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Evaluation of the Performance of Rainwater Harvesting Systems for Domestic Use in Tlalpan, Mexico City

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Abstract

Rainwater harvesting (RWH) as an alternative means of providing water in domestic contexts, is viewed as an effective supply option worldwide. In Mexico City, the water situation is critical and the provision of water services to the population represents a formidable challenge for the city's water utilities. The main objective of this study is to evaluate the potential for RWH to supply domestic properties in Tlalpan, 1 of 16 delegations in the city with one of the highest percentages of homes unconnected to the distribution network. Results show RWH can meet 88% of household water demand during the 6 month wet season, with an annual saving of 55%. Modelling a World Health Organisation minimum demand of 20 l/p/d as a means of resilience management in the event of a water crisis, 6-month and annual savings were 99% and 80% respectively. The minimum tank size to achieve wet season savings of 90% was 6 m^3 in two precipitation bands and tank sizes of 13,000 – 17,000 L were sufficient in 3 out of 4 to prevent overspill. The report concludes RWH is a viable method of providing water in the south of the city and should be part of an integrated water management solution.

Keywords: Isla Urbana; Mexico City; Pipas; Rainwater Harvesting; Water Crisis; Water Supply.

1. Introduction

The issue of water scarcity is a significant and increasing threat to the environment, human health, development, energy security and the global food supply. Growing populations with increased wealth and consumptive behaviour, combined with current water management policies, will see the demand for water rise exponentially, while supply becomes more erratic and uncertain [1].

In Mexico, a country of 125 million people [2], the population quadrupled during the period 1950 to 2010. The migration was from mostly rural to predominantly urban areas with now more than 75% of the population living in urban zones, while the availability of water in the country during this time has been significantly reduced [3].

Mexico City suffers from multiple and inter-related problems regarding the quality and availability of its water supply, which so far the Government has failed in addressing adequately [4, 5]. It is the capital of the country and also one of the most vulnerable areas to water scarcity. Currently the water situation is critical, with projections to 2030 indicating that the availability of water per capita in the Valley of Mexico (where the city is located) is only going to get much worse, necessitating the search for additional, sustainable sources to help redress the problem now [6].

In addition to water scarcity; land subsidence as a result of aquifer overexploitation, inefficient water use, concerns about the reuse of wastewater in agriculture, low share of wastewater treatment, child mortality linked to gastroenteric diseases and limited cost recovery, are all problems which seriously affect the city [7]. As a result of the ageing infrastructure and land subsidence, the thousands of kilometers of primary and secondary pipes in the supply system

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leak almost 40% of the water they are tasked with distributing [7]. Government initiatives thus far been unable to keep up with repairing these leaks, which results in more water being pumped to meet the demand and further exacerbating the unsustainable feedback loop. Water policies have favoured large-scale infrastructure projects such as the Lerma-Cutzamala system, responsible for supplying the metropolitan area with approximately 31.4% of its water [8]. These solutions are incredibly energy intensive, equivalent to the entire energy demands of the nearby city of Puebla, as the water must be pumped 1000 m vertically over mountains before reaching the population of the metropolitan area [7].

Somewhat counter-intuitively, while Mexico City's residents lack access to water, the urban area also receives a significant amount of precipitation during the well-defined rainy season, from late May through to early October [9]. A United Nations Environment Programme [10] report advocated for the inclusion of rainwater harvesting as an important resource in water management policies and one that can reduce negative impacts on water-stressed basins. Studies globally have shown RWH is an effective means of augmenting existing supply capabilities and can produce significant water savings in various contexts all over the world [11-13].

In the Valley of Mexico, frustratingly from a RWH perspective, the rain that falls in the urban area is currently not valued or utilised to such an extent that it currently expels more rain water from the basin than it manages to recharge in the main aquifers [14]. The geography of the city, located on the flat bed of what was once a series of lakes, has no natural drainage outlet meaning that the rainwater does not flow into streams or rivers to replace surface and ground water sources. Only 10% [15] is estimated to find its way back to the aquifer while the remainder is collected in the drains, mixed with sewage and pumped straight out of the valley.

A unique feature of Mexico City compared to other global contexts where RWH has been adopted is that most of the residents already have an existing cistern or form of water tank at their property due to the year-round intermittent supply [16]. As this is generally the most expensive component of a RWH system, connecting this through an effective conveyance and filtering system could be an achievable solution. In light of the confirmed need to find additional water sources to supply the city, RWH should be a part of an integrated solution to the water crisis which is given serious consideration [4, 5].

1.1. Study Area

One of the delegations with the lowest connectivity to the network is Tlalpan located in the south of the city. Large parts of the delegation are peri-urban and contain many informal settlement areas where connection to centralised water distribution infrastructure is difficult. It has an estimated population of 646,715 and of the 175,983 private dwellings, 27.5% do not have access to piped water from the network inside their homes [17]. These communities must rely almost solely on water delivery trucks, colloquially known as pipas, for their supply. These pipas can either be a public or private service and the price range can vary greatly depending on government subsidy rate and the type and quality of vendor. Reliability and speed of service can also vary, with some households having to request another pipas delivery almost immediately after they have received one due to the slow turnaround time between request and delivery [18]. Safety is also a great concern as in the under-developed areas of the delegation; road quality is poor with surfaces and sizes insufficient for large and heavy vehicles trying to navigate to their delivery point. To date, publically available information on the pipas program is scarce or non-existent and no serious attempts have been made to evaluate how rainwater harvesting could help mitigate against reliance on these during the rainy season in Mexico City.

1.2. Objective

The main objective of this study then is to determine the amount of rainwater available throughout Tlalpan and subsequently the potential for RWH to meet potable water demand and mitigate against pipas reliance in the area. In addition, as cisterns are the most expensive component of a RWH system, the study will estimate the smallest tank size which will still provide 90% demand satisfaction during the rainy season. A method of estimating the tank size required to prevent any overspill during the rainy season is also presented.

For these objectives, the study will use systems designed and installed by Isla Urbana, a social enterprise based in Mexico City who has carried out a significant number of installations of RWH systems, particularly in the south of the city. Figure 1. shows a typical system as designed by Isla Urbana.

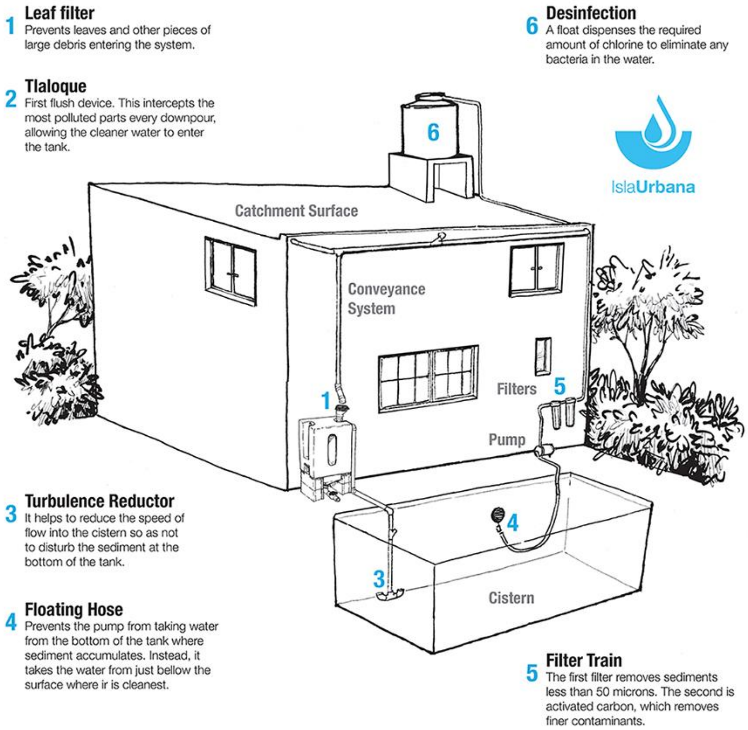


Figure 1. Typical RWH system as designed by Isla Urbana. The components as installed by Isla Urbana system are numbered 1-6 and the more general components labelled. Source: Author's compilation based on existing Isla Urbana graphic design

