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Stochastic modelling of the performance of an onsite rainwater harvesting system in Mediterranean climates – North Israel as a case study

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ABSTRACT

Aims: Model the performance of onsite RWH (rainwater harvesting) system, in Mediterranean climates characterised by dry summers and winters with highly variable rainfall patterns.
Study design: The study is based on stochastic Monte-Carlo simulation.
Place and Duration of Study: 56 years daily rainfall data from Haifa, Israel was used as model input.
Methodology: A stochastic model was developed for quantifying the storage capacity needed, as a function of rainfall frequency and depth, roof area, number of residents, specific water use (toilet flushing and laundry) and the efficiency required from the system. Maximum volumes were calculated. Two performance indicators were defined and calculated: WSE (water saving efficiency) - proportion of water used within the house supplied by the RWH system; and RUE (rainwater use efficiency) - proportion of rainwater that was used.
Results: The required maximum storage capacity and WSE decreased with increasing number of residents for a given roof area, and increased with an increase in roof area for constant number of residents. For variable storage volumes, RUE increased with increasing storage capacity and reached maximum value faster with an increase in residents' number and a decrease in the roof area. The model predicted the storage capacity for avoiding extra costs (due to oversized tank volume) while keeping high system efficiency.
Conclusion: The model enables to determine WSE and RUE for specific storage volumes or to determine the desired WSE and calculate the needed storage. This modelling approach can be implemented to other climatic regions.

Keywords: Rainwater harvesting, stochastic modelling, water saving, Mediterranean climate

1. 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 [1, 2]. Rainwater, which is a renewable freshwater source, could 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 [3]. Numerous studies investigating the harvested rainwater quality were conducted in Australia, Canada, Denmark, Germany, India, Japan, Spain, New Zealand, Thailand, and the United States [4, 5, 6, 7, 8]. However, less information and clear definition on rainwater tank sizing are available [9, 10, 11, 12]. The correct tank sizing is important in order to avoid extra costs when the tank is

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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 instances: Jenkins et al. [13] developed two behavioral algorithms to describe the operation of a RWH system during a given time interval. The 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 one, yield before spillage (YBS) algorithm, assumes that the demand is withdrawn before spillage is determined. Fewkes [14] used collected data to verify and refine a rainwater collection sizing model based on YAS algorithm. The refined model was used to develop a series of dimensionless design curves relating collection area, demand, rainfall level, system efficiency and storage volume. Fewkes and Butler [15] evaluated the accuracy of behavioral models, for the sizing of rainwater collection systems using different time intervals and different reservoir operation. Villarreal and Dixon [16] generated a computer model to quantify the water saving potential of the rainwater collection by analyzing the water saving efficiency. The analysis of several scenarios allowed the authors to suggest suitable sizes of rainwater tanks. Khastagir and Jayasuriya [17] presented a methodology for optimal sizing rainwater tanks considering the annual rainfall at the geographic location, the demand for rainwater, the roof area and the desired supply reliability. Ghisi [9] 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.

The objective of this study is to develop a stochastic model to estimate the optimal rainwater tank size depending on the rainwater demand, number of residents and the catchment size (roof area), when the daily rainfall at the location area was considered as the stochastic parameter. The model was developed for Mediterranean climate (Haifa, Israel), characterised by long dry summers (literally) and winters with highly variable rainfall patterns. Nevertheless, similar methodology may well be implemented to other climatic regions.

2. MATERIALS AND METHODS

2.1 Study site

Daily rainfall data was 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 was measured during the rainy season, at the meteorological station. The figure illustrates the fluctuations in the rainwater depth, which are significant, and should be considered when designing the storage tank size.

