Policy Research Working Paper 8898

Lifelines: The Resilient Infrastructure Opportunity

Background Paper

Three Feet Under

Urban Jobs, Connectivity, and Infrastructure

Jun Rentschler
Johannes Braese
Nick Jones
Paolo Avner

World Bank Group
Climate Change Group
Global Facility for Disaster Reduction and Recovery
June 2019

Policy Research Working Paper 8898

Abstract

This paper analyses the degree to which infrastructure reliability and urban economic activity in several African cities is impacted by flooding. It combines firm-level micro data, flood maps, and several spatial data layers across cities through a harmonized geospatial network analysis. The analysis shows that a significant share of jobs in cities is directly affected by floods. It further details how transport infrastructure is subjected to significant flood risk that disproportionally affects main roads in many cities. While direct flood effects are revealed to be significant, this work further shows how knock-on implications for the entire urban economy might be even larger. Regardless of the direct flood exposure of firms, flooded transport networks mean that disruptions propagate across the city and drastically reduce the connectivity between firms. Access to hospitals is also found to be reduced significantly—even during relatively light flooding events: From a third of locations in Kampala, floods mean that people would no longer be able to reach hospitals within the "golden hour"— a rule of thumb referring to the window of time that maximizes the likelihood of survival after a severe medical incident. Overall, this study showcases the use of high-detail city-level analyses to better understand the localized impacts of natural hazards on urban infrastructure networks.

This paper is a product of the Global Facility for Disaster Reduction and Recovery, Climate Change Group. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at jrentschler@worldbank.org and jbraese@worldbank.org.

Three feet under: The impact of floods on urban jobs, connectivity, and infrastructure

Jun Rentschler[1], Johannes Braese[1], Nick Jones[1], Paolo Avner[1]

[1]*Global Facility for Disaster Reduction and Recovery, World Bank, Washington DC, USA*

Acknowledgements: This working paper contributes to the World Bank's 2019 flagship report *Lifelines* on resilient infrastructure. The authors thank Charles Fox, who provided invaluable support and developed the GostNets network analysis tool used in Section 4. The study has also benefited from helpful comments, feedback, and inputs by Andrii Berdnyk, Marga Cantada, Scott Ferguson, Stephane Hallegatte, Steven Rubinyi, Ben Stewart, Mercedeh Tariverdi, and Joshua Wimpey.

JEL classification: R41, O18, Q54

Keywords: Resilience; infrastructure; cities; urban flooding

1. Introduction

In all parts of the world, cities are providing jobs and improved livelihoods to an ever growing number of people. Through the density of social and economic activity, people living in or moving to cities gain easy access to services, jobs, and markets. Analogously, firms benefit from facilitated access to large and diverse labor markets. The benefits from spatial proximity are made possible through infrastructure systems that increase connectivity and efficiency. Transport infrastructure for example connects people to markets and jobs, and connects firms to suppliers, consumers, and markets. In providing the backbone of most economic activity, infrastructure systems thus play a crucial role for anything from meeting the basic needs of people, to supporting sustainable and resilient livelihoods and enabling ambitious economic endeavors.

However, the functioning of infrastructure and the urban economy can be threatened by natural hazards. Urban flooding in particular is a major cause of disruptions in cities across the world, and especially in developing countries. From Buenos Aires to Dar es Salaam, Amman, Dhaka, and Jakarta – around the world, urban flooding is a frequent and devastating occurrence, and the resulting disruptions extend well beyond just the flood-zone. Of course, urban flooding is directly damaging public assets, affecting people's homes and assets, and destroying the productive assets of firms. But beyond the direct impacts, floods are also causing knock-on effects on infrastructure networks well beyond the flooded areas. As one road segment is flooded, traffic across the entire city is disrupted, thus affecting people's access to jobs and the smooth functioning of supply chains. The indirect costs of urban flooding are real and often significant.

In order to better assess this threat, this analysis addresses three topics. First, it analyses how economic activity and road transportation infrastructure is exposed by urban flood risk. Second, the network-level effects of floods on urban connectivity and accessibility are assessed. Finally, it investigates whether flood risk affects infrastructure disruptions at the level of an individual firm. To address these questions, flood maps, employment density maps, infrastructure maps, and geocoded firm-level micro data is used for the 13 cities of Abidjan, Accra, Addis Ababa, Bamako, Cotonou, Douala, Dar es Salaam, Freetown, Kampala, Kigali, Monrovia, Nairobi, and Zanzibar.

The analysis finds that a significant fraction of economic activity is exposed to flood risk – though the level exposure varies significantly across cities. In Kampala, about 10% of all jobs are directly located in flood risk zones. Indeed, large fractions of the road network in these cities are located in areas that are potentially prone to flooding, often with depths that make traversing the roads impossible. In Kampala, hydrological flood models estimate flood depths at several road segments to exceed one meter (or three feet). Moreover, the impacts of flooding are felt not only in directly exposed flood zones, but across the entire city. Connectivity between firms is estimated to be affected significantly with travel times more than doubling for a quarter of all firms. Urban flooding is also estimated to make hospitals inaccessible to a third of all locations within the "golden hour", i.e. the 60 minutes window following a critical medical incident beyond which survival rates are reduced drastically.

The remainder of this study is structured as follows. Section 2 outlines the types of data that are crucial to conduct city level hazard assessments, including high-resolution flood maps, and open source infrastructure network data. Section 3 presents evidence from a pooled dataset of up to 3,000 firms from 13 major cities in Sub-Saharan Africa, showing that infrastructure disruptions are transmitted across city-wide networks and affect firms in- and outside of flood zones. Section 4 applies a geospatial network analysis tool to assess the direct exposure of jobs, road networks, and urban connectivity. Section 5 concludes.

2. Data

This section provides an overview of the data types and sources that are crucial for assessing the impacts of flooding on the urban economy. For this purpose it briefly discusses flood maps (Section 2.1), employment data (Section 2.2), Open Street Map network data (Section 2.3), and firm-level data from the World Bank's Enterprise Surveys (Section 2.4).

2.1. Flood maps

Flood risk information is typically communicated through flood maps that describe the spatial extent of flooding. For the purpose of this study, three different flood maps were used. This section will briefly present each of them: i) flood maps produced through the SSBN global flood model, ii) flood maps produced by a tailored flood model, and iii) empirical flood maps produced through community mapping. Table 2 in Annex 5.1 provides an overview of the availability of different flood maps for 13 cities in Sub-Saharan Africa.

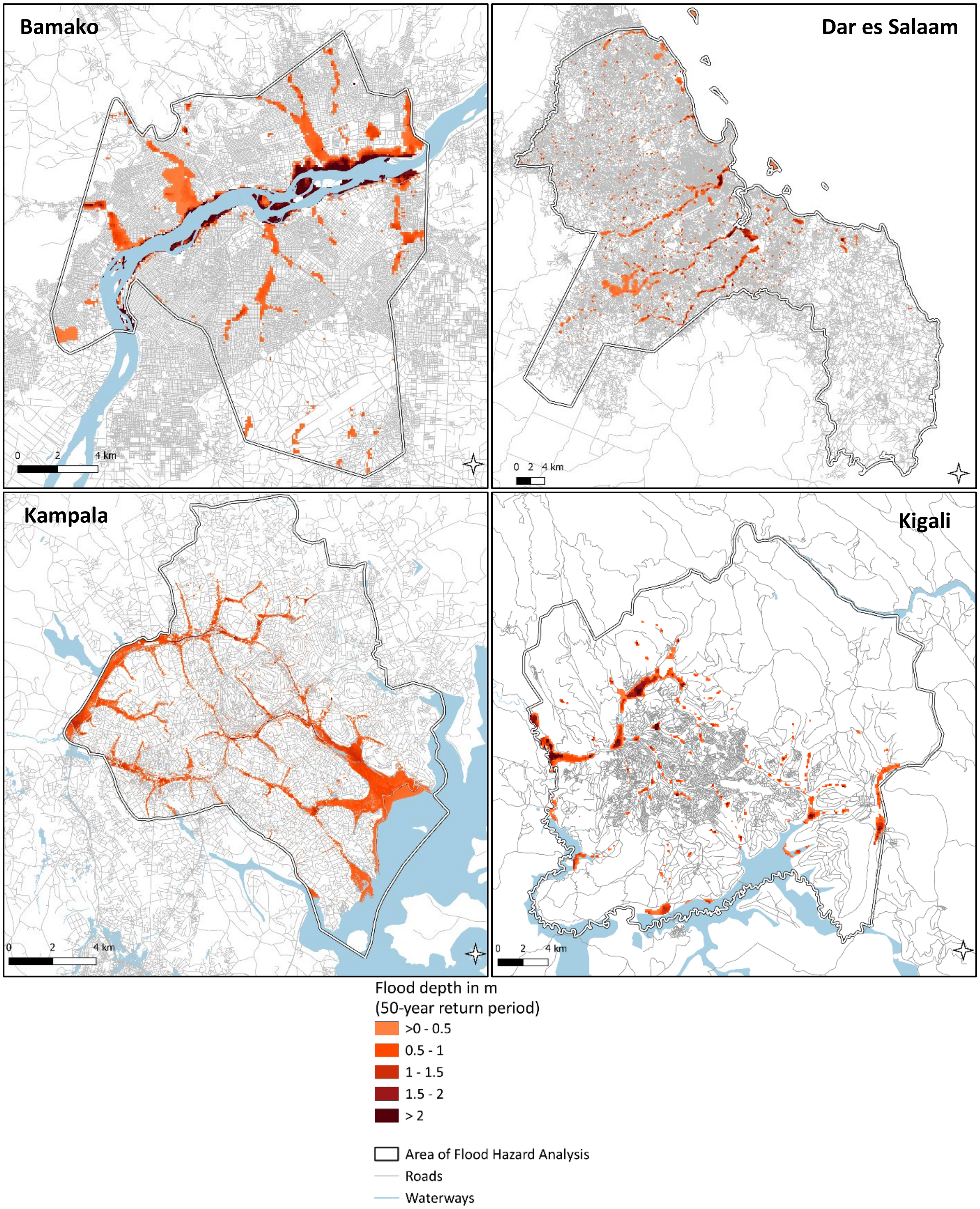
2.1.1. SSBN-modelled flood maps

The main flood data used in this analysis are city-level flood maps derived from the SSBN global flood map.[1] The underlying flood model has a resolution of 90 meters, and considers floods that are either fluvial (i.e. caused by overflowing bodies of water) or pluvial (i.e. caused by a saturation of the absorption capacity of the ground or drainage systems). In this analysis, fluvial and pluvial maps were combined to assess the full extent of potential flooding.

SSBN flood maps are available for several return periods, that denote the average repeat interval of an event with a certain intensity. Here, return periods of 10, 50, and 100 years are considered. Flood model estimates provide the extent of flooding as well as the expected flood depth in each grid cell for each return period. By using a common methodology in all cities, SSBN flood maps are useful for analyses comparing the effects of flood risk in different regions. The availability of different return periods and the assignment of different flood depths allows for the differentiation between flood risk of varying severity along two dimensions. However, these flood maps can be impervious to local built infrastructure.

