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Oasis of Resilience? An Empirical Investigation of Rain Water Harvesting Systems in High Poverty, Peripheral Communities

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Oasis of resilience? An empirical investigation of rain water harvesting systems in high poverty, peripheral communities

Daniel P. Aldrich[1] and Courtney Tan[2]

Abstract: The southeastern mayorality of Mexico City known as Xochimilco has some of the highest poverty, unemployment, male suicide, and illegal land use rates in the region. Lakes and aquifers have dried up due to mismanagement and overall water quality is poor. NGOs and governments have sought to increase the water resilience of residents through experimental projects such as the installation of rainwater harvesting systems. The September 2017 Mexico earthquake cut off many households in the area from formal water infrastructure, serving as a kind of natural experiment to test the impact of these interventions on community resilience to shocks. Using geocoded, quantitative data on more than 700 residential households (half of which have rain water harvesting systems) and qualitative interviews with 40 households collected after the earthquake we seek to understand the relationship between demographic, environmental, and technical factors and resilience outcomes in Xochimilco. Better physical infrastructure including electricity and water grid connections enhanced resilience while vulnerable conditions (such as illiteracy and women headed households) correlated with reduced resilience. Overall, already vulnerable populations seem less likely to receive rainwater harvesting systems which have demonstrated positive outcomes. Our findings bring with them a number of policy recommendations for residents, NGOs, and disaster managers.

Keywords: resilience, water infrastructure, rainwater harvesting systems, sustainability, earthquake, Mexico City, GIS

Introduction

The southeastern borough of Mexico City known as Xochimilco has some of the highest poverty, unemployment, male suicide, and illegal land use rates in the region. Of its 400,000 residents, at least 15,000 live in informal or illegal settlements in the area and water insecurity is high. Xochimilco faces dual threats from floods and water shortages. Over the past two decades, 23 floods have affected 34,000 people–and lakes and aquifers have dried up due to mismanagement and water quality is poor (Eakin et al. 2016). Diarrheal diseases due to water contamination are 1.6 times more prevalent in the area than across the country of Mexico.

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Water resilience has proven a challenge at local, regional, and national levels in Mexico and across the world. Estimates put some 15% of Mexican residents across the nation without access to piped water (Fuentes-Galván et al. 2015). Many residents in Xochimilco rely on market-based water supplies such as water trucks (known as *pipas*) as connections to the regional water grid, but delivery is sparse and unreliable. Even for those residents formally connected to the grid, water may be available only sporadically (White, Fowler, and Karnchanapimolkul 2018), with some reporting water available from taps only twice a month (Kimmelman 2017).

NGOs and governments around the world have sought to increase water access for residents through low cost, easy to maintain projects, such as rainwater harvesting systems (Akter and Ahmed 2015). These tanks collect rainwater via roofs, funneling it into storage (often through filters, traps, or similar mechanisms) for household use. Under the proper conditions – such as the use of carbon or other filters - rainwater harvesting can produce water which meets national and international standards for drinking (Gispert et al. 2018). These systems may also build resilience for households by providing an additional source of water for all uses (washing, flushing toilets, drinking, etc.) during shocks which limit or suspend access to standard water utility infrastructure. For those without any access to piped or trucked water, rainwater harvesting may be their sole source of this critical resource.

The September 2017 Mexico 7.1 magnitude earthquake cut off many households from the formal water grid, serving as a kind of natural experiment to test the impact of these interventions on water fragility and community resilience, defined here as "a neighborhood's capacity to weather crises such as disasters and engage in effective and efficient recovery through coordinated efforts and cooperative activities" (Aldrich 2012). Anecdotal reports indicate that almost all residents in

Xochimilco lost access to the formal water infrastructure for weeks, if not months, and that damaged mountain roads prevented *pipas* from delivering water in a timely manner.

However, households with rainwater harvesting (RWH) systems continued to have access to water, a condition improved by meteorological conditions in Xochimilco. Rain fell for days after the shock and helped replenish their reservoirs. One volunteer with an NGO reported that an entire community came to rely on a single rain water harvesting system with a nearly full 5000 liter storage tank. One resident stated that 40 people - including her extended family and neighbors - visited or camped near her home to access drinking water and operational toilets. Her RWH became a focal point of the community as families filled up her garden area, transforming it into an informal community center (Interview with NGO leader 23 April 2018).

This paper seeks to answer four main questions about water resilience and interventions which can enhance or reduce it using a new dataset. *First*, given the precarity of the water grid in Mexico and more specifically in Xochimilco, we analyze what drives demand for private sector water delivery in this rural, underdeveloped area. For this initial analysis, and throughout our quantitative investigations, we look at the impact of a variety of infrastructure systems – water, transportation, telecommunication, and so forth – along with demographic characteristics of households in the area. *Second*, our paper seeks to shed light on the question of which factors correlate with the installation rate of the rainwater harvesting systems. That is, given broad variation in the time of installation over the period of this study – from days to years - why some households received systems earlier than others is unclear.

Third, we seek to understand patterns behind the installation of these rain water harvesting systems to see if any factors correlate with their adoption. Through regression analysis we seek to disentangle the impact that systemic, environmental, and demographic factors have on the likelihood of a *manzana*, a geographic unit equivalent to a U.S. Census Block Group, receiving a RWH project. While we may hope to find that the most vulnerable populations who have the highest need are most likely to receive them, research on a variety of related developmental aid and disaster assistance has shown that such resource allocation decisions are rarely apolitical. Scholars have shown that international aid flows to countries that have relevant political and historic ties (such as membership on important international committees or colonial interests), rather than to those with the most need (Werker 2010). At the individual and family level, post-disaster aid has also been tied to ethnic factors like caste rather than damage from the crisis or poverty (Aldrich 2012).

Fourth and finally, we seek to illuminate whether these rain water harvesting systems increased resilience to water fragility in poor communities. Here our analysis draws on qualitative and quantitative data to better illuminate precisely how a rain water harvesting system may change outcomes for residents. We are especially interested in how the presence (versus absence) of these systems changed societal relations and social ties.

This paper contributes to the existing literature on water resilience and rainwater harvesting in several ways. First, it is among the first to use a large-scale dataset drawing from physical and social infrastructure data to understand social, demographic, and environmental patterns in water resilience. Most studies on rainwater harvesting projects have relied on case study or small N studies (Barkin 2006, Sosa-Rodriguez 2010) or large-N studies of topology, geology, and meteorology relying on regional data as their approaches without specific attention to community demographics and socioeconomic conditions (Abdullah and Rahman 2015).

Next, rather than using only a single analytical approach, we use mixed methods. We employ geospatial census data from Mexico’s National Institute of Statistics and Geography

(INEGI), along with large scale household level surveys and smaller, qualitative interviews with borough residents to better triangulate our findings. By working at the manzana level in Xochimilco, we can talk about the impact of hyperlocal environmental, demographic, and system factors on a variety of outcomes of interest.

Finally, our paper uses systematic inference to offer concrete policy recommendations for residents, NGOs, and city managers alike. As our data allow us to better understand the interaction between water, transport, and telecommunication infrastructure along with demographic characteristics and communal outcomes, we are positioned to suggest efficient ways to deepen resilience for vulnerable populations.