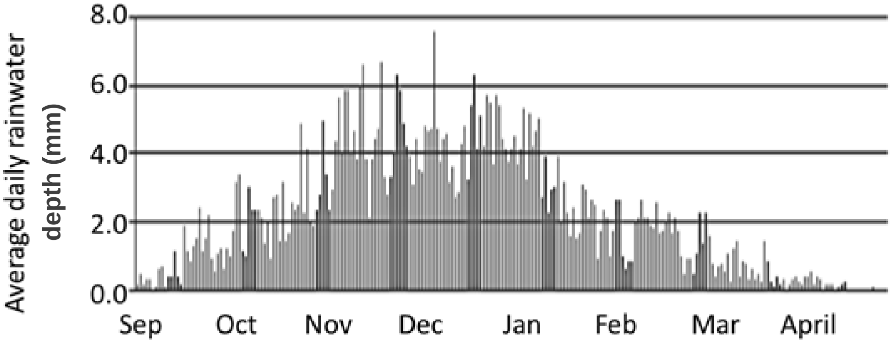

Figure 1. Haifa Port meteorological station - Daily precipitation distribution- perennial average (56 years). Rainy season September-April, dry season May-August.

2.2 Model description

2.2.1 Input data

2.2.1.1 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 (eq 1).

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

$$P(t) = Random(0-1) \quad (2)$$

Where:

- R(t) is the predicted daily rainwater depth (mm/d) for day t (t= 1→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 parameter estimation by minimizing the squared error function.
- P(t) is the probability (0≤ P ≤1) - a number which is randomly chosen by the model (uniform distribution).

2.2.1.2 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 [8, 18]. 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 $1m^2$) common in Israel: (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 slope of 1%. The roofs placed at the Technion University 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; Model 525, *Texas Electronics INC*) was placed near the system that recorded rainfall recorded at a resolution of 10 minutes. 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 (eq. 3):

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

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:

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

2.2.1.3 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, clothes washing and garden irrigation [1, 2, 14, 16, 19]. 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 the 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. Domestic in-house water demand in Israel is evaluated as 153 litre/capita/day (L/c/d), of which 44% (68 L/c/d) can be used (toilet flushing 55 (L/c/d); laundry (13 L/c/d) [20]. This value was used as input to the model, and the cumulative water demand can be calculated by:

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

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

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

2.2.2 Model algorithm

The model was written in MATLAB and based on yield after spillage (YAS) algorithm, in which the water supplied from the storage tank after rainfall has been added to the storage facility 14, 15]. The model is a daily model, i.e. it uses a daily time-step. For simplicity, it was assumed that at the end of summer (or the beginning of the rainy season), the rainwater storage tank is empty.

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

$$V_{(t)} = \mathrm{Min}\begin{Bmatrix} V_{(t-1)} + V_{(t)}^{rain} - V_{(t)}^{demand} \\ V_{Max} \end{Bmatrix} \tag{6}$$

Where: V(t-1) and V(t) are the volumes of water in the tank at day t-1 and t respectively; V_{max} is the storage tank volume.

If the storage tank is completely filled ($V_{(t)} > V_{max}$), 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 ($V_{(t)}$), than freshwater from the urban water supply is provided to overcome this shortfall, and calculated as:

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

Where: $V_{(t)}^{fresh}$ is the amount of freshwater provided; and Abs($V_{(t)}$) is the absolute value of $V_{(t)}$.

After this calculation $V_{(t)}$ is set to 0.

2.2.3 Simulations scenarios

The study was divided in to two stages: In the first one the maximum volume in which all the 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. Thirty scenarios were simulated and analysed: five roofs sizes (75, 100, 150, 200 and 400 m^2) and six number of residents (4, 8,12,24,48 and 64). Each scenario was run for a whole year with a daily time-step. 100 year-long random simulations were performed with stochastic (Monte-Carlo) rainfall input yielding 100 possible maximum storage tank volumes that were statistically analyzed.

