Stochastic modelling of the hydraulic performance of an onsite rainwater harvesting system in Mediterranean climate

H. Muklada, Y. Gilboa and E. Friedler

ABSTRACT

The performance of onsite rainwater harvesting (RWH) system in Mediterranean climate was assessed. A stochastic model quantifying the necessary storage, as a function of rainfall (frequency, depth), roof area, residents' number, specific water use (toilet flushing, laundry) and the required efficiency was developed. Two performance indicators were calculated: water saving efficiency (RSE) – proportion of water used supplied by the RWH system; and rainwater use efficiency (RUE) – proportion of rainwater actually used. The maximum storage capacity and WSE decreased with increasing number of residents for a given roof area, and with an increasing roof area for constant number of residents. For variable storage volume, RUE increased with increasing storage capacity and reached a maximum with an increase in residents' number and a decrease in the roof area. The model enables to determine WSE and RUE for specific storage volumes or to determine the desired WSE and calculate the necessary storage.

Key words | alternative water source, Mediterranean climate, rainwater harvesting, stochastic modelling, water saving

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INTRODUCTION

Onsite rainwater harvesting (RWH) is an ancient method which served as an alternative source of water in many places in the Middle East and all around the world. However, with the establishment of central water supply systems, the use of onsite RWH systems has generally stopped. Today due to increased water shortage on one hand, and urban flooding on the other, there is a renewed interest in onsite RWH. Interest in onsite RWH extends from water-scarce regions where the motivation is increasing the amount of available water, to water-ample ones where the motivation is primarily prevention and reduction of urban runoff as well as environmental awareness.

RWH has been acknowledged as a potential source to supply water and to promote significant potable water savings (Ghisi *et al.* 2007; Gires & de Gouvello 2009). Rainwater, which is a renewable freshwater source, may be used in various non-potable applications at the household level in urban areas. Rainwater, being the main source of freshwater in both natural and human-managed ecosystems, has significant untapped potential for being harvested (Umapathi *et al.* 2013). Numerous studies investigating the harvested rainwater quality were conducted in Australia, Canada, Denmark, Germany, India, Japan, Spain, New Zealand, Thailand, and the United States (Uba & Aghogho 2000; Evans *et al.* 2006; Despins *et al.* 2009; Jones & Hunt 2010; Farreny *et al.* 2011). However, less information and clear definition on rainwater tank sizing are available (Ghisi 2010; Ward *et al.* 2010, 2012; Campisano & Modica 2015). The correct tank sizing is important in order to avoid extra costs when the tank is oversized and low efficiency when it is undersized. Several tools were developed for estimating the required tank size and to predict the system performance. For instance, Jenkins *et al.* (1978) developed two behavioral algorithms to describe the operation of a RWH system during a given time interval. The

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first algorithm is yield after spillage (YAS), where the amount of water provided by the rainwater collection system, in which the withdrawal occurs after the rainfall has been added to the storage facility and spillage, has been determined. Whereas the second, yield before spillage (YBS) algorithm, assumes that the demand is withdrawn before spillage is determined. Mitchell (2007) investigated the impact of these two computational operating rules and reported that the YAS operational rules underestimated yield and volumetric reliability for a given set of storage, while the YBS operational rule produced an overestimate. Therefore, the author recommended using the YAS operating rule in preference to the YBS, as its estimates are less sensitive to variations in storage and provide conservative values for yield and volumetric reliability. Fewkes (1999) used collected data to verify and refine a rainwater collection sizing model based on the YAS algorithm. The refined model was used to develop a series of dimensionless design curves relating collection area, water demand, rainfall level, system efficiency and storage volume. Fewkes & Butler (2000) evaluated the accuracy of behavioral models, for the sizing of rainwater collection systems using different time intervals and different reservoir operations. Villarreal & Dixon (2005) generated a computer model to quantify the water saving potential of rainwater collection by analyzing the water saving efficiency (WSE). The analysis of several scenarios allowed the authors to suggest suitable sizes of rainwater tanks. Khastagir & Jayasuriya (2010) presented a methodology for optimal sizing of rainwater tanks considering the annual rainfall at the geographic location, the demand for rainwater, the roof area and the desired supply reliability. Ghisi (2010) analyzed the influence of rainfall, roof area, number of residents, potable water demand and rainwater demand on rainwater tank sizing, by using computer simulations. The author indicated that rainwater tank sizing for houses must be performed for each specific situation, i.e., considering local rainfall, roof area, potable water demand, rainwater demand and number of residents. Raimondi & Becciu (2014) who estimated the tank size by using an analytical probabilistic approach showed that the probability of complete rainwater use strongly depends on the period of regulation.

