifications presented in Table 5, our conclusion about the absence of effects of DRM policies remains unchanged.

6. Final remarks

Natural disasters have caused significant human and economic damage in various regions across the globe, prompting empirical economists to investigate strategies for alleviating these adverse impacts (Kellenberg and Mobarak, 2008; Van Westen et al., 2008; Healy and Malhotra, 2009; Sant'Anna, 2018; Ji and Lee, 2021; Bakhsh et al., 2021). In this context, Brazil faces challenges in disaster mitigation, with the absence of effective disaster risk management (DRM) policies being a potential contributing factor. Given its sizeable territorial scale and middle-income status, the nation remains particularly susceptible to catastrophic events, accentuating the high importance of policies to mitigate climate change's repercussions (Kellenberg and Mobarak, 2008; Raschky, 2008; Caselli and Reynaud, 2020).

Our study investigates whether municipal DRM policies effectively reduce the proportion of individuals affected by disasters in the Brazilian context. We analyze the efficacy of flood risk mapping, supervision of flood-prone areas, and flood warning systems. Combining municipal-level flood disaster records for 2020 with information on policy adoption collected in 2019, we employ an instrumental variables approach as our preferred empirical strategy. This approach is necessary because adopting these policies is endogenous to municipalities, so various unobserved socioeconomic, political, and geographical factors may influence it. Despite the strong correlation in the first-stage regression between the adoption rates of neighboring municipalities and DRM policies—particularly for flood risk mapping and flood warning systems—our 2SLS results indicate that these policies are ineffective in reducing the share of flood-displaced individuals. These findings remain consistent across multiple robustness checks.

This observed lack of effectiveness in specific DRM policies may be attributed to several factors. Firstly, the relatively recent establishment of Brazil's new regulatory framework for disaster risk management in 2012 suggests that some policies may require a longer period to achieve full efficacy. Additionally, limited financial resources constrain local authorities' ability to implement effective policies, as the majority of municipal budgets are allocated to current expenditures, leaving little for necessary infrastructure and training. Furthermore, many municipalities lack a dedicated budget for civil defense, further hindering policy implementation and maintenance. Coordination and cooperation challenges among various agencies and sectors, along with differing adoption timelines across municipalities, contribute to the fragmented and inconsistent application of DRM policies. Therefore, continuous monitoring is necessary to assess the performance of DRM policies over time and identify areas for improvement.

A closer examination of studies documenting successful DRM policies offers valuable insights into the factors that enhance their effectiveness. For instance, Ji and Lee (2021) emphasize that counties in the United States receiving funding for mitigation projects, such as infrastructure reinforcement and the relocation of properties in high-risk areas, experienced significant reductions in future property damage. These findings underscore the critical role of robust governance and well-maintained infrastructure in improving the effectiveness of disaster risk reduction measures. Similarly, Davlasheridze et al. (2017) emphasize the importance of cumulative investments in ex-ante mitigation and planning programs, as well as improvements in structural projects, in reducing property damage in the context of hurricanes in the United States. Furthermore, Aerts et al. (2018) highlight the importance of integrating human behavior dynamics, such as risk perception and adaptive responses, into disaster risk reduction strategies,

Table A.1
Determinants of DRM adoption across Brazilian municipalities.

	(1) Flood mapping	(2) Flood supervision	(3) Warning system
Past flood shocks	0.066***	0.026***	0.025***
	(0.003)	(0.003)	(0.002)
Days with heavy rainfalls	0.046***	0.034***	0.005
	(0.012)	(0.011)	(0.009)
Log(Population)	0.087***	0.081***	0.041***
	(0.007)	(0.006)	(0.004)
Log(GDP Per capita)	0.054***	0.036***	0.015**
	(0.014)	(0.013)	(0.007)
Urbanization rate	0.119***	0.072**	0.059***
	(0.037)	(0.028)	(0.019)
Informality rate	−0.404***	−0.471***	−0.258***
	(0.136)	(0.109)	(0.076)
Share of area covered by water bodies	−0.03	−0.196	0.077
	(0.145)	(0.145)	(0.124)
R^2	0.237	0.15	0.13
F-test	242.265	137.554	116.212
Prob	(0.00)	(0.00)	(0.00)
Number of observation	5461	5461	5461

Notes: This table shows the results of a linear probability model estimated by OLS in which the dependent variable is a variable that assumes 1 when the municipality adopts one of the three DRM policies and assumes 0 otherwise. The explanatory variables are detailed in Section 4. The heteroscedasticity-robust standard errors are presented in parentheses. Significance: *** represents $p < 0.01$,** represents $p < 0.05$,* represents $p < 0.1$.

emphasizing the complementary role of private insurance in incentivizing proactive risk management and enhancing post-disaster recovery efforts.

One limitation of this study is that, given its cross-sectional nature and the lack of detailed data on the timing and quality of policy implementation across municipalities, we are unable to analyze the transition from pre- to post-adoption of DRM policies. This limitation prevents within- and between-municipality comparisons over time and may leave our estimates susceptible to confounding factors that evolved after policy implementation. The absence of longitudinal data also restricts a deeper analysis of how contextual nuances, such as institutional and financial capacities, influence the effectiveness of these policies across municipalities. Future research should prioritize the collection of longitudinal data and the development of frameworks capable of capturing the multifaceted dynamics of DRM policy implementation.

Lastly, the findings presented in this study cannot be directly generalized to other countries. The quality of DRM policies can substantially differ among countries, thereby directly influencing their potential impacts. This raises the need for future studies to investigate whether and how preemptive policies are associated with direct and indirect effects on flood damage in other contexts, particularly in low- and middle-income contexts where there is still little evidence on the subject. Furthermore, subsequent studies should examine the importance of possible mechanisms and evaluate how these policies can assist municipalities in mitigating the damage stemming from flood events.

CRediT authorship contribution statement

Pedro Jorge Alves: Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ricardo Carvalho de Andrade Lima:** Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucas Emanuel:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Table A.1.

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