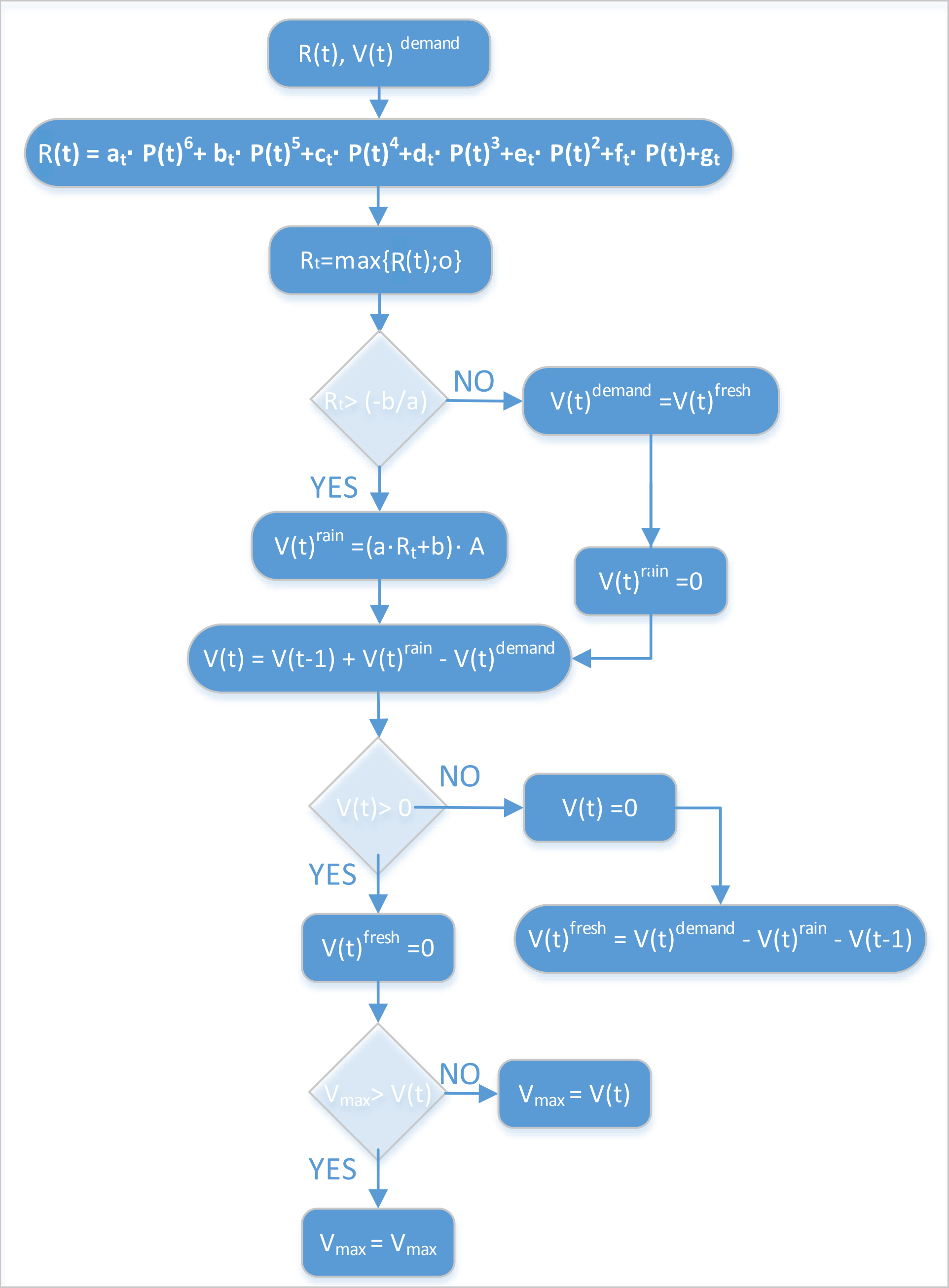

Figure 2. Flowchart of the simulation model for sizing the maximum volume of the storage tank

In the second stage, lower volumes of the storage tank (lower than the maximum values found in the first stage) were set prior to the simulation for evaluating the WSE and RUE of the system. WSE (water saving efficiency) that is defined as the proportion of water demand (of the two relevant uses) that is provided by rainwater (eq. 08). It should be noted here that the WSE was calculated only for the rainy season (Sept.-Apr.) The RUE (rainwater use efficiency that quantifies what proportion of the rainwater collected was used in-house (eq. 9).

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

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

3. RESULTS AND DISCUSSION

3.1 Input data

3.1.1 Rainwater data

As aforementioned, the model randomly selected probability and calculated rainwater depth (eq. 1) for each day. 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.

3.1.2 Roof type

The effect of roof type on the generated runoff, as calculated from the measured data, is presented in Table 1. In the table, the parameters of the linear empirical equation (eq. 3) are given. 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 one (a = 0.78). $R_{(y=0)}$ is the minimum amount of rainfall needed for runoff to start ($R_{(y=0)} = -b/a$). $R_{(y=0)}$ 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 summarise, 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%).