[1] http://www.fathom.global/

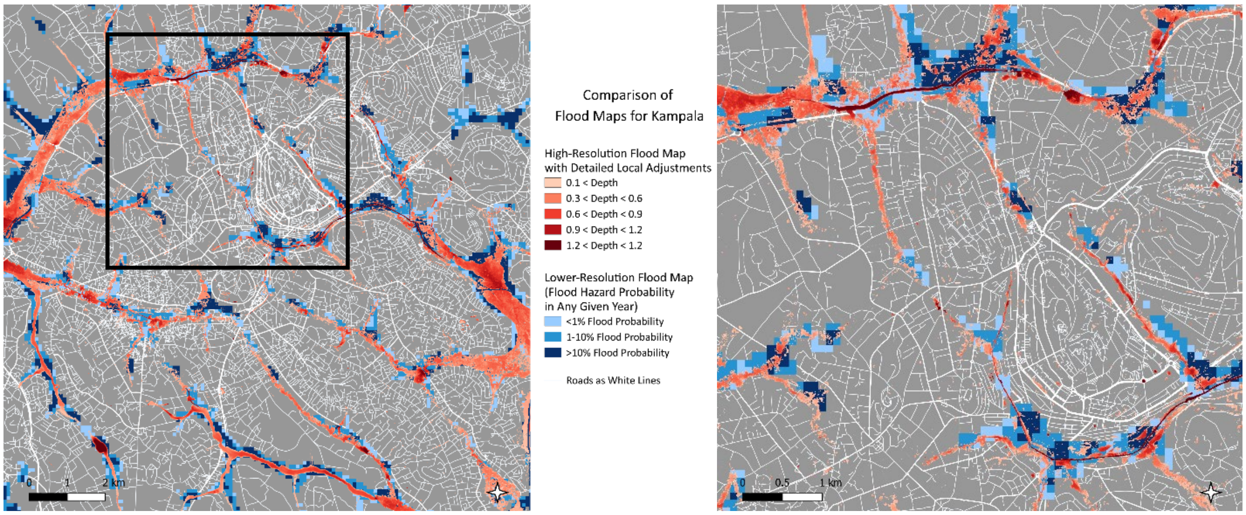
Figure 1: Flood maps for 50-year return period and area of analysis in, going clockwise from top left, Bamako (SSBN), Dar es Salaam (SSBN), Kigali (SSBN), and Kampala (other modelled)



2.1.2. Flood maps from city specific terrain models

The second type of flood model used in this analysis are flood models that are also derived using digital terrain models but are then refined by incorporating locally specific information. For this study, a tailored flood map was developed for Kampala (see Box 1). With 5x5 meters per grid cell, their spatial resolution is much finer. Like the SSBN models, they are available for return periods of 10, 50, and 100 years. While such flood models can be considered to be of greater accuracy, their availability is limited due to their higher cost of development.

Figure 2: Comparison of flood maps for Kampala. In red, the high-resolution map based on a flood model with local adjustments. In blue, the flood map based on the global SSBN flood model. Zoomed-in view on the right.



Box 1. Development of a high resolution flood map for Kampala

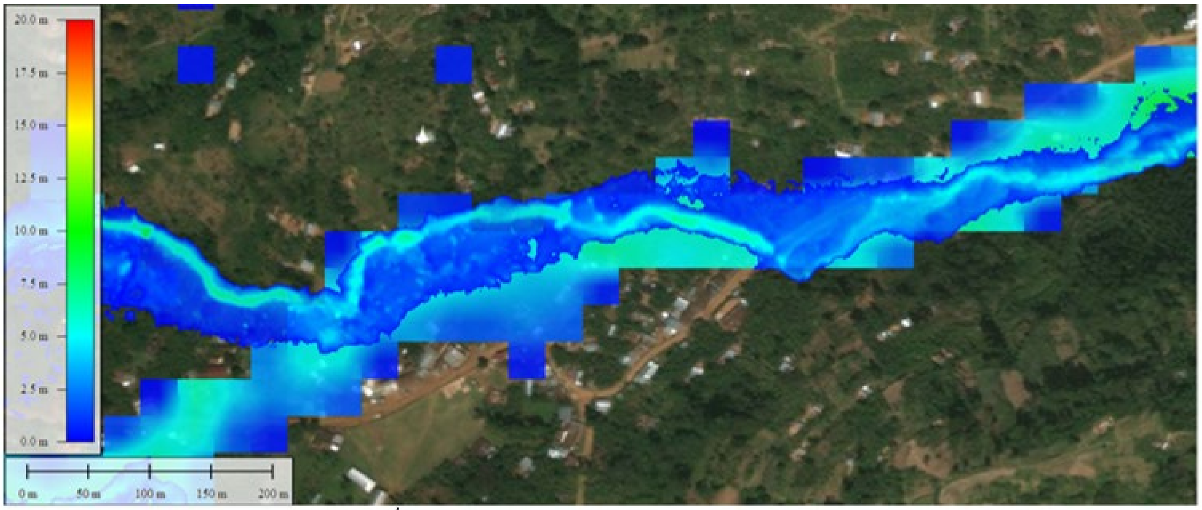
Contributed by Scott Ferguson[2]

Kampala is built across a number of small hills, intersected by streams and wetlands. Flooding is driven by localized heavy rainfall, rapid uncontrolled run-off from the dense urbanization, and insufficient space for water along the streams and heavily encroached wetlands. A flood model was developed to reflect these dynamics using the freely available HEC-RAS modelling software (Version 5.0.6). A single two-dimensional (2D) model was set up for the city and surrounding areas with a 20m computational cell size. The detailed features contained within the underlying LiDAR derived digital terrain model (DTM) were captured within the HEC-RAS 2D processing, thus retaining the small detail within the model that can significantly impact surface water flow. A variable roughness factor (Mannings 'n') was applied across the entire model based on the land use data provided by the Kampala Capital City Authority (KCCA). Automated cleaning of the DTM was carried out to remove artificial blockages such as bridges, culverts or other small blockages in the natural flow paths to ensure hydraulic connectivity.

A direct rainfall approach was used that simulates the full process of flooding resulting directly from rainfall (i.e. pluvial flooding), but also captures the process of run-off into streams and rivers and the resulting flooding that occurs from flow volumes exceeding the channel capacity and inundating floodplains. Generalized rainfall storm profiles were derived from Intensity-Duration-Frequency (IDF) curves produced using local rainfall data. Twenty-four hour unsteady simulations were run to ensure the full impact of the 6 hour storm was captured. Losses from the direct rainfall were based on soil type and land cover and were subtracted from the rainfall prior to application as effective rainfall in the model. A six-hour storm duration was selected based on local guidance, but sensitivity checks where conducted for three and twelve hour durations. The most essential data for this modelling process is the DTM. The example below shows the difference between a 30 STRM DTM based model, and a 2m resolution drone captured photogrammetry based DTM. The modelling process, inputs and software are identical in both.

[2] Contact: scottferguson0350@gmail.com

Figure 3 Flood model comparison using low- and high-resolution digital terrain data (STRM and Photogrammetry)



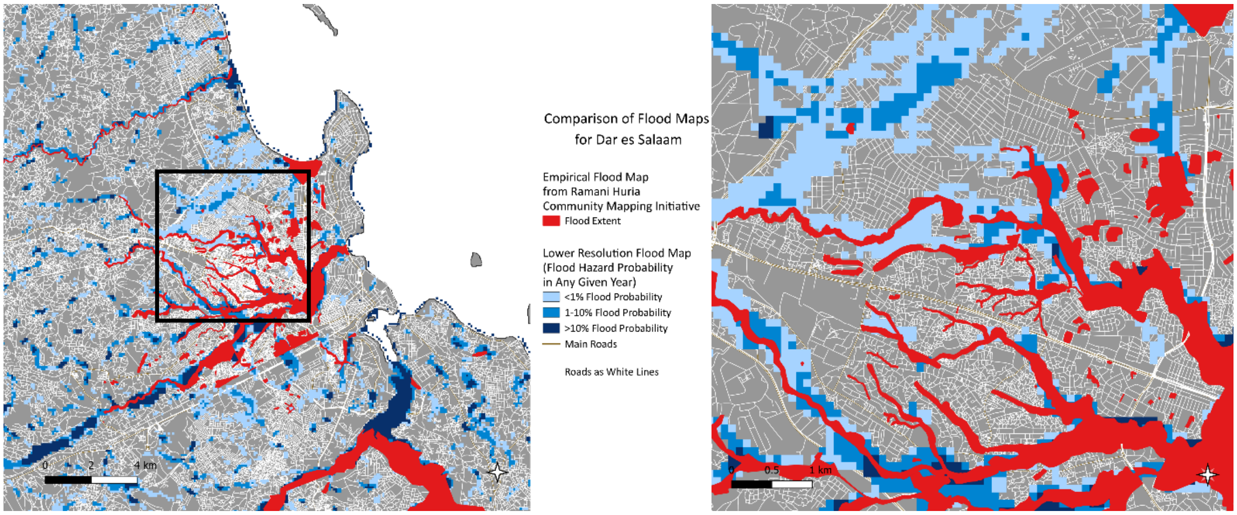
Uncertainty has two main sources. (1) The quality of the DTM, which in this case is considered good; and (2) the rainfall estimate, which itself is dependent on the overall rainfall for a given return period and the losses to apply relating to canopy capture and drainage system storage, and infiltration or other losses. The flood extents and flow paths are therefore considered reasonably representative, however, with no reliable calibration data, the exact return period attributed to the flooding is likely to be less certain. Production of the flood maps for three return periods took approximately 8 days' work, including pre and post model data processing and model development.

2.1.1. Community mapping

A third type of flood map is not based on a model, but instead uses local knowledge to identify historical areas of flooding. Such an empirical flood map is available for Dar es Salaam. Here, the community mapping initiative Ramani Huria[3] provides crowd-sourced information on the areas that had been flooded in recent flood events. By relying on actual observations, community mapping is better able to reflect non-modelled factors such as the quality of local drainage systems, thus increasing accuracy. However, the Ramani Huria map only provides flood extents and does not offer information on return periods or flood depths. Thus, it does not distinguish different levels of flood risk.

[3] http://ramanihuria.org/

Figure 4: Comparison of flood maps for Dar es Salaam. In red, the empirical map from a community mapping initiative. In blue, the flood map based on the global SSBN flood model. Zoomed-in view on the right.



2.2. Employment density data

Employment density maps are a useful tool to assess the spatial distribution of economic activity. They are derived by dividing an area into several spatial units, counting or estimating the number of jobs located in each unit, and then dividing the number of jobs in each unit by the area of the unit. This results in an indicator value that is greater for areas with more jobs per square kilometer. As the generation of economic value is driven by and therefore correlated with human labor, such that job density maps can serve as proxies for economic activity.

