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Superiority of water balance modelling for rainwater harvesting analysis and its application in deriving generalised equation for optimum tank size

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ABSTRACT

In an urban setup optimum size of rainwater tank is a critical factor, as the space required for the rainwater tank is limited and expensive. Several methods have been used for the analysis of potential rainwater harvesting. Some authors used Rippl method for rainwater tank sizing. However, through Rippl method, required size often becomes too big and not feasible in an urban space. This paper presents a water balance modelling concept for rainwater harvesting analysis and its application in determining optimum tank size for rainwater harvesting. Results of the daily water balance model were compared with an earlier study results through Rippl method using daily rainfall data for the city of Nablus (Palestine). Daily rainfall data was collected for the city and from the collected data, three years were selected as dry, average and wet years. Using a typical average rainwater demand and the roof sizes used in the published study, and daily rainfall data for the selected years, annual water savings were calculated for varying tank sizes. From the simulated results, it is clear that for tank sizes beyond certain threshold volumes, annual expected water savings remain unchanged. It is found that Rippl method calculated optimum tank sizes are almost double the optimum tank sizes determined through eTank simulations. Finally, several optimum tank sizes were calculated for different roof sizes and demands considering an average weather condition. It is found that the optimum tank sizes can be correlated with the roof size and rainwater demand, which can be incorporated into a single generalised equation for optimum tank size. The equation calculated results are very close to the original optimum tank sizes found through manual calculation.

1. Introduction

Rainwater tanks have been in use for many centuries, especially for the areas where some rainfall amounts are usual and can be used for human needs. For many remote and poor communities harvested rainwater is the only source of water and they adopt some basic treatments prior to consuming this water (Kerich, E.C., 2020). In the contemporary world, even some urban areas adopting and encouraging rainwater harvesting, mainly to reduce current high demands of potable water. Demands for both potable and non-potable water are increasing, whereas the source/availability of water is decreasing day by day, which forcing many urban authorities to use different alternative water sources, especially for non-potable purposes. Among different alternative water sources, rainwater harvesting is most fundamental, requiring inexpensive treatment. Compared to communal/centralised rainwater harvesting system, individual household level rainwater harvesting is easier to maintain as the onus falls to the house owner/user. For wider implementations of such sustainable option, many authorities around the world have been offering different forms of incentives to the end-users (Imteaz and Moniruzzaman, 2018). Also, some authorities imposing it as mandatory feature for the new building (Bashar et al., 2018).

In the rural areas, the space requirement for the tank was not an issue. However, in the current urban areas, as the cost of land is becoming more and more expensive, a size/space optimisation for an intended rainwater tank is necessary, which basically turns out to be a cost optimisation exercise. This reality lead to several investigations involving benefit-cost ratio and/or payback period analyses. As for example, Imteaz et al. (2021) presented climate change impacts on weather and spatial variabilities of rainwater savings for the city of Adelaide (Australia), Karim et al. (2021) presented detailed economic analysis of rainwater savings from commercial buildings in the city of Dhaka (Bangladesh), Bashar et al. (2018) presented reliability and economic analyses of rainwater savings from residential buildings for

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the six major cities in Bangladesh and Matos et al. (2015) presented detailed economic analysis of rainwater savings from a large commercial building in Portugal. Although, ultimate financial benefit is the critical decision making factor for rainwater tank implementation, often end-users are not convinced on possible monetary benefits presented and promoted by the authorities. It is obvious that before conducting any economic analysis, the potential water savings analysis needs to be accurate, as the core component of the economic analysis depends on the expected amount of water to be saved.

There have been several studies on water saving potentials or expected potable water savings through rainwater tanks and different investigators proposed different methods for assessing water savings potential. Goonrey et al. (2009) proposed an integrated decision-making framework for determining appropriate stormwater harvesting option based on both technical feasibility and associated costs. However, such integrated framework is often complex to deal with and requires expertise on some decision making. Moreover, this integrated framework was developed on monthly timestep, which often turns out to be very crude ignoring some fact such as spill, which is likely to occur during consecutive heavy rainy days. Imteaz et al. (2012a,b) reported flaws of using monthly timescale model compared to a daily timescale model assessing a case study in Nigeria. Mashford and Maheepala (2015) presented a water balance model to evaluate operation of rainwater tank, while assigning associated variables as piecewise distributed functions, which increasing the modelling complexity. A simple model is often warranted for a wider users acceptability.