The objective of this study was to develop a novel stochastic model to estimate the optimal rainwater tank size depending on specific demand for rainwater, number of residents and the catchment size (roof area), when the daily rainfall at the location area was considered as the stochastic parameter. Daily rainfall was taken from historical data, and probability functions were derived for each calendar day. The model was developed for Mediterranean climate (Haifa, Israel), characterized by long dry summers (literally) and winters with highly variable rainfall patterns. Nevertheless, a similar methodology may well be implemented to other climatic regions.

MATERIALS AND METHODS

Study site

Daily rainfall data were taken from Haifa Port meteorological station, located 30 m above sea level. The climate in the area is Mediterranean with an average annual rainfall of 538 mm/y (S.D. ±141 mm/y). The data expanded over 56 years, from August 1952 until July 2007. A day started at 8 am (local time) and ended at 7:59 am the next day. A day was defined as rainy if more than 1 mm rainfall was measured. The number of rainy days was 50 d/y on average (ranging from 35 to 69 d/y), spanning from September to May. The average number of dry days within the rainy season was 151 (range: 105–220). The average number of dry days between consecutive rainy days was 4.1 (S.D. 6.2 d), with a median value of 1 d and a 75 percentile of 5 d or less. The length of the dry period was 164 d/y (range 97–217). Figure 1 shows perennial daily average of rainfall as measured during the rainy season, at the Haifa Port meteorological station. The figure illustrates the fluctuations in the rainwater depth, which are significant, and should be considered when designing the storage tank size.

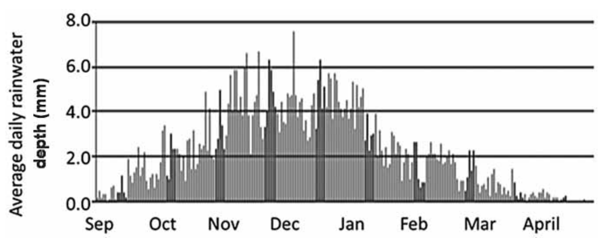

Figure 1 | Haifa Port meteorological station – daily precipitation distribution - perennial average (56 years). Rainy season September–April, dry season May–August.

Model description

Input data

Rainwater data. As aforementioned, daily data from Haifa Port meteorological station over 56 years were analyzed, providing 56 data entries for each day, ranging from zero to the maximum rainwater value that was measured over the examined period. It was assumed that there is no dependency in the daily rainfall depth between consecutive days, although some of the rain systems in the region last more than one day. Hence, for each day, a cumulative probability function was drawn as a function of rainwater depth. Then, a sixth degree polynomial approximation function of rainfall depth vs. probability was derived for each calendar day (Equation (1)).

$$R(t) = Max \begin{Bmatrix} a_t \cdot P(t)^6 + b_t \cdot P(t)^5 + c_t \cdot P(t)^4 + d_t \cdot P(t)^3 \\ + e_t \cdot P(t)^2 + f_t \cdot P(t) + g_t \\ 0 \end{Bmatrix} \quad (1)$$

$$P(t) = \text{Random}\,(0 - 1) \quad (2)$$

where:

$R(t)$ is the predicted daily rainwater depth (mm/d) for day t ($t = 1 \rightarrow 365$).

The *Max* function was added in order to ascertain that rainwater depth is always non-negative (the result of the polynomial approximation can become negative below a certain probability threshold).

- a_t, b_t, c_t, d_t, e_t, f_t and g_t are the polynomial coefficients for day (t). These were obtained for each day by minimizing the squared error function.
- $P(t)$ is the probability ($0 \leq P \leq 1$) - a number which is randomly chosen by the model (uniform distribution).

Roof area size and type. Five roof area sizes were simulated in the model: 75, 100, 150, 200 and 400 m^2.

Since the performance of the RWH systems is sensitive to the runoff coefficient, the roof type may affect the generated rainwater runoff (Liaw & Tsai 2004; Farreny *et al.* 2011). Therefore, a field experiment was conducted, during the rainy seasons of 2007 and 2008 to determine the rainwater-runoff coefficient for three types of roof (each having a horizontal area of 1 m^2): (1) concrete at a slope of 1%; (2) tile at slope of 30%; and (3) isolated steel sheets that are used for roofing tall buildings (*Iskoorit*™) at a slope of 1%. These three types roof materials are common in Israel. The experimental roofs were placed at the Technion Campus (Haifa, Israel) 1 m above the roof of one of the buildings, with their slopes facing west; the dominant direction of rain events at this region. Each roof was fitted with a gutter leading to a 55 L collection tank. An automatic micro rain gauge (tipping bucket; *Texas Electronics INC.*, Model 525) that recorded rainfall at a temporal resolution of 10 minutes was placed adjacent to the system. The results from this field experiment (55 rain events) served for developing linear empirical equations, for estimating the effect of the roof type on the correlation between rainfall and the roof runoff, as follows (Equation (3)):

$$d_{i(t)}^{runoff} = Max \begin{Bmatrix} a_i \cdot R(t) + b_i \\ 0 \end{Bmatrix} \quad (3)$$

where $d_{i(t)}^{runoff}$- the specific daily rainwater runoff generated (generated runoff divided by the roof area) (L/(m^2·d)) for each roof type (i); a_i – the slope of the line (L/(mm·m^2)), for each roof type; $R_t(t)$- daily rainwater depth at day t (mm/d) and b_i – the intercept with the Y-axis (L/m^{2}·d), for each roof type.

