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Abstract[1]

We evaluate whether floods and landslides are more likely when rain falls inside versus outside protected areas (PAs). We use monthly municipality data for the period 2000-2015 in Guatemala and monthly district data for the period 1992-2019 in Costa Rica. We define relevant catchment areas using water flows to population centers of administrative units. Then, we calculate the precipitation inside and outside PAs within the relevant catchment areas, and test how the frequency of floods and landslides is affected by whether rain falls inside or outside PAs. We use a two-way fixed effect panel data model. For Guatemala, we find no robust statistically significant effects on these types of disasters. However, in Costa Rica, we find that shifts in precipitation towards PAs reduce floods significantly. These results were highly robust. We also find effects on landslides in densely populated districts, as well as reductions in flood-related deaths.

JEL classifications: Q54, Q28, Q24
Keywords: Disasters, Floods, Landslides, Protected areas, Precipitation

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1. Introduction

Since the 1950s, the number of heavy precipitation events have increased over most areas where observational data are available (IPCC, 2021). Additionally, changes in weather variability, climate change, population growth and expansion of human settlements have taken place (IPCC 2014). All these affect the likelihood of disasters. This is of special importance in developing countries where the costs of disasters can be higher (Noy, 2009, and Cavallo et al., 2021). In the context of a changing climate, where extreme weather events are expected to increase, it is necessary to understand the role of policy interventions and infrastructure development in mitigating disasters.

There is growing attention to the mitigation of impacts of events such as floods and storm damage through investment in green infrastructure, or nature-based solutions, involving ecosystem protection or restoration. Unlike development of built infrastructure, these measures can address the underlying drivers of natural disasters (Kumar et al,. 2020). Forest, mangroves, and wetlands provide regulation of the hydrological cycle, soil erosion control and storm protection that help to diminish the damages of floods and landslides in local population (Calder and Aylward, 2006; Barbier, 2006; Bradshaw et al., 2007; Das and Vincent, 2009; Das and Crépin, 2013; Barbier et al., 2013; Tan-Soo and Pattanayak, 2019). The goal of protected areas (PA) is to protect and conserve ecosystems and the services they deliver (Dudley, 2008; Mace, 2014; IUCN, 2015). As such they have the potential to provide a nature-based solution to climate-related disasters for downstream populations. In contrast to other environmental objectives of Pas such as carbon sequestration, which offer global benefits but may be of limited importance locally, the role of Pas in disaster mitigation would benefit local populations directly.

While the water regulation benefits of forests are well established, there is a lack of evidence on whether Pas effectively deliver disaster reduction effects in practice. Therefore, evaluating the impact of establishing protected areas on the occurrence of a weather-related disaster is key for developing countries in general, but in particular for those in Central America, where vulnerability to water-related disasters is high (IPCC, 2021). There are several reasons why PAs might not be associated with reductions in disasters. First, protected areas might be located in areas where they do not provide this service. For instance, they might be placed downstream of population centers. Second, even if they are located upstream of population centers, the types of vegetation that they might be protecting do not necessarily decrease disasters. Third, even if protected areas are located upstream in areas that can sustain vegetation that regulates water flows, weak enforcement could mean that the effects of the PA on land use are minimal. Exploring whether PAs can generate these services is key because this is the most-used tool to protect forests.

We estimate how changes in precipitation patterns toward PAs may affect the frequency of floods and landslides in Guatemala and Costa Rica. The period of analysis is 2000-2015 with monthly data at the municipality level in Guatemala, and 1992-2019 with monthly data at the district level in Costa Rica. Guatemala is one of the poorest countries in the Latin American region (Ullmann et al., 2014), with very high concentration of wealth in some areas. Costa Rica has a GDP per capita almost three times larger than the GDP per capita in Guatemala. Additionally, Costa Rica's protected areas cover 25 percent of the land,[2] while in Guatemala, they cover 20 percent (UNEP-WCMC and IUCN, 2022). However, both Guatemala and Costa Rica have been highly affected by extreme events.

With a two-way fixed effect model, we exploit exogenous variation in the distribution of water that falls inside and outside PAs within the watershed in a given month. We have monthly variation of the treatment status as well as monthly information on natural disasters. We estimate the effects of shifts in precipitation towards PAs on floods and landslides, by precipitation levels, population density, poverty levels and slopes.

We contribute to the literature on disasters in several ways. First, we identify the relevant watersheds by administrative units using population centers, and within these units, we measure precipitation inside versus outside PAs. This goes beyond previous key studies that consider effects of forest within administrative units where they are located (Bradshaw et al., 2007 and Ferreira and Ghimire, 2012). We are able to test whether PAs within a watershed have effects on other municipalities. This also addresses the issue that protection within a municipality might not have an effect on disasters because it is not located upstream of the population centers of the municipality. Second, municipalities or districts with large areas of PA upstream of population centers may differ from those with small areas of upstream PA, in ways that influence occurrence of disasters such as population density and levels of development. Our empirical strategy controls for this potential source of bias through administrative unit fixed effects, while time fixed effects account for monthly and annual weather patterns and other time events that affect the region as a

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[2] http://www.sinac.go.cr/ES/docu/Paginas/asps.aspx

whole. We also exclude municipalities with no upstream PAs, which strengthens the assumption that trends in natural disasters in the absence of PAs would be parallel.

Our goal is to estimate whether occurrence of natural disasters resulting from heavy rainfall is lower when the location of the precipitation event is protected, compared with when the location of the precipitation event is unprotected. This requires the assumption that the effect of rainfall on protected land would be the same as the effect on unprotected land in the same watershed in the absence of protection within the municipality. This assumption is weaker than the assumption that cross-sectional administrative units with and without upstream PAs are similar in their characteristics. The main concern to the validity of this strategy is that protected areas tend to be in areas with higher slopes than in areas with lower slopes (see Pfaff et al., 2009). This could occur within municipalities. However, higher slopes generate more disasters, so this would bias the estimated coefficients against our hypothesis that PAs reduce disasters. In our results, we include a robustness test that shows that in low-sloped municipalities, where differences within a municipality tend to be lower, the estimated effect is very similar to municipalities with high slopes.

In Guatemala, we find no statistically significant effects that shifts in precipitation reduce floods and landslides. These results are highly robust. For the lineal model, the estimated effects were statistically insignificant during different seasons, and for different levels of population density and of poverty. For the Poisson model, results were similar except for landslides, in which we find some statistically significant reductions. However, in Costa Rica, we find that the effects of shifts in precipitation towards PAs are negative and statistically significant when we consider both floods and landslides. This is mostly driven by the reductions in the number of floods. We also show evidence that the effects of shifts of precipitation towards PAs reduce the number of flood-related deaths. The effects on landslides were also negative across specifications, but only statistically significant for areas with high population density.

We show evidence that supports the fact that shifts in precipitation towards PAs is not related to differences in slopes between areas with and without protection within watersheds. These effects are most likely originated by differences in land uses between PAs and non-PA areas. There is evidence that PAs have an impact on forest conservation (Andam et al., 2008, and Pfaff et al., 2009). These effects, however, usually take time. This implies that probably, the implementation of PA would not generate impacts on disasters immediately.