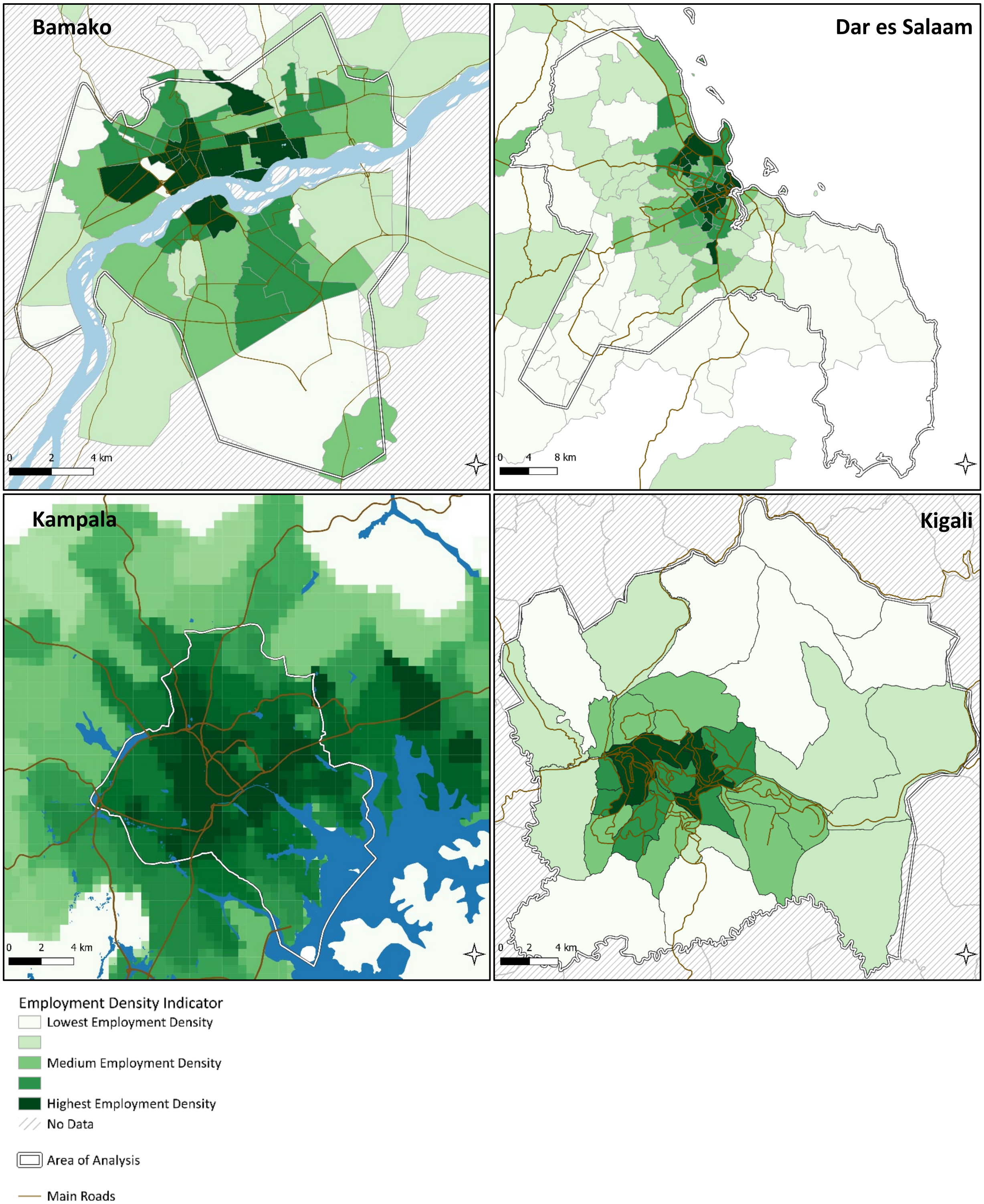
Information on the spatial distribution of employment are typically hard to come by in developing country cities. This represents a real bottleneck for producing a number of policy-oriented analytics including accessibility to employment analyses to understand areas that are disconnected from labor markets or exposure of economic activity to natural hazards as in this study.

For this analysis, employment density maps were obtained or produced for four African cities, overcoming recurrent data scarcity issues on the spatial distribution of employment. In Kampala, the employment density map has been constructed based on a travel survey conducted by the Kampala Capital City Authority in 2013 that included employment data and their projection to 2018. The job density distributions for Dar es Salaam and Kigali are based on firm listings in the respective city. In Bamako, the employment density map is constructed from business registries of the city that indicated total payroll and with assumptions on the sector specific average hourly wage per worker and.

An analysis of economic activity in a city also requires a consistent definition of urban extents. In cities with rapid population growth, this is not an easy task. Especially when estimating the fraction of jobs affected or roads flooded, the extent of the area of analysis can significantly influence the estimates. Section 4 limits all analyses to the region of the city as defined by OpenStreetMap (see section 2.3). Figure 5 outlines employment density data and the area of analysis for the cities of Bamako, Dar es Salaam, Kampala, and Kigali.

In the maps shown in this work, darker colors indicate greater job density. It should be noted that the maps presented are intended to be interpreted within a city, where one area can be compared to a different area within the same city. Due to differences in the threshold values aimed at improving legibility, the comparisons of densities across cities is not possible.

Figure 5: Employment density and area of analysis in, going clockwise from top left, Bamako, Dar es Salaam, Kigali, and Kampala



2.3. OpenStreetMap network data

The transportation network data and the city outlines used in this analysis are sourced from OpenStreetMap (OSM)[4]. OSM is a free project that creates and continuously updates a crowd-sourced map of the whole world. By providing contributors with extensive manuals on how to provide and edit data, OSM achieves standardized data across different regions. Specifically, OSM classifies roads according to different categories such as motorways or residential streets that allow for the differentiation between roads of varying importance. It should be kept in mind that the road network data used here do not account for local infrastructure measures that were implemented specifically to increase a road's resilience to flooding but are rather described to provide an overall picture of exposure of the road network to flooding based on spatial overlap.

2.4. Enterprise Survey

This work also employs firm-level micro data provided by the World Bank Enterprise Survey (ES). Through asking firms in most developing and emerging economies in the world a set of uniform questions, the dataset provides a unique opportunity to compare business activity in different countries. This analysis is based on ES firm observations for a set of 13 large cities in Africa.

In chapter 3, infrastructure disruptions are analyzed through three dependent variables of disruptions experienced by firms: *Blackouts*, defined as the average annual hours without electricity supply, *water disruptions*, defined analogously as the average annual hours of water supply outages, and *transport problems*, an indicator ranging from zero to four that describes the degree to which transport is perceived as an obstacle to business with higher values indicating a greater obstacle.

As firms' non-randomized location was available, each firm could be classified according to their flood exposure using the flood maps described above. To get a large sample of flood-exposed firms for chapter 3 a methodology was developed to combine flood maps from several sources into a common flood exposure variable. After each firm's exposure was determined using its city's respective flood map, a unified binary variable was defined (*Flood-threatened*): It takes the value one if (a) a firm is located in a zone with flood hazard probability greater than 1 percent in any given year according to combined pluvial and fluvial SSBN flood probability maps with return periods of 10, 50, and 100 years, or if (b) a firm is exposed to flooding greater than 5 centimetres in a locally tailored modelled flood with a 50-year return period, or if (c) it is located in the area of the empirical flood map in Dar es Salaam. The variable takes the value of zero for all other firms in the cities for which flood maps were available. This results in a dataset with 3,094 firms from 13 cities of which 329 firms, or about 11 percent, are in flood-threatened areas.

Chapter 3 uses Enterprise Survey weights that are rescaled within each city to account for the firms outside the city boundaries that were dropped. In the pooled regressions, each city is given equal weight: this results in firms in cities with fewer observations having greater relative weight. Consequently, it prevents imbalance in the results due to the differing number of observations in each city. Note that the Enterprise Survey weights were not designed to be spatially representative at the city-level.

3. Firms, flood exposure and infrastructure in 13 cities in Africa

This section explores the determinants of infrastructure disruptions for firms in 13 African cities. Using geocoded Enterprise Survey data and flood maps, it demonstrates that infrastructure disruptions should primarily be conceived as system-wide problems that affect all firms in the system.

[4] https://www.openstreetmap.org

3.1. Indicators of infrastructure quality

This section analyzes the quality of infrastructure services perceived by firms and the role of flood exposure in explaining service disruptions. It aims to answer the following question: what is the impact for firms of being directly exposed to floods compared to the being indirectly impacted? In other words, do firms which are directly exposed to floods have significantly worse outcomes than firms situated outside of flood zones?

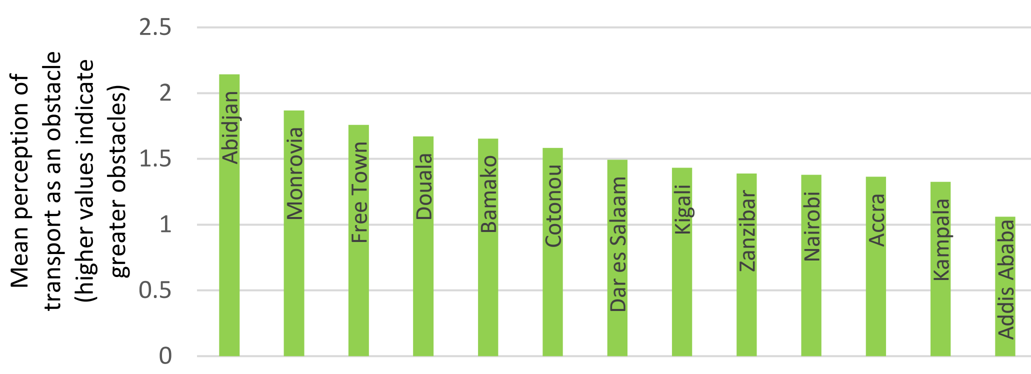
While infrastructure disruptions indeed physically occur with increased frequency and intensity in certain hotspots, infrastructure systems are networks that transmit the adverse effects of disruptions across wide areas. The level of localization however varies across different types of infrastructure. For instance, in the case of electricity, a disruption in one location (e.g. a tree falling on transmission lines during a storm) will affect whole segments of the distribution network.

Electricity outages: The spatial distribution of electricity outages is assessed using ES data on firm-level power outages. For each firm, the number of hours without electricity in an average month is calculated. In addition, firms are asked to assess what percentage of their sales they are losing due to power outages. It is found that firms in cities with longer outages forego higher sales, on average. Still, some variation exists.

Insufficient water supply: While electricity outages are usually felt with the highest immediacy, disrupted water infrastructure similarly affects firms in many cities in our samples. Based on the Enterprise surveys we calculate the share of firms in each city that experienced insufficient water supply in the year before the survey was carried out. These disruptions of firms relying on water as an input for production or the provision of services are likely to impose significant economic costs.

Transportation disruptions: Turning to transportation infrastructure, our analysis shows that the firms suffer from significant disruptions in all 13 cities in our sample. The ES relies on a subjective measure to assess transportation infrastructure disruptions experienced by firms. Firms assess transport as an obstacle to their operations on a scale from 0 ("no obstacle") to 4 ("very severe obstacle"). A comparison of the average level of transport disruptions is pictured in Figure 6.