By multiplying $d_{i(t)}^{runoff}$ by the roof area A (simulated as 75, 100, 150, 200 and 400 m^2), the daily volume of rainwater runoff available for storage ($V_{i(t)}^{rain}$), is calculated as follows:

$$V_{i(t)}^{rain} = d_{i(t)}^{runoff} \cdot A \quad (4)$$

Water demand and number of residents. In most countries untreated or minimally-treated harvested rainwater is used for non-potable uses, such as toilet flushing, laundry and garden irrigation (Fewkes 1999; Villarreal & Dixon 2005; Ghisi *et al.* 2007; Furumai 2008; Gires & de Gouvello 2009). This is practiced in order to ensure that public health is not compromised. In regions having Mediterranean climate (such as Haifa), most garden irrigation is performed during the dry summer, while rain events occur only during the winter making the use of the harvested rain for garden irrigation is unfeasible. Hence, only toilet flushing and laundry were considered in this study. The specific demand for the harvested rainwater was considered as a constant deterministic value. Domestic in-house water demand in Israel is evaluated as 153 L/(person·day) (L/(p·d)), of which 44% (68 L/(p·d) = 55 (L/(p·d)) for toilet flushing + 13 L/(p·d) for laundry) can be supplied by the harvested rainwater (Friedler 2008). This value was used as input to the model, and the cumulative water demand was calculated by:

$$V_{(t)}^{demand} = 68 \cdot N \quad (5)$$

where: $V_{(t)}^{demand}$ is the rainwater demand for toilet flushing and laundry (L/d); 68 is the domestic in-house specific water demand used for toilet flushing and laundry (L/(p·d)); and N is the number of residents (c).

Six possible residents population sizes in a single house were examined in the model 4, 8, 12, 24, 48 and 64 residents.

Model algorithm

The model was written in MATLAB and based on YAS algorithm, in which the water supplied from the storage tank after rainfall has been added to the storage facility (Fewkes 1999; Fewkes & Butler 2000). The model is a daily model, i.e. it uses a daily time-step. Since the rainy season starts after a long dry summer (105–220 consecutive dry days), the storage tank at the beginning of winter (the rainy season) was considered as empty.

The daily mass balance of water in the rainwater tank is given by:

$$V_{(t)} = Min \left\{ \begin{matrix} V_{(t-1)} + V_{(t)}^{rain} - V_{(t)}^{demand} \\ V_{Max} \end{matrix} \right\} \quad (6)$$

where: $V_{(t-1)}$ and $V_{(t)}$ are the volumes of water in the tank at day $t-1$ and t, respectively; and V_{Max} is the storage tank volume.

If the storage tank is completely filled ($V_{(t)} > V_{\mathrm{Max}}$), the excess rainwater generated is released as overflow ($V_{(t)}^{overflow}$) and the water volume available for the next day is V_{Max}.

If the daily rainwater demand is higher than the volume of rainwater available in the storage tank, than ($V_{(t)}$) becomes negative and potable water from the urban water supply network is provided to overcome this shortfall, and calculated as:

$$V_{(t)}^{fresh} = Abs(V_{(t)}) \quad (7)$$

where: $V_{(t)}^{fresh}$ is the amount of freshwater provided from the water supply network; and Abs($V_{(t)}$) is the absolute value of $V_{(t)}$.

In this case (demand for rainfall is higher than available rainwater), after the above calculation $V_{(t)}$ is set to 0.

The stochastic Monte-Carlo modelling was applied as follows. For each day, a random number (0–1) was drawn by the computer, then the algorithm described in Figure 2 was executed. Once this has terminated another day started with the same procedure repeatedly from the first to the last day of the rainy season. Then, the whole process was repeated 100 times (100 random rainy seasons).

Simulations scenarios

The study was divided into two stages. In the first stage the maximum volume in which all the roof rainwater runoff is used (in other words, system utilization efficiency of 100%) was calculated by the simulation model. Figure 2 depicts a schematic flowchart for this simulation. A total of 30 combinations were simulated and analyzed: five roof sizes (75, 100, 150, 200 and 400 m^2) and six residents' population sizes (4, 8, 12, 24, 48 and 64 people). Each option was run for a whole year with a daily time-step. 100 year-long random simulations were performed with stochastic (Monte-Carlo) rainfall input as described above yielding 100 possible maximum storage tank volumes (for each option) that were statistically analyzed.