2. Method

To model the potential for RWH in Tlalpan where Isla Urbana has installed a number of systems, a survey of 1186 properties was carried out at the time of installation. The data was later analysed to ascertain information relating to catchment surface, number of occupants per household and tank size. The data was filtered to remove incomplete entries or properties that were non-domestic, leaving a sample size of 1034 properties. A further survey of 10 properties was carried out at a later date in Tlalpan to ascertain a figure for average potable water demand per person per day.

The properties, within their colonias (neighbourhoods), were approximately divided into four precipitation bands relating to their location and proximity to the four weather stations based on data mapped in Google Maps. From here, the data was filtered to obtain averages for the different inputs for each precipitation band: rainfall data; catchment surface; runoff and filter coefficient; average household occupancy and tank size.

To model the system performance and to determine the ideal rainwater tank capacity, a computer model developed by Ghisi, Tres & Kotani [19] called Netuno was used. This tool has previously been applied in the south-east of Brazil to estimate the potential for water savings using RWH. Information about its validation can be found in Rocha [20]. The model takes into account daily rainfall data, catchment surface, household water demand, number of people per dwelling, coefficient for losses and tank size.

2.1. Rainfall Data

Daily rainfall data was obtained from the National Water Commission (CONAGUA), across four weather stations in Tlalpan: Calvario 61; Al Pedregal; Ajusco and El Guarda. Figure 2. shows the different precipitation bands within Mexico City and the approximate location of the weather stations within Tlalpan. Figure 3. shows a satellite view of Tlalpan, with the urban and peri-urban areas visible. The daily rainfall data ranged from 1961-2008 but did not cover the same period for all stations and some records were missing, meaning consecutive daily data was not possible for all of this period. To include change in precipitation due to climate change, it was decided to only include the most recent 20 years (El Guarda, 15 years) where full daily rainfall data was available.

Figure 2. Precipitation bands of the Federal District with the sixteen delegations labelled.

(Tlalpan is in the south of the city, with four different precipitation bands visible. Source: Author's compilation based on existing Isla Urbana graphic design)

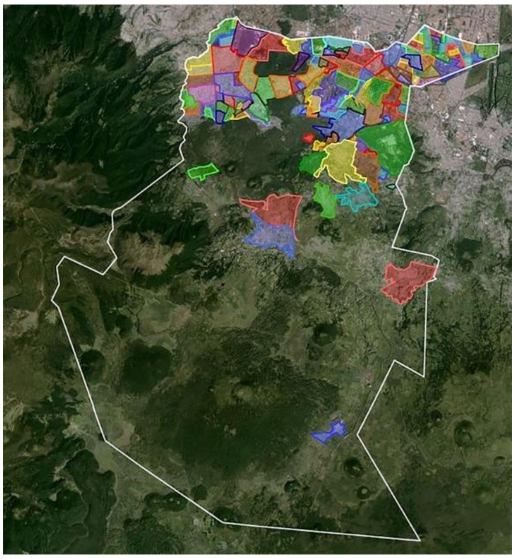


Figure 3. Satellite image of Tlalpan delegation in the south of the city.

(The Al Pedregal precipitation band in the north is the most urbanised zone, generally with better connection to grid water. As we move further south to the Ajusco and El Guarda precipitation bands, the numbers of properties connected to the grid is reduced. Properties in these bands rely most on water from the pipas trucks. Source: Map of colonies of the Delegation)

2.2. Catchment Surface

Values were obtained for average catchment surfaces across the properties within the different precipitation bands. It is important to note that the initial survey of 1034 properties only included the catchment surface where the RWH system was installed and not the total roof area available to the property. The modelled results therefore could underestimate the potential for water savings which a property could achieve.

2.3. Average Number of People per Dwelling

The modal number of people per dwelling was calculated for each precipitation band from the properties surveyed.

2.4. Coefficient for Losses

The coefficient for losses takes into account water losses between the roof and cistern, including evaporation and first flush. In the literature, values for roof runoff coefficients used in modelling typically range from 0.7-0.95 [21] In a study carried out by KANRRC [22] it was suggested that roof absorption losses dominated for rainfall events less than 3 mm, resulting in a low runoff coefficient. Roof material was therefore included in the survey and any day with less than 3 mm rainfall was taken as a zero precipitation day.

2.5. Tank Size

From the survey in Tlalpan, the median tank sizes (lower tank) across the precipitation bands were calculated to model current average hydraulic performance. No data was available on the size of the roof tanks and so these were not included in the model.

2.6. Water Availability

The total volume of rainwater V available for capture in each precipitation band was estimated using Equation 1. where: R equals monthly rainfall amount; an average roof size and R_c runoff coefficient.

$$V = R \times A \times R_c \quad (1)$$

2.7. Water Demand

This study assumes a single value for water demand for daily time-steps, as applied by a number of similar studies [12, 23]. In addition, the study assumed that water from the cistern was only used for internal purposes. Rainwater demand was modelled as 100% of potable water demand, i.e. it is used for all internal purposes. It should also be noted again that this investigation for potable water savings is primarily for houses which are unconnected to the main water network or have extremely intermittent supply (1-2 days a week) and rely largely on pipas. They therefore are extremely conscientious and efficient water users (using informal greywater systems to flush toilets etc.) and so demand is typically lower than for properties in other parts of the city where water availability is much greater. Tortajada [7] refers to 20 litres per capita per day as being typical in some of the poorer areas of Mexico City, and which the World Health Organisation (WHO) quotes as a minimum to meet a person's basic cooking and hygiene needs.

This was taken into consideration before carrying out a water demand survey of 10 properties within the Ajusco and Al Pedgreal precipitation bands, which represent peri-urban and urban areas respectively. Participants were asked three different questions relating to their demand: 1. How long it took them to use all the water in their cistern? 2. How frequently they had to request a pipas delivery? 3. How often they used their pump to supply their roof tank per week? In this way, it is possible to obtain three values for water demand which participants estimate they use and from this, take an average to obtain one more reliable figure for the water demand. The figure could then be divided by the number of people living at the property to discern a figure for the daily amount of litres used per person (l/p/d). Participants were also asked if they used the water for any external uses, to test the assumption that water is solely for internal end-uses.