Several studies focused on determining optimal rainwater tank size based on specific local conditions; i.e. Preeti and Rahman (2021) for Australian capital cities, Notaro et al. (2017) for Sicily and Khan et al. (2017) for Bangladesh. Some researchers used a simple technique named Rippl method for the sizing of rainwater tank; i.e. Shadeed and Alawna (2021) through presenting case study in West Bank (Palestine), Matos et al. (2014) through case study of a commercial building in Portugal and Santos and Taveira-Pinto (2013) through citing a case study from Vila Real (Portugal). Shadeed and Alawna (2021) showed that through using Rippl method, differences of results between monthly-scale calculations and daily-scale calculations are minimal. Through Rippl method optimum storage size is determined through calculating the maximum positive cumulative difference between a sequence of prespecified withdrawal and known inflows. Basically, as per Rippl method, all the inflows are captured within the proposed storage size while having some withdrawal from the tank/storage and outcome through Rippl method provides a bigger tank size, which might be feasible for a detention storage. In an urban scenario, a big size tank is often not feasible due to space/cost limitation. Overcoming these limitations, a daily-scale water balance modelling concept has been widely adopted by many studies and some recent examples of such uses are, Khan et al. (2021), Imteaz et al. (2021), Alim et al. (2020), Santos et al. (2020), Imteaz and Moniruzzaman (2020), Imteaz and Moniruzzaman (2018), Moniruzzaman and Imteaz (2017) and Haque et al. (2016). Using Rippl method, Shadeed and Alawna (2021) proposed some residential tank sizes for the city of Nablus (Palestine), which are apparently quite big. In an urban area, the size, space and hence the cost of the tank is a crucial factor. For the accurate estimation of optimum tank size, this paper presents detailed rainwater tank harvesting analysis in an urban setting using a daily water balance model and compares the results with the findings of Shadeed and Alawna (2021). Then through water balance modelling approach considering an average weather condition, optimum tank sizes depending on different roof sizes and demands were determined based on visual inspection of simulated tank size vs. water savings curves under different independent variables. Also, as such modeling task requires tool, extensive data and expertise, to make it easy for general end-users this study derived a generalised equation, which can be used by general end-users to determine optimum tank size based on any roof area and demand for the city of Nablus. While many studies focused on determining optimum tank size, none of the studies accomplished deriving such simple generalised equation for the determination of optimum tank size.

The structure of the current paper is: 'Section 2' describes detailed methodology and data collection; 'Section 3.1' describes detailed results on water savings; 'Section 3.2' describes detailed anlysis on expected reliability of fulfilment of rainwater demand; 'Section 3.3' outlines derivation of generalised equation; 'Section 4' summerises the overall study and critical findings, and 'Section 5' provides the associated references.

2. Methodology and data

Shadeed and Alawna (2021) presented optimum sizes of rainwater tanks using Rippl method for the 11 governorates in the West Bank area of Palestine. Fig. 1 shows the location of Nablus within the region of West Bank. Out of the 11 studied regions, daily rainfall data is available only for Nablus. For all other regions, the analyses were done with monthly rainfall data. As mentioned earlier, for water balance modelling, a monthly-scale model is not accurate. As such, for the current study, only the Nablus area within West Bank was selected and the daily rainfall data was collected from the Palestinian Metrological Department. The daily rainfall and demand data was fed into an earlier developed daily water balance model, eTank (Imteaz et al., 2017). The brief summary of the eTank model is that from the incoming rainfall amount, a certain percentage is deducted as losses. The remaining amount is multiplied with the roof area to convert it to runoff from the roof, which is then diverted to the rainwater tank having certain volume. This calculation proceeds in daily basis and runoff from a current day is added with the accumulated water in the tank from the preceeding days (if any). Daily, from the stored water (if available), the assigned