In the second stage, lower volumes of the storage tank (lower than the maximum values found in the first one) were set prior to the simulation for evaluating the WSE and rainwater use efficiency (RUE) of the system. WSE is

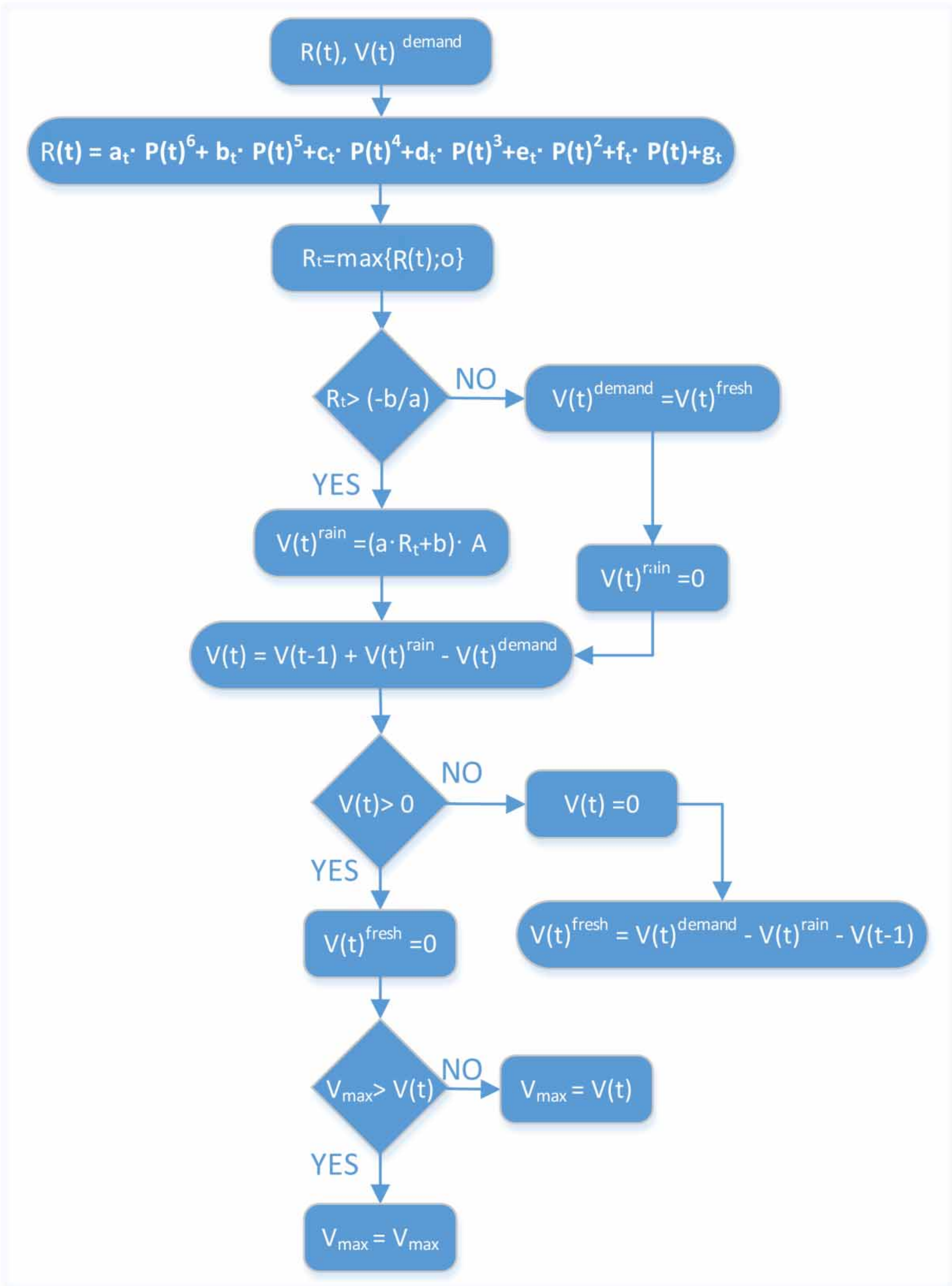

Figure 2 | Flowchart of the simulation model for sizing the maximum volume of the storage tank.

defined as the proportion of water demand (of the two relevant uses) provided by the harvested rainwater (Equation (8)). It should be noted that the WSE was calculated only for the rainy season (September–April) The RUE quantifies the proportion of the rainwater harvested that was actually used (Equation (9)).

$$WSE = \frac{V^{rain}}{V^{demand}} \tag{8}$$

$$RUE = 1 - \frac{V^{overflow}}{V^{rain}} \tag{9}$$

RESULTS AND DISCUSSION

Input data

Rainwater data

As aforementioned, the model randomly selected probability and calculated rainwater depth for each day (Equation (1)). The average simulated rainwater depth was 574 mm/y (100 model runs), fell in line with measured values at Haifa Port meteorological station (538 mm/y). The range of the simulated rain depth was 300–900 mm/y very similar to the range of the measured data (292–925 mm/y). Further, the stochastic simulation results were not found to be statistically different from the measured data, indicating satisfactory representation of measured data.