Figure 6: Average perception of transport as an obstacle to business across cities. Higher values indicate perception as a greater obstacle

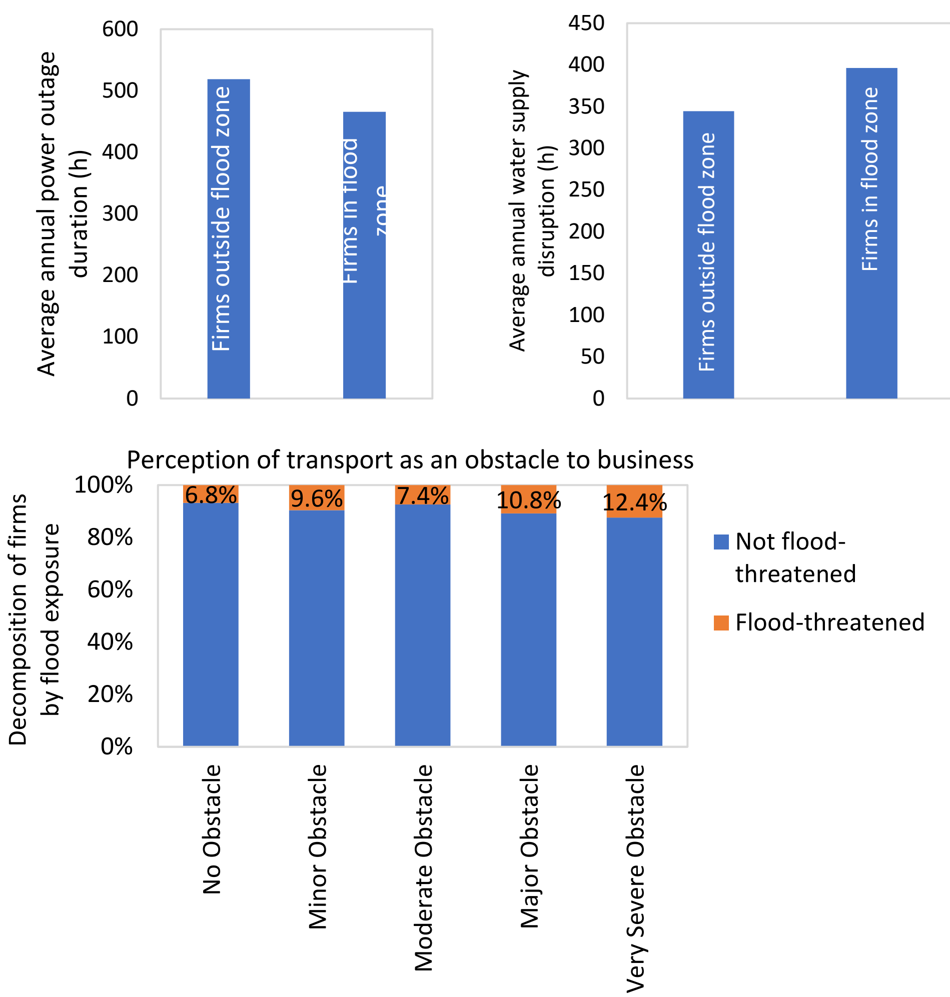


The perception of transport disruptions seems relatively uniform across cities. Infrastructure disruptions affect everyone

3.2. Does flood exposure explain infrastructure disruptions in cities?

The two-dimensional relationship between flood exposure and each of the three disruption variables are described in the graphs in Figure 7. The relationship between firms' exposure to floods and water outages experienced is positive, as could be expected. Considering water, firms in flood-prone areas experience higher annual hours without water supply. For transportation, the descriptive results are as expected also as expected. The share of flood-threatened firms is lower for those with minor transport problems and, on average, increases to a higher share of flood-threatened firms for those perceiving transport to be a major obstacle to their business operations. Overall, no clear relationship between flood exposure and infrastructure disruptions is visible. Counterintuitively, it appears as if firms in flood-threatened areas experience lower electricity supply disruptions than their counterparts. But because electricity is mainly transmitted either through above ground power lines or locally produced by generators, there is no reason a-priori why electricity disruptions would affect firms located in flood-prone areas more.

Figure 7: Average yearly duration of power and water supply outages and perception of transport as an obstacle by flood-threatened and non-threatened firms in 13 African cities



These descriptive statistics, while mostly showing expected relationships, are quite weak, with low differences in disruptions depending on the location of firms. Also and more importantly these graphical representations cannot provide clear evidence of the association between disruptions and flooding. This is because they are susceptible to distortions caused by firm characteristics correlated with both flood exposure and infrastructure disruptions. In order to overcome such distortions, regressions can be used that control for industry- and city-level fixed effects and several other firm characteristics. Table 1 summarizes the results of three weighted regressions with such controls that include standard errors clustered at the city-level. Overall, one main message emerges: system-wide disruptions are more important than individual firm-level characteristics. We interpret this as the ripple effect of floods dominating the direct effects, i.e., whether a firm is directly affected by a flood only marginally contributes to the costs that floods it already faces through system wide network disruptions.

Table 1: Results from weighted OLS regression, city-level normalized survey stratification weights applied. Standard errors in italics, clustered on cities. Abidjan city-level fixed effects omitted to allow estimation of model. Significance levels: *** 0.01, ** 0.05, * 0.10.

Dependent:	Blackouts	Water disruptions	Transport problems
Firm age	0.217	8.145**	-0.001
years of official registration	*(1.46)*	*(2.89)*	*(0.00)*
Employment	-0.912*	0.494	0.001
number of full time employees	*(0.50)*	*(0.90)*	*(0.00)*
State ownership	3.128	-0.656	0.015
in %	*(5.81)*	*(7.00)*	*(0.02)*
Export orientation	-0.214	4.232	-0.000
% of total sales	*(1.45)*	*(3.69)*	*(0.00)*
Generator ownership	69.452	126.011	0.054
Dummy	*(50.81)*	*(289.08)*	*(0.15)*
Distance to city centre	-0.001	0.008	-0.000
At the ward-level, in meter	*(0.00)*	*(0.01)*	*(0.00)*
Flood-threatened	28.583	54.883	0.150
Dummy	*(70.41)*	*(262.29)*	*(0.14)*
ISIC Sector Fixed Effects	YES	YES	YES
Accra	519.455***	212.819	-0.875***
City-level fixed effect	*(53.64)*	*(170.65)*	*(0.05)*
Addis Ababa	185.962***	-189.789*	-1.629***
City-level fixed effect	*(56.07)*	*(87.65)*	*(0.07)*
Bamako	-140.272*	-539.146***	-0.131
City-level fixed effect	*(68.80)*	*(101.07)*	*(0.08)*
Cotonou	941.516***	-530.813***	-0.871***
City-level fixed effect	*(64.91)*	*(81.03)*	*(0.06)*
Dar es Salaam	710.536***	-83.131	-0.568***
City-level fixed effect	*(57.76)*	*(89.47)*	*(0.04)*
Douala	338.875***	-334.603***	-0.817***
City-level fixed effect	*(62.92)*	*(64.68)*	*(0.06)*
Free Town	705.323*	-1568.848	-0.631
City-level fixed effect	*(332.75)*	*(1738.63)*	*(0.49)*
Kampala	362.801***	-588.947***	-1.097***
City-level fixed effect	*(41.15)*	*(158.44)*	*(0.04)*
Kigali	-62.963	-392.183***	-1.045***
City-level fixed effect	*(43.32)*	*(79.57)*	*(0.05)*
Monrovia	282.523***	3.248	-0.500***

City-level fixed effect	*(44.93)*	*(133.91)*	*(0.09)*
Nairobi	72.405	-280.767**	-0.950***
City-level fixed effect	*(40.63)*	*(102.24)*	*(0.06)*
Zanzibar	362.305***	-380.033*	-0.920***
City-level fixed effect	*(65.27)*	*(180.00)*	*(0.08)*
N	2217	828	2600
R^2	0.185	0.115	0.124

Out of the other firm characteristics, few significantly impact infrastructure disruptions. Considering blackouts, we see that larger firms on average experience a lower duration of electricity outages in a year. This is true even when controlling for the ownership of a generator. Water disruptions seem to correlate strongly with a firm's age: older firms face significantly worse water supply throughout the year. Transport problems are not significantly associated with any variable at the firm level. There is also no evidence that the quality of infrastructure services is spatially clustered within a city: a firm's distance to the city center, as measured from the center of this firm's ward, is not a good determinant of the disruptions it experiences.

In this multivariate analysis, no relationship between flood exposure and any of the disruption variables persists. The negative association between flood exposure and power supply disruptions observed in the descriptive statistics vanishes. While the coefficients point in the directions we could expect to be true for all three types of infrastructure, i.e. associating flood exposure with greater disruptions, the relationships are clearly insignificant in all three cases. This suggests that location in a flood zone is not an important determinant of infrastructure disruptions.

The infrastructure disruptions of a given firm, however, might not only be influenced by whether the firm location itself is in an area that is likely to be flooded. If, for example, the firm is located on a small hill that is surrounded by flood exposed areas, a flood will likely cut-off its access to transport infrastructure as well. As a proxy for this proximity to a flood zone, a variable is introduced that indicates whether any other firm in the spatial unit of the analyzed firm is flood-threatened (see Table 3 in the appendix). It should be noted that due to the definition of administrative boundaries and data availability the size of the spatial units varies considerably between cities. This new variable, however, is clearly insignificant in all three cases, again indicating that flood exposure, be it direct or indirect, does not have a large impact on infrastructure disruptions.

The only group of factors that is able to explain a large fraction of the variance in the infrastructure disruptions is the city-level fixed effects. These are highly significant and of large size in most of the cities for all three types of disruptions. This leads to a simple conclusion: it is not firm characteristics that explain infrastructure disruptions, it is the quality of the overall system. The interconnectedness of firms on the power, water, and transport grids cause disruptions to ripple throughout the system and rarely affect only individual firms. The quality of an infrastructure system is primarily determined at the city-level and then affects all firms within this city to a much larger degree then the characteristics of each individual firm. The same point is made by a related set of regressions described in Table 4 in the appendix. Here, the city-level fixed effects are replaced by a variable that, for each firm, describes the mean disruption level of all other firms in the city. Again, firm-level characteristics are insignificant while, in the case of power outages and transport disruptions, the overall city-wide disruption level is the strongest predictor of an individual firm's disruption level. As infrastructure is determined by interconnected systems, infrastructure disruptions are experienced by everyone connected to these systems.

Robustness analyses using different classifications of flood threats

The relationship between infrastructure disruptions and flood exposure is subjected to two robustness tests. The first robustness test consists in testing whether the relationship between disruptions and firms' location in flood prone-areas is stronger when we focus on the *heavily flood-threatened firms*. Results show that there is no change in the relationship between firm characteristics and disruption variables using this. The second robustness check consists in creating a continuous variable of flood severity instead of the binary variable to indicate whether a firm is located in a flood-prone area. Here again no significant effect of flood exposure on power, water, or transport infrastructure disruptions can be observed (see appendix A.4).

