Physical Risks & the Cost of Capital of Infrastructure Investments

Flood damage factor estimation and bond yields in U.S. airports

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Contents

Executive Summary

EDHEC*infra*'s March 2022 survey of investors in infrastructure revealed that infrastructure investors are overwhelmingly concerned about physical and transition risks, ranking them as the first or second ESG data-related need. Despite the pressing need for asset-level physical risk data, infrastructure investors currently have very limited access to this type of information at the asset level, let alone the ability to conduct a systematic assessment of the financial implications of physical climate hazards.

In this paper, we develop a methodology to calculate the potential damage associated with different types of physical risks at the asset level, and conduct a practical implementation for flood damages in the airport sector in the United States. We then use these results to analyse the relationship between airports' capital costs and exposure to physical climate risk.

A large proportion of US Airports faces sizeable climate physical risks

Using a new dataset of 470 airports, including over 1,000 runways and more than 800 terminal buildings, we use a 30-meter resolution flood model for a 50-year return period (2% probability) and an airport-specific damage function to calculate damage factors at the airport level.

The damage factor results are striking: the top 25% large airports by damage factor show an average damage 26% i.e., a one-in-fifty year flood event would total destroy 26% of the airport. The top 10% exhibit an average damage factor of 44%. Some of the most important airports globally by passenger traffic fall into these high risk groups. For example, Miami Int. Airport, Philadelphia Int. Airport, Newark Liberty Int., and La Guardia Airports, all in the top 10% and could be almost entirely destroyed by a flood event that has a 2% chance of occurrence. The airport sector is also chronically underfunded, meaning that most airports have not been able to modernize their 40-year old infrastructure and adapt to the challenges created by climate change.

Our results coincide with the FAA's assessment of the 13 US airports that are the most at risk of storm surges, but include many more airports and therefore offer a much richer and granular set of results.

Physical climate risks are not priced by capital markets

Next, we look at the impact of physical risks on the cost of debt of infrastructure companies and whether investors in revenue bonds issued by airports price physical climate risks. Using a hand-collected dataset of 2,000+ revenue bonds issued by US airports, our analysis concludes that physical climate risk is not currently priced in the cost of debt of US airports.

Since no prior analyses for the infrastructure asset class have examined whether climate change impacts are priced, this analysis represents a significant contribution and analytic path to understanding climate change and infrastructure investments.

These results suggest that the frequent claim that all future climate risks are already priced by markets is not true and that instead large risks which are expected to increase with climate change are currently unaddressed in capital markets, despite investors' acknowledgement of the importance of this topic.

1. Introduction

Climate change is increasing the frequency, intensity, and unpredictability of physical events such as wildfires, floods, and droughts (CCRI, 2021). Indeed, climate-related events have almost tripled from 1980 to 2019 (Chalmers and Basu, 2020).

According to stress-test analysis carried out by Swiss RE (2018), the world economy could lose up to 18% of its GDP due to climate change if no mitigation action is taken, with the US and Europe economies standing to lose 10% and 11% respectively. Moreover, property and infrastructure damage from natural disasters accounted for two-thirds (estimated at US$220 billion) of all insured natural disaster losses in 2017 worldwide (Morgan Stanley, 2018).

Floods and storms are the most common types of climate-related events accounting for 44% and 28% of all climate events from 2000 to 2019, respectively (UNODR, 2020). Furthermore, the UN Office for Disaster Risk Reduction (UNODR) reported that the number of major flood events has more than doubled, while the incidence of storms grew by 40% during the same period.

Just in the United States, and according to the US Department of Homeland Security (DHS), 90% of natural disasters involve flooding. Consequently, floods in the United States are responsible for more economic damage and loss of life and property than any other natural disaster (Department of Homeland Security, 2021).

The impacts of physical risks exacerbated by climate change are becoming a primary concern for governments and regulators. In 2015, the G20 Finance Ministers and Central Bank Governors asked the Financial Stability Board (FSB) to assess how the financial sector can take account of climate-related issues.

As a result, the FSB established the Task Force on Climate-related Financial Disclosures (TCFD) to develop voluntary climate-related financial disclosures. The TCFD includes recommendations for the assessment and reporting of both risks and opportunities from transition and physical climate change impacts. Several nations have now made TCFD-aligned disclosure requirements mandatory (i.e., Brazil, Hong Kong, New Zealand, Singapore, and the United Kingdom) or aligned to their recommendations (TCFD, 2021).

Investors are increasingly concerned about climate risks (see Figure 1). An ESG survey by EDHEC*infra* to over a hundred asset managers and asset owners worldwide revealed that investors in infrastructure are overwhelmingly worried about physical and transition risks, ranking them as the first or second ESG data need by almost 80% of the respondents.

The finding also suggests that these and other ESG-related risks are not fully reflected in asset prices today (Blanc-Brude et al., 2022). As a result, infrastructure investors and operators are trying to understand the physical risks of their investments to adequately prepare for the climate challenge ahead (Chalmers and Basu, 2020).

Geolocated information about firms' physical assets (vis-à-vis their financial information) is critical to assess the financial impacts of physical climate risks adequately (Bressan et al., 2022). However, despite the pressing need for asset-level physical risk data, investors currently have very limited access