Roof type

The effect of roof type on the generated runoff, as calculated from the measured data, is presented in Table 1 which presents the parameters of the linear empirical equation (Equation (3)). The correlations between runoff and rainfall were high for all examined roof types ($R^2 \geq 0.93$ and $p < 0.05$). 'a', the regression line slope, expresses the relationship between rainfall and the generated roof runoff after runoff commenced. Hence, the closer 'a' is to 1, the higher the proportion of rainfall that is converted to runoff. Of the three roof materials examined tiles had the highest rain to runoff conversion rate (a = 0.91) while concrete had the lowest (a = 0.78). $R(y=0)$ is the minimum amount of rainfall needed for runoff to commence ($R(y=0) = -b/a$). $R(y=0)$ actually represents the depression storage of the roof, which is analogous to depression storage in open spaces. For the examined roof types, runoff from the concrete roof started after 2.3 mm of rain as compared with 0.37 and 0.041 mm for the tile and steel-sheets roofs, respectively. The findings were expected as steel-sheets have less and smaller crevices and less water is consumed for wetting the roof material than tile or concrete roofs. To summarize, the runoff from the concrete roof started after the largest rainfall depth as it required the largest amount of rainfall for filling small depressions in the roof before runoff commenced and it generated the lowest volume of runoff for each rainfall event. The tile roof generated the largest volume of runoff for each rainfall event (largest 'a'), although runoff from the steel-sheets roof started after the lowest rainfall depth (lowest $R(y=0)$). The high runoff generated by the tile roof is probably attributed to its high longitudinal slope (30%). It should be noted that apart from depression storage on the roof itself delivery losses from the roof to the storage tank were not considered.

Table 1 | Values of the linear regression equation parameters for assessing the effect of the roof type on the relationship between rainfall and roof runoff

Roof type	a l/(mm·m²)	b l/(m²·d)	$R^{a}_{(y=0)}$ mm	n^{b}	R^2
Concrete	0.78	−1.8	2.3	47	0.93
Steel sheets	0.80	−0.033	0.041	45	0.98
Tiles	0.91	−0.34	0.37	36	0.97

[a] $R_{(y=0)}$ – rainfall depth above which runoff commences.
[b] n – number of rainfall events (observed).

Maximum volume of the storage tank and potential WSE

The maximum volume of the storage tank and the potential WSE were analyzed for the 30 examined combinations, each executed for 100 random runs. The maximum volume of the storage tank, is the volume that ensures harvesting and using all the runoff generated (RUE = 100%, Equation (9)). Figure 3 depicts an example of the obtained results for a 150 m² from the 100 stochastic runs where it can be seen that the smaller the population size the more dependent is the storage volume on the annual rainfall.

For brevity in the following sections only the results for the concrete roof (most common roof type in Israel) are presented.

The maximum storage volume ranged from 0.46 m³ and WSE of 4%, for roof area of 75 m² and 64 residents, to

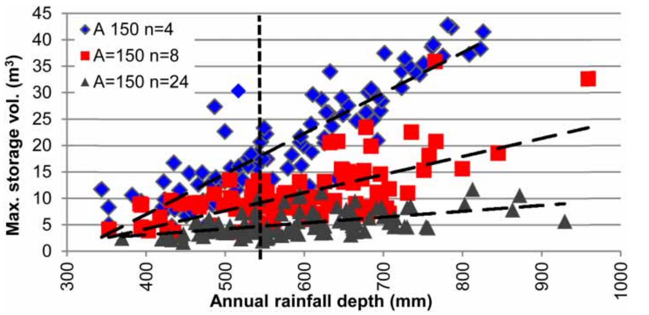

Figure 3 | Maximum storage volume for 150 m^2 roof as a function of annual rainfall and number of residents. Symbols – Maximum volumes obtained from each simulation (100 stochastic simulation runs). Vertical dotted line – average annual rainfall in Haifa, Israel; diagonal dotted lines – linear regression.