There are several factors that can explain the difference in the results between Guatemala and Costa Rica. First, the location of protected areas in relation to towns and the fraction of coverage differ between the countries. These two factors partly explain why protected areas can have different effects on the likelihood of disasters. Second, enforcement of protected areas regulations in Costa Rica is very strict. Deforestation within protected areas is almost negligible (see Pfaff et al., 2009). However, there is evidence of extensive deforestation in protected areas in Guatemala (see Bullock et al., 2019). Third, economic conditions also differ between these countries. This might also generate different effects of protected areas. For instance, poorer housing infrastructure can be highly sensitive to weather anomalies, and the presence of PAs may not make a significant difference in these situations. Fourth, data quality may vary between these countries. Media and government institutions are the primary source of flood and landslide data. These two types of organizations may operate differently, which could lead to differences when reporting and declaring floods and landslides.

This analysis can be improved in different ways in future research. First, robustness tests of different forms of defining watersheds can be conducted. This is especially important because precipitation and land use from different locations can affect different types of disasters. Second, even when clustered at the municipality level, standard errors can be improved because there may be a correlation in the error term between municipalities within the broadest definition of watersheds. Third, the role of forest within protected areas as a mechanism through which protected areas affect floods and disasters can also be further explored.

This paper is organized as follows. In Section 2, we provide the background for the paper. In Section 3, we present de data. In Section 4, we discuss the empirical strategy. In Section 5, we show the results. Finally, in Section 6, we present the conclusions.

2. Background

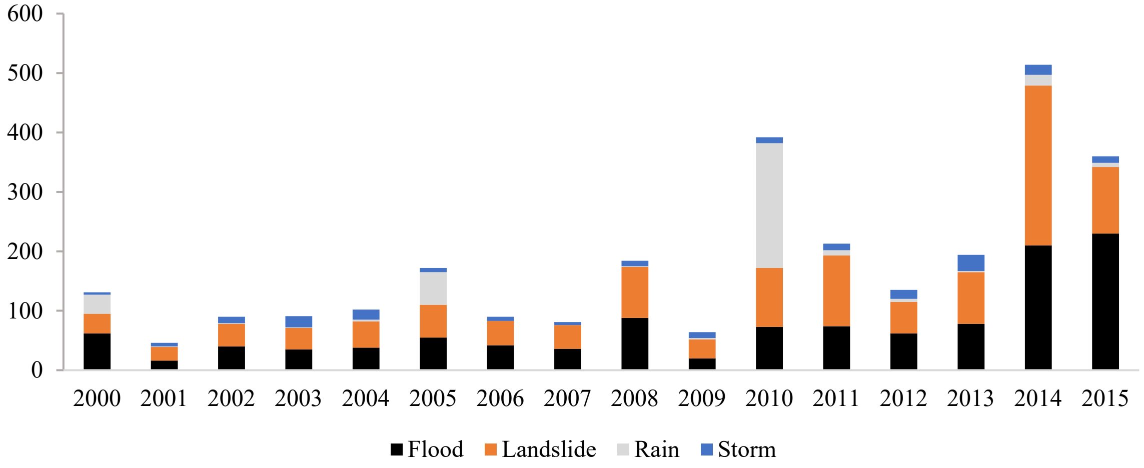
2.1 Disasters in Guatemala and Costa Rica

In Figures 1 and 2, we present the number of disasters for Guatemala and Costa Rica. Both countries have been highly affected by extreme events. In Guatemala, for most of the years, floods and landslides are the most common type of water-related events. During the period of analysis, the highest number of this type of disasters was 514, which occurred during 2014. In Costa Rica, floods and landslides are also the most common water-related disasters, except in 2016 and 2017. In 2007, Costa Rica reached more than 1,400 water-related disasters.

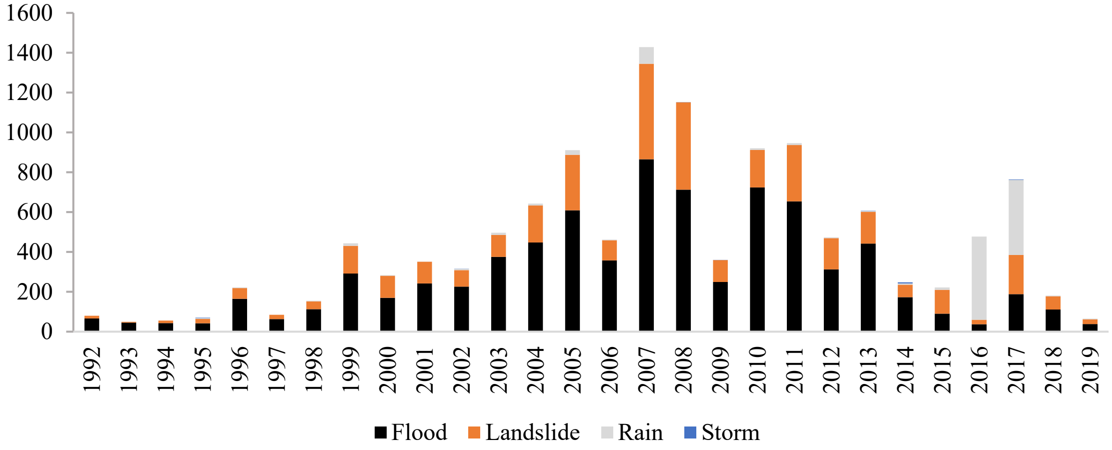
Figure 1. Water-Related Disasters per Type and Year in Guatemala and Costa Rica

(Number of disasters)

Guatemala 2000-2015



Costa Rica 1992-2019

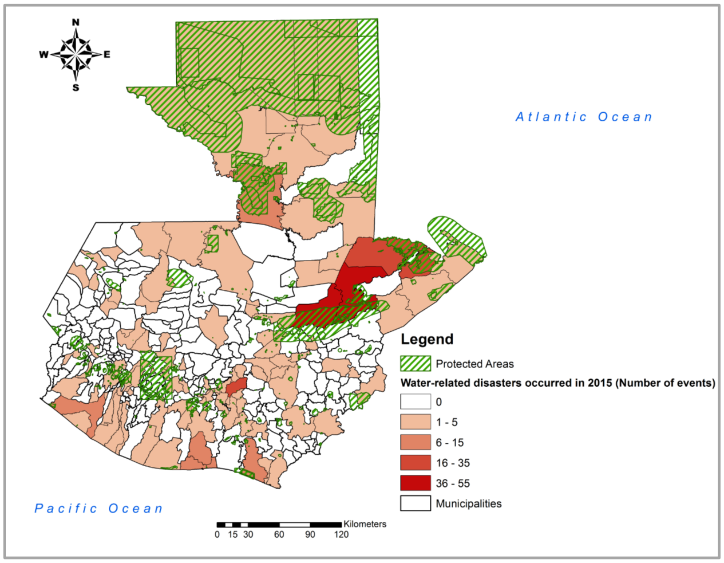


Source: Authors’ calculations with Desinventar Data.