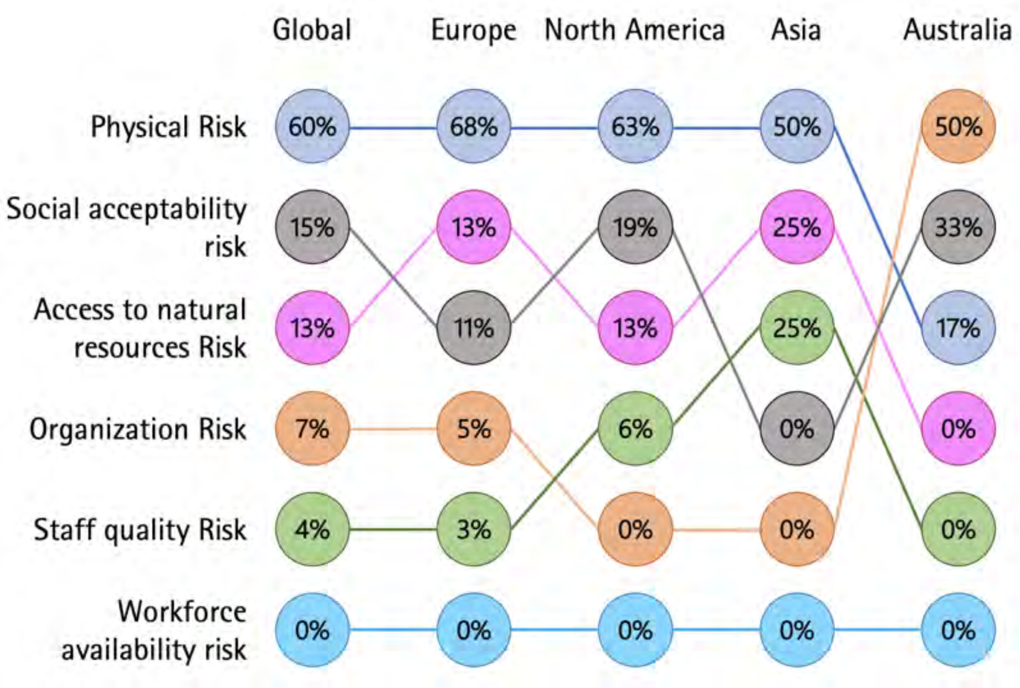

Figure 1: EDHECinfra survey on ESG risks

to information about physical risks at the asset level. Moreover, when available, information about these risks does not allow a systematic assessment of the financial losses associated with physical hazards.

To close the information gaps mentioned above and provide investors with a clear metric for physical risks assessment, in this paper, we develop a methodology to calculate the potential damage associated with different types of physical risks at the asset level.

The proposed methodology can be applied to any asset type and scaled up to cover all listed or unlisted infrastructure assets. Moreover, the results allow investors to rank assets according to the potential damage they face, and incorporate this information into their investment decisions. The proposed methodology follows the work of Bressan et al. (2022).

As a case study, we apply the proposed methodology to airport facilities in the United States (US) in section 4. According to the Airports Council International (ACI), Airports in the US alone mobilized almost half of all global passengers in 2021. Moreover, 20 of the top 50 world's busiest airports by passenger traffic in 2021 are located in the US (The Port Authority of NY and NJ, 2022). We also focused the analysis on the most common and devastating type of physical risk: Flooding.

Having determined a large result set for US airport exposures to physial risk, we then test for a potential relationship between airport bonds yields and exposures to catastrophic flooding risk in section 5.

2. Airport facilities and flooding risk

The International Air Transport Association (IATA) estimated that the aviation industry contributed 1% of the global GDP in 2019 (IATA, 2021). This figure dropped to 0.4% once COVID19 hit the sector, with a slowly projected recovery in the coming years. Airport infrastructure is critical to the financial sustainability of the industry. However, the functioning of many airports is now threatened by operational and financial risks resulting from climate change.

Airports require a large flat land area to enable aircraft to take off and land safely. Despite the substantial variations in the scale of airport facilities, even small airports require considerable amounts of land (more than 5 square kilometres or 500 hectares).

Therefore, airports are frequently sited at the periphery of urban areas where locations offer a balance between land availability at a low cost and accessibility to the urban core (Rodrigue, 2020). In addition, airport facilities tend to be located in low-lying coastal areas to avoid aerial obstructions.

Consider that air planes require longer runways at higher altitudes to achieve the same lift because the air density is lower. Indeed, 60% of all commercial airports are at an altitude of less than 500 feet (150 meters). Many airports are also located in coastal areas because they serve regions of high population density, often located close to the sea (Pek and Caldecott, 2020).

All these factors make airport infrastructure very sensitive to the impacts of climate change, particularly rising sea levels and flooding, which can put many airports at risk of temporary or permanent inundation.

Indeed, as climate change exacerbates, weather-related disruptions to airport operations are likely to grow more frequent, diverse, and severe. Consequently, less resilient airports (most likely the oldest ones) will suffer increasing physical damage. Therefore, they will also experience growing operating costs. Such airports may face increasing difficulty raising capital and maintaining their credit ratings and reputation (Pek and Caldecott, 2020).

However, the average airport terminal in the United States is over 40 years old. For example, Denver International Airport, the youngest large hub airport in the United States, opened in 1995 with a capacity of 50 million fliers, but in 2019, it handled more than 69 million (The New York Times, 2021).

This means that most airport infrastructure was designed and constructed in an era when climate change was not on the radar of governments, private investors, or the wider public as it is today (Airports Council International –ACI–, 2018). [1]

Therefore, one can reasonably assume that the construction specifications of airport facilities, in most cases, have not considered the potential physical impacts of climate change.

As mentioned before, flooding is the most common climate-related type of event, with 90% of natural disasters in the United States involving flooding. Flooding (fluvial, pluvial, and coastal) can cause damage to (over) ground infrastructure, underground infrastructure, and airport equipment leading to disruption or halting of airport operations.

[1] In 1989, the the United Nations established the Intergovernmental Panel on Climate Change (IPCC) to provide a scientific view of climate change and its political and economic impacts.

On the land-side, flooding of ground transport links (roads and rail tracks) can make the airport inaccessible, hampering the ability of passengers and staff to reach the airport.

Coastal flooding (i.e., flooding caused by the sea) is an important risk for airports to consider (Yesudian and Dawson, 2021). An increasing sea level compounds the risk of floods brought by storm surges, high tides, tsunamis, etc. In addition, sea-level rise can raise coastal water tables, resulting in groundwater hazards threatening the structural integrity of shallow infrastructure (Befus et al., 2020).

A further risk is land subsidence at airports constructed on 'reclaimed' land. Finally, while flooding caused by fluvial and pluvial floods is temporary, coastal flooding (i.e., flooding caused by sea-level rise) may lead to permanent inundation of low-lying airports.

In late October 2012, when Hurricane Sandy hit New York City, seawater overflowed the edges of La Guardia Airport, flooding portions of the facility's long E-W runway and damaging navigation and lighting systems. The damage at La Guardia could have been worse had the storm surge struck 9 hours earlier during the high tide.

This scenario would have raised floodwaters an additional 3 ft (0.9 m) to a height of up to 13 ft (4 m) above ground level, likely entering the terminal buildings and resulting in associated shutdowns, cancellations, and additional physical damage (Grigss, 2020).