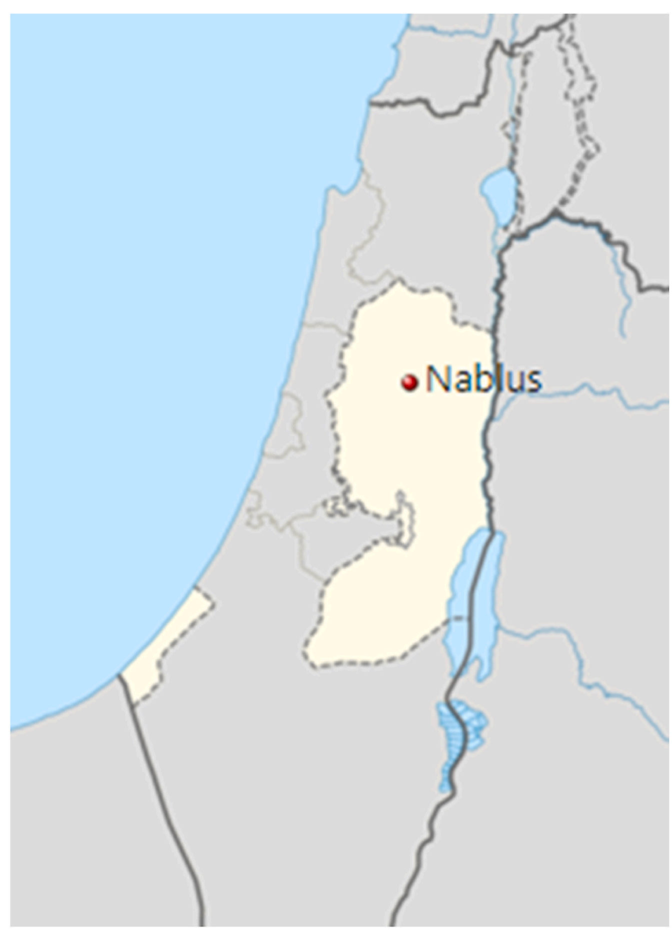

Fig. 1. Location map of the study area.

rainwater demand amount is deducted. If at any stage the tank becomes full, the subsequent runoff amount is lost as overflow. If ther is no water in the tank, it is assumed that the rainwater demand will be fulfilled from normal townwater (potable) supply and model calculates total such water needed in a year for the selected scenario. The mathematical formulations of the daily water balance model are outlined below:

The equation for cumulative water stored in the tank at the end of a day,

$$S_t = V_t + S_{t-1} - D \tag{1}$$

$$S_t = 0, \text{ for } S_t < 0 \tag{2}$$

$$S_t = C, \text{ for } S_t > C \tag{3}$$

where, S_t is the cumulative water accumulated in the rainwater tank (L) after the end of the tth day, V_t is the harvested rainwater (L) on the tth day, S_{t-1} is the storage in the tank (L) at the beginning of the tth day, D is the daily rainwater demand (L), and C is the capacity of rainwater tank (L).

Amount of townwater supplied to the tank can be expressed with the following equation:

$$TW_t = D - S_t, \text{ for } S_t < D \tag{4}$$

where, TW_t is the townwater use on tth day (L).

Amount of rainwater savings is calculated using the following equation:

$$RWS_t = D - TW_t \tag{5}$$

where, RWS_t is the rainwater savings on the tth day (L).

Amount of overflow from the tank is calculated using the following equation:

$$OF_t = S_t - C, \text{ for } S_t > C \tag{6}$$

where, OF_t is the overflow on the tth day (L).

Reliability is calculated with the equation:

$$R_e = (N - U)/N \times 100 \tag{7}$$

where, R_e is the reliability of the tank to be able to supply intended demand (%), U is the total number of days in a year when the tank was unable to meet the intended demand (i.e. total number of days in a year when, $S_t < D$). N is the total number of days in a particular year.

As it is important to investigate the effect of weather variability on rainwater harvesting (Ekwueme and Agunwamba, 2021) from the available data, three years were selected as dry, average and wet years. With the availability of longer period data, such classification is usually done in a way that the dry, average and wet years are the years having close to 10 percentile, 50 percentile and 90 percentile annual rainfall amounts respectively. For the current study, longer period daily data was not available. The daily rainfall data was available only for the period of 2012–2019, which was used for the current study. For the current study, the selection of different weather years was based as: the year having second highest rainfall was selected as wet year, the year having second lowest annual rainfall was selected as dry year and the year having average annual rainfall was selected as average year.