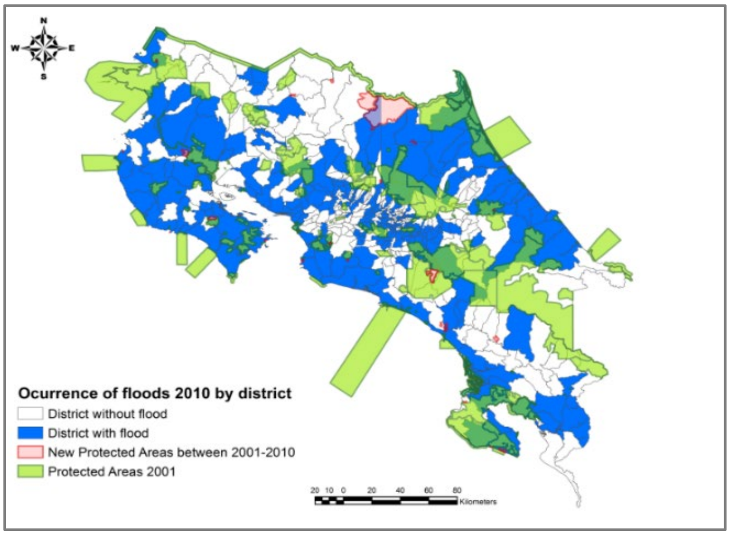
As can be seen in Figure 2, in Guatemala and Costa Rica, disasters and protected areas are located across regions. Some of the disasters occur far away from protected areas, but they also occur close to protected areas. However, in Guatemala, we observe some concentration of disasters in areas in the east, close to the Atlantic (red municipalities). In Costa Rica, there are districts not affected by floods (white districts) in 2010.

Figure 2. Number of Water-Related Disasters per Municipality and Protected Areas

Guatemala 2015



Costa Rica 2010



Source: Authors’ calculations with Desinventar Data.

Protected areas are also located across regions in both countries. In Guatemala, however, there is a very large concentration of protection in the north (Petén). The rest of the country has well distributed but small coverage of PAs. Costa Rican protected areas are well distributed. However, there is some concentration in the coasts and in the mountains. Protection is focused on natural beauty sites (PAs next to the ocean and volcanos) and protection of remote forest areas (mountains). There is no evidence that disaster mitigation plays a role in determining the locations of PAs (Robalino et al., 2020).

2.2 Mechanisms for Effects of PAs on Disasters

There are different mechanisms through which protected areas can affect hydrological disasters. PAs could affect the likelihood of disasters in local populations through hydrological or other indirect mechanisms. In Guatemala and Costa Rica, PAs are largely located in forested locations. When they are effective, PAs will therefore reduce deforestation (Andam et al., 2008; Pfaff et al., 2009; Blackman et al. 2015). Evidence shows that often this impact is not large given that many PAs are located in isolated places far away from roads and cities and in highly sloped land (Pfaff et al., 2009). Even if PAs are established in places where deforestation would have occurred, the effects of forests on the local hydrology vary strongly as a function of forest type and age, geomorphology, shape of the catchment and soil conditions (Bosch and Hewlett, 1982). Therefore, the effects of PAs on the number of disasters will depend on whether they actually reduce deforestation and the characteristics of the land and forest that is being protected.

Several indirect mechanisms also exist through which PA implementation can have a positive or negative impact on the consequences of flood and landslides on local populations and the sign can be positive or negative. First, PAs can have ambiguous impacts on local populations' employment and wages. On the one hand, they may diminish land availability for agriculture, reducing wages and employment for agricultural workers (Robalino, 2007). Some PAs are located in low-sloped land and close to markets, where they generate important impacts on deforestation (Pfaff et al., 2009). There is also evidence that land conservation, for instance, through payments for ecosystem services, in areas with high deforestation threat can increase poverty levels, and this might be linked to reductions in demand for unskilled labor (Villalobos et al., 2022). Lower real income may increase vulnerability of local populations to floods and landslides because of their diminishing capacity to construct more resilient building structures. Reduction in land availability can also increase migration to other regions, reducing exposure of local populations to flood and landslides in rural areas (Donner and Rodríguez, 2008; McLeman and Smit, 2006; Strobl, 2012). On the other hand, Pas could potentially attract more tourists[3] (Eagles et al. 2002; Reinius and Fredman, 2007), and this can lead to an increase in investment in infrastructure (Eagles et al., 2002; Khadaroo and Seetanah, 2007). Moreover, an increase in the number of visitors can have positive impacts on employment and wages of local populations (Robalino, 2007; Andam et al., 2010; Sims, 2010; Ferraro et al., 2011; Ferraro and Hanauer, 2011; Robalino and Villalobos, 2015). As consequence, local populations can reduce their vulnerability to flood and landslide damages by improving housing infrastructure. However, this effect can be buffered because the presence of natural protection can discourage households' self-insurance[4] from extreme weather events (Mahmud and Barbier, 2016). Moreover, increased income can attract migration from other regions (Wittemyer et al,. 2008), increasing the population exposure.

Additionally, the increase of economic activity because of the PA establishment can lead to higher tax collection by local governments. This could increase investments in infrastructure and facilities, reducing flood and landslides impacts on local populations (Ferreira et al., 2013). However, higher economic activity and tourist arrivals can lead to increased public investment in roads and other infrastructure construction that may change the land characteristics or promote economic activities that reinforce the occurrence of floods and landslides and their negative effects on humans (Gössling, 2002; Newsome et al., 2013).

2.3 Effects of Forests on Disasters

The relationship between forest cover and water-related disasters has been explored significantly more than the relationship between PAs and disasters. For instance, Ferreira and Ghimire (2012) and Ferreira et al. (2013) found that there does not exist a relationship between forest cover, floods and flood fatalities using cross-country analyses. However, in a more disaggregated analyses, it has also been shown that mangroves decrease mortality from storm surges in India (Das and Vincent, 2009) and reduce the economic impacts of hurricanes in Central America (del Valle et al., 2020). Deforestation has been found to increase the number of days flooded per month in large

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[3] In Costa Rica, all National Parks and most of the public Natural Reserves receive tourists. The effects of the implementation of PAs on the number of tourists that a region receives can also potentially vary.

[4] In their paper, Mahmud & Barbier define self-insurance as household efforts to reduce the impact of a disaster.

catchments during heavy-rainfall periods in Malaysia (Tan-Soo and Pattanayak, 2019) and increase the number of landslides in Georgia (Brander et al., 2018).

Bhattacharjee and Behera (2017) found that forest cover has an inverse relationship with the flood damage using data for the period 1998-2011 in India, suggesting that increasing forest cover significantly contributes to reducing the number of people affected and human fatalities during floods. Similarly, Brookhuis and Hein (2016) found that the relation between catchment's forest cover and floods control service is non-linear; and they also indicate that even small levels of deforestation can lead to a significant increase in flood risks in Trinidad. They use a non-linear regression specification that relates forest cover and flood damage for nine catchment areas.

Most of the studies that test the effect of forest ecosystem services on the occurrence of climatic disasters use panel data at different geographic scales. Some studies use data at the national level (Ferreira and Ghimire, 2012; Ferreira et al., 2013), others at the state level (Bhattacharjee and Behera 2017); and others at the district level (Das and Vincent, 2009) or the watershed level (Tan-Soo et al., 2016). Generally, studies focused at the district or watershed level use monthly data panels, while the studies focused at the national level use annual data panels.

When linking forest cover with disaster impacts using administrative data, the unit of analysis can limit the effects that are modeled. For example, forests that influence the likelihood of disasters might be in another administrative unit or located downstream or in a different watershed of population centers within the same unit. An exception, where forest is measured upstream of a watershed can be found in Brookhuis and Hein (2016).