Some airports are starting to build resilience against climate events. Actions mainly apply to green-field developments and include assessments of vulnerabilities to climate and weather risks, minimum design levels –MDLs, and upgrading of critical infrastructure.

For example, in 2016, 1 km of road surrounding the shoreline next to Changi Airport in Singapore was raised by 0.8 m (above the Singapore Government's sea level rise projection for 2100) to serve as a levee for district-level flood protection, as well as a fixed flood barrier.

After Hurricane Sandy, La Guardia Airport in New York replaced its outdated central electrical substation placing it well above the 100-year flood elevation. Norway's low-lying coastal runways now must be built at least 7 meters above sea level (Airports Council International –ACI–, 2018).

The United States Federal Aviation Administration (FAA) designated 13 of the nation's 47 largest airports at-risk from future storm surges and flooding from extreme events (Melillo et al., 2014). The list of airports at risk includes 11 large airports in the contiguous United States (i.e., the United States excluding Alaska and island territories)

- John F. Kennedy
- La Guardia
- Philadelphia International
- Newark Liberty International
- Ronald Reagan Washington
- Miami International
- Tampa International
- Ft. Lauderdale International
- Louis Armstrong International
- Oakland International, and
- San Francisco International

Indeed, our results show that all these airports (except Oakland International, which was not part of the analysis) are in the top 25% of the United States airports when ranked by potential damage from flooding. We come back to this result in chapter 4.

In the next section, we develop a methodology to calculate damage factors associated with flood hazard at the asset level.

3. Physical Risk: methodological approach and data sources

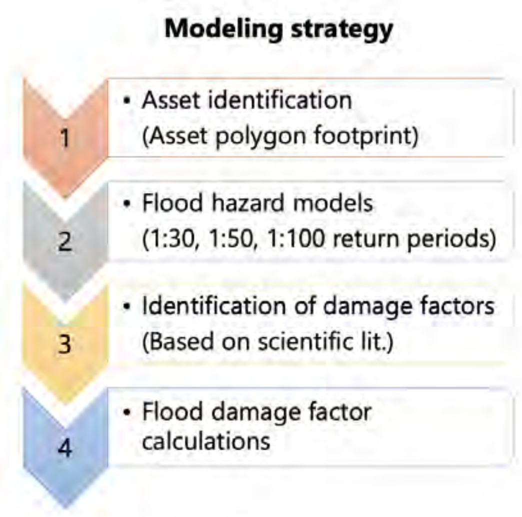

Figure 2: Steps to calculate asset-level flood damage factors

Here we introduce a methodological approach to calculate, at the asset level, the potential damage that could occur from extreme weather events. This section outlines the sequential steps of the methodology with a practical example: flood damage to the airport infrastructure in the United States.

The methodology includes four steps: Asset identification, hazard model definition, damage factor identification, and damage factor calculation. The methodology is based on the one developed by Bressan et al. (2022).

These steps can be applied to any sector, region, and physical climate-related risk. In this paper, we apply the proposed methodology to airport assets in the United States and flood risk (see Figure 2).

The first step, **asset identification**, consists of identifying the physical footprint of a particular type of asset. This step also requires defining the main components of the asset for the analysis since not all the physical characteristics of the asset may be identifiable or relevant for the calculations. For example, in the case of airport facilities, we focused on two of the main physical components of an airport: terminal buildings and runways (Rodrigue, 2020).

We use Open Street Maps (OSM)[1] to demarcate the footprints (also known as polygons) of terminal buildings and runways. OSM is an open-source, editable geographic database with vast amounts of geospatial information, mainly covering transport infrastructure and buildings. This makes OSM suitable for the identification of airports and their main components.

However, it is worth noting that since OSM is a volunteer project, its database is not complete, especially in sparsely areas. This means that the geographical information may be incomplete for some asset types (e.g., offshore wind farms, solar farms).

The second step involves identifying **hazard models** for extreme weather events material to infrastructure assets. Today, many agencies and research institutions specialize in developing hazard models for droughts, floods, storms, extreme precipitation, wildfires, and other physical climate risks.

Stochastic modelling approaches usually involve historical climate data, including precipitation, sea levels, weather patterns, storm intensities and frequency, and temperature data, digital terrain models to predict the probability of occurrence of events.

[1] Open Street Maps (OSM) database is freely available at https://www.openstreetmap.org

Since flooding is the main physical risk faced by airport infrastructure, our analysis focuses on this type of climate-related risk. We use a flood model[2] that estimates water depth from flooding at any location based on a digital terrain model (DEM), historical precipitation and temperature data, and terrestrial biome data. The selected flood model has the following features:

1. Global coverage (i.e., every single country in the world)
2. Multiple return periods (i.e., 30, 50, and 100 years). This paper only includes results for a 50 year return period (i.e., a flood event with a 2% probability of occurrence)
3. Flood sources: pluvial and fluvial
4. Resolution of 1 arc second (i.e., 30 meters)

A 30-meter resolution means that the flood model generates flood depth values for each 30-meter-by-30-meter patch of land. In this case study, "land" is the contiguous United States (i.e., inland territories excluding Alaska).

Figure 3 illustrates the asset identification and hazard model steps for La Guardia International airport.

The third step consists of **identifying damage factors** by asset-type and weather event. In the case of flooding, a damage function describes the relationship between damage to an asset (e.g., airports) and hydraulic characteristics of a flood (e.g., flooding depth or sediment load) (Notaro et al., 2014).

Practical applications usually focus on direct tangible damages to public and private properties (e.g., buildings, cars, roads) as a function of inundation depth. Direct tangible damage is preferred because it allows assessment in monetary costs (Büchele et al., 2006).