The selected years and the corresponding annual rainfall amounts are presented in the Table 1. Demand and loss amounts are kept same as in the study of Shadeed and Alawna (2021); a typical household water demand of 432 L/day and a loss (for evaporation and leakage) of 20% were considered. With the mentioned data, eTank model was simulated for a series of tank sizes with different roof areas, and corresponding annual water savings as well as reliabilities under all the scenarios were calculated. Reliability is the percentage of the days (in a year) when the rainwater tank is able to fulfil the intended demand. Simulated water savings were compared with the calculated tank sizes using Rippl method as presented in Shadeed and Alawna (2021). A series of plots presenting water savings and reliability versus tank size are presented and from these plots threshold/optimum tank sizes were determined. An optimum tank size is the one, beyond which an increase in tank size will not render any additional water savings. Then, several optimum tank sizes were determined for varying roof sizes (100 m^2–300 m^2) and demands (200–600 L/day) for an average weather condition. Finally, based on these optimum tanks sizes, an equation is derived to calculate optimum tank size depending on roof size and demand, which can be used for the purpose of design.

Table 1
Selected years and corresponding rainfall amounts.

Weather	Year	Annual Rainfall (mm)
Dry	2015 (October) – 2016 (September)	497.8
Average	2017 (October) – 2018 (September)	565.8
Wet	2012 (October) – 2013 (September)	700.8

3. Results

eTank model was simulated with the mentioned demand, loss and daily rainfall data for the three selected years. To compare with the results of Shadeed and Alawna (2021), the roof sizes considered are 100 m^2, 150 m^2, 200 m^2, 250 m^2 and 300 m^2, which were used in the study of Shadeed and Alawna (2021). The following section describe the results of simulated water savings through eTank, and comparision with the Rippl method in regards to optimum tank size.

3.1. Water savings analysis

Fig. 2 (a, b, c, d, e) show the annual water savings versus tank sizes plots under three weather conditions for different roof areas (a: 100 m^2, b: 150 m^2, c: 200 m^2, d: 250 m^2 and e: 300 m^2). From the Fig. 2a it is clear that for smaller size roof (100 m^2), in dry and average years annual water savings do not increase for the tank sizes beyond 15,000 L. However, with the availability of more rainfalls in a wet year, this threshold tank size is increased to 20,000 L. It is to be noted that as per Shadeed and Alawna (2021), through Rippl method the optimum tank size for the same roof area and demand is 49,000 L, which is more than double the optimum tank size calculated in this study. Fig. 2b shows the water savings versus tank sizes plots for the roof area of 150 m^2. From the figure it is found that in dry and average years, the optimum tank size, beyond which an increase in tank size does not yield increase in water savings is 30,000 L. However, in a wet year, this threshold tank size is 40,000 L. It is obvious that for a bigger roof size, the optimum tank size is likely to increase. It is noteworthy that according to Shadeed and Alawna (2021), through Rippl method the optimum tank size for the same roof is 75,000 L, which is almost double the optimum tank size found in this study. For a roof size of 200 m^2, the optimum tank size in a dry year is 45,000 L; whereas in average and wet years the optimum tank size is increased to 50,000 L. As dry and wet years are extreme scenarios, considering only the average weather condition, with the roof sizes of 250 m^2 and 300 m^2, the optimum tank sizes are 70,000 L and 83, 000 L, respectively. These tank sizes are quite big in an urban setup, however such type of analysis would help the end-users to decide appropriate tank size depending on their need and available roof size. Another feature can be noticed from the set of figures is that with the increase in roof size the differences of annual water savings between the average and wet years become narrower. This is due to the fact that in a wet year with the larger catchment (i.e. roof area) more runoffs getting into the tank, causing it to overflow frequently, which will eventually reduce the difference between the wet year and average year water savings.