Motivation

While scholars have long emphasized the importance of understanding social and ecological drivers of water resilience in the context of climate change (Falkenmark and Rockström 2008), “the role of water in building resilience of social-ecological systems in an era of rapid change is complex, and remains poorly understood” (Falkenmark 2017). Climate change is amplifying preexisting challenges in our communities and creating new shocks and stressors. Rising temperatures, loss of natural resources and biodiversity, regular coastal flooding, and water precarity and access will continue to press on developed and developing nations alike. Whether droughts in California, Zero Day in Cape Town, South Africa, or the challenges of water availability in medium sized cities like Bangalore across Southeast Asia, policy makers have come to recognize the need for deeper resilience in water systems (Subramanian 2017)

Mexico City and its surrounding boroughs face steep challenges with water insecurity in suburban and rural regions, as the water riots in 2014 in Sao Bartolo Ameyalco drove home. Even for those who have a connection to Mexico’s aging water grid, there is no guarantee that water will flow. Some women in Xochimilco spend hours climbing up and down hills to reach *pipas*, or water trucks from private delivery firms. Other times rural villagers may pay for delivery by donkey as their homes are too far from standard delivery routes. These families can spend up to 10 percent of their income on purchasing water from private sources (Kimmelman 2017).

The 18 September 2017 7.1 magnitude earthquake in Mexico killed 369 people across six Mexican provinces, injured 6000, and destroyed many homes and businesses. The earthquakes also disabled the already fragile public water grid, cutting off thousands from clean potable water, creating a kind of natural experiment to measure resilience across communities plagued with pre-existing water scarcity. The households in Xochimilco equipped with RWH systems reported that they became sources of community resilience in a time of need, offering extended family members and neighbors water harvested from heavy rainfall in the days following the earthquake. The resilience of these households is in part, thanks to Isla Urbana, a non-profit organization active in the region since 2012 and responsible for the installation of 1,500 RWH systems throughout the greater Mexico City area.

Water Resilience and Rain Water Harvesting

As of 2015, 844 million people lacked access to clean drinking water across the globe. Broadly speaking, water stress, *or lacking access to a sufficient supply of water*, affects two billion people worldwide (UNDP 2019). The uptick in drought, deforestation, inclement weather, dry spells, natural hazards, and political unrest underscores the importance of water resilience, reflected in the United Nation’s Goal 6: clean water and sanitation, and in water technologies that offer an alternative to dependence on public water supplies. *Water resilience* is defined here as “transforming degraded ecosystem services in landscapes through manipulation of water flows and water characteristics” (Falkenmark 2017).

In countries such as Mexico and Brazil public water supplies are strained, unreliable, expensive, or scarce - all issues further amplified in a crisis. Rainwater harvesting (RWH) systems offer a low-cost alternative source and supply of water for households and small holder farmers (Barkin 2006), which reduces dependence on the public water grid and minimizes flooding. Standard RWH systems consist of three elements: a catchment surface (i.e. rooftop or road surface), delivery system, and storage system (i.e. tank or barrel) (Worm and van Hattum 2006). Runoff from the catchment surface (most commonly rooftops for household RWH systems) is captured by the delivery system (primarily gutters and drainpipes) and then delivered to a storage tank, often above ground. Rainwater harvesting systems in urban areas are considered ideal alternative sources of water because they reduce both the demand for piped water from public water supplies and flooding from rainwater runoff from impervious surfaces, such as streets and sidewalks (Karim, Bashar, and Imteaz 2015). In urban and rural areas alike, RWH systems offer resilience to extreme variability in climate and rainfall.

In Bangladesh, agriculture - the single largest producing sector of the economy - is highly vulnerable to disaster and climate induced shocks, drought chief among them (Abdullah and Rahman 2015). Rainwater harvesting has offered a viable cost-effective solution to small holder farmers whose agricultural yields have suffered from rising temperatures in the summer months, saline affected environments, and water table depletion from groundwater extraction for irrigation. A study of South Agrabad in Chittagong city, Bangladesh, an urban zone prone to both flooding in urban areas and drought-induced water scarcity, estimated that RWH systems could potentiality minimize stagnant storm water up to 26% (Akter and Ahmed 2015). Geospatial hydrologic modeling simulations suggest that the process of capturing rainwater in urban areas of South Agrabad could supplement city water supply annually up to 20 liter/person/day. In another study

(Karim, Bashar, and Imteaz 2015), researchers found that RWH systems atop 6-story apartment buildings in Dhaka, Bangladesh could harvest between 250–550 kL of rainwater per year from a catchment area of 140–200 m^2, yielding cost-benefits in wet and average seasons and reducing the demand from the city water supply.

In Wageningen in the Netherlands, researchers (Agudelo-Vera et al. 2012) found that RWH systems in residential areas could reduce dependence on piped water at rates as high as 52%. Similarly, in Caruaru, the most populated city in the Agreste Region of Brazil, researchers estimate (Dos Santos and de Farias 2017) that RWH systems could significantly reduce household dependency on an already strained water infrastructure. In this region, the public water supply safe for drinking reaches only 60% of the population and is distributed nine days a month in urban areas and only five days a month to rural areas. Installing RWH systems in Caruaru would effectively reduce the demand for potable water from the public water supply by 31% in an average season. In a wet season, researchers estimate a reduction in demand as high as 58%.

In addition to liberating communities from the high cost and scarcity of public water, RWH systems also have the potential to be more resilient to changes in climate, compared to other methods. For example, in Brisbane, Melbourne, Perth and Sydney, Australia, researchers found that the rainwater yields from 3 kL tanks were more resilient to variation in climate compared to runoff water from dams (Coombes and Barry 2008). More specifically, these researchers estimate that in a worst-case climate change scenario, individuals could expect a reduction in the range of 5% to 8% across RWH systems; whereas, reductions across the runoffs into dams ranged from 19% to 53%.

This research project evaluates the interventions of an NGO in Mexico known as Isla Urbana, founded by Enrique Lomnitz and Renata Fenton who created their first water project in