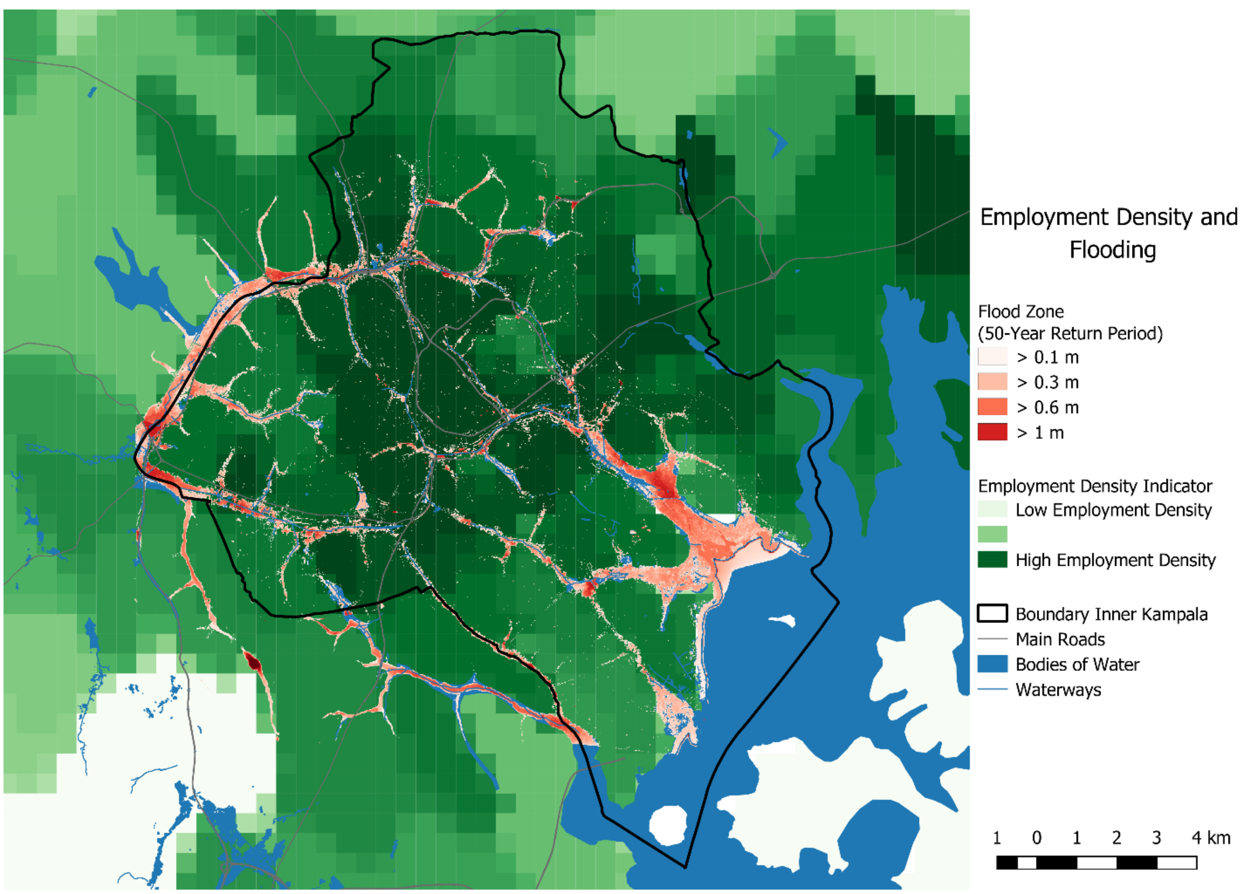
4. The influence of flooding on the urban economy

This section analyses flood hazards in relation to the distribution of employment and the transportation network in Kampala, Bamako, Dar, and Kigali. It assesses the direct exposure of jobs (Section 4.1) and transport infrastructure (Section 4.2) to flood risk, and shows how flooding can reduce connectivity across the whole city (Section 4.3).

4.1. The flood exposure of jobs

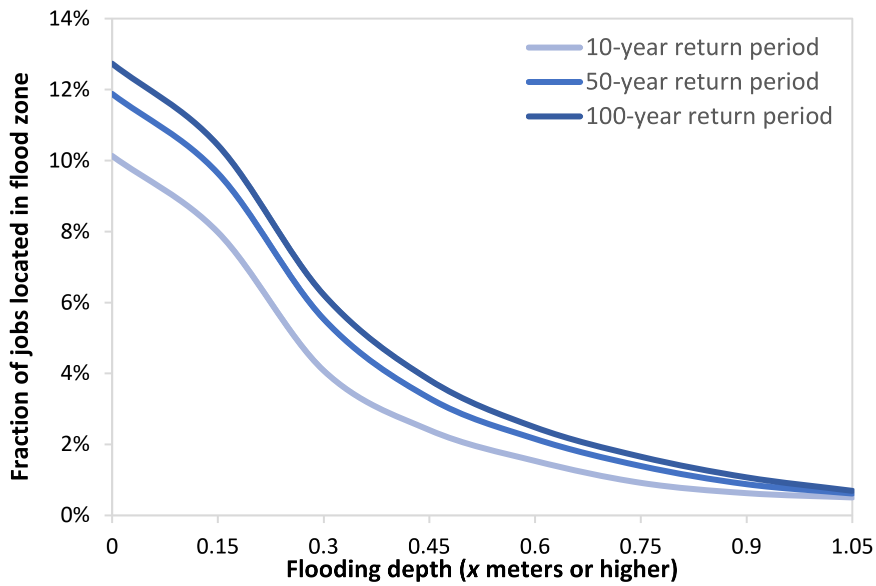
In order to assess to what extent economic activity in a city is impacted by potential flooding, this section overlays employment density maps with flood maps. Figure 8 shows employment density and the extent of a modelled flood with a return period of 50 years in Kampala. The area of analysis for which the flood map was constructed, here referred to as Inner Kampala, is outlined with a black line.

Figure 8: Employment density and 50-year flood zones in Kampala



The modelled flood zone takes a ring-like shape around the inner city of Kampala. In Inner Kampala, 12% of all jobs are directly located in flood zones with a return period of 50 years. Out of these jobs, a considerable fraction is affected by significant flood depths: In a 50 year flood, 10% of all jobs in Inner Kampala would be affected by flooding with a water depth of more than 15 centimeters. In Kampala, floods with 10-, 50-, or 100-year return periods have relatively similar effects on employment as shown in Figure 9. Generally, most jobs are only affected by relatively shallow depths as evident in the fast decline of the fraction flooded with increasing flood depth.

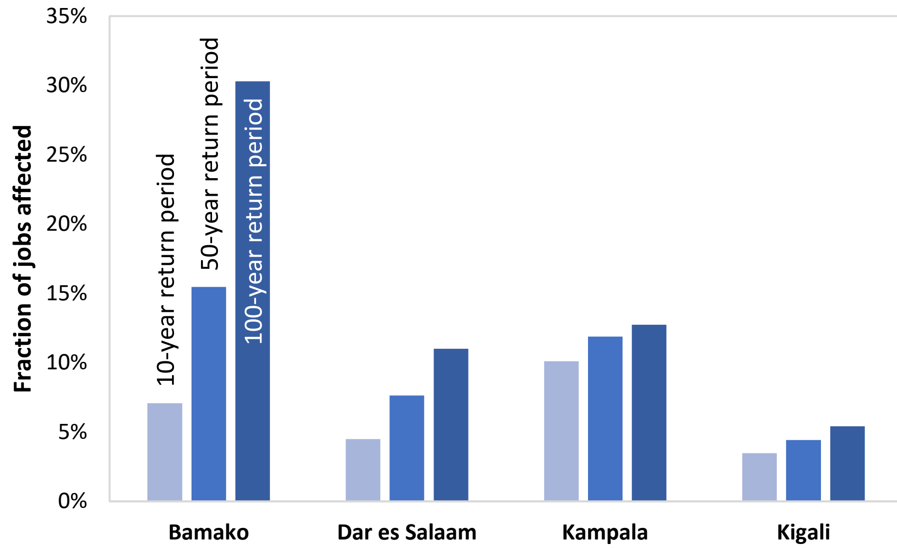
Figure 9: Fraction of all jobs in Kampala that are directly located in a flood zone and the associated flood depth



The exposure of jobs to flooding varies significantly across cities. Figure 10 compares the fraction of jobs located in flood zones in Bamako, Dar es Salaam, Kampala, and Kigali. It should be noted that the point estimates for the percentage of jobs affected by a certain flood depend on the defined area of analysis: Assuming that cities are more likely to be located in flood zones close to rivers or the sea, extending the area of analysis could reduce the area of flooding and consequently the relative share of urban jobs located in flood zones. For the sake of consistency, the area of analysis corresponds to the city boundaries defined by OSM.

Valuable comparisons between cities can be drawn from the rate with which exposure increases as flood events become more extreme. In Kampala and Kigali, the share of flood exposed jobs stays relatively flat as flood events intensify. Most firms affected by a catastrophic event (e.g. with a 100-year return period) are also likely to be affected by less intense and more frequent events. In these it is more the flood depth rather than the flood extent that increases for higher intensity events. This could mean the residents and firms in flood zones are sensitized to the risk of flooding due to frequent exposure. On the contrary, in Bamako and Dar es Salaam the extent of flooding increases significantly for higher return periods. Especially in Bamako, an extreme event has a drastically wider reach than lower intensity events. This implies that a majority of people exposed to a low-probability event will not be exposed to more frequent smaller events. As a result, they may be less prepared and have a lower capacity to respond and recover. A likely explanation for these different dynamics lies in the topography of the respective city areas.

Figure 10: Fraction of jobs in Bamako, Dar es Salaam, Kampala, and Kigali directly located in flood zones for 10, 50, and 100 year return periods

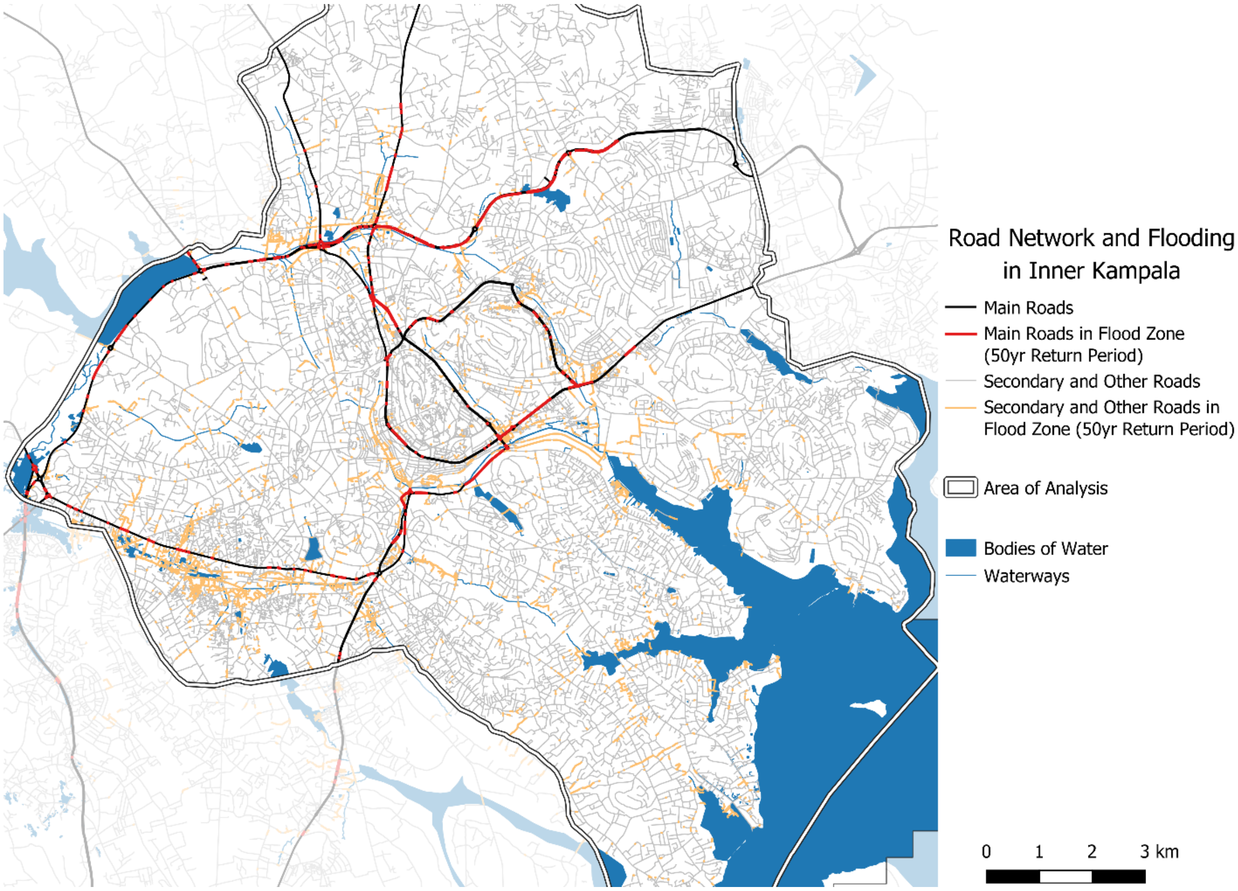


4.2. Road transportation networks and flooding

In addition to the direct effect of firm locations being submerged in water, floods also indirectly affect many businesses. In fact, indirect effects of floods may be significantly larger than the immediate direct impacts. By slowing down traffic or closing off roads, flood zones disrupt transport networks that firms depend on. In the case of a flood, employees and customers are unable to reach businesses, input materials are not delivered to production sites, and finished products cannot be transported to their destination on time. Such impacts present significant disruptions to the operations of businesses of all sizes and can cause large economic damages, even for firms that are not located in flood zones.