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)	$R_{(y=0)}$* mm	n**	R²
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

* $R_{(y=0)}$ Rainfall depth above which runoff commences; ** n – number of rainfall events (observed)

For brevity in the following sections (3.2-3.3) only the results for the concrete roof (most common roof type in Israel) are presented.

3.2 Maximum volume of the storage tank and potential water saving efficiency

The maximum volume of the storage tank and the potential water saving efficiency were analysed for the 30 examined combinations (5 roof sizes x 6 population sizes in the house), 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%, eq.9). Figure 3 depicts an example of the obtained results for a 150 m^2 from the 100 stochastic runs.

The maximum storage volume ranged from 0.46 m^3 and WSE of 4%, for roof area of 75 m^2 and 64 residents, to a maximum storage volume of 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 is highly dependent on the roof area, where larger roofs generate more runoff that required larger storage tank to increase the potential WSE (Figure 4 a, 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 has a significant effect on the maximum storage volume and on the potential WSE (Figure 4 b, d). As the number of residents increased (for the same roof area) the maximum storage volume decreased, due to higher water demand. At the same time 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 decreases from 194 to 23 m^3 and the WSE decreases from 82 to 20% when the number of residents increases from 4 to 64, respectively. It is worth noting that in this example the number of residents increased by sixteen-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 the WSE for varying number of residents are much more pronounced when the roof area is larger. These findings emphasise 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.

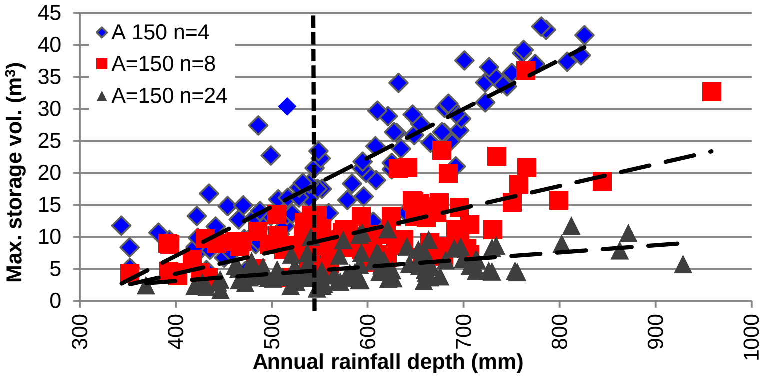

Figure 3. Max storage volume for 150 m^2 roof as a function of annual rainfall and number of residents