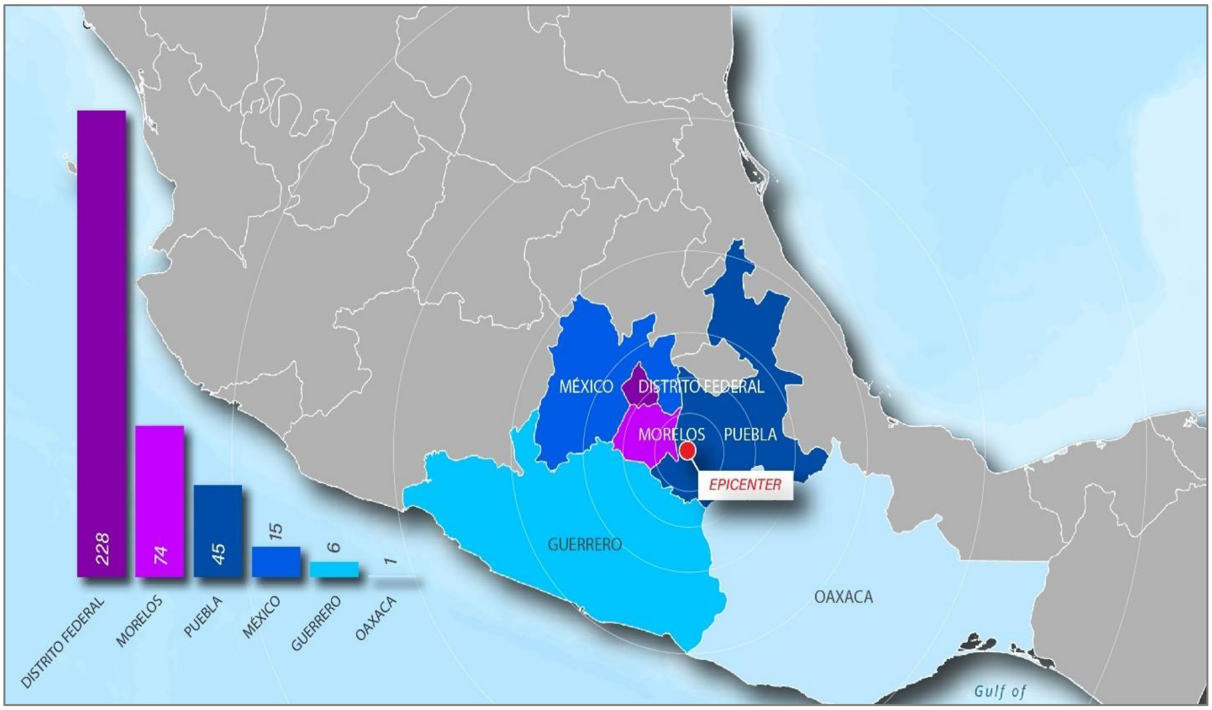
2009. Their initial designs for RWH systems were more complex and less sustainable, making scaling difficult and inefficient. Partnerships with public and private institutions, funders, and users in urban and rural areas led to gradual changes in their designs, resulting in the Tlaloque (First-Flush) (Segev 2015) mechanism, prominent in their current design, efficiently captures and filters rainfall. Household installations of their systems require community and household buy-in. Families must cover 10-20% of the initial installation costs and community members attend an educational theatre about the importance of water. Members of the community are trained as local plumbers and engineers to maintain the RWH systems, which in turn builds local human capital and vocational capacity. The systems are designed to capture rain that can be used for up to 4-6 months, offering households independence from the public water supply. By using and maintaining a RWH system, households save on average $1,700 pesos that would have otherwise been spent on water trucks (Arroyo-Zambrano, Cerutti, and Gutiérrez 2016)

Xochimilco, Mexico

Xochimilco is one of 16 boroughs in Mexico City, making up 4% of Mexico City's total population of 8,985,339. The most recent census data reports total annual revenues of $8,861,719 pesos across all of Xochimilco, ranked last only second to La Magdalena Contreras and obscured by Miguel Hidalgo, reporting revenues of $641,766,646. Xochimilco, Tlalpan, and Milpa Alta, located in the southern part of Mexico City have the lowest reported rates of homes with piped water, at rates of 93%, 97%, and 87%, respectively.

Despite the high rates of water piping reported by public authorities, reports before the 2017 Puebla Earthquake suggest that water delivery was unreliable, at best (Segev 2015, Kimmelman 2017). Deliveries arrived anywhere between 3 and 30 days of planned dates, forcing household members to be home at all times to accept the water delivery. If no one was home, the order was cancelled, and the *pipas* moved on to the next order. This dependence on water deliveries reinforced a culture of poverty for women in households. Water becomes the center of their lives so that women find it nearly impossible to work outside of the home (Kimmelman 2017). A natural hazard in 2017 further exacerbated water resilience challenges for this area.

Figure 1: Epicenter and fatalities from the 2017 Puebla Earthquake



Data sources: Fatalities reported by The General Coordinator of Civil Protection of the State of Mexico Luis Felipe Puente reported on Twitter and the USGS

A magnitude 7.1 earthquake struck the Puebla area of Mexico on September 19, 2017 at 1:14pm local time (USGS 2017). The earthquake occurred 80 miles (130 kilometers) southeast of Mexico City where the greatest number of fatalities were reported. On October 4th, 2017, The General Coordinator of Civil Protection of the State of Mexico Luis Felipe Puente reported on Twitter (Puente 2017) that the earthquake resulted in 369 deaths across five provinces in Mexico (see Figure 1 above). The earthquake sent 1,900 people to the hospital with injuries and damaged more than 20,000 buildings and structures in the surrounding area (USAID 2017). Within hours of the earthquake, the Mexican Red Cross activated 500 volunteers, including doctors, nurses, and rescue units (IFRC 2017). Initial estimates of displaced individuals places economic losses at $160 million, or 0.01 per cent of Mexico's GDP (IDMC 2019). The damage to the water infrastructure was devastating. Pipes that connected households to local water grid were damaged in areas like San Gregorio, a rural community in Xochimilco.

Local residents in Xochimilco described high societal tensions as their standard providers of water failed. "It was a horrible situation," recalled one resident in an interview with Isla Urbana. "People were fighting for water" (quoted in White, Fowler, and Karnchanapimolkul 2018). Water prices for jugs of water quadrupled to some $90 for 20 liters.

Data and Methods

This study employs qualitative and quantitative data and statistical and spatial analyses to better understand the impact and role of rainwater harvesting projects. A total of 793 geocoded observations are represented across 552 unique manzanas in Xochimilco. *Manzanas*, a geographic unit equivalent to a United States Census Block, average 60 residents per unit. We also use qualitative data in the form of extended, open ended interviews with 40 families. Our work comes from a combination of two data sets: data collected by the NGO Isla Urbana on households with rainfall harvesting projects and a geospatial dataset on urban residential parcels from the National Institute of Statistics and Geography of Mexico. Table 1 below details the core variables under study in this project which takes place across 793 household across 552 unique manzanas.

We use this new and original dataset to investigate three outcomes of interest: demand for private water trucks in the dry season, time to installation (days) of RWH systems, and the presence / absence of rainwater harvesting system. Our fourth outcome of interest will draw from a much smaller qualitative sample of some 40 households who received the RWH systems from Isla Urbana. Our dataset builds on past research that has pointed to a variety of categories of data that may influence important resilience outcomes. We are especially interested in factors including water infrastructure, transportation infrastructure, utility infrastructure, communication infrastructure, socioeconomic status, and demographic characteristics (Aldrich and Sawada 2015; Sadri et al. 2018).