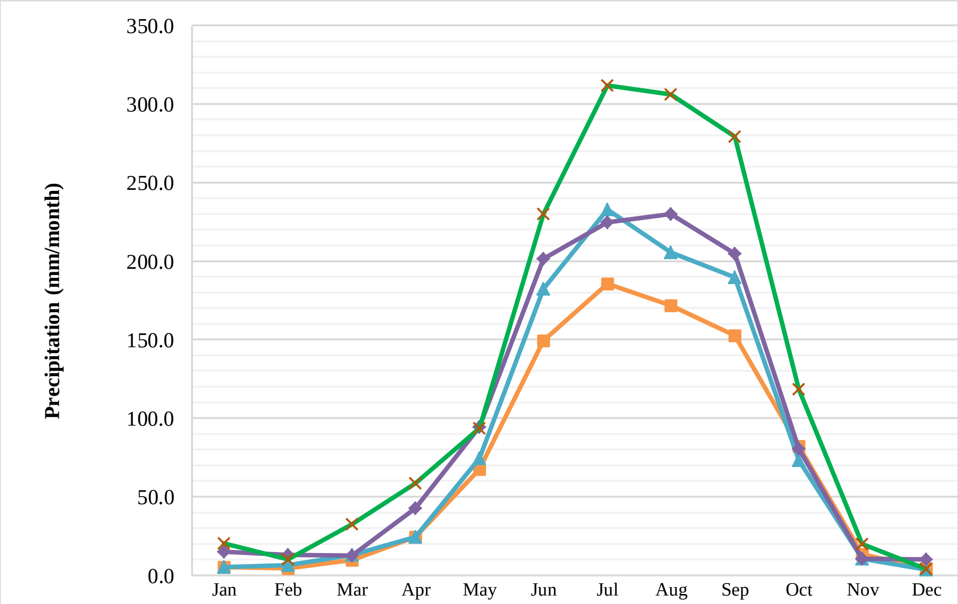
2.8. Ideal Tank Size

As Mexico City has a rainy season approximately 6 months in length, it was deemed most pertinent to calculate the smallest possible tank size which will still give a demand satisfaction of 90% over the 6 months June to November. In this way performance can be balanced with cost, as cisterns are generally the most expensive component of the system.

3. Results

3.1. Rainfall Data

Figure 4. shows that across the four weather stations there is a large amount of rainfall available, ranging from 870 mm per year in Calvario 61 to 1484 mm per year in El Guarda. This represents a 52% difference within the delegation, justifying the need to divide the delegation into precipitation bands.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Calvario 61	5.0	4.3	9.9	24.2	67.3	149.3	185.7	171.6	152.8	82.2	13.3	4.5
Al Pedregal	5.1	6.6	12.8	24.5	74.6	182.2	232.8	205.6	189.8	73.0	10.5	3.6
Ajusco	14.8	12.8	12.7	42.6	94.3	201.3	224.5	229.8	204.8	80.5	10.7	10.1
El Guarda	20.3	10.2	32.5	58.7	93.4	229.9	311.6	305.9	279.2	118.4	19.8	4.1

Figure 4. Monthly rainfall of the four weather stations in Tlalpan

A summary of the different inputs within the four different precipitation bands is summarised in Table 1.

Table 1. Summary of hydraulic details

Weather station	Sample size	Rainfall (mm/yr)	Catchment surface (m^2)	No. of people per household	Tank size (m^3)	Runoff & filter coefficient[a]
Calvario 61	333	870	60	5	10	0.72
Al Pedregal	416	1021	60	5	8	0.72
Ajusco	272	1139	55	4	10	0.72
El Guarda	13	1484	70	5	12	0.72

[a] Based on the properties surveyed, concrete slabs are the most common roof material in Tlalpan, which has a high runoff coefficient compared to other roof materials. A value therefore of 0.80 and 0.90 was chosen to account for roof and first-flush losses and filter losses respectively

3.2. Water Availability

Table 2. shows the monthly volume of rainwater that is available for each household to harvest based on the methodology already described and hydraulic details in Table 1.

Table 2. Average volume of rainwater that is available to harvest in each precipitation band

Month	Calvario 61		Al Pedregal		Ajusco		El Guarda	
	Rainfall (mm/month)	Volume (L)	Rainfall (mm/month)	Volume (L)	Rainfall (mm/month)	Volume (L)	Rainfall (mm/month)	Volume (L)
Jan	5	217	5	222	15	640	20	1022
Feb	4	188	7	285	13	553	10	514
Mar	10	427	13	553	13	549	32	1637
Apr	24	1043	25	1056	43	1838	59	2960
May	67	2907	75	3222	94	4074	93	4707
Jun	149	6452	182	7870	201	8695	230	11586
Jul	186	8020	233	10057	225	9698	312	15705
Aug	172	7415	206	8882	230	9926	306	15416
Sep	153	6599	190	8200	205	8847	279	14070
Oct	82	3551	73	3155	81	3479	118	5967
Nov	13	573	11	455	11	460	20	998
Dec	5	193	4	157	10	435	4	207
Total	870	37586	1021	44115	1139	49196	1484	74788

3.3. Potable Water Demand

Based on the 10 properties surveyed, water demand ranged from 22 l/p/d to 60 l/p/d with an average of 41 l/p/d, and no significant variation across the precipitation bands. In addition, all of the participants said the water was for internal end-uses only. It should be noted here the distinction between the total daily water demand and what is actually drawn from the cistern (which should be less). As explained previously, occupants in these underserved areas typically use informal greywater systems such as water collected from the shower to wash clothes, with this collected again and used to flush toilets. In this way, occupants may be using more than the figures listed above (as they recycle the water), but what they actually draw from the cistern ranges between 22 – 60 l/p/d. In this context, system performance was modelled across the bands for potable water demands 41 and 60 l/p/d representing expected and high daily consumption amounts respectively. In addition, a demand of 20 l/p/d was modelled representing the low demand as surveyed and in accordance with the WHO minimum amount to meet basic cooking and hygiene needs. This was modelled to see the potential for RWH in times of severe water crisis as part of a possible resilience management strategy in the city.

3.4. Potential for Potable Water Savings

An estimate for potential for potable water savings was estimated by comparing the monthly volume of rainwater that could be harvested with the different potable water demands in each of the precipitation bands. Figures 5 and 6. show the potential for potable water savings for 41 l/p/d and 60 l/p/d demand. The average annual volumetric savings for 41 l/p/d demand was 55%, with a range 45% to 66% in Calvario 61 and El Guarda respectively. Significantly though, during the six wet months June to November, average savings of 88% could be observed across the four precipitation bands for this demand. This indicates that under current conditions, RWH can effectively supply a household their entire water needs for the whole wet season. When the demand was increased to 60 l/p/d, the annual and 6-month average potential savings fall to 43% and 73% respectively across the regions.