2.4 Effects of Protected Areas on Disasters

PAs have been estimated to avoid USD 7 million per year in avoided flood management in United States coastal zone in Saint Louis County (Kousky and Walls, 2014). Very recent analysis for Costa Rica showed that PAs have two countervailing effects. In the case of Costa Rica, PAs can promote tourism and therefore urbanization, which is shown to be linked to an increase of the likelihood of disasters. However, those PAs correctly located upstream significantly reduce disasters, and these effects are significantly larger than the increase generated by the previously mentioned indirect effects (Robalino et al., 2020). Most studies relate the quantity of forest and disasters within administrative boundaries, like municipalities. However, communities within an administrative unit not only benefit from forest within that unit, but also from forest located in neighboring upstream areas. Also, sometimes communities are located upstream, and forest is located downstream, which implies that forest cannot have a hydrological effect over communities in the same municipality. Therefore, even if the estimates within the administrative units eliminate bias generated by other factors that are associated with forest and disasters, it is likely that these estimates are not capturing the overall effect of forest on the likelihood of disasters. Robalino et al. (2020) consider the altitude at which PAs and population inside the administrative unit are located. However, they do not account for potential effects of PAs in other administrative units on disasters. One possible strategy to address this problem was presented by Wu et al. (2021) when measuring the effects of forest on farm productivity. Using a similar strategy, we propose to calculate watershed areas of population centers within administrative units (municipalities or districts) and within those areas, measure precipitation inside and outside protected areas by month. This allows us to test if the presence of PAs at the site of precipitation reduces the likelihood of disasters.

3. Data

We use a municipality monthly panel between 2000 and 2015 in Guatemala,[5] which implies that we use 63,360 observations (12 months x16 years x 330 municipalities). In Costa Rica, we use a district monthly panel between 1992 and 2019, for a total of 150,528 observations (12 months x 28 years x 448 districts) in Costa Rica (see Table 1). We restrict this sample to municipalities or districts that have protected areas. Therefore, the number of observations in this analysis is reduced to 50,028 for Guatemala and 144,216 for Costa Rica.

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[5] In Desinventar the data from Guatemala are available until 2015.

Table 1. Number of Observations and Means across Municipalities and Months

Observations	**Costa Rica**	**Guatemala**
Period	1992-2019	2000-2015
Total Observations	150528	63360
Cross-section	448	330
Periods	336	192
Observations with PA	144216	50028
Cross-section units with PAs	436	282

Variables	**Means**	**Means**
Disasters^{+}		
Total disasters	0.0721	0.0415
Floods	0.0490	0.0212
Landslide	0.0231	0.0202
Deaths in disasters	0.0015	0.0166
Climate variables		
Rainfall (volume km3)	0.035	0.085
Rainfall in PAs (volume km3)	0.019	0.016
Geographic and socioeconomic conditions		
Watershed area (km2)	155.8	538
Protected areas inside watersheds (km2)	84.6	98.1
Average slope (degrees)	12.3	15.2
Population density (h/km2)	589.7	365
Poverty (%)$^{++}$	29.2	61.9

Source: Authors' calculations $^{+}$Average number of total disasters, floods and landslides, per municipality per month. ++In Guatemala poverty is defined as the percentage of people in poverty and in Costa Rica as the percentage of people without satisfaction of basic needs.

3.1 Disasters

Information from water-related disasters was obtained from the DESINVENTAR dataset, (https://www.desinventar.org), which collects data from official and media sources. This allows us to determine when and where each disaster occurred. Total disasters include floods, landslides, heavy rains, torrential floods, tidal waves, and tempests. We focus on floods and landslides in our analysis as they occur more often than the rest of disasters and are potentially affected by land uses upstream. As can be seen in Table 1, the average number of total disasters, floods and landslides in the period is larger in Costa Rica than in Guatemala. But for both countries, the number of floods is larger than the number of landslides.

3.2 Watersheds, PAs and Precipitation

To determine the amount of water that falls in and out of Protected Areas and reaches the population centers within the administrative units, we use three sources of information:

1. relevant upstream catchment delineation per population center within administrative units,
2. location of protected areas and,
3. rainfall quantity within and outside protected areas per month and per watershed.

To delineate the upstream relevant catchment per administrative unit, we first delineate an upstream catchment for each population center within the administrative unit and merge these areas for all the population centers within that administrative unit. To delineate the relevant upstream catchment per population center, we downloaded pre-defined water catchments produced by the hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS) at level 12 (smallest catchment)[6] for Guatemala and Costa Rica. Second, we downloaded a Digital Elevation Map (DEM) from NASA and merged them with the catchment's areas.[7] For each pixel of the DEM and each village within a municipality, we computed the flow length using the flow length tool in the ArcGIS surface hydrological toolset. Flow length is the distance traveled from any cell along the surface flow network to an outlet. For each cell (population center), we calculated the flow length to the closest headwater location or stream outlet. For each population center, we defined the upstream relevant catchment as all the pixels in the DEM for which the flow length was longer than the flow length of the population center. Olmstead et al. (2013) used this approach to define upstream catchments of a water quality monitoring station. Figure 3 show an illustrative example of the villages and watershed delineated for each village within a municipality. Finally, a macro-catchment per municipality is defined by merging the upstream catchment for all the population centers within a municipality.

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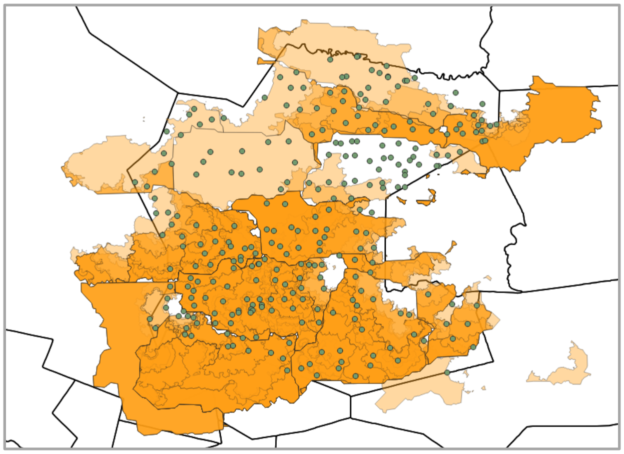
[6] https://www.hydrosheds.org/

[7] https://asterweb.jpl.nasa.gov/ There are 12 levels of catchment areas. We choose the smallest one. Some of the level 12 chatment areas might be upstream of towns and might also influence the likelihood of disasters. In the empirical strategy section, we discuss the implications of choosing a different level of watersheds on the estimation.

Figure 3. Watershed Delineation Using Flow Length for an Illustrative Municipality



* Lines denotes municipality boundaries, points denote population centers, orange polygons denote population watersheds, and the union of all orange polygons denote the municipality watershed.

Information on the PAs comes from the map of the Guatemalan System of Protected Areas (SIGAP). For Costa Rica, we use information about protected areas from the Atlas of Costa Rica developed by the Costa Rican Institute of Technology that also includes the year of creation. The area covered by PAs changes in time within watersheds of administrative units.

Finally, using the catchment by municipality and the location of PAs, we calculate the total quantity of the water that fell in each catchment per month per year, and which fraction of it fell over protected areas. To do that, we overlap watersheds, protected areas, and rainfall raster, and compute the weighted average rainfall (mm per m2) for catchments within and outside PAs. The rainfall raster data was produced by the Climate Hazard group InfraRed Precipitation with Stations, or CHIRPS (Funk et al., 2014). This is later multiplied by the area to get total water quantity and transformed to cubic meters.

Table 1 shows the average amount of rainfall (volume) in macro catchment areas of administrative units. In Costa Rica, the average amount of water in rainfall falling inside PAs is about 54 percent of the total amount of water in the watersheds. In Guatemala, this percentage is only 18.8 percent. The average size of watershed in Costa Rica is 155.8 km^2, while in Guatemala is 538 km^2. Therefore, by unit of area, precipitation in Costa Rica is higher than in Guatemala.