Table 1: Descriptive Statistics for the Large-N, Quantitative Analysis

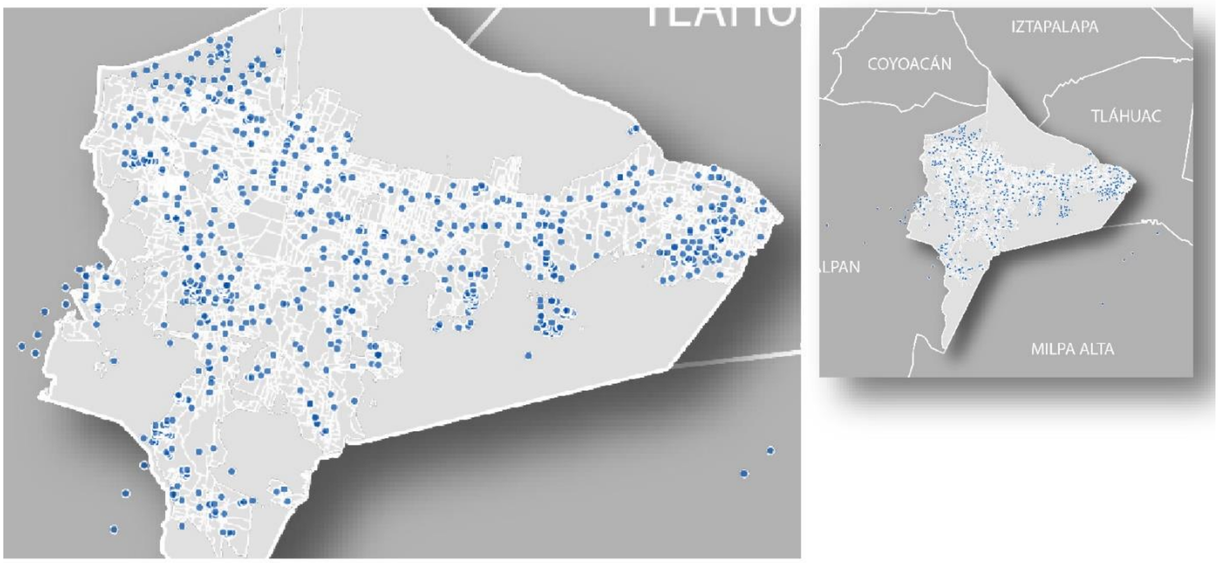
Dependent variables	Obs	Mean	Std Dev	Min	Max
Demand for private water trucks in dry season	286	1.77	2.97	0.00	24.00
Time to installation (days)	397	1544.67	545.20	0.00	2068.00
Presence / absence of rain water harvester	792	0.50	0.50	0.00	1.00
Water infrastructure					
Water grid connected	363	0.41	0.49	0.00	1.00
Percentage households w/ indoor toilet	626	0.89	0.07	0.46	1.00
Transportation infrastructure					
Road access	793	46.51	23.56	0.00	98.60
Utility Infrastructure					
Percentage of households with electricity	596	0.64	0.36	0.00	1.00
Communication infrastructure					
Percentage of households with cellphones	624	0.63	0.11	0.28	1.00
Socioeconomic status					
Population density	626	308.15	567.68	22.04	6152.92
Number of children	397	1.66	1.79	0.00	23.00
Percentage population 60 years and older	612	0.08	0.05	0.00	0.40
Percentage of population illiterate	513	0.03	0.02	0.00	0.09
Years of schooling	627	9.39	1.51	0.00	14.47
Unemployment rate	526	0.02	0.02	0.00	0.11
Percentage Catholic	626	0.83	0.09	0.54	1.00
Percentage of women headed households	622	0.22	0.09	0.00	0.91

Sources of data: National Institute of Statistics and Geography of Mexico and Isla Urbana surveys

To build our original dataset, we merged 397 geocoded households with RWH systems provided by Isla Urbana with 395 randomly selected households in Xochimilco without RWH systems. Combined, these 793 geocoded households were spatially joined with manzanas with the

Spatial Join tool in ArcGISPro to derive household indicators of water infrastructure, utility infrastructure, communication infrastructure, and socioeconomic status (see Figure 2). To capture water grid connectedness we have two separate measures: *the percentage of households with indoor toilets* and the percentage of those *households with a connection to the formal water grid*. *Road access* serves as our measure of transportation infrastructure, and offers a new and original offered in this study. A buffer of 800 meters, a distance commonly accepted as one's local neighborhood (Du Toit et al. 2007, Wood et al. 2017, Wood et al. 2008), was drawn around each of the 793 geocoded household points in ArcGISPro. Local streets, avenues, boulevards, highways, and interstates in Xochimilco were mapped and the total length of the road network was calculated with the *Summarize Within* function for each of the 793 800-meter buffers. The total length of roads within each buffer serves as the measure of a household's *road access*. For utility infrastructure measurements we capture the *percentage of households with electricity* and for communication infrastructure we look at the *percentage of households with cellphones*.

Figure 2: Geocoded households overlaid on 552 unique manzanas in Xochimilco



Note: Further illustrations are visualized at the manzana level to protect the identity of survey participants

For our socioeconomic status and demographic controls and variables, we have a diverse set of measurements of local conditions, including *population density* (people per square kilometer), *the number of children per household*, *percentage of the population 60 years and older*, the *percentage of population that is illiterate, average years of schooling in the community*, the *unemployment rate*, the *percentage of residents that are Catholic*, and the *percentage of women headed households*. We envision these as sufficiently diverse to capture both the physical infrastructure systems used by local residents along with the social systems that may build (or detract from) their resilience.

Results

We first analyze the factors driving demand for private sector water delivery to better understand the conditions where additional resilience measures might be most needed. Some households need to request as many as 24 *pipas*, or private water truck deliveries, during Mexico's dry season, which is typically November through April. Communities needing more private sector trucks are ones where that have not been helped by existing infrastructure. Household demand for water delivery itself may be monotonically higher with higher temperatures and lower humidity levels pushing household members toward more consumption. At the same time a variety of factors – infrastructure connectivity, household size, and other demographic characteristics may multiply this higher demand or alternatively ameliorate it.

Table 2 above provides the estimated OLS coefficients. Using a standard ordinary least squares (OLS) analysis of 153 households, we find two statistically significant factors, both of which involve connections to physical infrastructure systems, alter demand. In our dataset, having a higher percentage of homes connected to electricity and having more homes connected to the formal water grid reduced the predicted number of water trucks sought in the dry season.

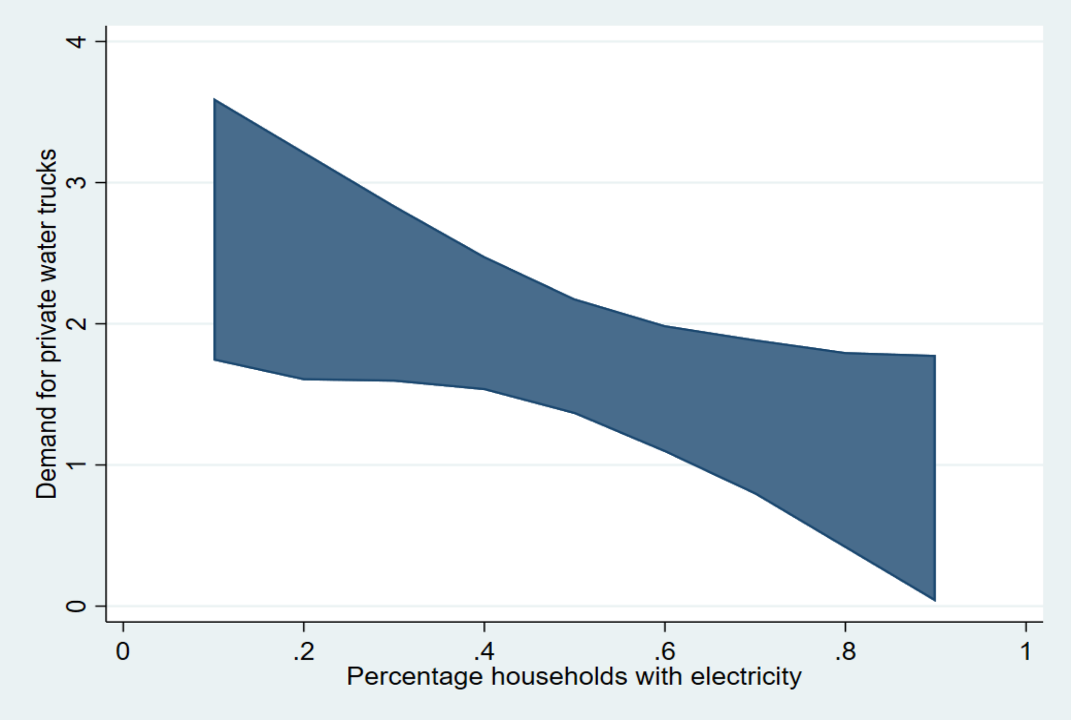
Table 2: What correlates with needing more water trucks in the dry season?