The 'networked' nature of infrastructure becomes apparent when overlaying the urban road map with flood risk zones. For this purpose, we use the same flood data as in the previous section and combine it with data on roads from the OSM project. Figure 11 shows how flooding is affecting the road network in the area of this analysis in Kampala

Figure 11: Road network and flooding in Kampala



In Kampala, 3.8% of all drivable roads are affected by a flood with a return period of 50 years. This overall percentage, however, does not consider the role a certain piece of road plays in the transportation network. Flooding of a small residential street used by several cars a day has a very different impact on accessibility than flooding of a highway that thousands of people depend on every hour. Therefore, OSM's classification of roads was used to analyze the flooding of roads by class of road.

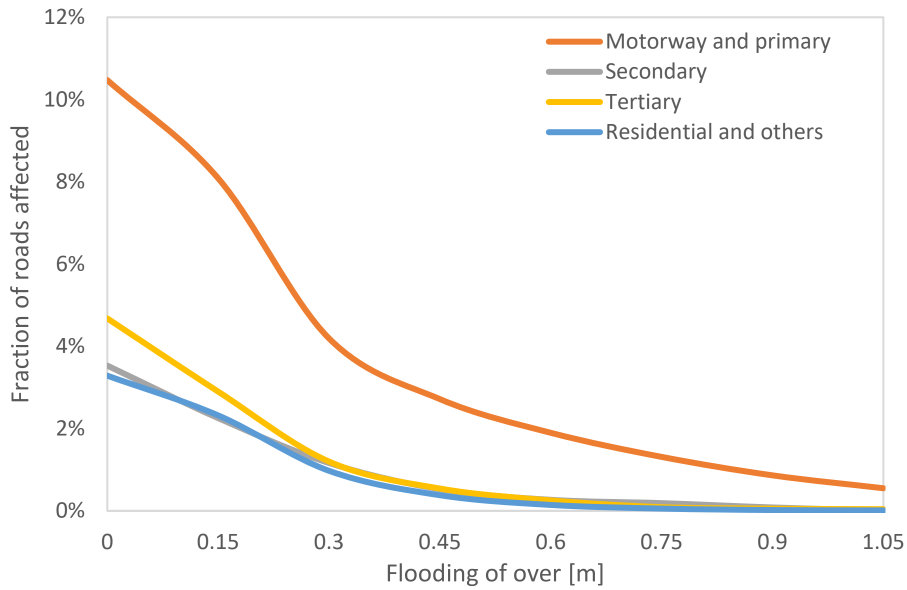
In Kampala, main roads such as motorways, trunk roads, and primary roads, are disproportionally located in flood zones (see Figure 12). In a 50-year flood, 11 km or about 10% of all main roads in the area of analysis are flooded. Looking at residential and other roads that make up the vast majority of roads in Kampala, the length of flooded roads is much greater with 45 km, but the fraction is much smaller with 3%. In Kampala, main roads are thus affected disproportionally by flooding.

As cars might be able to traverse roads with shallow flooding when reducing their speed, considering flood depth as an additional dimension can bring further insights. Still looking at a flood with a 50-year return period, 8% of all major roads are modelled to be flooded with a depth of greater than 15cm, thus blocking them off for most conventional cars[5]. Note that opposing road lanes that are visibly separated from each other by greenery or other non-pavement structures, as is the case for many of Kampala's highways, will

[5] Technically, flood depths of up to 20cm may be safe for most vehicles to navigate. However, in practice – and confirmed anecdotally – drivers tend to be risk averse as they cannot gauge exact water depths and thus avoid submerging and risking their vehicles.

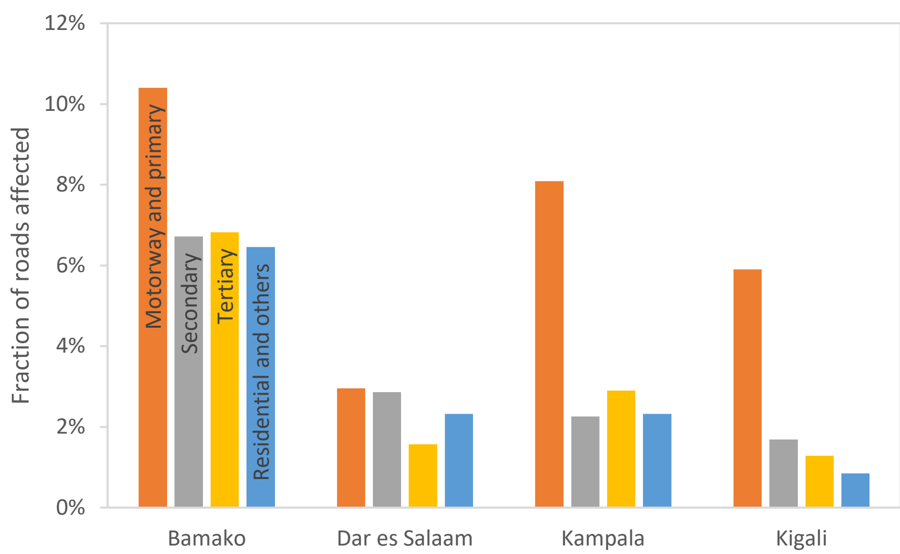
be accounted for as two streets in OSM which impacts the calculated length of roads in the city or flood zone.

Figure 12: Fraction of roads affected by flooding in Kampala by road type and flood depth



Just like in Kampala, main roads are disproportionally affected by flooding in Bamako and Kigali. Figure 13 compares the fraction of different types of roads flooded by more than 15cm in an event with a 50-year return period in the four cities. The high stress on main roads indicates significant indirect effects from transport disruptions to a flooded economy. At the same time, it suggests that flood protection measures can prove to be efficient investments. Concentrating flood mitigating efforts on main roads could already provide significant relief to the transportation network.

Figure 13: Fraction of roads in Bamako, Dar es Salaam, Kampala, and Kigali affected by flood depth of over 15cm in an event with 50-year return period



4.3. Impacts on connectivity and access

The disproportionally large share of main roads subjected to significant flooding described in the previous section already hints at the severe transport disruptions to be expected from flooding. Such indirect effects of flooding affecting the local infrastructure can end up causing larger disruptions to the economy then physical damage. In order to quantify these indirect effects, this section assesses how disruptions to the transportation network translate into increased travel times affecting firms and residents. This analysis therefore looks at how the transport network connects firms among themselves and people to jobs and services and how floods would impact this level of transport service.

First, a model of the street network is created for each city based on OpenStreetMap data. We used open source software library OSMNx to download, clean and simplify the raw road network data. The procedure employed utilizes OSM data on the directionality of each road segment (one-way or two-way), the road type (eg. highway, local street), and the geometry of the street network. In this way, we model each city's street network as a graph object. Each graph comprises nodes (the street intersections) and edges (the links between nodes). In the case of Kampala, the graph contains 12,700 nodes and 31,688 edges. Travel time for edge road segment is computed based on the road length and average travel speeds for the road type.

Secondly, we simulate the effect of flooding on road network connectivity. In addition to an unflooded model of the road network, we construct graphs representing travel times in each city during a 10-, 50- and 100-year flood event. This is accomplished by sampling at small intervals along each road segment, and disrupting each link where water depths exceed our 15-centimeter threshold. Next, we connect our points of interest - the geographic coordinates of our sample of businesses, as well as critical health facilities downloaded from OpenStreetMap - to the road network by snapping their location to the nearest street intersection. Finally, we conduct two sets of travel time analysis by using the Dijkstra shortest path algorithm: (i) inter-firm travel times; and (ii) access to hospitals.

Figure 14. Left: Distribution of travel times between firms for different flood scenarios in Inner Kampala. Right: Distribution of increases in travel times between firms in Inner Kampala for different flood scenarios in comparison to a no-flood baseline.

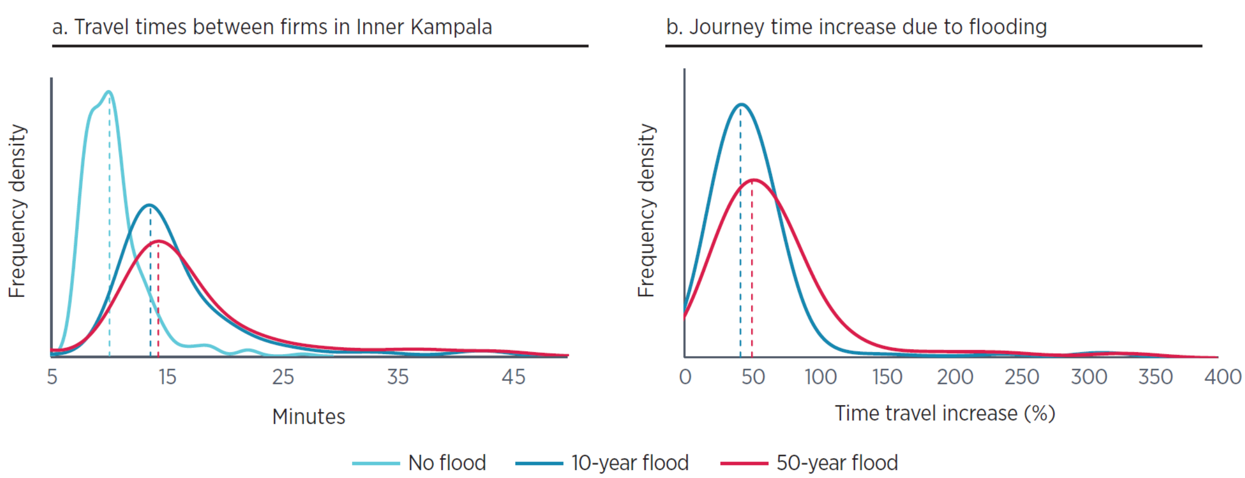


Figure 15. Increase in inter-firm connectivity for urban floods with 10 and 50-year periods