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

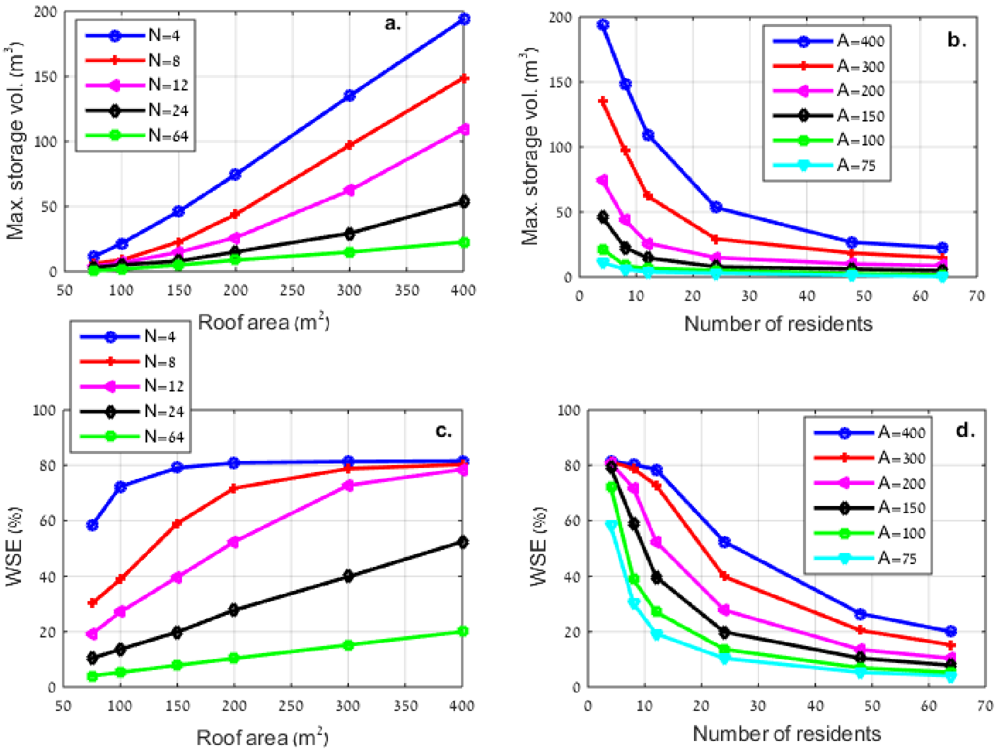

Figure 4. Maximum storage tank volume *vs.* roof area (a); Maximum storage tank volume *vs.* number of residents (b); Water saving efficiency (WSE) *vs.* roof area (c); WSE *vs.* number of residents (d)

Values are average values obtained from 100 model runs for each combination (roof area x number of residents)
A – Roof area (m^2); N – Number of residents

3.3 Rainwater use efficiency, water saving efficiency and storage tank volume

The above results performed for quantifying the maximum storage volume, in which all the rainwater runoff is stored and used (RUE = 100%), which in many cases leads to a large volume of the storage tank. However, rainwater harvesting systems do not always require the maximum storage volume tank and in most cases, lower volumes generate high (or at least satisfactory) WSE. Therefore, as aforementioned, in the second stage of the research the model was run with varying volumes of the storage tank and the WSE and RUE were calculated for each of the 30 combinations (roof area x 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 storage tank volume in the small volumes range and becomes much less sensitive to the tank volume as the tank volume increases. This is due to the fact that for small tank volumes 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 see that the maximum WSE (asymptotic / saturation value) decreases from ~80% for 4 person home to ~25% for 64 person home. It should be noted that WSE of 100% is never reached due to the stochastic nature of rainfall in the studied area (Mediterranean climate, as discussed above).

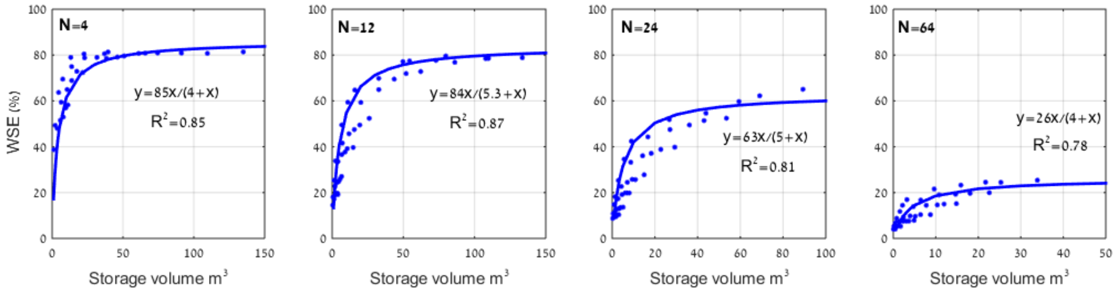

Figure 5. Water saving efficiency vs. the volume of the storage tank
N- Number of residents

The WSE for 4, residents house ranged between 39% to 81% as the roof area increased from 75m^2 to 400 m^2 (Figure 6 top left), for the examined storage volumes (10%, 30%, 50%, 70% and 90% of the maximum storage volume). The results indicated that the WSE for a storage tank sized 10% of the maximum volume ($0.1 \cdot V_{max}$) was the lowest, while no significant difference was found between storage tank sized 30-90% of the maximum volume. The same general pattern was observed for 12, 24 and 64 person houses, where storage tanks sized 10% of the maximum volume performed significantly worse than tanks sized 30-100% of the maximum volume. In other words, there was no significant advantage of the larger volume tank (0.9·Vmax) over the lower one (0.3·Vmax).