Figure 3: Example: airport's terminal and runways identification and flood model for a 50 year return period

Open Street Maps layer

Terminal buildings (yellow) and runways (Gray)

Flood hazard model for a 50 year return period

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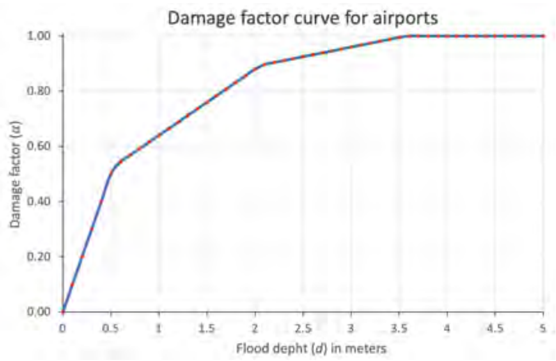
[2] - In this paper, we use the global flood model developed by RMS. https://www.rms.com/models/flood

Figure 4: Normalized damage factors for airport infrastructure



Next, damage factors are derived from damage functions. A damage factor scores assets according to the potential damage they could suffer given a hazard event. In the case of flooding, damage factors for an asset-type (e.g., airports) are normalized to fit in a curve function (Huizinga et al., 2017) ranging from 0 (no damage) to 1 (maximum damage, in which case the asset would require replacement or reconstruction).

In this study, we use the flood damage factors for airports developed by the Highway and Hydraulic Engineering Department of The Netherlands' Ministry of Transport, Public Works and Water Management (Kok et al., 2004) as shown in Figure 4.

The flood damage factor curve in Figure 4 follows the function

$$\alpha = MIN(d, 0.24d + 0.4, 0.07d + 0.75, 1)$$

Where α is the damage factor, and d the estimated water depth from flooding at any given geo-location.

One key advantage of the damage factor α scores is that they allow for the comparison of assets (in this paper, airports) in terms of the damage level that they could face given a weather event (e.g., a 1 in a 50-year flood event). Damage factors are hazard-type dependent but not asset dependent.

In other words, they can be used to assess and compare potential damage from a particular type of hazard across all infrastructure assets within an asset type and even across several asset types.

The fourth and final step, **calculation of damage factors**, combines steps 1 to 3 to generate asset-level flood damage factors. The following section presents the results of this process.

4. Physical Risk Exposures

We start this section with a description of the asset identification phase. Then we present the damage factor results for airport in the United States (contiguous[1]).

4.1 Airport asset identification

Table 1 summarizes the airports in the contiguous United States for which it was possible to simultaneously identify terminal buildings and runways. Identification in this context means obtaining a polygon or "GIS object" storing its geographic representation (i.e., XY coordinate pairs enclosing an area).

Table 1: Asset identification: Airports in the United States

Type	Airports	Runways	Terminals
Large airport	128	356	422
Medium airport	233	498	290
Small airport	109	181	121
Total	**470**	**1,035**	**833**

Source: Author's calculations

We identified 470 airports, including over 1,000 runways and more than 800 terminal buildings. Almost one-third of these airports are "large" and include major airline services with millions of passengers per year and major military bases. Large airport hubs receiving 1% or more of the annual U.S. commercial enplanements are also part of this group (US Federal Aviation Administration, 2022a).

Half the identified airports are "medium" size dedicated to regional airline service, regular general aviation, or military traffic. Medium airport hubs receiving 0.25% to 1.0% of the yearly U.S. commercial enplanements belong to this group. The rest of them are small airports.

Not surprisingly, large airports have more runways and terminal buildings than other airport types. On average, large airports have 2.9 runways and 3.2 terminal buildings per airport, whereas medium airports have 2.1 runways and 1.2 terminals. On average, small airports include 1.6 and 1.1 runways and terminals, respectively.

4.2 Damage factors

We calculated damage factors for each runway and terminal building in the United States. First, the flood depth values from the flood model were transformed into damage factors using the curve function described in Figure 4.

The 30-meter resolution of the flood model means that the United States territory is divided into 30 meters by 30 meters patches of land. Each patch comes with a value representing the flood "inundation" depth if hit by a 50-year flood event (i.e., a flood event with a 1 in 50 chance or 2% probability of occurrence any given year).

Next, the depth values within each runway and terminal building were extracted and averaged using the polygons from the asset identification phase. The final damage factor at the airport level is an average of its runway and terminal values.

The average damage factor for a small airport facing a 50-year flood event in the United States is 0.36 (3.6 on a 1 to 100 scale as shown in Figure 5). Moreover, the average damage factor for medium airports is 1.7 times higher (at 6.1), whereas it doubles for large airports (at 7.75).

However, there are significant variations in these averages. For example, the top 25% airports by damage factor (i.e., the fourth

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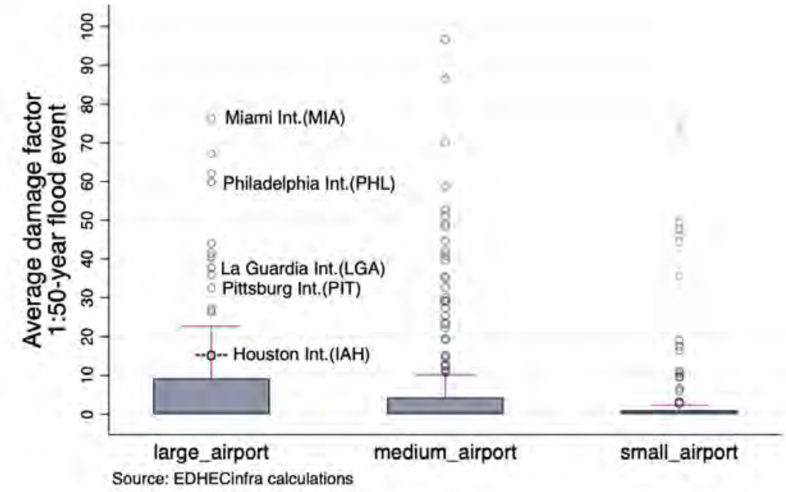
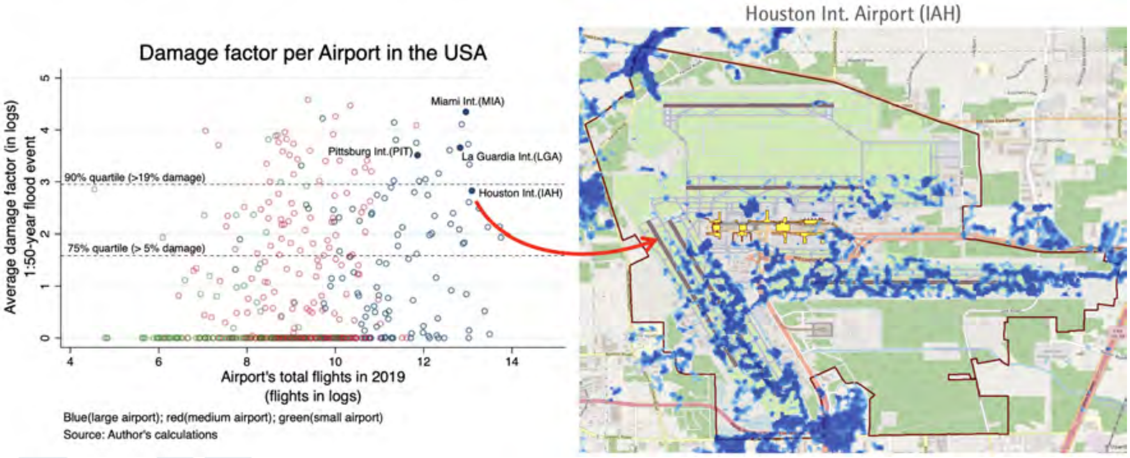
[1] The analysis only includes inland territories of the United States excluding Alaska