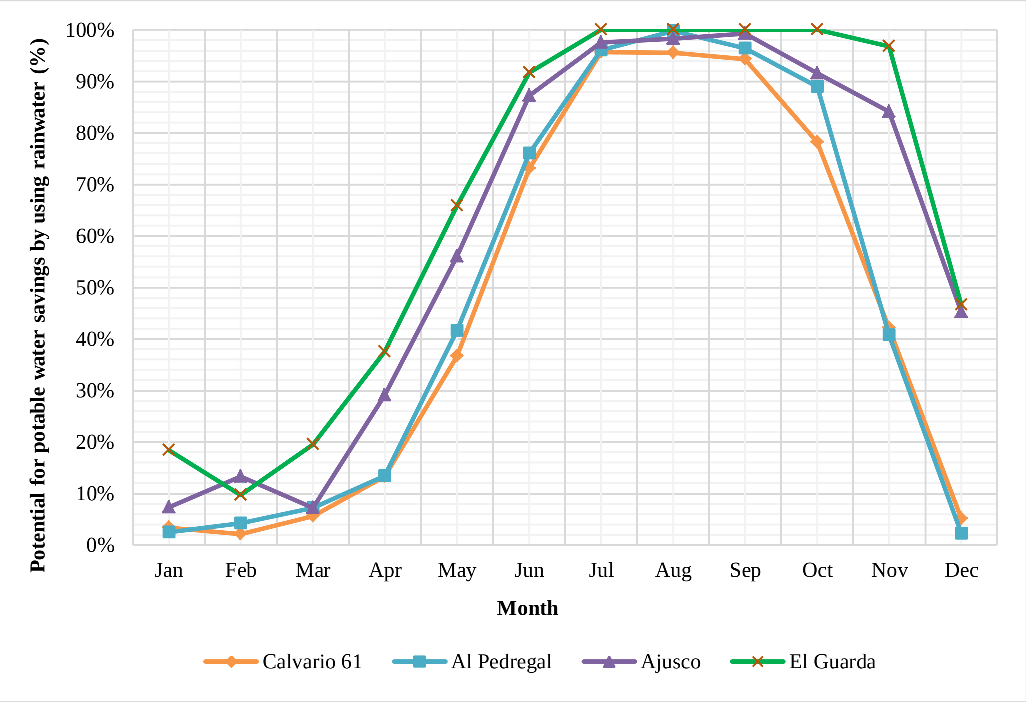


Figure 5. Potential potable water savings 41 l/c/d

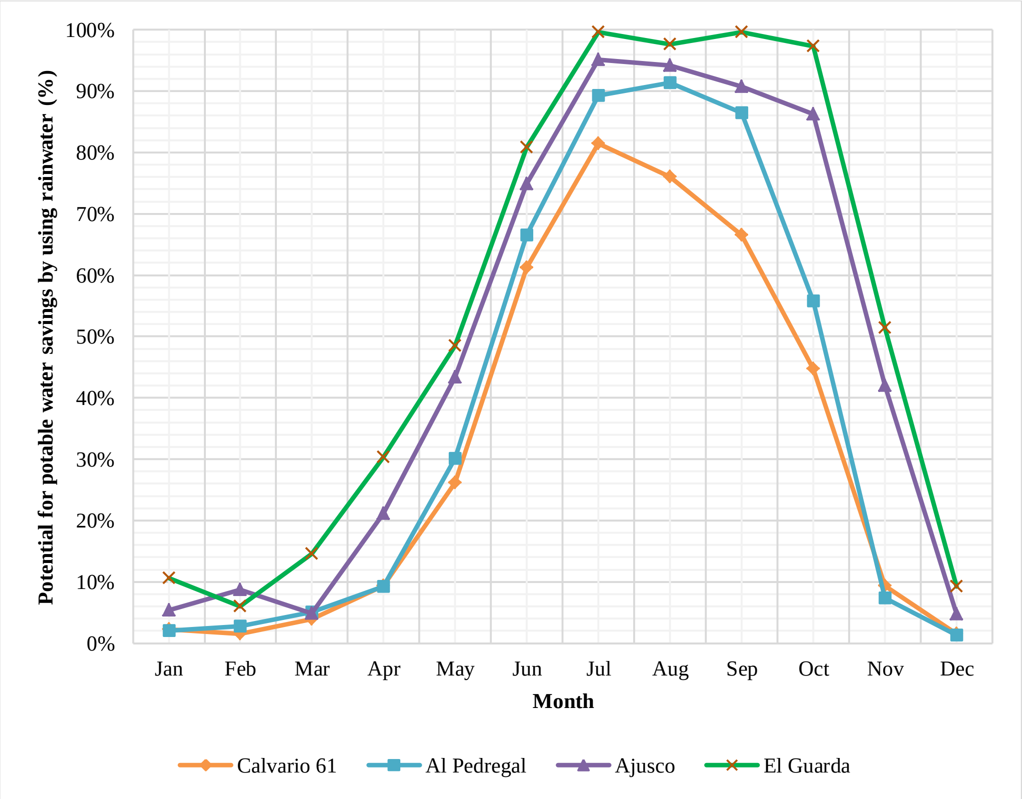


Figure 6. Potential potable water savings 60 l/c/d

3.5. Potential for Potable Water Savings Including Overspill

During the wet months, the results showed significant overspill at these demands. Figures 7 and 8. show the results for water savings including the overspill. During the months June to November, El Guarda, Ajusco and Al Pedregal spilled on average approximately 42% of the water they could have potentially captured at 41 l/p/d demand. During the three wettest months of the year (Jul – Sep), potential for water savings including overspill ranged from 241% in El Guarda to 108% in Calvario 61, with an average of 186% across El Guarda, Ajusco and Al Pedregal. During these wet months therefore, properties in these bands could increase their consumption in line with the water which is available to them.