The RUE in a 4 person house generally decreased as the roof area increased, since the daily water demand is lower than the generated runoff (Figure 6 bottom left). The RUE was found to be more sensitive to tank size than the WSE, with 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 increase 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) for the same increase in the roof area. It should be noted that for the combinations examined (roof area x 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 high proportion of the roof runoff was used. The results demonstrate the importance of using a model to predict the tank volume which allows determining the right tank volume (avoiding extra costs due to oversizing of the storage tanks, while keeping a satisfactory efficiency of rainwater harvesting system).

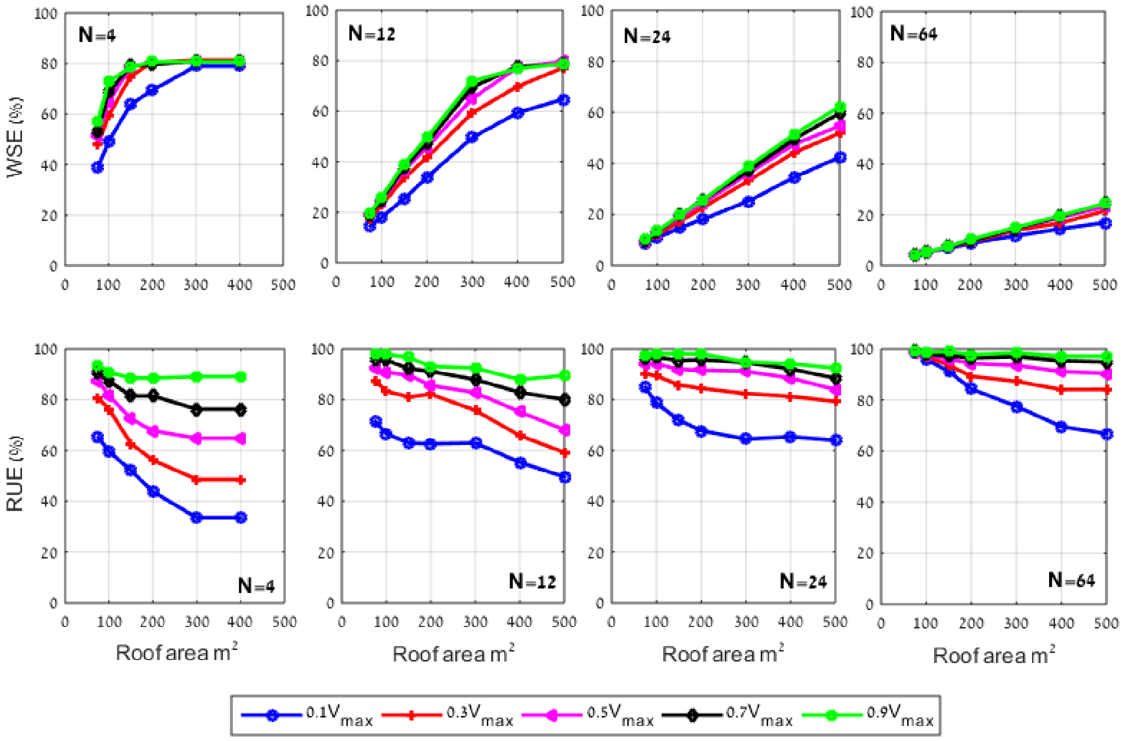

Figure 6. Water saving efficiency (WSE, top) and rainwater use efficiency (RUE, bottom) *vs*. roof area for different volumes of storage tanks (curves).
Each graph is for different number of residents (N)
Values are average values obtained from 100 model runs for each combination (roof area x number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

4. CONCLUSION

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

Quantifying the storage tank volume based on the WSE, emphasises the importance of considering the rainwater pattern, roof area 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 it is not needed to have the maximum storage volume and smaller volumes can achieve almost the same efficiencies (WSE & RUE). For example: one can assume a specific storage tank volume and by running the model receive the predicted WSE, or determine the desired WSE and calculate the required tank volume. The model was developed for semi-arid Mediterranean environment (Haifa-Israel), the same methodology may well be implemented to other climatic regions. Further development of the model would include representation of domestic water uses in a stochastic manner.

COMPETING INTERESTS

We hereby declare that none of the authors has any competing interest.

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