194 m^3 and WSE of 82% for roof area of 400 m^2 and 4 residents (Figure 4). As expected the maximum storage volume was found to be highly dependent on the roof area, where larger roofs generated more runoff that required larger storage tank to increase the WSE (Figures 4(a) and 4(c)). In other words, for the same number of residents, the maximum storage volume and the WSE increased with the roof area, due to an increase in the generated roof runoff volume. The number of residents also had a significant effect on the maximum storage volume and on the WSE (Figures 4(b) and 4(d)). As the number of residents increased (for the same roof area) the maximum storage volume decreased, due to higher water demand. The WSE also decreased meaning that the collected rainwater contributed smaller proportion of the water demand (although the RUE was 100% in all cases). For example, for a 400 m^2 roof the maximum storage volume decreased from 194 to 23 m^3 and the WSE decreased from 82 to 20% when the number of residents increased from 4 to 64, respectively. It is worth noting that in this example the number of residents increased by 16-fold, while the maximum storage volume decreased by 8.6-fold and the WSE only by 4.1-fold. Further, the differences between the maximum storage volumes and

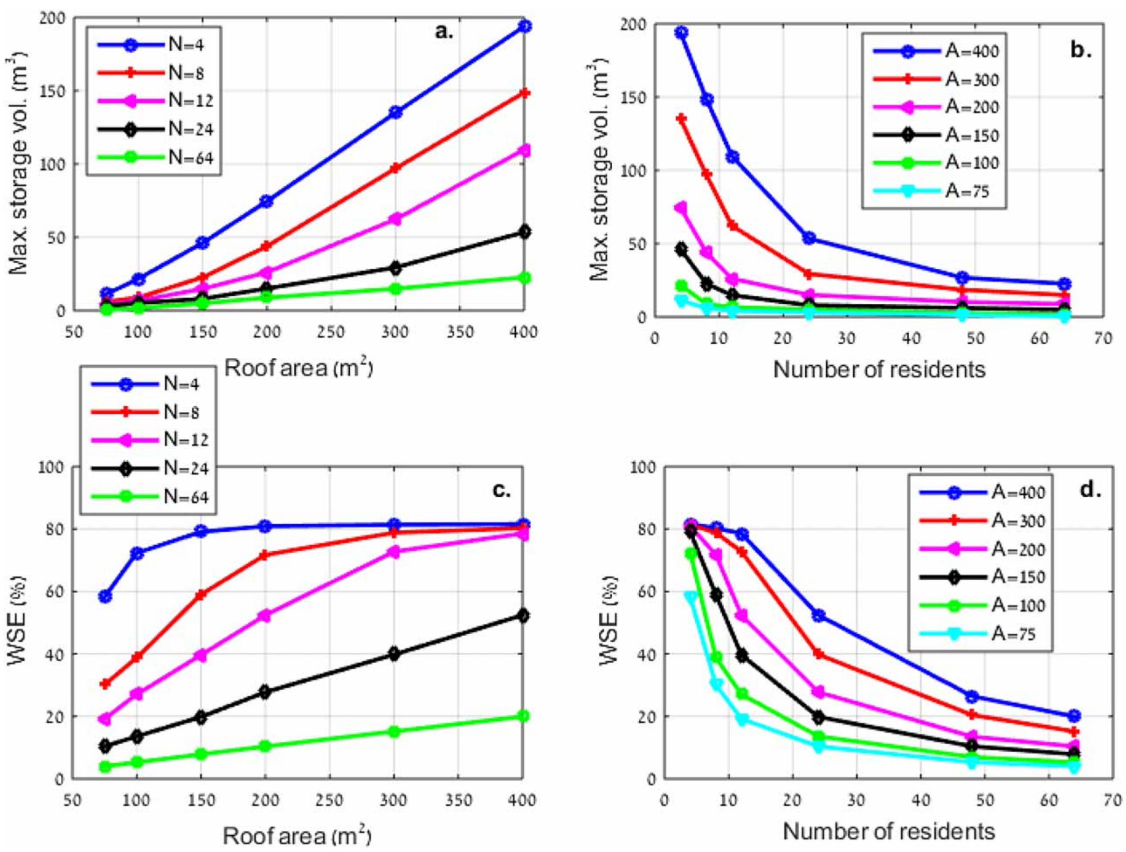

Figure 4 | Maximum storage tank volume vs. roof area (a); maximum storage tank volume vs. number of residents (b); water saving efficiency (WSE) vs. roof area (c); WSE vs. number of residents (d). Values are average values obtained from 100 model runs for each combination (roof area × number of residents). A – roof area (m^2); N – number of residents.

the WSE for varying number of residents are much more pronounced when the roof area is larger. These findings emphasize the importance of considering the roof area likewise the number of residents of each building, for calculating the volume of the storage tank and the expected WSE.

RUE, WSE and storage tank volume

In many cases the maximum storage volume (for which RUE is 100%) leads to a large storage tank volume. However, RWH systems do not always require the maximum volume and in most cases, lower volume tanks generate high (or at least satisfactory) WSE. Therefore, as aforementioned, in the second stage of the research the model was run with varying storage tank volumes and the WSE and RUE were calculated for each of the 30 combinations (roof area × number of residents).