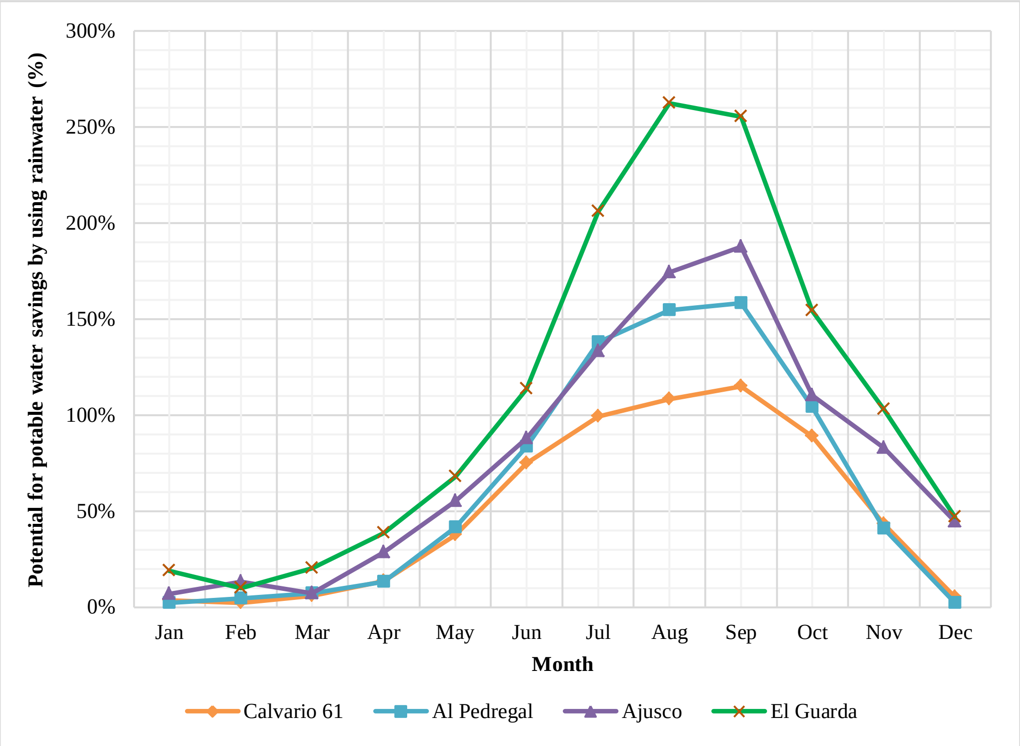


Figure 7. Water savings including overspill 41 l/c/d

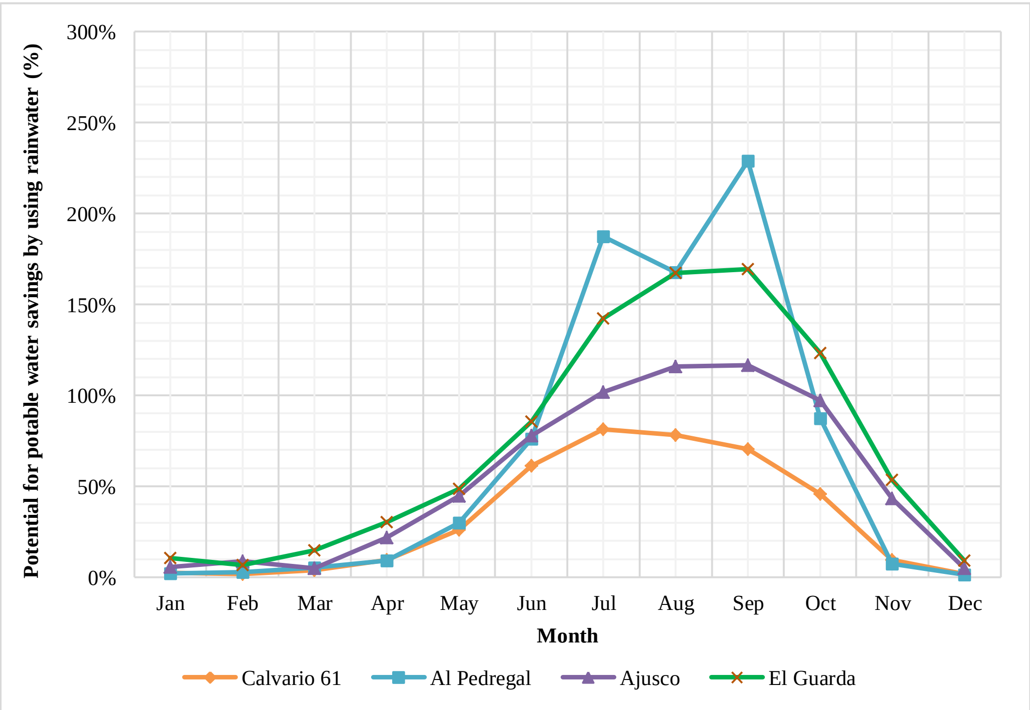


Figure 8. Water savings including overspill 60 l/c/d

3.6. Resilience Management

Figure 9. shows the results for a demand of 20 l/p/d and Figure 10. the water savings including overspill. The 6-month average potential for water savings across all bands was 99%. Significantly for this demand, annual averages ranged from 72% in Calvario 61 to 89% in El Guarda, with an average of 80% across all bands, meaning households can almost go an entire year solely on rainwater at this demand with existing average tank sizes and catchment surfaces.

As Figure 10. shows, at this demand households will be spilling a significant amount during the wet months and so it would not be necessary to manage consumption to such a low level for the entire year.

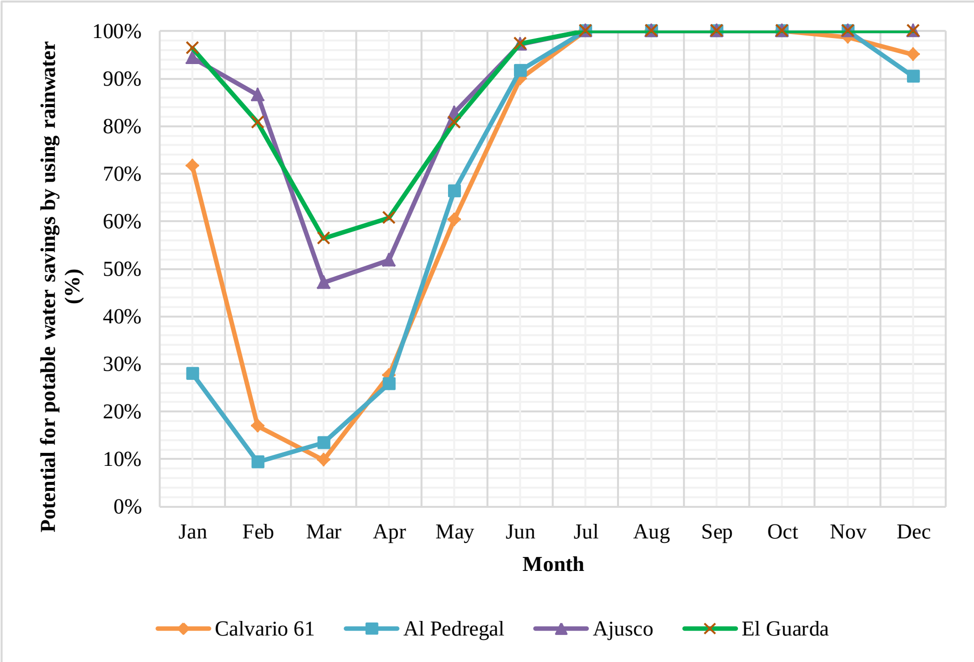


Figure 9. Potential potable water savings 20 l/c/d

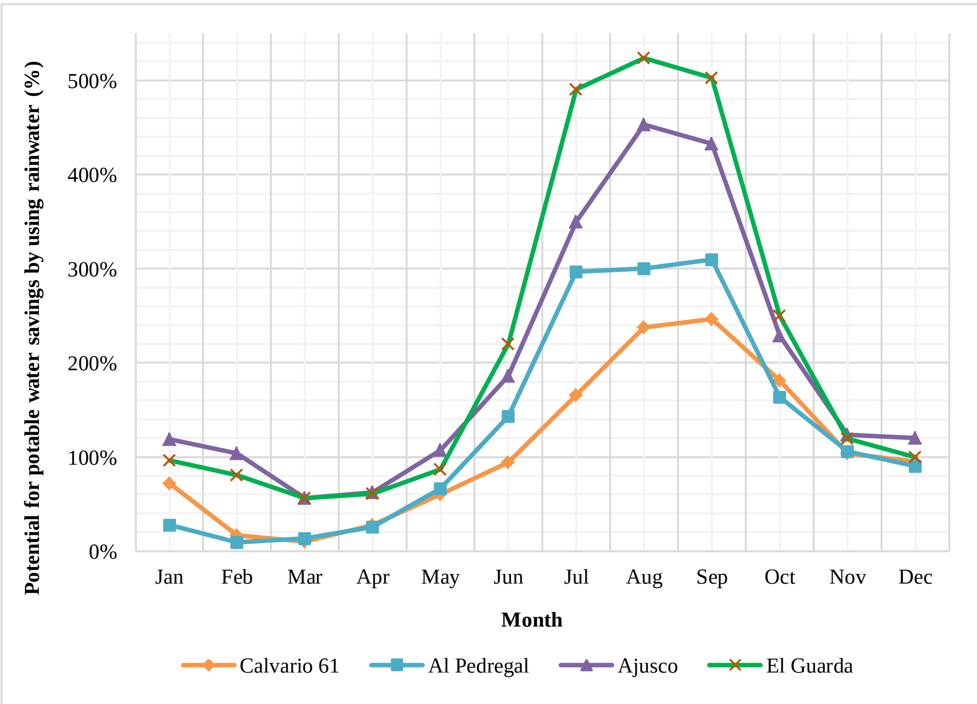


Figure 10. Water savings including overspill 20 l/c/d

3.7. Rainwater Tank Size

Ideal rainwater tank capacities to maximise performance were determined for households in the different precipitation bands, across the expected demand of 41 l/p/d using the computer simulation Netuno. Tank sizes were modelled between 5 m^3-15 m^3 representing the smallest tank size Isla Urbana install (if there is not an existing one) and the maximum commercially available size from a leading supplier. Figure 11. shows the 6-month average potential potable water savings for the expected demand of 41 l/p/d, across the precipitation bands with the 90% satisfaction line displayed. As can be observed, for the bands Ajusco and El Guarda, 6-month average savings of 90% with a tank size of 6 m^3 can be achieved. This is entirely achievable when we consider that this tank size is lower than the existing average cistern size in households as obtained in Table 1.