In Costa Rica, the average slope of the districts' watersheds is 12.3 percent while in Guatemala the average slope in the municipality watersheds is 15 percent. We can also observe that Costa Rica is a more densely populated country. We use two different definitions of poverty rates for each country, so they cannot directly be compared, but one can easily conclude that poverty rates in Guatemala are very high.

4. Econometric Specification and Identification

The main objective of this paper is to estimate the impact of PAs on the water-related disaster occurrence by comparing the number of disasters in periods when precipitation upstream from a population center fell in PAs with periods when upstream precipitation fell outside a protected area. The period of analysis will be 2000-2015 and 1992-2019 with monthly data at the municipality and district level for Guatemala and Costa Rica, respectively. PAs vary in space, but only 25 percent of the land of PAs were created during the period of analysis in Guatemala, and there is almost no change in protection in Costa Rica. Therefore, our treatment variable is defined by the amount of water that falls inside the PAs, which depends on location and intensity of precipitation of that specific month as well as the location of the PA.

We describe our identification strategy in an example in Table 2. First, we are going describe how we estimate the effects of an intervention that consists in a shift in the distribution of precipitation from areas outside to inside PAs. Then, we are going to discuss what assumption we need so that the estimated effect of this intervention can be interpreted as the effect of implementing a PA. We assume, for this illustration, that precipitation occurs discretely either inside or outside a PA within a municipality watershed. For simplicity, we also assume that the total precipitation in both periods and both groups is the same. The only change is the distribution of the precipitation from areas outside PAs in period 1 to areas inside PAs in period 2 for the treated unit in column 1. Municipalities with PAs might be significantly different to municipalities without PAs in many dimensions that affect the number of disasters, including slopes, land use, population density and poverty levels. In order to avoid the bias that these differences can generate in our estimates, we do not use municipalities without PAs. As controls, we use municipalities that have PAs, but where precipitation occurred outside PAs in both periods (column 2).

However, there might still be differences between those treated observations in column 1 and those observations in column 2 that are not related to the shifts in precipitation towards PAs. In particular, municipalities with larger areas of PA upstream of population centers will have a greater number of months in which precipitation falls within PA boundaries. Those with small areas of upstream PA will have more of their rainfall outside PA boundaries. This latter type of municipalities might have more agriculture, and therefore different land uses, than municipalities where precipitation often occurs inside PAs. So, the numbers of disasters might be different even if precipitation is outside PAs in both groups of municipalities. These differences can be estimated by comparing cell A with cell C, i.e., the difference between Municipality X (likely to have precipitation within PA boundaries) and Municipality Y (unlikely to have precipitation within PA boundaries) in a period when upstream rainfall occurred outside PAs for both municipalities. We use this difference to estimate the magnitude of this bias. In the second period, when precipitation occurs within PA boundaries only for Municipality X, the difference between the number of disasters for Municipality X (B) and Municipality Y (D) will capture the effects of both the precipitation shift towards PAs and the prior difference A-C. Therefore, by subtracting (A)-(C) from (B)-(D), we obtain our estimate of the effect of having rainfall pass through a PA instead of passing outside a PA.

Table 2. Number of Observations and Means across Municipalities and Months

	Municipality X (1)	**Municipality Y** (2)	Difference
Period 1 Before rain shifts in the treated group	It rains outside PAs (A)	It rains outside PAs (C)	A-C
Period 2 After rain shifts in the treated group	It rains inside PAs (B)	It rains outside PAs (D)	B-D
Difference			Estimated effect (B-D)-(A-C)

This example also allows us to explain in a simple form our main identification assumptions. First, as in other difference in difference approach, we need to assume parallel trends. This implies that in the absence of the PA, the trend between Period 1 and Period 2 in the number of disasters for Municipality X would have been the same as for Municipality Y.

Second, in order to interpret this estimate as the effects of the presence of PAs, we also need to assume that, within column 1, the average number of disasters would have been the same if precipitation occurs inside the area where the PA was located if the PA had not been implemented. This might seem as a strong assumption, but it is significantly weaker than using as control observations those that do not have PAs, as the difference in characteristics of municipalities between those that have and do not have PAS differ significantly more than areas inside the same municipality watershed that have and do not have PAs. Also, even if this occurs, one can reasonably expect that PAs would tend to be in areas with higher slopes than in areas with lower slopes (see Pfaff et al., 2009). Higher slopes generate more disasters. So, this will bias the estimated coefficients against our hypothesis that PAs reduce disasters. In our results, we will also include a robustness test that shows that in low-sloped municipalities, where differences within a municipality tend to be lower, the estimated effect is very similar to municipalities with high slopes.

Third, protected areas can also trigger changes in nearby land uses. If they do, control observations will be contaminated. There is evidence that this type of spillover is present in Costa Rica (Robalino et al., 2017, and Robalino et al., 2015). The analysis for the most recent data finds that buffers of protected areas are associated with decreases in deforestation (Robalino et al., 2015). We would then find that control observations would generate less disasters due to protection, and therefore, bias results against the hypothesis that PAs reduce disasters.

To generalize the specification, we presented we use a two-way fixed effect model with a panel. We can control for municipality fixed effects and month and year fixed effects. Time-invariant information such as biophysical and geographic variables (slope, altitude, distance to the coasts, density of rivers, etc.) are captured by the fixed effect coefficients.

The following equation describes the empirical estimation:

$$Y_{it} = \beta_0 + \tau A_{it}^{PA} + \beta_1 A_{it} + \alpha_{i,s} + \delta_t + \mu_{it} \quad (1)$$

where, Y_{it} is the number of disasters in municipality i during month t. The amount of precipitation that fell inside a protected area in the catchment areas of municipality i during the month t is denoted by $A\tau_{it}^{PA}$. Then, Ait is the total amount of water that passes through the catchment area of municipality i during the month t, δ are time fixed effects (year and month), α represents municipality-season fixed effects and μ_{it} is the error term in municipality i during month t.

The coefficient τ is the effect on the number of disasters per month when one cubic kilometer of precipitation fell in a protected area, relative to the base case, which is outside a PA. We are controlling by the total amount of water that rains in the watershed. So, for a given level of total precipitation, one unit more of rainfall in a PA implies that there will be one unit less of rainfall outside a PA. Therefore, τ measures the effect of redistributing one cubic kilometer of rainfall from areas outside a PA towards an area inside a PA. This is equivalent to the example we showed previously.

The advantage of using this specification is that unobserved municipality factors that are fixed over time and time factors that affect all municipalities will not bias the estimated effect, allowing us to address the bias resulting from the non-random siting of PAs. Municipalities' fixed characteristics, such as population, altitude, slope, and precipitation, might be correlated with the presence of PAs and the likelihood of disasters. So, municipality fixed effects will eliminate this source of bias. Also, time variables and precipitation might be correlated with economic activities, for instance in agriculture, that could also affect land use and therefore likelihood of disasters. By including time fixed effects, we can eliminate this other source of bias.

However, just like in the example, we required the assumption that the error term might not be correlated to changes in precipitation. Additionally, in order to interpret the estimated effect of the shift in precipitation from outside to inside PAs, we need an additional assumption. In average, one unit of rainfall in the area where the PA was located, if it had not been implemented, would have generated the same number of disasters as if that unit of rainfall would have been located in the unprotected area of the watershed. While this might not be the case, we discussed that the potential bias that this might generate would bias our coefficients against our hypothesis.