Variable	OLS regression (standard errors)
Water grid connected	-1.70* (0.801)
Percentage households w/ indoor toilet	-2.740 (6.543)
Road access	-0.016 (0.017)
Percentage of households with electricity	-2.279* (1.021)
Percentage of households with cellphones	-1.861 (5.171)
Population density	0.000 (0.000)
Number of children	-0.034 (0.093)
Percentage population 60 years and older	4.338 (13.270)
Percentage of population illiterate	-19.384 (28.210)
Years of schooling	0.353 (0.445)
Unemployment rate	14.119 (20.756)
Percentage Catholic	2.993 (3.866)
Percentage of women headed households	1.221 (3.719)
Constant	2.260 (7.516)

N=153, * = p <.05

To illustrate this relationship in a more visual way which incorporates measures of our uncertainty about our predictions (King, Tomz, and Wittenberg 2000), we ran a series of simulations where we held all of the other variables in the analysis at their means while allowing the percentage of households with electricity to vary. Figure 3 below illustrates this relationship and the 95% confidence intervals around our predictions.

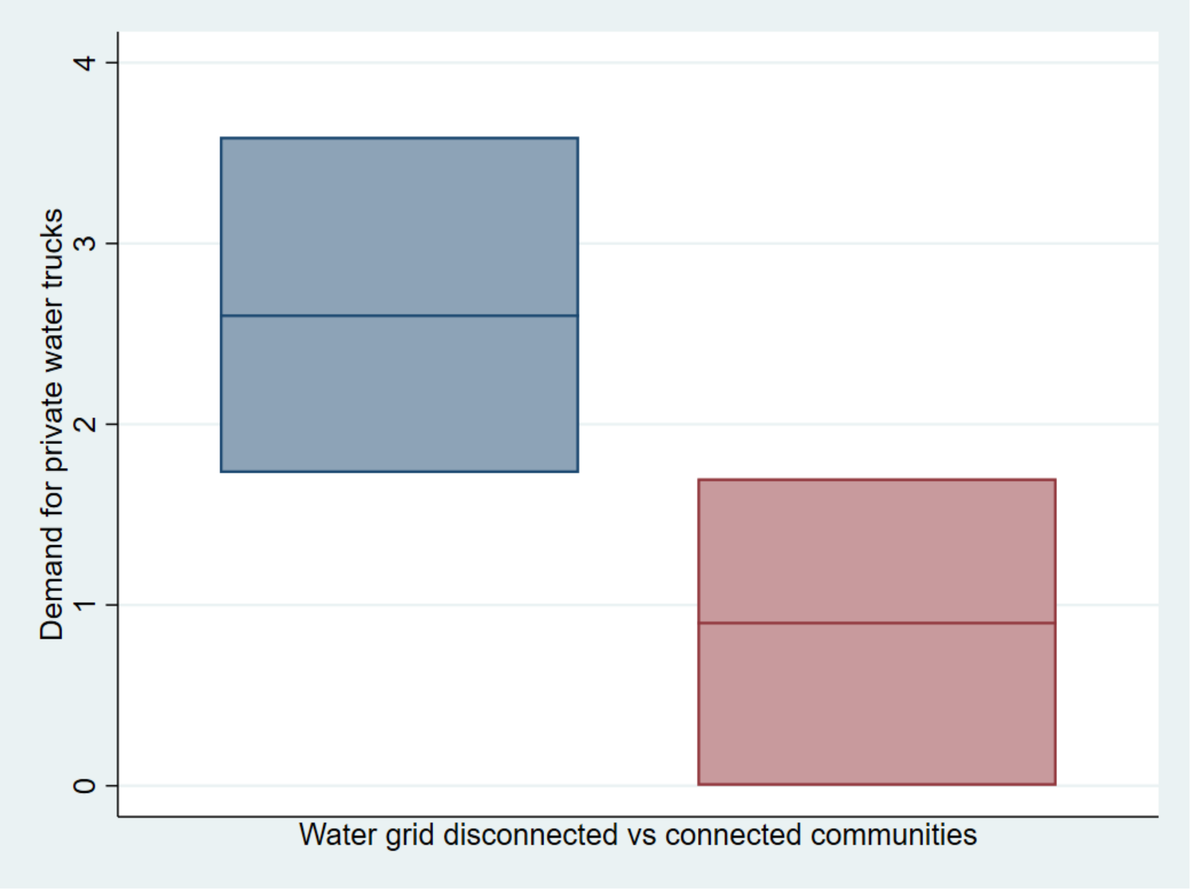
Figure 3: Better connected communities require fewer private water trucks in the dry season



Note: N = 153, number of simulations = 1,000, OLS model. All variables (water grid connected, percentage households w/ indoor toilet, road access, percentage of households with cellphones, population density, number of children, percentage population 60 years and older, percentage of population illiterate, years of schooling, unemployment rate, percentage Catholic, and percentage of women headed households) held at their means except for percentage of households with electricity, which varied between 0 and 1 (100%). The shaded area indicates the 95 percent confidence interval around the predicted value.

We also illustrate the relationship between formal water grid connections and the demand for water trucks using the sample simulation technique, holding other variables at their means and looking at the predicted outcomes in two categories, as seen below in Figure 4.

Figure 4: Water grid connected communities seek fewer water trucks in the dry season



Note: N= 269, number of simulations = 1000. OLS model. Pearson chi2(10) = 105.9721, Pr = 0.000. All variables except for water connection held at their means. Horizontal line is predicted average, with top and bottom of boxes representing 95 percent confidence intervals around those predictions.

Having established that physical infrastructure connectivity reduced the need for additional water truck demand in the dry season, we next look at why some areas received rainwater harvesting projects earlier than others through an investigation of the speed of installation since the Xochimilco project began in earnest nearly a decade ago. Some received them in a week from the start of the installation period which others had to wait as long as 2000 days (roughly five and a half years). As before, we use a standard OLS model to find correlates with the speed of installation.

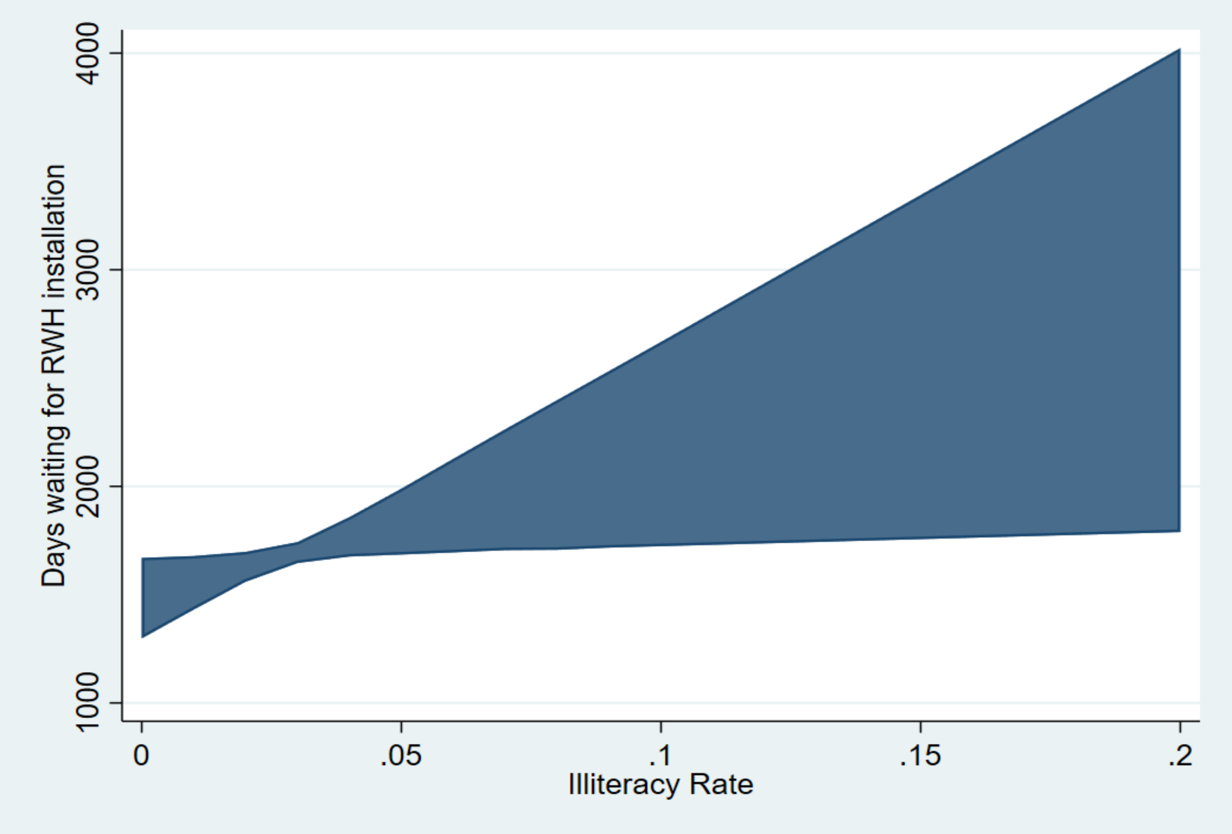
Table 3: What correlates with the speed of installation?