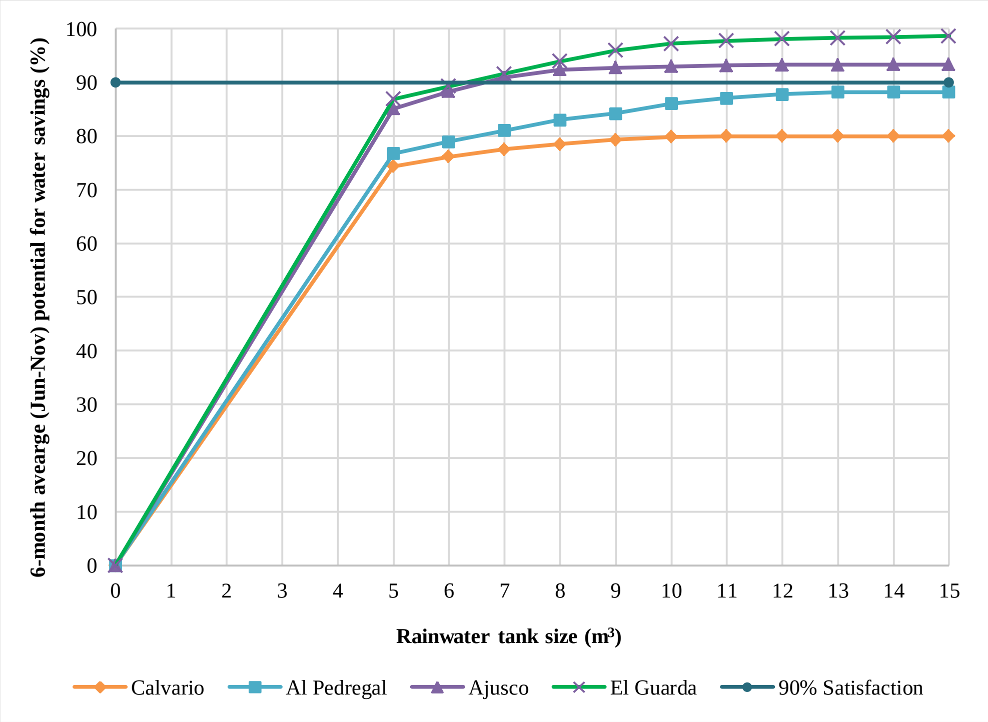


Figure 11. 6-Month average potential potable water savings with varying tank sizes

Given the significant amount of overspill observed in the results, it was deemed salient to investigate the tank size which would be sufficiently large to prevent any overspill so that all water could be (in theory) captured during the rainy season. As demand is a factor in overspill, the calculation assumes households will increase their demand to the higher limit of 60 l/p/d during the rainy season. From this, the tank sizes were increased in intervals of 1,000 L beginning from a 10,000 L tank (Figure 12.), until no overspill was observed as a function of captured rainwater. Due to the significant rainfall in the El Guarda band, a tank size of 20,000 L was still not sufficient to prevent any overspill at this demand. Tank sizes of 13,000-17,000 litres in the other bands were sufficient to prevent any overspill and wastage of water.

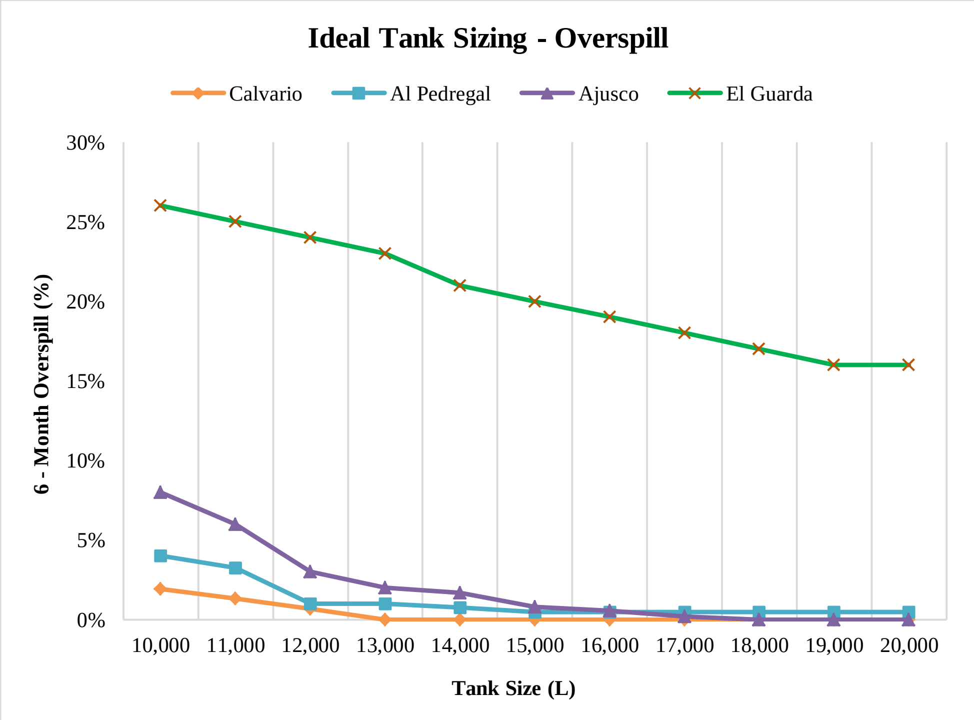


Figure 12. Tank sizes to prevent overspill

3.8. Potential for Rainwater Harvesting to Mitigate Reliance on Pipas

Assuming it is possible to install a RWH system in the 27.5% of homes in Tlalpan with no piped water inside their homes, it was estimated how many litres of water could be harvested and how many pipas trucks this would keep off the road in the entire delegation over a ten year analysis period. No data was available on the percentage of homes in each precipitation band with no access to piped water, so an average of the different inputs (Table 3) across the precipitation bands was deemed appropriate to model the whole delegation. When the figures were tested through the model, annual potable water savings of 55% and 6-month savings of 90% could be observed, with the total annual volume of water harvested 41m^3. Taking 27.5% of the 175,983 domestic homes in Tlalpan with no access to piped water inside of their homes, leaves 48,395 unconnected households. If each of these had an average RWH system as above, they could collectively harvest 1,979,300 m^3 (1m^3 = 1000 L) of water annually, with ten years savings of 19,793,000 m^3. The average number of people per household is 5 as above, meaning RWH systems could benefit almost a quarter of a million people if they were installed. In terms of savings in pipas journeys, taking the average delivery amount as one tank full i.e. 10 m^3 as above, over a ten year period, almost 2 million pipas could be kept off the road. This is a hugely significant figure from just one delegation when the issues of pollution, greenhouse emissions relating to pollution and road safety which affect the city are considered.