Figure 5: Average Damage Factor by Airport Size Group



Source: EDHECinfra calculations

Figure 6: On the left: Damage factors per type of airport and flights. On the Right: Houston Int. Airport's 50-year flood model



Blue(large airport); red(medium airport); green(small airport)
Source: Author's calculations

quartile) have an average damage factor of 26, and the top 10% (i.e., the 90th percentile), an average damage factor of 44, corresponding to an average water depth of approximately 0.5 meters (see Figure 5).

However, an inundation depth of one meter could increase the damage to runways and terminal buildings to over 60%. That could be the case of Miami International Airport (MIA) with an estimated damage factor of 76, Newport News Williamsburg International Airport (PHF) at 67, and Philadelphia International Airport (PHL), estimated at 60 (see Figure 7).

Looking at the 4th quartile and 90th percentile is important because some of the most important airports globally in terms of passenger traffic are in the United States and fall into this group.

MIA, PHF, PHL, Louis Armstrong New Orleans International Airport (MSY), Newark Liberty International Airport (EWR), La Guardia Airport (LGA), Ronald Reagan Washington National Airport (DCA), Pittsburgh International Airport (PIT), and John F. Kennedy International Airport (JFK), all in the 90th percentile, could be severely damaged if a 50-year flood event impacts them (Figure 7).

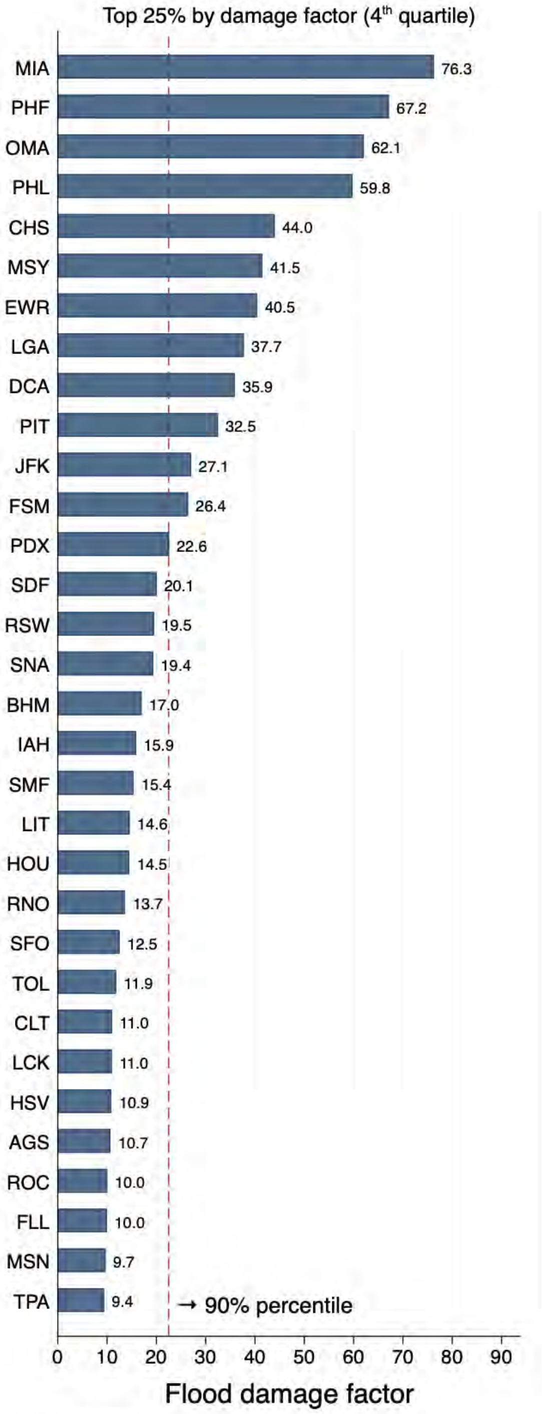
JFK, San Francisco Int. Airport (SFO), Charlotte Douglas Int. Airport (CLT), EWR, George Bush Intercontinental Airport (IAH), MIA, FLL, PHL, and LGA are all among the busiest airports by passenger mobilized (US Federal Aviation Administration, 2022b) and number of flights. All of them are in the 4th quartile of potential flooding damage.

Changes in the severity and frequency of precipitation patterns due to climate change will continue affecting transportation systems, especially low-lying infrastructure, which is the case for many airport facilities. Moreover, storm drainage systems for highways, tunnels, airports, and city streets could prove inadequate, resulting in localized flooding (Melillo et al., 2014).

Indeed, airports in the United States are on average 40 years old, meaning that most of the sector's infrastructure was planned and developed well before climate change became a public concern.

Moreover, the airport sector is chronically underfunded (Airports Council International –ACI–, 2022b) meaning that most airports have not been able to modernize their infrastructure and adapt to new challenges brought by climate change.

Figure 7: Flood damage factors for large airports in the United States under a 1 in a 50-year flood event (2% probability of occurrence any given year)



IATA codes as Airport's Identifiers
Source: Author's calculations

5. Physical Risk and Bond Yields

In this section, we analyze the statistical relationship, if any, between airports' capital costs as captured by bond yields and their relative exposure to physical damage by flooding, as estimated above.

Unlike other parts of the world, airports in the United States of America are predominantly Government owned and run either as a department of a city or through an authority: the Government owns the equity of the airports and runs the airport as a business unit.