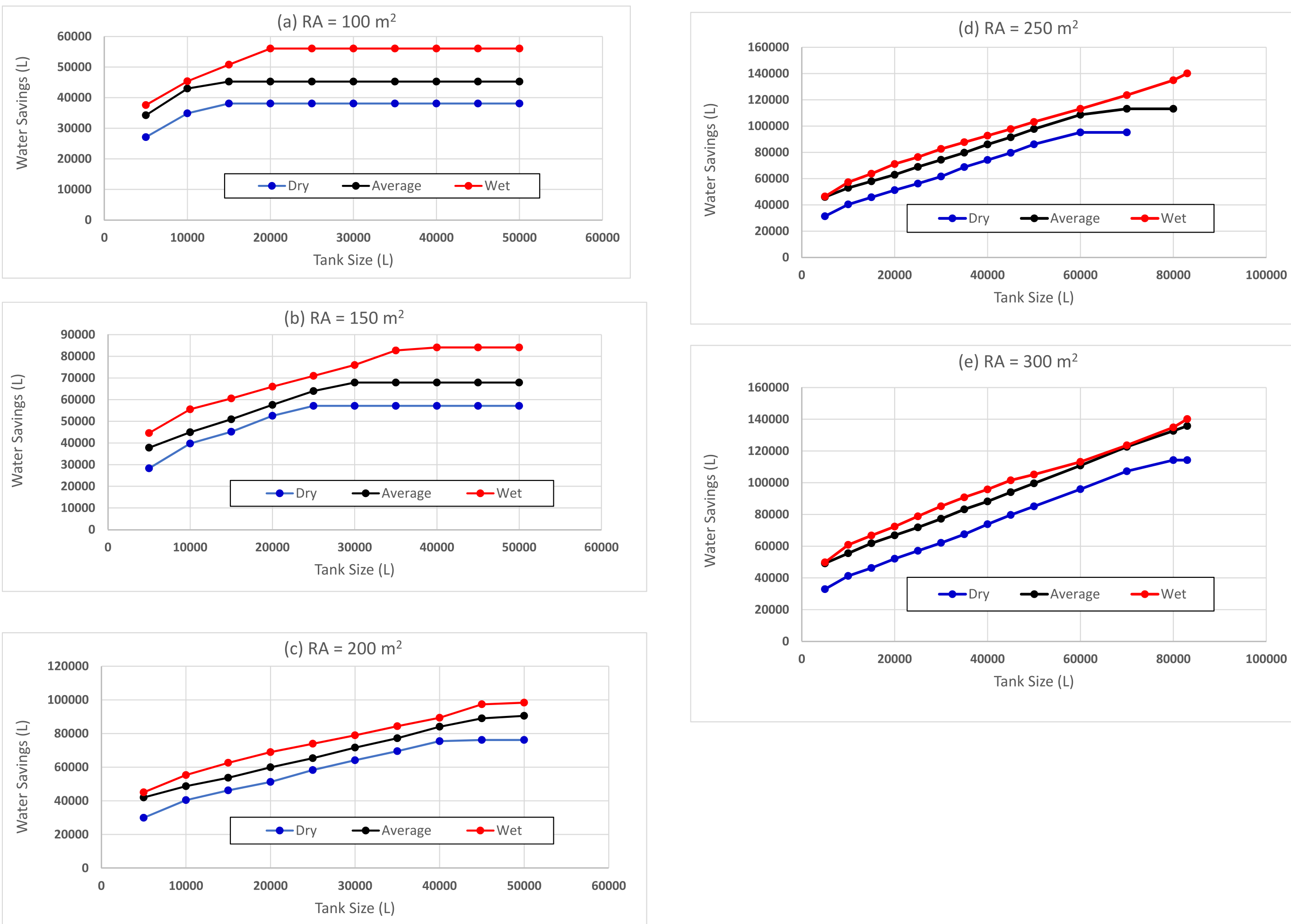

Fig. 2. Water savings versus tank size graphs under different weather conditions for different roof areas: (a) 100 m^2 (b) 150 m^2 (c) 200 m^2 (d) 250 m^2 and (e) 300 m^2.

3.2. Reliability analysis

Fig. 3 (a, b, c, d, e) show the reliabilities versus tank sizes plots under dry, average and wet weather conditions for different roof areas (a: 100 m^2, b: 150 m^2, c: 200 m^2, d: 250 m^2 and e: 300 m^2). From the figures it is clear that the reliability versus tank size plots under different weather conditions follow the similar patterns as in the case of annual water savings. Like the annual water savings, for a particular condition there is an optimum tank size, beyond which an increase in tank size does not render a higher reliability. Patterns of all the water savings versus tank size curves are same and the threshold tank sizes for all the cases are same as in the cases of water savings, i.e. optimum tank sizes are same for both the variables (annual water savings and reliability). From the figures (a, b & c) it is clear that with smaller roof sizes (up to 200 m^2) even with a large tank (50,000 L), in an average year the maximum achievable reliabilities are 27%, 42% and 56% with a tank size of 100 m^2, 150 m^2 and 200 m^2 respectively. However, with larger roof areas (250 m^2 and e: 300 m^2) and very big tank size (>80,000 L) a reliability of 90% is achievable in wet years. It is to be noted that accommodation of such big size tank in an urban setting is often difficult and costly. Moreover, a wet weather condition seldom occurs.