Table 3. Average of the hydraulic details across the precipitation bands

Input	Value
Rainfall	Ajusco
Roof area (m^2)	60
Tank size (L)	10000
No. of people per household	5
Runoff Coefficient	0.72
Demand (l/p/d)	41

3.9. Sensitivity Analysis

A sensitivity analysis was carried out to ascertain the effect of the four key variables on the annual yield in each precipitation band. As the distribution of the data was known, low and high values were taken as a standard deviation either side of the mean or median values (depending on the measure of central tendency used). The base case annual yield was estimated using the average values already obtained from Table 1. in each precipitation band. Each variable was then individually set to the corresponding high and low estimates to develop the ‘tornado chart’ (Figure 13). The sensitivity of the results to changes in each variable could then be individually identified. Each band showed different sensitivity to the various variables. Roof area and number of occupants were two characteristics in each band which showed large variation in yield when the values were adjusted from low to high around the base case (all other variables were held constant). In the worst performing areas (Al Pedregal and Calvario 61), an increase in roof size of 18 m^2 and 20 m^2 could increase the yield by 28% and 48% respectively. Given that the original survey included only connected roof area and not total roof area, it is possible households in these bands could potentially avail of these extra potential water savings if all the roof was connected.

3.10. Discussion

3.10.1. Current RWH Policies in Mexico City

Currently, the Mexico City water authority SACMEX, has not invested in any large-scale rainwater harvesting programme, either for domestic rooftop harvesting or aquifer recharge. This is despite the Water Law of 2003 which calls for rainwater harvesting to be installed in new buildings and encourages its implementation in existing constructions [24]. Rainwater was also included in the Law for Climate Change Adaptation and Mitigation of 2012 but has yet to materialise into a structured RWH implementation plan. Existing literature and accepted opinion on the water situation in Mexico City has acknowledged the fact that the "availability of water has already reached its maximum viable point in spite of all technological innovations and large infrastructure development" [4]. One of the most common disadvantages cited globally against RWH is the significant space requirement for the storage tank [25]. However, in Mexico City where the majority of the population already own a cistern, this is less of an issue and presents the city with a unique, currently unexploited opportunity.

3.10.2. Comparison of RWH Policies throughout the World

In Brazil, the government has launched several rainwater harvesting programs for small-scale and domestic agriculture. Around 700, 000 cisterns have been built for this purpose in semi-arid regions of the country [26]. A study by Ghisi et al. [12] in south-eastern Brazil, found RWH to be a potentially very significant source of water to meet the demand. In Australia, rainwater harvesting is commonplace with many state governments making them mandatory in new housing developments [11, 27]. In Germany, local governments in many towns award grants and subsidies for construction of rainwater tanks and seepage wells [28]. In countries with less water availability such as Spain, RWH is being looked at as an option although uptake so far has been slow. Morales-Pinzón et al. [29] found RWH to be undervalued in Cataluña, Spain where systems have only been installed in low density areas and in individual houses. In Singapore, RWH schemes have included high-rise buildings, airports, and integrated systems using the combined run-off from industrial complexes, aquaculture farms and educational institutions [28]. In India, rooftop rainwater harvesting systems are now compulsory for new buildings in 18 of India's 28 states and four of its seven federally-administered union territories [30].

3.10.3. Opportunities for Future Study

The ideas and methods presented in this study can be used in similar contexts throughout the Mexico City metropolitan area and further studies may look to carry out a larger survey of water demand, breaking it down at a Delegational level as currently figures range from 20-600 L [7] which make it difficult to scale-up and estimate the potential to supply demand across the city. The authors also recommend additional studies into the potential for RWH to offset aquifer overexploitation if implemented on a much larger scale, in both domestic and commercial contexts. There also exists fertile ground for research into the potential for RWH to delay the construction of further large-scale infrastructure projects (extending the Cutzamala system for example) and for its ability to mitigate against flooding in high-risk areas.

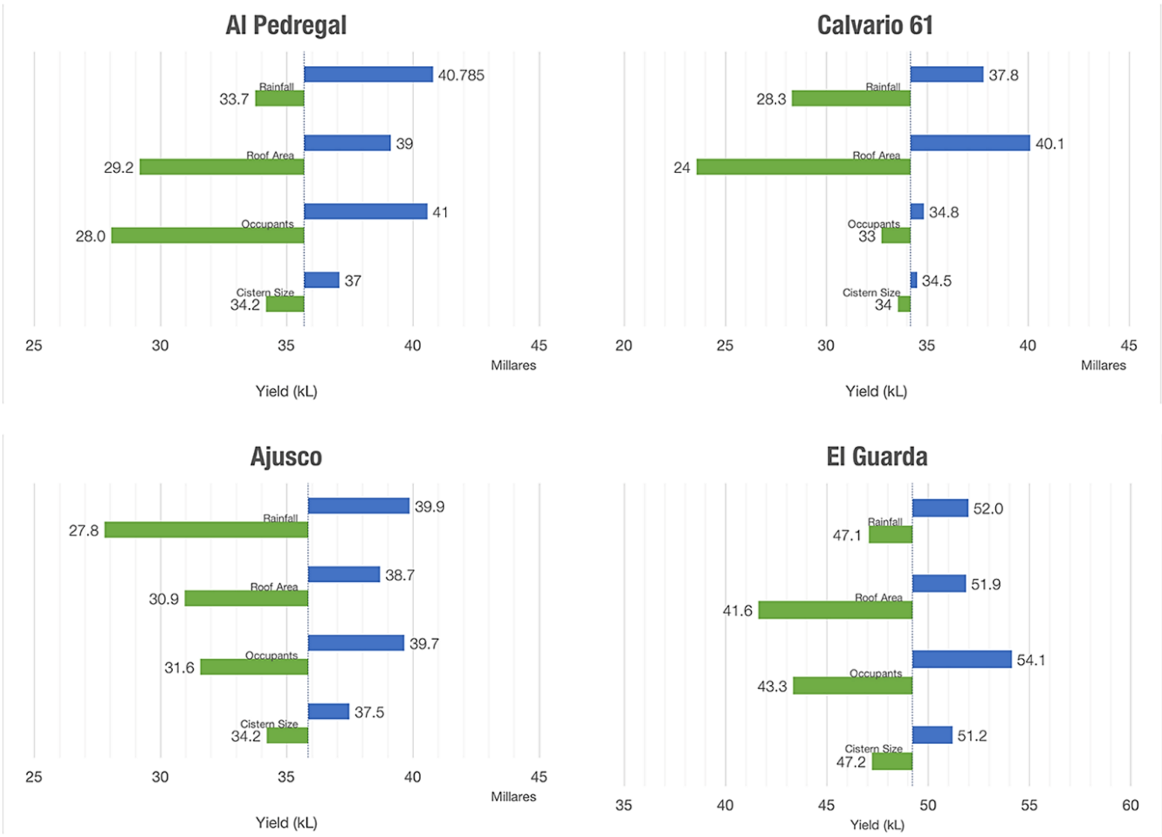


Figure 13. Annual yield varied by key factors

4. Conclusion

The availability of water for households in some areas of Mexico City is severely limited, with families unconnected to the network having to rely on pipas for delivery. In Tlalpan, where there is a high percentage of people not connected to the network, the potential for potable water savings by using rainwater was assessed across different precipitation bands. Results of the research performed indicate there is a large amount of annual rainfall available in the delegation, ranging from 870-1484 mm, with significant variation in amount across areas. The average 6-month saving for the expected and above average demands of 41 and 60 l/p/d across the bands was 81%. The annual saving across the bands and demands was 49%. The overspill graphs showed that demand could be increased during the wetter months. A tank size of 6 m^3 could still provide 90% of potable water to families in two of the bands during the wet months. The report also found that large-scale implementation of RWH could positively impact a large number of people in Tlalpan and dramatically reduce the need for pipas, resulting in much fewer journeys made per year, helping with traffic, safety and pollution issues in the city.