Variable	OLS regression (standard errors)
Water grid connected	-37.27
	(92.14)
Percentage households w/ indoor toilet	-622.52
	(736.34)
Road access	5.809***
	(1.93)
Percentage of households with electricity	140.33
	(117.11)
Percentage of households with cellphones	-1250.042**
	(588.96)
Population density	-0.136***
	(0.05)
Number of children	-4.62
	(11.37)
Percentage population 60 years and older	1492.44
	(1482.38)
Percentage of population illiterate	6774.942**
	(3347.54)
Years of schooling	208.83***
	(52.00)
Unemployment rate	2449.42)
	(2488.07)
Percentage Catholic	-392.70
	(420.93)
Percentage of women headed households	812.4297**
	(407.90)
Constant	709.53
	(841.46)

Note: N=200. p < .05**, p < .01 ***

We find a number of statistically significant variables that (positively) increase the number of days before installation, including road access, illiteracy rates, years of schooling, and percentage of women headed households. We also find a number of variables with negative correlations, including households with cellphones and population density. Hence more vulnerable communities seemed to wait longer for installation. To illustrate the relationship between illiteracy rates in the community and time to household installation, we again run a simulation, holding all of the other variables at their means and allowing illiteracy rates to vary. Figure 5 below shows how higher illiteracy rates resulted in longer delays before installation.

Figure 5: Illiteracy Rate and Installation Delay

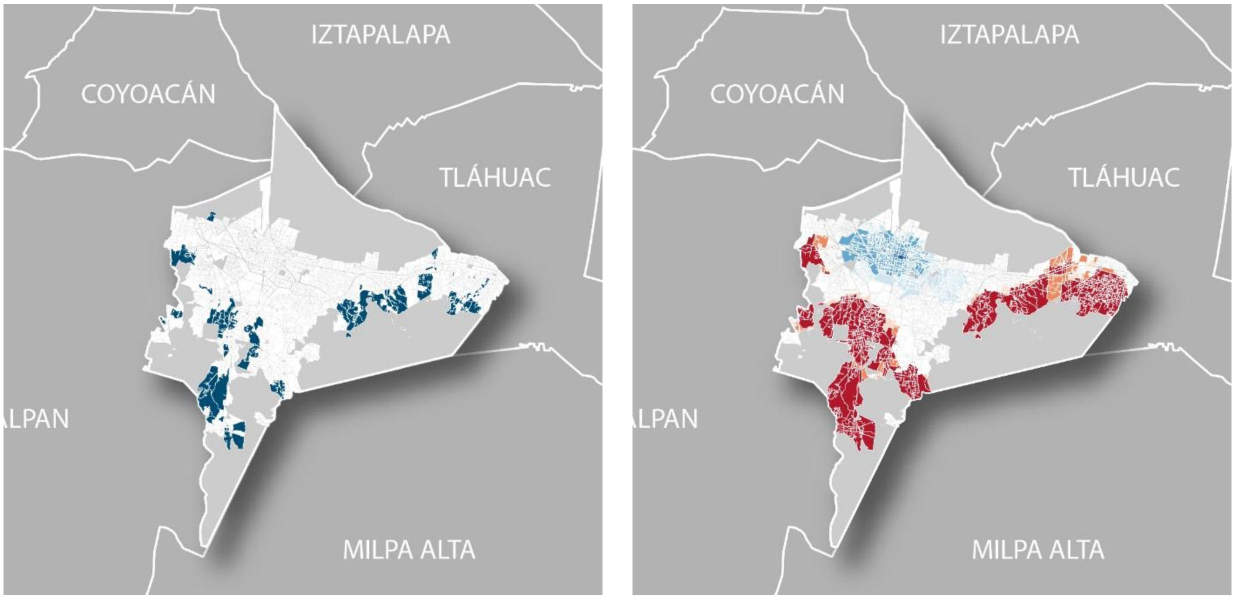


N= 200, simulations = 1000. All variables held at their means except for illiteracy rate, which follows the actual range found in our sample. The predicted value is at the center of the blue mass, which represents the extent of the 95 percent confidence intervals around those predictions.

Having investigated demand for private water provision and also delays in the installation of potentially resilience building interventions, we now seek to answer if the geographic distribution of clusters of manzanas with rainwater harvesting projects are statistically significant. Figure 5 below displays two maps: manzanas with RWH systems and a map displaying an analysis of clustering. To test for statistically significant clustering, we first used a Hot Spot Analysis (the Getis-Ord Gi* (pronounced G star)) to identify statistically hot (displayed in dark red) and cold (displayed in dark blue) spots, visualized in “Hotspot Analysis of RHW in Xochimilco” in Figure

6. The initial analysis reveals that there are several statistically significant geographies of spatial clustering of RWH systems, and a single geography where they are absent. To further validate these findings, we used The Spatial Autocorrelation (Global Moran's I) tool, which allows us to test our null hypothesis, stating that the spatial distribution of RWH systems in Xochimilco is random. A positive z-score and statistically significant p-value from the Global Moran's I analysis reveals that the distribution of RWH systems in Xochimilco are more spatially clustered than we would expect if the overall process of installations were random.

Figure 6: Map and Hot Spot Analysis of Manzanas with Rainwater Harvesting Projects



Manzanas with RHW in Xochimilco

Hotspot Analysis of RHW in Xochimilco

Note: Data Source: Isla Urbana and INENG. Global Moran's I Summary. Moran's Index: 0.063111 (Expected Index: -0.000159). Variance: 0.000006, z-score: 26.698526, p-value: 0.000

The spatial distribution of manzanas with rainwater harvesting projects in the dataset is more spatially clustered than would be expected if underlying spatial processes were random. Given the non-random nature of the spatial distribution of these projects, what factors make it more (or less) likely that a community or neighborhood will receive one? Table 4 below displays the estimated OLS regression coefficients for factors which correlate with the installation of rainwater harvesting projects in households. Three variables have statistically significant negative correlations with installation, namely road access, years of schooling and illiteracy, while two have positive relationships, namely cell phone access and population density. More vulnerable and less resource rich communities seem less likely to receive RWH projects in our dataset.