Finally, it is important to note that disasters, floods and landslides constitute count dependent variables. As equation (1) suggests, we use a linear model. However, as robustness test, we also use a Poisson model for count data for most of the specifications.[8]

Another challenge is defining of the relevant watershed. Different types of disasters can be affected by precipitation in different locations. Close by precipitation and water flows have an impact on landslides and flash floods. So, the relevant land use should also be relatively close. However, there are some types of floods, such as flows in towns close to rivers, which can be affected by precipitation far away because it affects river flow. Selecting the smallest watersheds may be problematic for this type of disaster because we are not considering PAs in other watersheds upstream of a population center, which could potentially affect the likelihood of floods, especially for towns near rivers. However, it is important to consider that by selecting larger

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[8] The use of a linear model with count data can generate heteroskedasticity issues but would not bias our estimated coefficients. This issue is less of a concern given the number of observations we have in our analysis. Additionally, we use clustered standard errors.

watersheds (for instance level 1, which has larger watersheds), we will also be assigning treatment when there is really no treatment effect because a significant portion of rainfall within PAs in a level 1 watershed may not end up in the municipality. This occurs because a municipality might not be in the same sub-basin of a PA or because the upstream sub-basin is too far away to have an effect.[9] In general, this problem increases as watershed size increases. Therefore, there is a trade-off for choosing large versus small watersheds in terms of bias. We choose level 12 (the smallest one) because when defining the municipality watershed we merge many level 12 watersheds. We do this because we construct them based on population locations within municipalities and because population centers within a municipality might be in different watersheds. This aggregation attenuates the effect of choosing small watersheds as we consider various level 12 watersheds for one municipality, and some of them are upstream of other watersheds. In fact, the relevant watersheds are in average larger than municipalities in Guatemala and larger than districts in Costa Rica.[10] However, testing different levels of watersheds would be useful for future work. Another option for addressing this issue is to merge upstream watersheds, which the data allow.

5. Results

In this section, we present our estimates of the effect of total rainfall on the number of floods and landslides. As we discussed in our empirical identification strategy, if the amount of rainfall in PAs increases, one would expect that the number of disasterd would decrease, as more rainfall would go through protected areas that regulate flows, instead of going through areas outside PAs. First, we estimate the effects on both disasters (floods plus landslides), the effect on floods and landslides separately and by precipitation season.[11] Second, we test if there are heterogeneous effects using population density and poverty levels. Third, we explore the intensity of the disasters by using deaths caused by floods and landslides as dependent variable. Fourth, we discuss splits by the level of slopes and discuss what they imply in term of bias.

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[9] For example, one of the level 1 watersheds in Guatemala is about one quarter of the country.

[10] The average size of a district is around 106 square kilometers and the average size of the “relevant” watersheds we constructed is around 250 square kilometers in Costa Rica. In Guatemala, the average size of a municipality is around 330 square kilometers, and the average size of watershed is around 538 square kilometers.

[11] We use the traditional definition of precipitation seasons in the region, which is divided into the dry season (November, December, January, February, March and April) and the rainy season (May, June, July, August, September and October).

5.1 Main Results Effects

In Table 3 panel A, we show that the effects of shifts in precipitation towards PAs on the number of disasters in Guatemala are not statistically significant for the linear model (column 1). We also explore the effects on floods and landslides separately, but they are also statistically insignificant (column 2 and 3). Even when we focus on the effects during the rainy season, results are statistically insignificant (column 4 and 5). When we use the Poisson model, we do not find significant effects for floods and landslides together and for floods at a 5% level (column 1). However, we find that a highly statistically effect on landslides (column 3). During the rainy season, the effect on floods and landslides together becomes statistically significant at a 5% level (column 5). We conclude that the effects are mostly statistically insignificant and non-robust for Guatemala.

Table 3. Effect of Shifts in Rainfall towards PAs on Floods and Landslides and by Season

	Floods and landslides	**By type of disaster**		**By season^{+}**	
		Floods	**Landslides**	**Dry**	**Rainy**
	(1)	(2)	(3)	(4)	(5)
A. Guatemala					
Linear					
Rainfall in PA (km3)	0.0411	0.181	-0.140	0.537	-0.110
	(0.194)	(0.217)	(0.138)	(0.721)	(0.266)
Observations	49,800	49,800	49,800	24,786	25,014
Poisson					
Rainfall in PA (km3)	-1.529*	-0.656	-6.569***	5.517*	-2.281**
	(0.803)	(0.900)	(2.203)	(3.052)	(0.974)
Observations	42,179	28,497	33,319	8,795	20,610
B. Costa Rica					
Lineal					
Rainfall in PA (km3)	-0.984***	-0.878***	-0.107	-0.705**	-1.113***
	(0.336)	(0.279)	(0.117)	(0.321)	(0.418)
Observations	143,814	143,814	143,814	71,706	72,108
Poisson					
Rainfall in PA (km3)	-2.339***	-1.742**	-3.701***	3.475*	-3.446***
	(0.685)	(0.804)	(1.327)	(1.996)	(0.750)
Observations	139,459	132,983	119,762	44,825	69,264

Source: Authors calculations. *** p<0.01, ** p<0.05, * p<0.1. $^{+}$Dry from December to April, Rainy from May to November. For the linear model, clustered standard errors at administrative unit level in parentheses. For Poisson, standard errors in parentheses. Poisson drops cross-section observations (municipalities or districts) with all zero outcomes. Control variables: total rainfall (current, lagged, square, cubic and interacted with the wet season), month fixed effects and municipality-season fixed effects. Poisson with the same control variables except that instead of municipality-season fixed effects with municipality fixed effects and region-season dummies.

In Table 3 panel B, we show that the effects of rainfall shifts towards PAs decrease significantly the number of floods and landslides in Costa Rica (column 1). The effect is large when we consider that the average amount of water that passes through a PA in those districts that have PAs is 0.019 km3. So, in the absence of that shifts, those districts would have had 0.018[12] more disasters per month, which is more than 25 percent of the average number of disasters.[13] The effects are especially large for floods, which is statistically significant and large (column 2). The estimated number of floods without the shift in precipitation towards PAs would have increased in 34 percent.[14] For the linear model, there is no statistically significant effect on landslides, but the sign is the expected. However, the effect becomes statistically significant when using Poisson (column 3).

We also explore the effect of the rainfall shifts towards PAs during the dry and rainy season separately in Costa Rica in Table 3. Disasters depend on different factors. So, even non-extreme precipitation shocks can cause disasters. In some places that suffer even small changes in specific socio-economic, infrastructure and geographic characteristics, average levels of precipitation can have the potential to generate floods or landslides. Consistent with this, we observe disasters in the dry season, but also statistically significant effects of shifts of rainfall towards PAs. However, the impact is larger during the rainy season in Costa Rica. When we use the Poisson model, we confirm the result during the rainy season but not during the dry season.

5.2 Population Density and Poverty Heterogeneous Effects

We also test if socioeconomic characteristics can generate changes in the estimated effects. First, we test the effects by population density levels in Table 4. Again, for the linear model, we find no statistically significant effects of precipitation shifts towards PAs in Guatemala in both high and low population density municipalities (columns 1 and 2). When we use Poisson, all models in high population density areas are not statistically significant (column 3). We only find statistically significant effects for landslides and not for floods in low population density areas (column 4). We again conclude that the effects are mostly statistically insignificant and non-robust in Guatemala.

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[12] 0.019 km3 of average rainfall in PAs times 0.984 the estimated effect of a movement of 1 km3.