As a result, it is not possible to observe any equity market returns for these airports. However, these airports require large capital investments that, instead, are financed through municipal bonds.

Importantly, most of the airport bond issuance consists of so-called 'revenue bonds,' i.e., the only security for the investor is the net revenues of the airport.[1]

As a result, these funds are at risk if some event impacts the airport's revenues. This includes large or catastrophic destruction caused, for example, by flood events. With increasing extreme weather events caused by climate change, understanding if investors currently price the risk of climate change in bonds issued by airports in the US is critical.

Prior studies have identified a link between climate risk exposures and asset prices. Bernstein et al. (2019) and Painter (2020) find that investors discount asset prices in relation to climate change risks in real estate and municipal bonds, respectfully. Likewise, Giglio et al. (2021) are able to extract a climate change associated discount rate from housing prices.

Baldauf et al. (2020) argue that this link between investor risk exposures and climate change contingent on the prior beliefs of investors: if they accept the science of climate change, then investors are more likely to discount asset values based on climate risks.

When considering the infrastructure asset class, no prior studies have examined whether climate change impacts are priced. As a result, this study provides a significant contribution to understanding climate change and infrastructure investments.

5.1 Approach

The methodology in Painter (2020) allows for an estimation of investor risk premium for investing in municipal bonds with climate exposures. Following this paper, we examine whether investors in airports in the United States of America (US) do demand a risk premium for investing in assets that have a higher climate exposure. U.S. airports were chosen as estimates of climate risk, asset values and most importantly, revenue bond issuance from the airports were readily available. We estimate the following model of the net cost of issuing bonds for airports:

$$\textit{Total annualised issue costs} = \beta_1 * \textit{ Climate risk} + \beta_2 * \textit{ Bond controls} + \beta_3 * \textit{ State} \times \textit{ Year FE} + \epsilon$$

Where:

- Annualized issue cost is the sum of yield on issue as well as annualized gross spread of the bond. Gross spread is the difference between what the underwriter paid and the price on issue. As the bonds have

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[1] There is also an inclusion in the bond prospectuses that stipulate that other specific funds can be used as security. However, the airport's revenues remain the larger component of the security.

varying time to maturity and this spread is paid only once, it is converted into a geometric average over the issue life. This is then summed with the yield on issue to obtain total annualized issue cost;

- Climate risk, is the airport-level damage factor in the 1-50 year flooding scenario;
- Bond controls are a series of variables employed in prior research on the annualized issue costs (see Dougal et al., 2019; Butler, 2008): bond rating, size, time to maturity, tax regime of municipal bonds (federal or state tax exemption) amongst other factors.
- Finally, State and Year fixed effects – the standard errors are clustered by the county issuer.

5.2 Data & Summary Statistics

Municipal bond data is obtained from Bloomberg for the revenue bond issues from 1 January 2018 to October 2022 issued by airports in the US.

Only 'pure play' airports are considered: that is, the airport authority or municipality and materially backed by revenues from one airport only.[2]

We obtain data for 42 airports from around the US on the Gross Spread, Yield on Issue, Maturity, Face Value of Maturity, taxation status, details on whether the bond is callable or insured and credit rating on issue.

This yields 2,190 bonds in total. Credit ratings are converted to numerical values following Cantor and Packer (1997). Where there is ratings disagreement between S&P and Moody's, we have taken Moody's ratings as the default rating. This is due to the consistency in coverage of the Moody's v.s. S&P ratings.

The Damage Factor for airports that issued each bonds is obtained from the results above.

The summary statistics in Table 2 shows that bonds with some level of climate exposure (damage factor > 0) do have higher mean and median annualized cost of issuance.

Interestingly, these bonds have a higher credit rating (lower number, implies better credit-worthiness).

Furthermore, the airports with a higher climate risk tend to have a lower issue size, on average, but a longer term to maturity.

Table 3 presents the summary statistics for the bonds based on term to maturity and credit rating.

Here we observe that bonds with a longer term to maturity (greater than 25 years), have on average, a higher issue cost, higher yield but a lower climate exposure.

When credit ratings are considered, we observe that the issuance cost and yield increase as credit rating decreases (a higher number in rating, implies decreasing credit-worthiness).

However, this decrease is not monotonic with some credit rating 'buckets' having a higher issuance cost than less credit worthy buckets. Interestingly, bonds issued by airports with a higher credit rating, exhibit higher climate risk, on average than other rating categories.

5.3 Regression Results

Regression results are presented in table 4.

We can observe that when a simplified regression model with limited explanatory variables (model 1) is employed, the Climate risk variable is positive and statistically significant.

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[2] Some airport bonds, such as Philadelphia are backed by two airports, one General Aviation and the other International Airport that is classified as a Large Hub by the Federal Aviation Administration. Given the size disparity, it is fair to conclude that the revenues of the large hub airport would support the issuance of the revenue bonds.

Table 2: Descriptive Statistics

	Climate Exposed Bonds				Non-Climate Exposed Bonds			
	N	Mean	Median	SD	N	Mean	Median	SD
Total Annualised Cost (%)	1616	0.026	0.026	0.010	574	0.024	0.023	0.009
Windsorised Annualised Cost	1616	0.026	0.026	0.010	574	0.024	0.023	0.009
Gross Spread (%)	1616	0.338	0.336	0.141	574	0.358	0.366	0.103
Yield (%)	1616	2.299	2.230	0.972	574	2.053	1.936	0.902
Issue Size (MM$)	1616	18.6	6.4	39	574	19.2	6.7	54.2
Max maturity (Years)	1616	12.051	10.989	7.465	574	11.364	10.244	7.356
Callable	1616	0.522	1.000	0.500	574	0.479	0.000	0.500
Insurance	1616	0.003	0.000	0.056	574	0.000	0.000	0.000
Rating	1616	5.150	5.000	1.023	574	5.685	6.000	0.844
AMT	1616	0.433	0.000	0.496	574	0.373	0.000	0.484
Fed exempt	1616	0.431	0.000	0.495	574	0.448	0.000	0.498
State exempt	1616	0.746	1.000	0.436	574	0.653	1.000	0.476
CUSIPS/Issue	1616	17.128	19.000	6.245	574	17.009	18.000	4.908

Total annualised cost is the cost of issuance (annualised gross spread + yield on issue), Gross spread is the underwriter's discount, Yield is the yield on issue of the bond, Issue size is the $ face value on issue, Max maturity is the number of years until maturity, Callable is a dummy variable where it is 1 if the bond has a call provision 0 otherwise. Insurance is a dummy variable equal to 1 when the bond is insured and 0 otherwise. Rating is the numeric credit rating score converted employing the Cantor and Packer (1997) methodology. AMT, Fed-exempt and State exempt are dummies equaling 1 when the bond is subject to alternative minimum tax, exempt from Federal taxes or exempt from State taxes, respectfully. CUSIPS/Issue is the number of unique lines of bonds were issued in the bond issue. Bond Market is the yield on the munciple bond index at the date of issue.