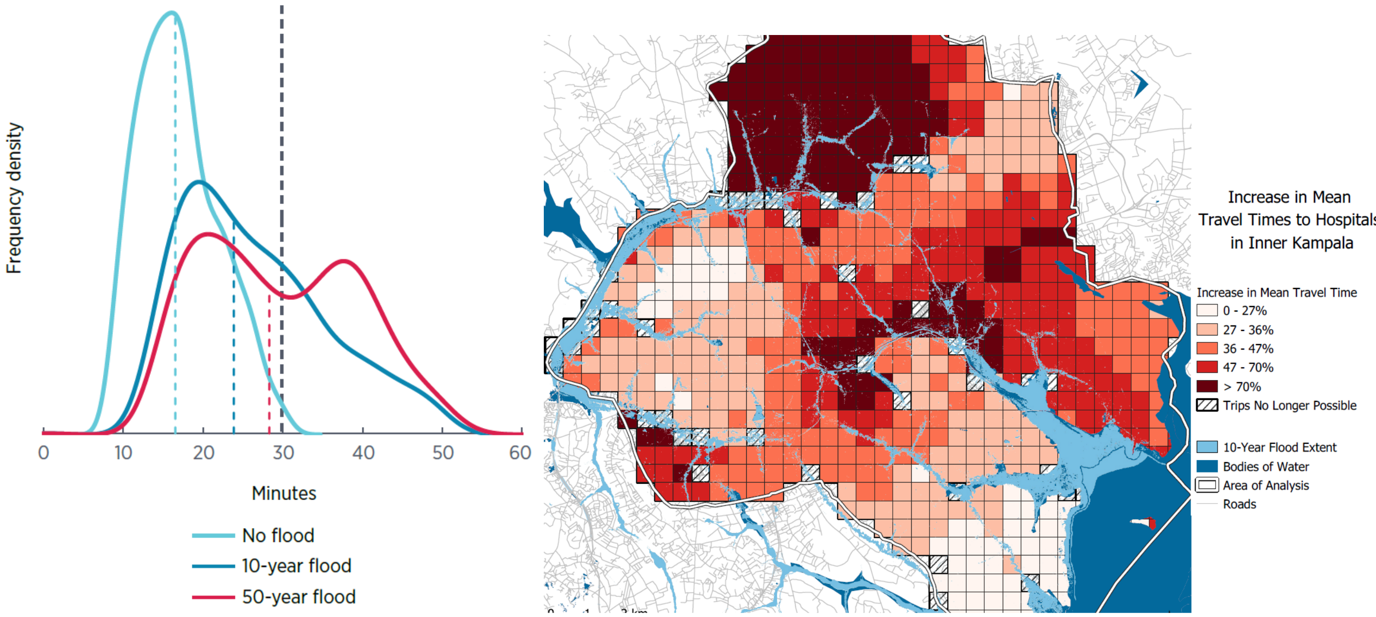
		10-year return period (% of all firms)	50-year return period (% of all firms)
Increase in inter-firm travel times due to flooding in Kampala	**Less than 25%**	0.3%	0.0%
	25% - 50%	52.8%	42.3%
	50% - 75%	9.8%	14.7%
	75% - 100%	2.9%	3.9%
	More than 100%	26.7%	27.4%

Connectivity between firms in Kampala declines significantly due to flooding, according to our model. Considering the population of other firms to represent customers and suppliers, reduced inter-firm connectivity is detrimental to economic health of businesses in Kampala. The increase in travel times between pairs of firms ranges from 54% (10-year flood) to 69% (100-year flood) on average. Interestingly, travel time disruption in a 10-year flood event comes close in severity to the impacts of a 100-year flood event. While larger floods cause extensive property damage, more frequent 'nuisance floods' also impose major impacts on firm connectivity, posing a constraint to private sector growth. In our modelled 50-year flood scenario, most journey times increase by some 25%-75%, but for the ten percent of most affected firm pairs, journey times more than double.

We now turn to households' accessibility to important services (in this case hospitals) and how it it is altered by flood events. Accessibility to hospitals also declines significantly due to flooding. Within Inner Kampala, mean transport times to a hospital are just over 17 minutes. In our model of the 50-year flood event, this journey time rises to 30 minutes. Due to impassable roads and the need to take more circuitous routes in a flood event, for 17% of city locations the mean journey time at least doubles. Moreover, 7% of trips from city locations to hospitals become impassable.

A common rule of thumb in emergency response states that the survival rate for life threatening health issues drops significantly after the "golden hour", i.e. 60 minutes after the incident (Campbell, 2017). Absent flooding, some 98% of city locations have mean journey times to hospitals below 30 minutes. Assuming that ambulances are based at hospitals, a one-way travel time of less than 30 minutes implies a round-trip of less than the 60-minute threshold. However, journey times exceed this level for 30% of city locations in a 10-year flood, and 44% of locations in a 50-year flood. The additional travel times to reach critical facilities may impose severe consequences on residents seeking urgent medical care. As the above estimated travel times do not account for the potentially significant impact of congestion (both in the flood and no-flood scenarios), the true disruptive impact of floods for accessibility is likely to be even larger in practice.

Figure 16 Left: Mean travel times from all locations in Inner Kampala to health care facilities for different flood scenarios. Right: A map of Inner Kampala showing the road network and health facilities.



5. Conclusion

This study demonstrates how city-level risk assessments can shed light on the exposure and vulnerability of urban populations to urban flooding. The results of the analyses show that the impacts of natural shocks are highly localized and the design of urban prevention measures needs to take such granularity into account. In addition, the results demonstrate clearly that infrastructure networks (in this case the urban road network) transmit local disruptions across wider areas – however, this transmission often occurs in uneven ways depending on network characteristics, thus affecting certain neighborhoods more heavily than others.

The analysis conducted for this study also highlights that urban flood risk assessments should not only take into account asset damages associated with natural shocks – such as urban flooding, but also account for the impact on people (e.g. due to lost access and connectivity) and firms (as supply chains also propagate shocks). To enable such analyses, the availability of high-resolution data is critical. In particular, the development of realistic flood maps is important, to take into account not only topography but also existing protection and drainage infrastructure. Overall, the city-level risk assessments presented in this study can help prioritize, tailor, and improve urban risk management and infrastructure upgrading projects.

References

Campbell, J. 2017. International Trauma Life Support for Emergency Care Providers, Global Edition. New York: Pearson Education Limited.

Rentschler, J., Kornejew, M., Hallegatte, S., Obolensky, M., & Braese, J. (2019). Underutilized potential: The business costs of unreliable infrastructure in developing countries. *World Bank Policy Research Working Paper*.

Appendix

A.1. Flood map availability

Table 2 provides an overview over availability and use of the different types in the cities analyzed here, and Figure 1 pictures the flood maps for four cities.

Table 2: Flood map availability in 13 African cities; Key: ⨂ = available and used in section 4, O = available but not used in section 4, - = not available. In Section 4, all available flood maps were used.

City \ Flood map type	SSBN	Tailored model	Community mapping
Abidjan	⨂	-	-
Accra	O	⨂	-
Addis Ababa	⨂	-	-
Bamako	⨂	-	-
Cotonou	⨂	-	-
Douala	⨂	-	-
Dar es Salaam	⨂	-	O
Freetown	⨂	-	-
Kampala	O	⨂	-
Kigali	⨂	-	-
Monrovia	⨂	-	-
Nairobi	⨂	-	-
Zanzibar	⨂	-	-

A.2. Descriptive statistics from Enterprise Surveys

Figure 17 provide evidence for the significant economic cost of power outages to firms (also see Rentschler et al., 2019). Plotting outages and resulting sales losses as city-wide averages, it is clearly visible that firms in cities with longer outages forego higher sales, on average. Still, some variation exists. Businesses in Freetown, Sierra Leone, for example, experience the highest sales losses but the city ranks fifth in our panel for outage durations. This hints at the differing ability of firms to cope with and adapt to power outages.

Figure 17: Power outages and resulting sales losses. Average electricity downtime across cities

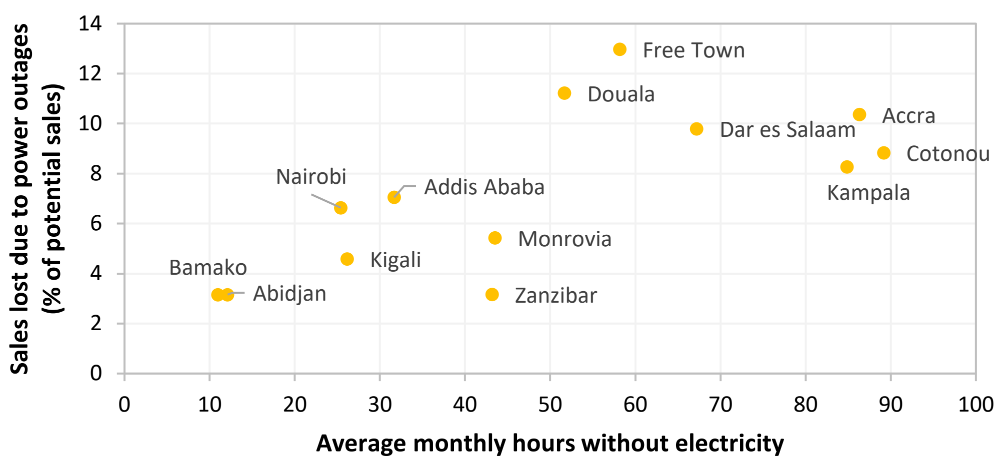
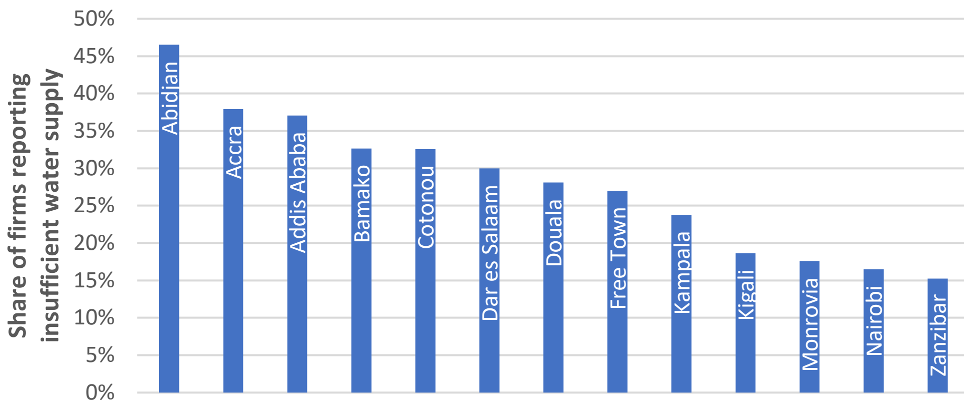


Figure 18 shows the share of firms in each city that experienced insufficient water supply in the year before the survey was carried out.

Figure 18: Fraction of firms with insufficient water supply across cities



A.3. Infrastructure disruptions and proximity to flood threat

Table 3: Results from weighted OLS regression, including dummy indicating whether any other firm in the analyzed firm's spatial unit is flood threatened, city-level normalized survey stratification weights applied. Standard errors in italics, clustered on cities. Abidjan city-level fixed effects omitted to allow estimation of model. Significance levels: *** 0.01, ** 0.05, * 0.10. Note that the size of spatial units (determining the 'proximity to flood' variable) varies between cities due to the definition of administrative boundaries and data availability.