[13] As shown in Table 1, the average number of disasters is 0.0721. So, an increase of 0.018 would have represented more than 25 percent.

[14] 0.019 km2 of average rainfall in PAs times 0.878, which is the estimated coefficient, divided by 0.049, which is the average number of floods per month per district.

However, for the case of Costa Rica, we find statistically significant effects. They all show that shifts of rainfall towards PAs reduce the number of floods and landslides (negative signs). We also observe that in districts with high population density, the estimated effects on floods are statistically insignificant but larger in magnitude (more than double) than for low population density. For landslides, the estimated effect in high population density is statistically significant and larger than the one in low population density districts. These results were robust to changes in the functional form specification (linear and Poisson).

Table 4. Effect of Shifts in Rainfall towards PAs on Floods and Landslides by Population Density Levels^{+}

	Linear Model		**Poisson Model**	
	(1)	(2)	(3)	(4)
Guatemala	**High pop density**	**Low pop density**	**High pop density**	**Low pop density**
Floods and landslides	-0.377	0.0131	-1.816	-1.860**
	(1.092)	(0.196)	(4.290)	(0.845)
Observations	26,774	23,026	21,787	19,095
Floods	-0.579	0.182	5.204	-1.040
	(0.378)	(0.219)	(8.724)	(0.924)
Observations	26,774	23,026	13,432	14,171
Landslides	0.202	-0.169	-2.982	-10.97***
	(0.858)	(0.148)	(5.138)	(2.756)
Observations	26,774	23,026	19,086	13,116
Costa Rica	**High pop density**	**Low pop density**	**High pop density**	**Low pop density**
Floods and landslides	-4.240	-1.207***	-8.293***	-1.501**
	(2.972)	(0.373)	(1.964)	(0.738)
	71,899	71,915	70,247	68,913
Floods	-2.430	-0.997***	-4.336*	-1.336
	(2.586)	(0.308)	(2.461)	(0.864)
	71,899	71,915	68,320	64,232
Landslides	-1.810***	-0.210*	-15.21***	-1.919
	(0.563)	(0.121)	(3.412)	(1.433)
Observations	71,899	71,915	64,887	54,469

Source: Authors calculations. *** p<0.01, ** p<0.05, * p<0.1. $^{+}$Cut-off points for population density is the median 200 h/km2 for Guatemala and 47 h/km2 for Costa Rica. For the linear model, clustered standard errors at administrative unit level in parentheses. For Poisson, standard errors in parentheses. Poisson drops cross-section observations (municipalities or districts) with all zero outcomes. Control variables: total rainfall (current, lagged, square, cubic and interacted with the wet season), month fixed effects and municipality-season fixed effects. Poisson with the same control variables except that instead of municipality-season fixed effects with municipality fixed effects and region-season dummies.

Second, we test the effects by poverty levels in Table 5. We find no statistically significant effects of shifts of precipitation towards PAs in Guatemala for the linear model in both high and low-poverty municipalities. When we use Poisson, we find statistically significant effects for landslides in high poverty areas. However, we also find a statistically significant and positive effect for floods in low poverty municipalities. This is a counterintuitive result, but the statistical significance is not robust when we use a linear model. We again conclude that the effects are mostly statistically insignificant and non-robust in Guatemala.

Table 5. Effect of Shifts in Rainfall towards PAs on Floods and Landslides by Poverty Levels^{+}

	Linear Model		**Poisson Model**	
	(1)	(2)	(3)	(4)
Guatemala	**High poverty**	**Low poverty**	**High poverty**	**Low poverty**
Both disasters	0.00553	0.108	-2.996***	4.587***
	(0.230)	(0.361)	(1.019)	(1.667)
Observations	23,621	26,179	19,632	22,547
Floods	0.162	0.210	-1.239	5.212***
	(0.324)	(0.322)	(1.216)	(1.826)
Observations	23,621	26,179	11,669	16,828
Landslides	-0.156	-0.102	-9.115***	6.198
	(0.206)	(0.0967)	(2.699)	(5.610)
Observations	23,621	26,179	16,396	16,923
Costa Rica	**High poverty**	**Low poverty**	**High poverty**	**Low poverty**
Floods and landslides	-1.162***	-1.330	-1.582**	-4.146***
	(0.398)	(0.823)	(0.795)	(1.279)
Observations	72,191	71,623	69,846	69,613
Floods	-0.983***	-1.080	-0.917	-3.079**
	(0.331)	(0.692)	(0.940)	(1.502)
Observations	72,191	71,623	65,045	67,938
Landslides	-0.179	-0.250	-2.372	-7.412***
	(0.131)	(0.276)	(1.523)	(2.482)
Observations	72,191	71,623	56,514	63,248

Source: Authors calculations. *** p<0.01, ** p<0.05, * p<0.1. $^{+}$Cutoff points for poverty are 66.34% in Guatemala and 28% in Costa Rica. For Costa Rica, we use the percentage of unsatisfied basic needs. For the linear model, clustered standard errors at administrative unit level in parentheses. For Poisson, standard errors in parentheses. Poisson drops cross-section observations (municipalities or districts) with all zero outcomes. Control variables: total rainfall (current, lagged, square, cubic and interacted with the wet season), month fixed effects and municipality-season fixed effects. Poisson with the same control variables except that instead of municipality-season fixed effects with municipality fixed effects and region-season dummies.

For the case of Costa Rica, they all show that shifts of rainfall towards PAs reduce the number of floods and landslides (negative signs). The magnitude of the coefficients are always larger in low-poverty districts than in high poverty districts for both linear and Poisson models. However, statistical significance is not robust between the models. In the Poisson model we find that low poverty areas are statistically significant for both floods and landslides. However, in the linear model, there are no statistically significant coefficients in low poverty districts. Therefore, we cannot make robust conclusions about the difference in the effects between high and low poverty districts in Costa Rica.

5.3 Impact on Intensity Using the Number of Deaths

One remaining question is if shifts in precipitation towards PAs affect not only the number of disasters but also, the damage that these disasters have on the population. To measure this, we use as dependent variable the number of disaster-related deaths (see Table 6). We find again that there are no statistically significant effects in Guatemala. In Costa Rica, the effects of precipitation shifts towards PAs decrease the number of flood-related deaths. The effect is statistically significant. This implies that if precipitation would not have shifted the average number of deaths in those districts would have been 32 percent higher than the average number of deaths due to floods.

Table 6. Effect of Shifts in Rainfall towards PAs on Disaster-Related Deaths by Type

Guatemala	**Floods and landslides**	**Floods**	**Landslides**
Deaths	0.171	0.00245	0.169
	(0.222)	(0.0111)	(0.223)
Observations	49,800	49,800	49,800
Costa Rica	**Floods and landslides**	**Floods**	**Landslides**
Deaths	-0.0184	-0.0253***	0.00689
	(0.0134)	(0.00791)	(0.0113)
Observations	143,814	143,814	143,814

Source: Authors' calculations. *** p<0.01, ** p<0.05, * p<0.1 Clustered standard errors in parenthesis at administrative unit level in parentheses. Control variables: total rainfall (current, lagged, square, cubic and interacted with the wet season), month fixed effects and municipality-season fixed effects.