3.3. Generalised equation for optimum tank size

In the previous sections water savings and reliabilities were calculated for different tank sizes and roof areas for a particular demand, 432 L/day, which was selected to compare the results with an earlier study conducted for the same city. For a particular demand it is observed that the threshold tank size linearly varies with the roof area, which can be represented by a linear equation. Similarly, for different demands, similar equations can be derived. The same model was used with the same rainfall and loss data with the same ranges of roof areas and tank sizes considering the daily rainwater demand as 200, 300, 400, 500 and 600 L/day. Optimum tank sizes for each combination of the variables were determined. Fig. 4 shows a set of plots representing relationships between the optimum tank size and the roof area. The figure also showing the equations of the best-fit lines, each line representing a particular demand. It is customary that with the increase of roof area, optimum tank size will also increase as increased roof area means higher rainfall capture (i.e. runoff). From the figure it is clear that individual relationship between the roof area and optimum tank size is linear. Again, a higher rainwater demand will require a higher tank size (i.e. optimum size). However, relationship between demand and optimum tank size is not linear. Also, with the increase in roof area, differences of optimum tank sizes for various demands are increasing. With the aim of deriving a generalise equation incorporating all the demands, the co-efficients and intercepts of all the above-mentioned linear equations were plotted against respective demand. Fig. 5 show the relationships of coefficients (Fig. 5a) and intercepts (Fig. 5b) with the demand. Using Excel best-fit trendline function, Fig. 5a can be represented with the following best-fit equation having R^2 value of 0.97.

$$Coefficient = -0.058*\ln(D) + 0.7025 \tag{8}$$

where, ‘D’ is the rainwater demand in “L/day”.