Table 4: What factors correlate with presence or absence of a RWH system?

Variables	OLS regression (standard errors)
Percentage households w/ indoor toilet	4.831 (3.177)
Road access	-0.036*** (0.010)
Percentage of households with electricity	-0.323 (0.547)
Percentage of households with cellphones	5.313*** (1.990)
Population density	0.00114** (0.001)
Percentage population 60 years and older	5.155 (4.719)
Percentage of population illiterate	-29.86** (12.559)
Years of schooling	-0.8793*** (0.203)
Unemployment rate	-13.544 (9.003)
Percentage Catholic	-3.525 (1.933)
Percentage of women headed households	-2.351 (1.809)
Constant	6.772 (3.417)

N=408. *** p<.01, **p<.05

Our final investigation is how social infrastructure and social cohesion may be altered by the installation of such projects. We coded qualitative interviews with 40 families in Xochimilco which did receive rainwater harvesting projects to understand the potential relationships between demographic factors and changes in social systems, and controlled for a variety of factors, including tenure in the community, household size, and education level. During interviews families were asked about their perceived levels of support from the community. As Table 5 below shows, the presence of a rainwater harvesting system had a statistically significant and positive relationship with the perception of community support, holding all other factors constant.

Table 5: Drivers of perception of community support

Variables	Coefficient	Standard Error	P>t
Presence/Absence of RWH system	.6188	.172	0.001
Education level	-.0034	.062	0.956
Household size	.0117	.029	0.691
Tenure in the community (years)	-.0011	.003	0.749
Constant	.256	.281	0.370

Note: N=33

Discussion

This paper investigated water resilience across impoverished, rural communities in Xochimilco, Mexico from a variety of angles. In our first section we discovered strong correlations between connections to water infrastructure and the demand for private water sources during the dry season. Households in manzanas that had their own electricity connections and formal connections to the water grid had measurably lower needs for private trucks, indicating that physical infrastructure– despite any challenges in reliability – serves as a source of water resilience.

Our second investigation looked at how quickly communities received these projects from the start of installation by a local NGO more than 5 years ago. Interestingly, a number of factors that likely indicate poverty and peripheral location, including road access, illiteracy rates, years of schooling, and percentage of women headed households, slowed down the predicted waiting period. In contrast, factors which likely correlate with more development, including households with cellphones and population density, sped up the process of installation.

Our third investigation first showed that the installation of RWH projects across Xochimilco was not spatially random. Instead, communities with more factors correlated with poverty and periphery, namely road access, years of schooling and illiteracy, were correlated with lower chances of installation. Two factors demonstrated positive relationships with installation, namely cell phone access and population density, showing that, as with installation speed, better connected and perhaps better developed areas were the ones receiving these projects.

Our fourth and final investigation illuminated the relationship between receiving a rainwater harvesting project and changes in social support. Controlling for a number of demographic factors, our qualitative interviews demonstrated a robust connection between a strong sense of community support and the presence of a rainwater harvesting project. Beyond improving the water resilience for households, these projects seem to also improve social connectedness and social ties. Broadly speaking, then, rainwater harvesting projects enhanced communities which received them, while their rapid installation seemed more likely in communities which already had resources and connections.

Conclusions

Water insecurity remains a major challenge for cities around the world including Bangalore, Beijing, Sao Paola, and Cape Town, which narrowly averted Day Zero (when the city would not be able to provide water to all residents through its standard pipe infrastructure). While typically better situated in terms of water access than these other cities, New Zealand, among others, faces likely seismic shocks which will sever connections to standard water infrastructure systems, but resilience need not come at a high price (Hrudey and Hrudey 2014). Where centralized grid provision of water has proven impossible, NGOs and bottom up solutions have filled the gap. In this way, rainwater harvesting can create the conditions for adaptive and even transformative infrastructure systems by building redundancy and response diversity into water provisioning (Simonsen et al. 2014, Eakin et al. 2016, Hatton et al. 2018, Demina 2019). In the same way all centralized distribution systems are by definition more vulnerable to shocks, we have investigated one way to move toward a bottom up, localized, decentralized approach.

Our investigation used a combination of census data, quantitative surveys, and qualitative interviews to understand demand driving private water provision and the factors which made installation of RWH systems more speedy and likely. Our data reinforce the adage that useful systems often contribute to populations which need them less, and that peripheral communities seem doubly disadvantaged. Communities facing economic and educational challenges – those with more poverty, illiteracy, and women-run households – were not prioritized for installation. Nevertheless, we found that physical infrastructure of the rainwater harvesting system helped maintain and even the strength of social infrastructure and ties for those households which actually received them.

Rainwater harvesting projects distributed equitably with need in mind could allow impoverished, rural communities in Mexico and elsewhere to sustain themselves and their families without needing to resort to further draining of the region's aquifer or carbon intensive water pumping procedures (Barkin 2006, Gispert et al. 2018). Their simple, sustainable design and relatively low cost and maintenance requirements can build redundancy and diversity into brittle water infrastructure systems for the most impoverished. While roof top area, topography and other factors can impact the yield of rain water harvesting projects, they have by and large demonstrated few downsides (Akter and Ahmed 2015).

Despite these positive aspects, a number of challenges remain to the broad use of rain water harvesting systems, including funding, scalability, and health and sanitation (WHO and UNICEF 2017). When investments in water storage are not guided by environmental health considerations, the increased availability of open water surface may increase the transmission of water-related diseases (Boelee et al. 2013). Nevertheless, filtration systems along with boiling can reduce these risks. Further, Mexico City plans to install 10,000 rainwater harvesting projects in Mexico City over the upcoming year. While this is a massive number of projects for a single NGO like Isla Urbana to handle, it is a drop in the bucket compared to the nearly 9 million residents of the city. Should decision makers prioritize crisis mitigation, they could increase the number of these projects installed across the region and by implementing benchmarking performance indicators, key stakeholders can easily track strategic targets, policy levers, sustainability, and lifecycle (Ganjidoost et al. 2018).

Rainwater harvesting projects placed into vulnerable and impoverished communities have tremendous potential to allow local families to access water despite unpredictable shocks like earthquakes and long-term stressors such as poor transportation and logistical infrastructure. While the highest form of redundancy would involve connecting all residents – with recognized land rights and without – to the grid, a more practical way to better protect and assist developing communities would be the precision placement of rainwater harvesting projects.

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Works Cited

Abdullah, Hasan Muhammad, and Md Mezanur Rahman. 2015. "Initiating rain water harvest technology for climate change induced drought resilient agriculture: scopes and challenges in Bangladesh." *Journal of Agriculture and Environment for International Development (JAEID)* 109 (2):189-208.

Agudelo-Vera, Claudia M., Wouter R. W. A. Leduc, Adriaan R. Mels, and Huub H. M. Rijnaarts. 2012. "Harvesting urban resources towards more resilient cities." *Resources, Conservation & Recycling* 64:3-12. doi: 10.1016/j.resconrec.2012.01.014.

Akter, Aysha, and Shoukat Ahmed. 2015. "Potentiality of rainwater harvesting for an urban community in Bangladesh." *Journal of Hydrology* 528:84-93.

Aldrich, Daniel P. 2012. *Building resilience : Social capital in post-disaster recovery*. Chicago: Chicago : The University of Chicago Press.