Good correlation was obtained between the WSE and storage tank volume (Figure 5). From the figure it can be seen that this correlation follows a saturation curve, meaning that the WSE increases significantly with the tank volume in the small volumes range and becomes much less sensitive to the tank volume as the volume increases. This is due to the fact that for small tanks the limiting factor is the volume available for storing the roof runoff, while as the tank volume increases, the limiting factor becomes the amount of water used by the residents (or in other words the number of residents). From the figure one can also see that the maximum WSE (asymptotic/saturation value) decreases from ~80% for four-person home to ~25% for 64 person home. It should be noted that WSE of 100% was never reached due to the stochastic nature of rainfall in the studied area (Mediterranean climate, as discussed above).

The WSE for a four residents house increased from 39% to 81% as the roof area increased from 75 to 400 m^2 (Figure 6 top left), for the examined storage volumes (0.1, 0.3, 0.5, 0.7 and 0.9 of the maximum storage volume). The results indicate that the WSE for a storage tank sized 10% of the maximum volume was the lowest, while no significant differences were found between storage tank sized 30–90% of the maximum volume. The same general pattern was observed for 12, 24 and 64 persons' houses. In other words, there was no significant advantage of the larger volume tank ($0.9 \cdot V_{Max}$) over the lower one ($0.3 \cdot V_{Max}$). The range of WSE calculated by the model fall within the ranges reported in the literature (e.g. Debusk *et al.* (2013), WSE 60–100%; Umapathi *et al.* (2013), WSE 1–67%; Burns *et al.* (2015), WSE 10–100%).

The RUE in a four-person house generally decreased with an increase of the roof area, since the daily water demand was lower than the generated runoff (Figure 6 bottom left). The RUE was found to be more sensitive to tank size than the WSE, with a much larger decrease of the RUE in the small tank volume ($0.1 \cdot V_{Max}$) from 65% to 34% (~50% decrease) than in the larger tank volume ($0.9 \cdot V_{Max}$, from 94% to 89%, ~5% decrease). As the number of residents in the house increased the decrease in the RUE diminished, yet here again the decrease in the small tank volume ($0.1 \cdot V_{Max}$) became significantly larger than all other tank volumes. For example, for a 64-person house (Figure 6 bottom right) the RUE of a $0.1 \cdot V_{Max}$ tank decreased from 99% to 68% as the roof area increased from 75 to 500 m^2 (32% decrease), while the RUE of a $0.3 \cdot V_{Max}$ tank decreased from 99% to 84% (15% decrease)

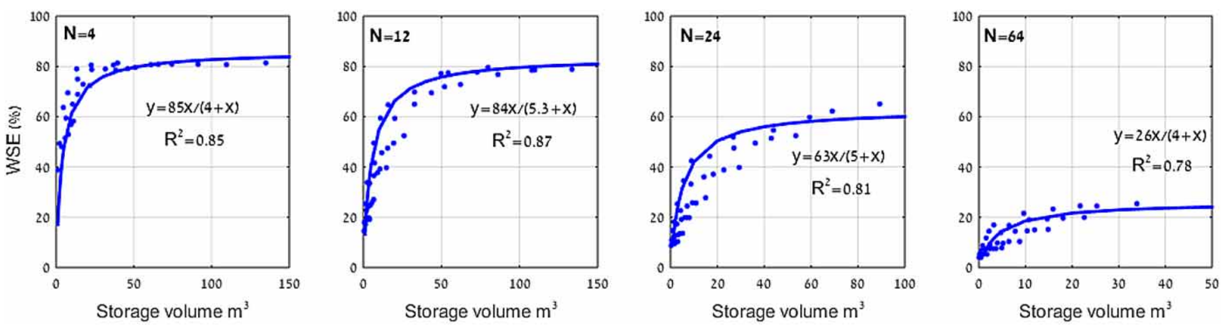

Figure 5 | Water saving efficiency (WSE) vs. storage tank volume (all roof sizes). N – number of residents.