Table 3: Further Descriptive Statistics

TTM*	Cost	Yield	Spread	Climate	Count
< 25 years	0.025013	2.159038	0.003423	0.683105	2034
≥ 25 years	0.035833	3.222	0.003613	0.054795	156
Rating	Cost	Yield	Spread	Climate	Count
4	0.024738	2.156659	0.003171	0.260274	598
5	0.026988	2.366139	0.003326	0.177169	597
6	0.02541	2.182933	0.003581	0.238356	805
7	0.026753	2.282732	0.003925	0.053881	142
8	0.027249	2.300833	0.004241	0.008219	48

*TTM: time to maturity

Table 4: Regression Results for dependent variable: Total Annualised Cost

Model	(1)	(2)	(3)	(4)	(5)	(6)
Climate Risk (Log)	0.000066**	0.000028♠	0.000296	0.000005	-0.000033**♠	-0.000259
	(0.000025)	(0.000026)	(0.000398)	(0.000018)	(0.000014)	(0.000321)
Size (log)	-0.000046	-0.000471	-0.000461	0.000214	-0.000317	-0.000321
	(0.000285)	(0.000257)	(0.00026)	(0.000198)	(0.000157)	(0.000162)
Maturity (log)	0.00758***	0.006814***	0.006788***	0.007402***	0.006914***	0.006939***
	(0.000295)	(0.000325)	(0.000323)	(0.000321)	(0.000297)	(0.000292)
Rating	0.002161***	0.000791	0.000902	0.002317***	0.001048**	0.000907**
	(0.000599)	(0.000581)	(0.000534)	(0.000555)	(0.000394)	(0.000393)
Callable		0.002529***	0.002551***		0.002356***	0.00233***
		(0.000328)	(0.00033)		(0.000267)	(0.000265)
Insured		0.002742	0.002723		0.002539	0.002565
		(0.002583)	(0.002585)		(0.002662)	(0.002654)
Fed-Exempt		-0.008632***	-0.008655***		-0.009487***	-0.009426***
		(0.000692)	(0.000702)		(0.000468)	(0.000452)
State-Exempt		-0.00605***	-0.006104***		-0.007047***	-0.006953***
		(0.000658)	(0.000649)		(0.000448)	(0.000447)
AMT		0.003775**	0.004314***		0.002309***	0.001658**
		(0.001516)	(0.001248)		(0.000693)	(0.000792)
CUSIPS/Issue		0.000421	0.000437		-0.000099	-0.000064
		(0.000518)	(0.000525)		(0.000293)	(0.000306)
Bond Market				(0.008301)***	(0.008996)***	(0.00891)***
State-year FE	Yes	Yes	Yes	No	No	No
				(0.000966)	(0.000979)	(0.001019)
Observations	2190	2190	2190	2059	2059	2059
R-square	0.796749	0.8626	0.8624	0.859035	0.9304	0.9299

Total annualised cost is the cost of issuance (annualised gross spread + yield on issue), Gross spread is the underwriter's discount, Yield is the yield on issue of the bond, Issue size is the $ face value on issue, Max maturity is the number of years until maturity, Callable is a dummy variable where it is 1 if the bond has a call provision 0 otherwise. Insurance is a dummy variable equal to 1 when the bond is insured and 0 otherwise. Rating is the numeric credit rating score converted employing the Cantor and Packer (1997) methodology. AMT, Fed-exempt and State exempt are dummies equaling 1 when the bond is subject to alternative minimum tax, exempt from Federal taxes or exempt from State taxes, respectfully. CUSIPS/Issue is the number of unique lines of bonds were issued in the bond issue. ** and *** denote significance at the 5% and 1% level, respectfully. ♠ not logged

However, when a more extensive model is estimated (Models 2, 3, 5 and 6 in table 4), the statistical significance drops to 0. We conclude that the statistical significance was driven by other factors, not the climate exposure. Similar results are found when the Yield on Issue is employed as the dependent variable (see appendix table 5).

In the initial regression, climate is found to be positive and statistically significant. However, this significance disappears when more pricing controls are added to the regression (Models 2 and 3).

In a different set of models (4 to 6 in table 4) using bond market yields instead of time fixed effects, we find a even higher model fit and still not significance of the climate risk factor in explaining the variance of bond yields.

In un-tabulated results, a regression with a credit risk and climate risk interaction variable was estimated. This was to control for the fact that airports with a lower climate impact might be considered better credit risks. It was found that the resulting variable was not statistically significant. As a result, it can be concluded that there is no interaction between credit rating and climate risk. Other robustness checks conducted included estimating the correlation between credit risk scores and climate risk factors, which was found to be low (13%) and not statistically different from zero.

These results imply that physical climate risks are not priced in the market for airport revenue bonds in the US, despite these risks being significant and the instruments being secured solely against the revenues of the airport company.

6. Conclusions

This study aimed to develop a methodology to calculate the potential damage associated with different types of physical hazards at the asset level. The methodology includes four steps that can be applied to any asset type and scaled up to cover all listed or unlisted infrastructure assets.

The main outcome of this approach to assessing physical risk is a damage factor that scores assets from 0 to 1 according to the potential damage they could suffer given a hazard event. Damage factors are hazard-type dependent but not asset dependent.

In other words, they can be used to assess and compare potential damage from a particular type of hazard across various infrastructure asset types; the same assessment exercise could be conducted for roads, ports, power plants, or other types of infrastructure.

Using this approach, asset managers and owners can evaluate physical risks in terms of potential damages across asset types within or across portfolios. The damage factors allow them to compare and rank assets according to the damages from climate hazards for better investment decision-making.