Arroyo-Zambrano, Tania Isabel, Omar Masera Cerutti, and Alfredo F. Fuentes Gutiérrez 2016. "Adopción e impactos de los sistemas de captación de agua de lluvia." *Unidad de Ecotecnologías*.

Barkin, David. 2006. "Building a future for rural Mexico." *Latin American Perspectives* 33 (2):132-140.

Boelee, Eline, Mekonnen Yohannes, Jean-Noël Poda, Matthew McCartney, Philippe Cecchi, Solomon Kibret, Fitsum Hagos, and Hammou Laamrani. 2013. "Options for water storage and rainwater harvesting to improve health and resilience against climate change in Africa." *Regional Environmental Change* 13 (3):509-519.

Coombes, P. J., and M. E. Barry. 2008. "The relative efficiency of water supply catchments and rainwater tanks in cities subject to variable climate and the potential for climate change." *Australasian Journal of Water Resources* 12 (2):85-100. doi: 10.1080/13241583.2008.11465337.

Demina, Anna. 2019.

Dos Santos, Sylvana Melo, and Maria Mariah M. W. E. C. de Farias. 2017. "Potential for rainwater harvesting in a dry climate: Assessments in a semiarid region in northeast Brazil." *Journal of Cleaner Production* 164:1007-1015. doi: 10.1016/j.jclepro.2017.06.251.

Du Toit, Lorinne, Ester Cerin, Evie Leslie, and Neville Owen. 2007. "Does Walking in the Neighbourhood Enhance Local Sociability?" *Urban Studies* 44 (9):1677-1695. doi: 10.1080/00420980701426665.

Eakin, Hallie, Amy M Lerner, David Manuel-Navarrete, Bertha Hernández Aguilar, Alejandra Martínez-Canedo, Beth Tellman, Lakshmi Charli-Joseph, Rafael Fernández Álvarez, and Luis Bojórquez-Tapia. 2016. "Adapting to risk and perpetuating poverty: household's strategies for managing flood risk and water scarcity in Mexico City." *Environmental Science & Policy* 66:324-333.

Falkenmark, Malin. 2017. "Water and human livelihood resilience: a regional-to-global outlook." *International Journal of Water Resources Development* 33 (2):181-197. doi: 10.1080/07900627.2016.1190320.

Falkenmark, Malin, and Johan Rockström. 2008. "Building resilience to drought in desertification-prone savannas in Sub-Saharan Africa: The water perspective." *Natural Resources Forum* 32 (2):93-102. doi: 10.1111/j.1477-8947.2008.00177.x.

Fuentes-Galván, María Lina, Xitlali Delgado-Galván, Hilario Charcas-Salazar, Jesús Mora-Rodríguez, Jose Luis Flores Flores, and Antonio Cardona Benavides. 2015. "Rooftop rainwater harvesting acceptance in three localities of Guanajuato, central Mexico." *Interciencia* 40 (6).

Ganjidoost, A., M.A. Knight, A.J.A. Unger, and C.T. Haas. 2018. "Benchmark Performance Indicators for Utility Water and Wastewater Pipelines Infrastructure." *Journal of Water Resources Planning and Management* 144 (3):04018003.

Gispert, Mireya, María Hernández, Enrique Climent, and María Flores. 2018. "Rainwater Harvesting as a Drinking Water Option for Mexico City." *Sustainability* 10 (11):3890.

Hatton, Tracy, Charlotte Brown, Robert Kipp, Erica Seville, Peter Brouggy, and Michelle Loveday. 2018. "Developing a model and instrument to measure the resilience of critical infrastructure sector organisations." *International Journal of Critical Infrastructures* 14 (1):59-79.

Hrudey, Steve E, and Elizabeth J Hrudey. 2014. *Ensuring safe drinking water: learning from frontline experience with contamination*: American Water Works Association.

IDMC. 2019. The ripple effect: economic impacts of internal displacement. Geneva, Switzerland: Internal Displacement Monitoring Centre.

IFRC. 2017. Mexico: Red Cross teams providing urgent rescue and first aid for earthquake victims. In *Panama/Geneva*: International Federation of Red Cross And Red Crescent Societies.

Karim, Md Rezaul, Mohammad Zobair Ibne Bashar, and Monzur Alam Imteaz. 2015. "Reliability and economic analysis of urban rainwater harvesting in a megacity in Bangladesh." *Resources, Conservation & Recycling* 104 (PA):61-67. doi: 10.1016/j.resconrec.2015.09.010.

Kimmelman, Michael. 2017. "A Parched and Sinking Capital." *The New York Times*, 2017/02/19/, A1(L). Accessed 2019/5/9/. http://link.galegroup.com/apps/doc/A481868013/AONE?u=mlin_b_northest&sid=AONE&xid=93411a35.

King, Gary, Michael Tomz, and Jason Wittenberg. 2000. "Making the Most of Statistical Analyses: Improving Interpretation and Presentation." *American Journal of Political Science* 44 (2):341-355.

Puente, Luis Felipe. 2017. ⚡ #Actualización. edited by @LUISFELIPE_P: Twitter.

Segev, Tchelet. 2015. "Hope for a Rainy Day: The Case of Isla Urbana's Rainwater Harvesting Systems." B.A. Undergraduate, Department of Urban Studies and Planning, Massachusetts Institute of Technology.

Simonsen, Sturle Hauge, Reinette (Oonsie) Biggs, Maja Schlüter, Michael Schoon, Erin Bohensky, Georgina Cundill, Vasilis Dakos, Tim Daw, Karen Kotschy, Anne Leitch, Allyson E Quinlan, Garry D Peterson, and Fredrik Moberg. 2014. Applying resilience thinking: Seven principles for building resilience in social-ecological systems. Stockholm Resilience Centre.

Sosa-Rodriguez, Fabiola S. 2010. "Impacts of Water-management Decisions on the Survival of a City: From Ancient Tenochtitlan to Modern Mexico City." *International Journal of Water Resources Development* 26 (4):675-687. doi: 10.1080/07900627.2010.519503.

Subramanian, Samanth. 2017. "India's Silicon Valley is Dying of Thirst." *WIRED*.

UNDP. 2019. "Goal 6: Clean water and sanitation." https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-6-clean-water-and-sanitation.html.

USAID. 2017. MEXICO – EARTHQUAKE: FACT SHEET #1, FISCAL YEAR (FY) 2017. edited by United States Agency for International Development.

USGS. 2017. Magnitude 7.1 Earthquake in Mexico. edited by U.S. Department of the Interior. The United States Geological Survey.

Werker, Eric. 2010. "Disaster Politics: International Politics and Relief Efforts." *Harvard International Review*.

White, Heather, Erica Fowler, and Peerakarn Karnchanapimolkul. 2018. Paper submitted for the completion of the Capstone Course at Northeastern University.

WHO, and UNICEF. 2017. "Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines."

Wood, Lisa, Paula Hooper, Sarah Foster, and Fiona Bull. 2017. "Public green spaces and positive mental health – investigating the relationship between access, quantity and types of parks and mental wellbeing." *Health & Place* 48:63-71. doi: 10.1016/j.healthplace.2017.09.002.

Wood, Lisa, Tya Shannon, Max Bulsara, Terri Pikora, Gavin McCormack, and Billie Giles-Corti. 2008. "The anatomy of the safe and social suburb: An exploratory study of the built environment, social capital and residents' perceptions of safety." *Health and Place* 14 (1):15-31. doi: 10.1016/j.healthplace.2007.04.004.

Worm, Janette, and Tim van Hattum. 2006. *Rainwater harvesting for domestic use*: Agromisa Foundation and CTA.