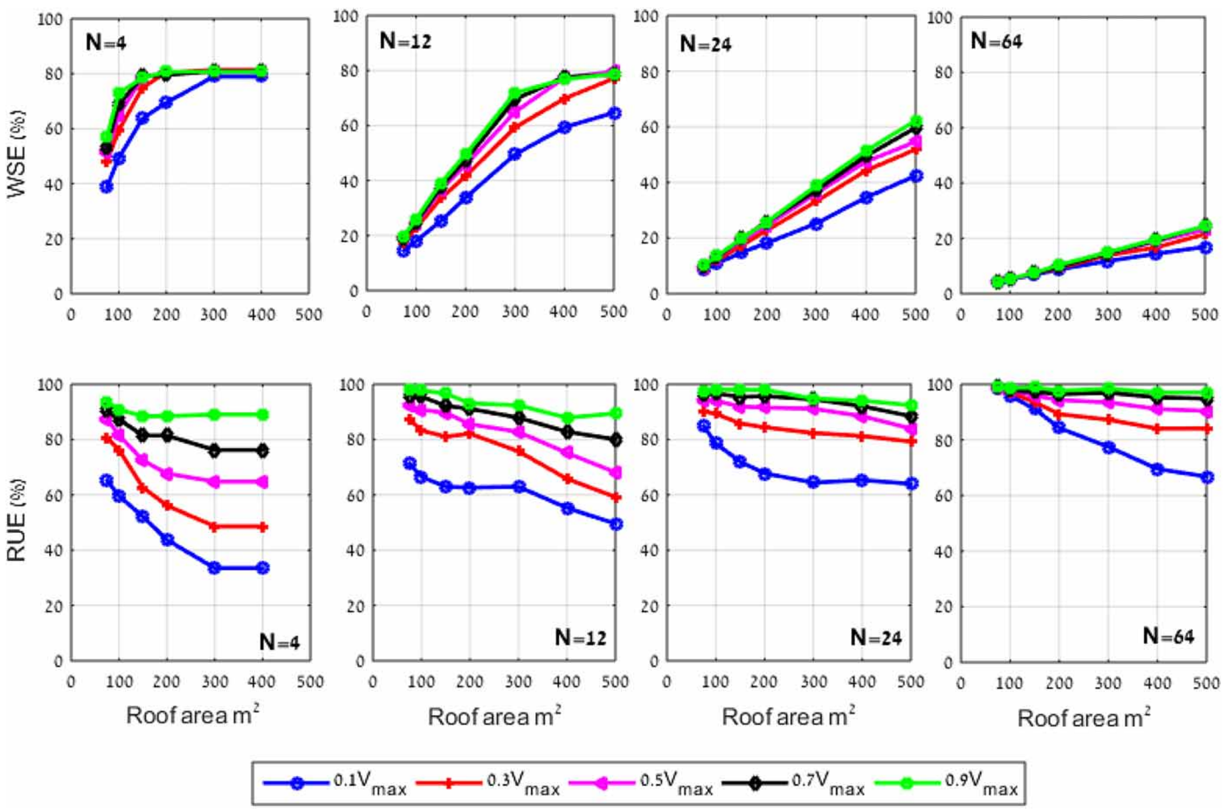

Figure 6 | Water saving efficiency (WSE, top) and rainwater use efficiency (RUE, bottom) vs. roof area for different volumes of storage tanks (curves). N – number of residents. Values are average values obtained from 100 model runs for each combination (roof area × number of residents).

for the same increase in the roof area. It should be noted that for the combinations examined (roof area × number of residents) the WSE decreased significantly with an increase of number of residents (meaning that a lower proportion of the water consumption was supplied by the rainwater harvested, while the RUE increased (but in a less pronounced manner) with increasing number of residents, meaning that higher proportion of the roof runoff was used. The results demonstrate the importance of using a model for determining the right tank volume (avoiding extra costs due to oversizing of the storage tanks, while keeping a satisfactory efficiency of RWH system).

CONCLUSIONS

A stochastic model to quantify the optimal size of rainwater storage tanks for residential homes was developed based on daily rainwater depth, non-potable domestic water demand (toilet flushing and laundry), number of residents and roof area, where rainfall was considered as the stochastic parameter. Daily rainwater depth was calculated from historical data, and probability functions were derived for each calendar day. Using this, the effect of the variable daily rainwater was studied while keeping the seasonal patterns.

Quantifying the storage tank volume based on the WSE, emphasizes the importance of considering the rainwater pattern, roof area, specific water demand and the number of residents. The model output exhibited good correlation between the WSE and storage tank volume, following a saturation curve pattern. This relationship is significant since it can be used for estimating the required storage tank depending on the desired WSE. It was demonstrated that in many cases the maximum storage volume is not really needed and smaller volumes can achieve almost the same efficiencies (WSE and RUE). For example, one can assume a specific storage tank volume and by running the model predict the WSE, or determine the desired WSE and calculate the required tank volume. The model demonstrated that no single optimal storage tank volume exists, since it depends on local weather patterns, roof size, specific demand for the harvested rainwater, number of residents in the house and the desired WSE. This means that for each setting the tank volume may be different and should be determined by the model or a similar simulation tool. The model was developed for Mediterranean climate (Haifa, Israel), but the same methodology may well be implemented for other climatic regions. In addition, the model can be used for examining the effects of extreme weather (or climate change) on WSE and RUE, using the developed probability curves to generate rainfall values for different return periods. Further development of the model would include representation of domestic water uses in a stochastic manner.

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