5.4 Slopes Splits and Potential Bias

As we previously discussed, one potential source of biased that can limit the possibility to interpret the estimated coefficients as the impacts of establishment of PAs on disasters is the fact that protected land within the watersheds might be different than unprotected land in dimensions that are related to the likelihood of disasters. One important dimension is the slope of the terrain. There is evidence that PAs tend to be in more sloped land in Costa Rica (Pfaff et al., 2009). If that is the case, precipitation in protected areas might generate more disasters not because land use is different than outside PAs but because slopes are different. If that is the case, if we restrict the level of slopes by looking at municipalities or districts with low average slopes, that tend to have also lower variation in slopes, the bias should decrease and one could expect that the differences in number of disasters is related to land uses inside PAs. We conduct this test in Table 7.

In Guatemala, we find that the effect of shifts in precipitation towards PAs on floods in low-sloped areas and for the whole sample are statistically insignificant for the linear and the Poisson models. However, for landslides, there are differences in the sign, magnitude and statistical significance between the estimated results for low-sloped municipalities and the whole sample. This could imply that the effect for landslides in Guatemala might come from high sloped areas where more bias is present. However, even in that case the sign of the estimated effect is negative, which suggests that PAs are overcoming the size of the bias.

In Costa Rica, the effects of shifts in precipitation towards PAs on floods are all negative and statistically significant. The estimated effects in low sloped districts are very similar in magnitude and significance to the estimated effects of the whole sample for both the linear and Poisson specifications. However, the magnitude of the effect on landslides for the Poisson model is larger for low slopes than for the whole sample. This confirms that the estimated effect for landslides is not coming from areas where bias might be more present (high-sloped areas). Therefore, we conclude that, in Costa Rica, the results are not driven by places where slopes are high and where bias might be more present.

Table 7. Effect of Shifts in Rainfall towards PAs on Disasters and by Slope Level

	(1)	(2)	(3)	(4)	(5)	(6)
		Linear			**Poisson**	
Guatemala	**Whole sample**	**Low slope^{+}**	**High Slope^{+}**	**Whole sample**	**Low slope^{+}**	**High Slope^{+}**
Floods and landslides	0.0411	0.0366	1.568*	-1.529*	0.789	0.0349
	(0.194)	(0.212)	(0.921)	(0.803)	(0.948)	(2.567)
Observations	49,800	26,821	22,979	42,179	21,685	20,494
Floods	0.181	0.0706	3.249*	-0.656	0.576	5.695
	(0.217)	(0.203)	(1.739)	(0.900)	(1.012)	(4.693)
Observations	49,800	26,821	22,979	28,497	16,837	11,660
Landslides	-0.140	-0.0341	-1.681*	-6.569***	3.265	-4.211
	(0.138)	(0.0360)	(0.962)	(2.203)	(3.682)	(3.542)
Observations	49,800	26,821	22,979	33,319	15,297	18,022
Costa Rica	**Whole sample**	**Low slope^{+}**	**High Slope^{+}**	**Whole sample**	**Low slope^{+}**	**High Slope^{+}**
Floods and landslides	-0.984***	-0.812***	-0.867	-2.339***	-3.125***	-0.233
	(0.336)	(0.286)	(0.598)	(0.685)	(0.913)	(1.074)
Observations	143,814	71,688	71,623	139,459	69,343	70,116
Floods	-0.878***	-0.701***	-0.768*	-1.742**	-1.987**	-0.445
	(0.279)	(0.259)	(0.434)	(0.804)	(1.006)	(1.394)
Observations	143,814	71,688	71,623	132,983	68,182	64,801
Landslides	-0.107	-0.112	-0.0996	-3.701***	-7.311***	-0.245
	(0.117)	(0.0733)	(0.279)	(1.327)	(2.212)	(1.734)
Observations	143,814	71,688	71,623	119,762	54,782	64,980

Source: Authors' calculations. *** p<0.01, ** p<0.05, * p<0.1 Clustered standard errors in parenthesis $^{+}$Cutoff points for slope are 16.14% in Guatemala and 11.93% in Costa Rica. For the linear model, clustered standard errors at administrative unit level in parentheses. For Poisson, standard errors in parentheses. Poisson drops cross-section observations (municipalities or districts) with all zero outcomes. Control variables: total rainfall (current, lagged, square, cubic and interacted with the wet season), month fixed effects and municipality-season fixed effects. Poisson with the same control variables except that instead of municipality-season fixed effects with municipality fixed effects and region-season dummies.

6. Conclusions

We evaluated the impact of rain falling within PAs compared with rain falling outside PAs on the number of floods and landslides in Guatemala and Costa Rica. We used monthly municipality data for the period 2000-2015 in Guatemala and district data for the period 1992-2019 in Costa Rica. We used a two-way fixed effect panel data model. So, we control for cross-sectional and time fixed effects. We also identify the relevant watersheds for administrative units based on the location of population centers. So, we are able to test when PAs within one municipality have effects on other municipalities that are in the same watershed.

We found no robust statistically significant effects on these type of disasters for Guatemala. In Costa Rica, we found that shifts in precipitation towards PAs reduce floods significantly. These results were robust in magnitude and sign, and most of them were statistically significant. The estimated magnitude is large as it represents about 34 percent of the average number of floods. The effects on flood-related deaths were about 32 population. We also found effects on landslides in districts with high population density.

To interpret these estimates as a results of the impact of implementing protected areas, we would need to assume that if precipitation falls within the boundaries of a PA, the effect of precipitation outside the PA (but in the same watershed) provides a valid counterfactual for the number of disasters that would have occurred if a PA had not been designated in that location. This implies that we would have to assume that within a watershed of a district or municipality the characteristics of PA areas are similar to the characteristics outside PAs. This might seem as a strong assumption, but it is significantly weaker than using as control observations that do not have PAs, as the difference in characteristics between those municipalities that have and do not have PAs differ significantly more than areas inside the same municipality. Also, even if this occurs, one can reasonably expect that PAs would tend to be in areas with higher slopes than in areas with lower slopes (see Pfaff et al. 2009). Higher slopes generate more disasters. Therefore, this issue biases the estimated coefficients against our hypothesis, that PAs reduce disasters. Additionally, the timing of the impact of PAs on deforestation is also relevant for the causal interpretation on disasters. There is evidence that PAs have an impact on forest conservation (Andam et al., 2008, and Pfaff et al., 2009). However, these effects usually take time, implying that there are also likely to be time lags between the implementation of a PA and any observed impacts on natural disasters.

There are also challenges measuring floods, landslides and precipitation. Government institutions and media are the primary source of information about floods and landslides. No significant methodological adjustments have been made to the way data is recorded in Desinventar. However, it is less obvious whether there have been any adjustments to, for instance, how these incidents are reported in the media. In our analysis, we include time dummies that should capture if these changes affect the overall number of disasters at the country level. Additionally, the rainfall raster used in the analysis might be too coarse for small watersheds. If this is the case, precipitation outside and inside protected areas would be highly similar. This will result in less variation in the analysis that can be used to estimate the effect, which increases our standard errors. This does not appear to be a serious issue in the case of Costa Rica because estimates are already statistically significant. This may, however, account for why we do not observe statistically significant impacts in Guatemala.

Future research can improve estimations in several ways. First, the delineation of the relevant watersheds can be improved. It would be relevant to test the robustness of the results when higher levels of watersheds are used. However, one should consider that if watersheds are too far away from the municipality, even if they are in the same large watershed, they might not have an effect. Second, standard errors might be underestimated even after clustering them at municipality level. Municipalities within the same large watershed might be correlated. If this is the case, clustering within larger watersheds might be helpful. Third, the role of forest within protected areas as a mechanism through which protected areas affect floods and disasters can also be further explored.

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