Damage factors can also be an input for the calculation of aggregate monetary total value-at-risk conditional to a particular climate-related extreme weather event. Financial assessments by Bressan et al. (2022) have advanced in this direction.

The TCFD recommendations on physical risks include a disclosure metric on "*projected or identified loss or damage to the business facility, supply chain, etc.*" (TCFD, 2021), which can be proxied using the damage factors resulting from this methodology. Moreover, TCFD-aligned disclosure requirements are gaining momentum and are now mandatory in several countries.

Based on our analysis, there are two main challenges to overcome in order to scale up this methodology to all infrastructure assets. They are in steps 1 (asset identification) and 3 (identification of damage factors).

First, the asset identification phase requires obtaining polygons representing the asset's footprint and components which are not always easy to compute using GIS software or computer vision algorithms.

Second, identifying damage factors requires both sector- and hazard-specific engineering knowledge.

Our case study for airport facilities in the United States yielded interesting results. First, some of the main airports in the US could be severely damaged if hit by a 50-year flooding event, with an estimated damage factor above 44 for airports in the 90th percentile and a damage factor above 26 for airports in the 4th quartile.

Just in the United States, the airport sector supports more than 11.5 million jobs and generates more than US$1.4 trillion in economic activity (Airports Council International –ACI–, 2022a).

However, this industry could be significantly affected by a combination of more frequent, unpredictable, and severe weather disruptions and relatively old infrastructure that is unprepared to face climate change. As mentioned above, the average airport terminal is over 40 years old.

The United States Federal Aviation Administration designated 11 large airports in the contiguous United States at moderate to high risk from future storm surges and flooding. Our analysis positioned 10 of them in the 4th quartile of damage, confirming the accuracy of our calculations.

However, there are a couple of ways to improve these results. For example, one can consider additional return periods (e.g., 30, 100, 200 years) to better understand the risk profile of an asset to a particular hazard type. Second, different representative concentration pathways (RCPs) can be incorporated into the hazard models to account for different climate scenarios.

Our damage factors' estimates are conservative because they rely on a sector damage function for a country with a long history of water management and flood-related engineering solutions.

In addition, the flood model we use here is based on event frequency from previous decades. As a result, lower resilience to flooding in other regions (i.e., in our case, the United States) and increased frequency and intensity of flood events will only result in greater damages than the ones estimated here.

We use our damage factors estimations to understand some of the financial implications of physical risks. More specifically, we analyzed the relationship between airports' capital costs proxied by bond yields and physical climate risk proxied by the airports' flood damage factors. Considering that flood events are now exacerbated by climate change, we argue that if investors currently price flood risks, this effect should be reflected in the bond's issuing costs. The analysis only considers airports in the United States.

Our initial regression analysis shows that flood physical risk may seem positively and statistically related to the issuing costs of bonds. However, the significance of this relationship disappears when more pricing controls are added to the regressions. Therefore, we conclude that physical climate risk is not currently priced in airports' revenue bonds in the US.

There are a few ways to improve the quality of these estimations. For example, the analysis could consider damage factor estimations for different return periods. Also, the research could be expanded to other types of physical climate risks. Nevertheless, since no prior analyses for the infrastructure asset class have examined whether climate change impacts are priced, this analysis represents a significant contribution and analytic path to understanding climate change and infrastructure investments.

Table 5: APPENDX: Regression Results - DV: Yield on Issue

Model	(1)	(2)	(3)	(4)	(5)	(6)
Climate (Log)	0.005488**	0.002605♠	0.025781	-0.000669	-0.003531***♠	-0.029803
	(0.002249)	(0.002177)	(0.034023)	(0.00151)	(0.00106)	(0.022571)
Size (Log)	0.010362	-0.030542	-0.029606	0.036179	-0.015134	-0.015458
	(0.027344)	(0.024823)	(0.025188)	(0.018741)	(0.014604)	(0.014811)
Maturity (log)	0.743761***	0.666908***	0.664514***	0.724714***	0.676529***	0.679305***
	(0.029456)	(0.034205)	(0.034072)	(0.032215)	(0.031084)	(0.030683)
Rating	0.187902***	0.049591	0.059967	0.202096***	0.073428	0.058052
	(0.055772)	(0.056324)	(0.053164)	(0.05114)	(0.037896)	(0.036232)
Callable		0.246459***	0.248512***		0.228016***	0.225355***
		(0.03113)	(0.031433)		(0.025295)	(0.025392)
Insured		0.163841	0.162153		0.143227	0.146246
		(0.171191)	(0.171378)		(0.177813)	(0.177)
Fed-Exempt		-0.861031***	-0.863287***		-0.949351***	-0.94295***
		(0.060709)	(0.061172)		(0.044019)	(0.04354)
State-Exempt		-0.604475***	-0.609851***		-0.707449***	-0.697703***
		(0.064378)	(0.062639)		(0.043862)	(0.044334)
AMT		0.31538**	0.366944***		0.168028***	0.099046
		(0.133277)	(0.126052)		(0.055745)	(0.061785)
CUSIPS/Issue		0.072749	0.07347		0.020147	0.023176
		(0.052888)	(0.053403)		(0.029599)	(0.030134)
Bond Market				(0.840816)***	(0.909229)***	(0.90042)***
State-year FE	Yes	Yes	Yes	No	No	No
				(0.084022)	(0.079856)	(0.083021)
Observations	2190	2190	2190	2059	2059	2059
R-square	0.794283	0.8626	0.8624	0.861591	0.9361	0.9356

Total annualised cost is the cost of issuance (annualised gross spread + yield on issue), Gross spread is the underwriter's discount, Yield is the yield on issue of the bond, Issue size is the $ face value on issue, Max maturity is the number of years until maturity, Callable is a dummy variable where it is 1 if the bond has a call provision 0 otherwise. Insurance is a dummy variable equal to 1 when the bond is insured and 0 otherwise. Rating is the numeric credit rating score converted employing the Cantor and Packer (1997) methodology. AMT, Fed-exempt and State exempt are dummies equalling 1 when the bond is subject to alternative minimum tax, exempt from Federal taxes or exempt from State taxes, respectfully. CUSIPS/Issue is the number of unique lines of bonds were issued in the bond issue. ** and *** denote significance at the 5% and 1% level, respectfully. ♠ not logged.

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