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6. References

[1] World Bank. High and Dry: Climate Change, Water, and the Economy. World Bank, Washington, DC. (2016).

[2] Consejo Nacional de Población (CONAPO). (2010). Proyecciones De La Población 2010 - 2050. [Projection of the Population 2010 – 2050].

[3] Comisión Nacional del Agua (CONAGUA). (2010). Statistics on Water in Mexico. 2010 Edition, 1-15.

[4] Delgado-Ramos, Gian Carlo. "Water and the political ecology of urban metabolism: the case of Mexico City." Journal of Political Ecology 22, no. 9 (2015).

[5] Jiménez, Blanca. "The unintentional and intentional recharge of aquifers in the Tula and the Mexico Valleys: The Megalopolis

needs Mega solutions." In Rosenberg Symposium, Buenos Aires, Argentina. 2010.

[6] SEMARNAT. (2012). Informe de la situación del medio ambiente en México [Report of the situation of the environment in Mexico]. Retrieved from http://app1.semarnat.gob.mx/dgeia/informe_12/06_agua/cap6_1.html.

[7] Tortajada, Cecilia. "Water management in Mexico City metropolitan area." Water Resources Development 22, no. 2 (2006): 353-376. doi.org/10.1080/07900620600671367

[8] Romero Lankao, Patricia. "Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities?." Environment and Urbanization 22, no. 1 (2010): 157-178. doi.org/10.1177/0956247809362636

[9] Magaña, Víctor, Joel Pérez, and Matías Méndez. "Diagnosis and prognosis of extreme precipitation events in the Mexico City Basin." GEOFISICA INTERNACIONAL-MEXICO- 42, no. 2 (2003): 247-260.

[10] Barron, Jennie. Rainwater harvesting: a lifeline for human well-being. UNEP/Earthprint, 2009.

[11] Coombes, Peter J., John R. Argue, and George Kuczera. "Figtree Place: a case study in water sensitive urban development (WSUD)." Urban Water 1, no. 4 (2000): 335-343. doi.org/10.1016/S1462-0758(00)00027-3

[12] Ghisi, Enedir, Diego Lapolli Bressan, and Maurício Martini. "Rainwater tank capacity and potential for potable water savings by using rainwater in the residential sector of southeastern Brazil." Building and Environment 42, no. 4 (2007): 1654-1666. doi.org/10.1016/j.buildenv.2006.02.007

[13] Hajani, Evan, and Ataur Rahman. "Reliability and cost analysis of a rainwater harvesting system in peri-urban regions of Greater Sydney, Australia." Water 6, no. 4 (2014): 945-960. doi.org/10.3390/w6040945

[14] Labadie, J.L, Valdivia, J.M., Sánchez, A.G., Hermosillo, O.M., Orozco, M.F., Llana, C.V.P., Barragán, P.M. Repensar La Cuenca: La Gestión De Ciclos Del Agua En El Valle De México, 1, no. 1 (2010): 1–26.

[15] Burns, E. "¿De Dónde Vendrá Nuestra Agua?" Guía hacia la Sustentabilidad en la Cuenca de México. Guardianes de los Volcanes y Fondo Mexicano para la Conservación de la Naturaleza. México, Comisión Ambiental Metropolitana-Programa, UAM. (2006).

[16] Instituto Nacional de Estadística y Geografía [Institute of Nacional Statistics and Geography] (INEGI) (2010a). Retrieved from http://www3.inegi.org.mx/sistemas/sisept/default.aspx?t=mamb287&s=est&c=32905

[17] Instituto Nacional de Estadística y Geografía (INEGI) (2010b). Panorama sociodemográfico del Distrito Federal [Socio-Demographic Outlook of the Federal District]. Retrieved from http://documents.mx/documents/delegaciones-panorama-df.html.

[18] Isla Urbana. (2015). Encuestas de Seguimiento en la delegación Tlalpan [Questionnaire in the delegation Tlalpan]. August 2015.

[19] Ghisi E, Tres ACR, Kotani M. Netuno—aproveitamento de aguas pluviais no setor residencial [Neptune—a computer programme to evaluate potable water savings and rainwater tank capacity in the residential sector] (In Portuguese). (2004).

[20] Rocha, V.L. Validação do algoritmo do programa Netuno para avaliação do potencial de economia de água potável e dimensionamento de reservatórios de aproveitamento de água pluvial em edificações. (2009). [Validation of the Algorithm of the Netuno Computer Programme to Assess the Potential for Potable Water Savings and Sizing of Rainwater Tanks for Rainwater Usage in Buildings]. Master's Dissertation. School of Civil Engineering, Federal University of Santa Catarina, Florianópolis, Brazil, 2009.

[21] Sharma, Ashok K., Donald Begbie, and Ted Gardner, eds. Rainwater Tank Systems for Urban Water Supply. Iwa Publishing, 2015. 1-18. doi.org/10.2166/9781780405360

[22] KRANRRC. Harvesting For Sustainable Water Resources Development and Climate Change Adaptation in an Arid Region (N-E of Iran), Khorasan Razavi Agricultural & Natural Resources Research Center and The Institute For Global Environmental Strategies. (2011).

[23] Palla, A., I. Gnecco, and L. G. Lanza. "Non-dimensional design parameters and performance assessment of rainwater harvesting systems." Journal of Hydrology 401, no. 1 (2011): 65-76. doi.org/10.1016/j.jhydrol.2011.02.009.

[24] Ley de Aguas Nacionales. (2003). [National Water Law].

[25] Islam, Kamal Ziaul, Md Sirajul Islam, Jean O. Lacoursière, and Lisa Dessborn. "Low cost rainwater harvesting: An alternate solution to salinity affected coastal region of Bangladesh." American Journal of Water Resources 2, no. 6 (2014): 141-148. doi.org/10.12691/ajwr-2-6-2

[26] Heijnen, H. Enhancing economic resilience in North Eastern Brazil by harnessing rain. Rainwater Harvesting Implementation Network (RAIN), Amsterdam. (2013).

[27] Associates, M. J. (2007). The cost-effectiveness of rainwater tanks in urban Australia. Waterlines (Vol. 2008).

[28] Rainwater Harvesting Organisation. Rainwater Harvesting in Germany. Centre for Science and Environment. (2017).

[29] Morales-Pinzón, Tito, Rodrigo Lurueña, Joan Rieradevall, Carles M. Gasol, and Xavier Gabarrell. "Financial feasibility and environmental analysis of potential rainwater harvesting systems: A case study in Spain." Resources, Conservation and Recycling 69 (2012): 130-140. doi.org/10.1016/j.resconrec.2012.09.014

[30] Walton, B. India Cities Focus on Rainwater Harvesting to Provide Clean Drinking Water. Circle of blue. (2010).