Dependent:	Blackouts	Water disruptions	Transport problems
Firm age	0.157	8.330**	-0.001
years of official registration	*(1.42)*	*(2.82)*	*(0.00)*
Employment	-0.930*	0.505	0.001
number of full time employees	*(0.50)*	*(0.91)*	*(0.00)*
State ownership	3.159	-0.902	0.015
in %	*(5.81)*	*(6.83)*	*(0.02)*
Export orientation	-0.194	4.044	-0.000
% of total sales	*(1.46)*	*(3.80)*	*(0.00)*
Generator ownership	67.939	109.900	0.051
Dummy	*(52.15)*	*(286.74)*	*(0.15)*
Distance to city centre	-0.000	0.006	-0.000
At the ward-level, in meter	*(0.00)*	*(0.00)*	*(0.00)*
Flood-threatened	3.564	97.719	0.181
Dummy	*(70.34)*	*(269.44)*	*(0.15)*
Proximity to flood	97.199	-339.909	-0.142
Other firm in ward is flood-threatened	*(82.77)*	*(332.85)*	*(0.21)*
ISIC Sector Fixed Effects	YES	YES	YES
City-level Fixed Effects	YES	YES	YES
N	2217	828	2699
R^2	0.186	0.120	0.125

A.4. Flood exposure and firm disruptions: robustness checks

In the main analyses, firms are characterized as flood-threatened if they are located in a zone with flood hazard probability greater than one or if they are exposed to flooding greater than 5 centimetres in a modelled flood with a 50-year return period. This classified a moderately large number of firms as flood-threatened. It could be the case that this low threshold obfuscates the effects of flooding on infrastructure disruptions among those firms that are more heavily flood threatened. To assess this hypothesis, the analyses are repeated with a dummy variable for firms that can be described as *heavily flood-threatened*. The variable takes the value one if firms are located in an area with flood hazard probability greater than 10 percent in any given year, if they are exposed to flooding greater than 5 centimetres in a modelled flood with a 10-year return period, or if they are exposed to flooding greater than 20 centimetres in a modelled flood with a 50-year return period when no 10-year flood map is available. This methodology classifies 130, or about four percent, of the 3094 firms as heavily flood-threatened. Results from regressions of the three types of infrastructure disruptions on flood-threat and firm characteristics are described in Table 4. There is no change in the relationship between firm characteristics and disruption variables. For water disruptions and transport problems, heavily flood-threatened firms do not experience different disruptions than not flood-threatened firms. Blackouts, however, seem to be shorter among firms that are heavily flood-threatened, an effect that is significant with a p-value below 0.1.

Table 4: Results from weighted OLS regression including mean disruption levels for all other firms in a city, city-level normalised survey stratification weights applied. Standard errors in italics, clustered on cities. Significance levels: *** 0.01, ** 0.05, * 0.10.

Dependent:	Blackouts	Water disruptions	Transport problems
Firm age	-0.242	7.954**	-0.001
years of official registration	*(1.51)*	*(3.23)*	*(0.00)*
Employment	-1.109**	0.739	0.001
number of full time employees	*(0.51)*	*(0.65)*	*(0.00)*
State ownership	4.463	-2.493	0.016
in %	*(5.68)*	*(5.10)*	*(0.02)*
Export orientation	0.151	4.091	-0.000
% of total sales	*(1.33)*	*(3.34)*	*(0.00)*
Generator ownership	66.276	87.193	0.072
Dummy	*(43.57)*	*(251.90)*	*(0.14)*
Distance to city centre	0.000	0.003***	0.000
At the ward-level, in meter	*(0.00)*	*(0.00)*	*(0.00)*
Flood-threatened	20.580	86.709	0.151
Dummy	*(71.76)*	*(281.37)*	*(0.14)*
City-level blackouts	0.986***		
Mean blackouts of other firms in cities	*(0.08)*		
City-level water disruptions		0.316	
Mean water disr. of other firms in cities		*(0.43)*	
City-level transport problems			1.020***
Mean trans. prob. of other firms in cities			*(0.08)*
ISIC Sector Fixed Effects	YES	YES	YES
City-level Fixed Effects	NO	NO	NO

N	2217	828	2600
R^2	0.162	0.079	0.108

Table 5: Results from weighted OLS regression using a more restrictive classification for flood threat, city-level normalised survey stratification weights applied. Standard errors in italics, clustered on cities. Abidjan city-level fixed effects omitted to allow estimation of model. Significance levels: *** 0.01, ** 0.05, * 0.10.

Dependent:	Blackouts	Water disruptions	Transport problems
Firm age	0.274	8.117**	-0.001
years of official registration	*(1.49)*	*(2.69)*	*(0.00)*
Employment	-0.916*	0.479	0.001
number of full time employees	*(0.50)*	*(0.91)*	*(0.00)*
State ownership	3.438	-2.367	0.015
in %	*(5.68)*	*(7.88)*	*(0.02)*
Export orientation	-0.206	4.063	-0.000
% of total sales	*(1.45)*	*(3.66)*	*(0.00)*
Generator ownership	65.613	132.431	0.049
Dummy	*(51.01)*	*(289.14)*	*(0.15)*
Distance to city centre	-0.001	0.009	-0.000
At the ward-level, in meter	*(0.00)*	*(0.01)*	*(0.00)*
Heavily flood-threatened	-122.712*	336.997	-0.090
Dummy	*(62.69)*	*(321.16)*	*(0.13)*
ISIC Sector Fixed Effects	YES	YES	YES
City-level Fixed Effects	YES	YES	YES
N	2217	828	2600
R^2	0.185	0.116	0.123

While the approaches used thus far allows for the unification of different types of flood maps and increases the statistical power of the analysis, it also limits the information in the data by coding flood exposure as a binary variable. For instance, there is no distinction between two firms inundated by 10 centimeters and by 1 meter in a flood, but they are likely to factor flood hazard into their decisions very differently if they are aware of it. To exploit variation in the severity of flood-affectedness, a subsequent analysis is conducted for Accra and Kampala only, where high-resolution flood maps for an event with a 50-year return period are available. These flood maps are used to assign an exact flood depth value in centimetres to each firm and the previous regressions are re-run for Accra and Kampala, again including industry- and city-level fixed effects, control variables, and standard errors clustered at the city-level. Results of the regressions on annual hours of power outage, annual hours of water supply disruptions, and perception of transport as an obstacle to business are summarized in Table 6. Note that due to perfect multi-collinearity, state ownership was dropped from the analysis in this sub-sample. However, again no significant effect of flood exposure on power, water, or transport infrastructure disruptions can be observed. Even accounting for the severity of flood danger, no clear relationship between infrastructure disruptions and individual firm characteristics is found, highlighting again the importance of considering infrastructure disruptions as a system-wide phenomenon.

Table 6: Results from OLS regression for Accra and Kampala only, city-level normalized survey stratification weights applied. Standard errors in italics, clustered on cities. Significance levels: *** 0.01, ** 0.05, * 0.10.

Dependent:	Blackouts	Water disruptions	Transport problems
Firm age	-7.202	4.022	-0.002
years of official registration	*(16.62)*	*(1.12)*	*(0.00)*
Employment	-0.507	3.664*	-0.002
number of full time employees	*(0.78)*	*(0.37)*	*(0.00)*
Export orientation	-1.933	15.154	0.003
% of total sales	*(4.25)*	*(3.24)*	*(0.01)*
Generator ownership	156.538	-839.320	-0.272
Dummy	*(153.67)*	*(267.09)*	*(0.05)*
Distance to city centre	0.000	-0.004	-0.000
At the ward-level, in meter	*(0.00)*	*(0.00)*	*(0.00)*
Flood depth	195.818	514.279	0.158
50-year return period, in cm	*(120.66)*	*(530.84)*	*(0.09)*
ISIC Sector Fixed Effects	YES	YES	YES
City Fixed Effects	YES	YES	YES
N	443	198	642
R^2	0.079	0.287	0.082

A.5. Characteristics of flood prone firms

While there appears to be no clearly observable influence of flood exposure on infrastructure disruptions, the common methodology to identify flood-exposed firms can still be used to assess whether firms with certain characteristics are more likely to be flood-affected. It has been long established that certain household characteristics such as wealth are correlated with flood exposure at the city-level. This dataset provides the opportunity to analyze whether such relationships also exist at the firm level and across several cities in the developing world. In this section, weights are again used as specified above.

A simple way to analyze the characteristics of firms located in flood-threatened areas is to pool them and compare them to all non-threatened firms along several variables. Both sets of firms appear fairly homogeneous with respect to their economic industries. Some observable differences exist, though: Flood-threatened firms are more often associated with the production of fabricated metals, motor vehicles, and the provision of air transport. Other differences seem coincidental: flood-threatened firms are more often classified as part of the textile, but less often the clothing industry (see Table 7). Looking at other characteristics, firms in flood-threatened areas are slightly more likely to be publicly owned, are less export focused than their counterparts and have slightly lower number of employees and temporary employees. Whereas roughly 50% of firms in both groups own a generator, the percentage of overall electricity used by the firm that was generated using the generator is almost 10 percentage points lower for flood-threatened than for non-threatened firms (22% vs 32%). No clear differences are observable in firm age. While these results illustrate the heterogeneity of firms located in flood-threatened areas, they should only be interpreted as descriptive. More specifically, some of the differences in characteristics between firms might be explained or obfuscated by differences in other characteristics. Furthermore, as the share of firms classified as flood-threatened varies between cities, differences between cities might be ascribed to flood-affectedness. One way to control for such collinearities and city-wide effects is to use regression.

Table 7: Fraction of firms in industry by that are and are not flood-threatened, city-level normalised survey stratification weights applied.

Share of firms in industry	Not flood-threatened	Flood-threatened
Food and beverages	0.0617	0.0361
Tobacco	0.0003	0
Textiles	0.0072	0.0179
Clothing	0.0408	0.0211
Leather products	0.0056	0.0013
Wood products	0.0084	0.0183
Paper products	0.0012	0.0009
Printed products	0.0259	0.0231
Coke, petrol refinery	0.0067	0.0008
Chemicals	0.0186	0.0146
Rubber and plastics	0.0099	0.0085
Other non-metallic minerals	0.0076	0.0070
Basic metals	0.0041	0.0025
Fabricated metals	0.0270	0.0404
Machinery	0.0080	0.0020
Electrical machinery	.00063	0.0052
M; Radio	0.0003	0
Radio, TV, Communication devices	0.0001	0
Motor vehicles	0.0052	0.0351
Other transport equipment	0.0008	0
Furniture	0.0526	0.0485
Recycling	0.0026	0
Construction	0.0634	0.0444
Vehicle trade and repair	0.0937	0.0662
Wholesale trade	0.1403	0.1555
Retail trade	0.1951	0.1963
Hotel and Restaurants	0.1298	0.1298
Land transport	0.0387	0.0303
Air transport	0.0035	0.0109
Auxilliary transport activities	0.0130	0.0301
Post and telecom	0.0060	0.0058
Programming	0.0157	0.0475
Sum	1	1
N	3,279	331

In order to disentangle the characteristics of flood-threatened firms, a binary logistic regression is employed to explain whether a firm is flood-threatened or not based on the firm's observed characteristics, its economic sector, and the city it operates in. Coefficients from the logistic regression that includes fixed effects for sectors and cities are reported in Table 8. At the 5% significance level, greater ownership of the firm by the state is positively and greater export orientation is negatively associated with location in a flood zone. These results could hint at a greater efficiency of private companies in reacting to flood hazards and an increased awareness of flood risk among internationally oriented firms. Firm age, number of employees, and ownership of a generator are not significantly associated with being located in a potential flood zone when controlling for industry- and city-specific fixed effects. This illustrates that, across cities in the developing world, there is no one archetypical flood-threatened firm: instead, flood hazard can affect firms of all sizes and ages.

Table 8: Results from weighted logistic regression, city-level normalised survey stratification weights applied. Standard errors in italics, clustered on cities. Significance levels: *** 0.01, ** 0.05, * 0.10.

Dependent:	Flood-threatened
Firm age	0.015
year of official registration	*(0.01)*
Employment	-0.001
number of full time employees	*(0.00)*
State ownership	0.027**
in %	*(0.01)*
Export orientation	-0.011**
% of total sales	*(0.01)*
Generator ownership	-0.195
dummy	*(0.31)*
ISIC Sector Fixed Effects	YES
City Fixed Effects	YES
N	2675
Pseudo-R^2	0.1136