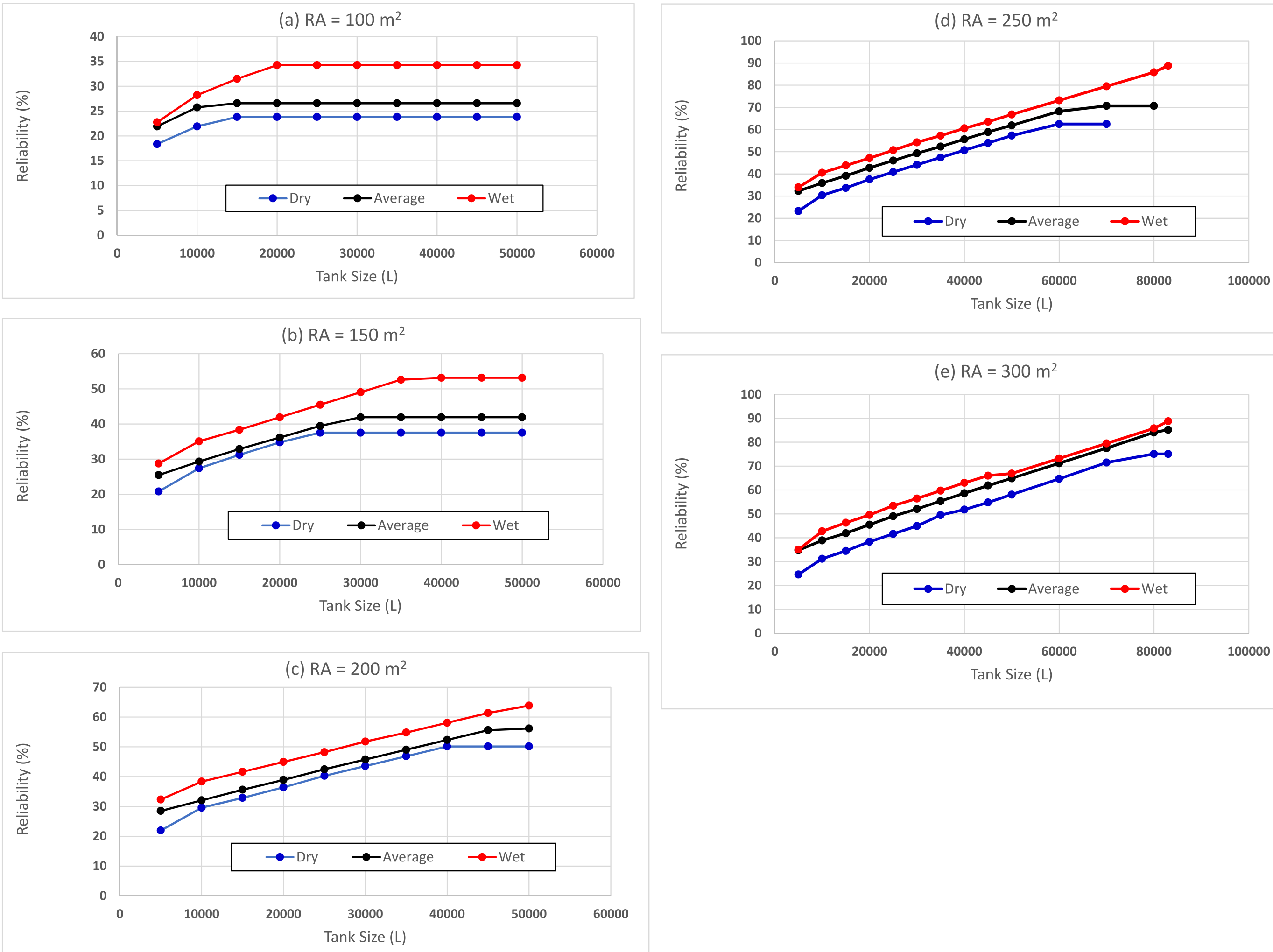

Fig. 3. Reliability versus tank size graphs under different weather conditions for different roof areas: (a) 100 m^2 (b) 150 m^2 (c) 200 m^2 (d) 250 m^2 and (e) 300 m^2.

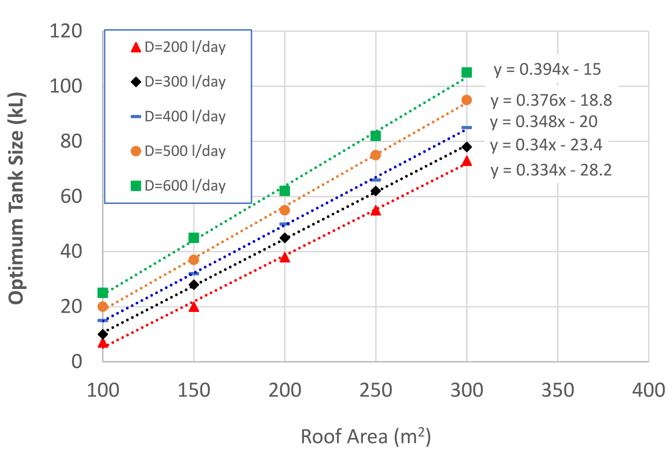

Fig. 4. Optimum tank size versus roof area curves for different demands.

Similarly, using Excel best-fit trendline function, Fig. 5b can be represented with the following best-fit equation having an R^2 value of 0.98.

$$Intercept = 11.397 * e^{0.0015*D} \tag{9}$$

Incorporating above two equations in a linear equation, the final generalised equation for the optimum tank size would be:

$$Optimum\ Size = (-0.058 * \ln(D) + 0.7025) * RA - 11.397 * e^{0.0015*D} \tag{10}$$

where, 'RA' is the roof area in m^2 and the optimum size is in "kL". The derived equation is able to provide optimum tank size for any demand and roof area. Advantage of having such equation is that instead of using a modelling tool (which requires appropriate tool, rigorous data as well as expertise) for rainwater tank size design, one can use such derived generalised equation to derive optimum tank size to be installed depending on particular needs and circumstances.

To assess the accuracy of the developed equation, equation is used to calculate optimum tank sizes for 25 different combinations of roof areas and demands. Fig. 6 shows the comparison of equation calculated optimum tank sizes with the original manually calculated optimum tank sizes. The calculated values provide a correlation coefficient of 1.0, meaning an excellent correlation. It is to be noted that an R^2 value of 1.0 does not necessarily mean a perfect match, rather it means both the datasets are having excellent correlation. In addition to the calculated values, Fig. 6 also shows an ideal 45° line and it can be seen that all the points (i.e. calculated values) are very close to the ideal line, which ascertains the accuracy of the derived equation in calculating optimum tank size.

4. Conclusions

Being an easily achievable sustainable feature, rainwater tank has

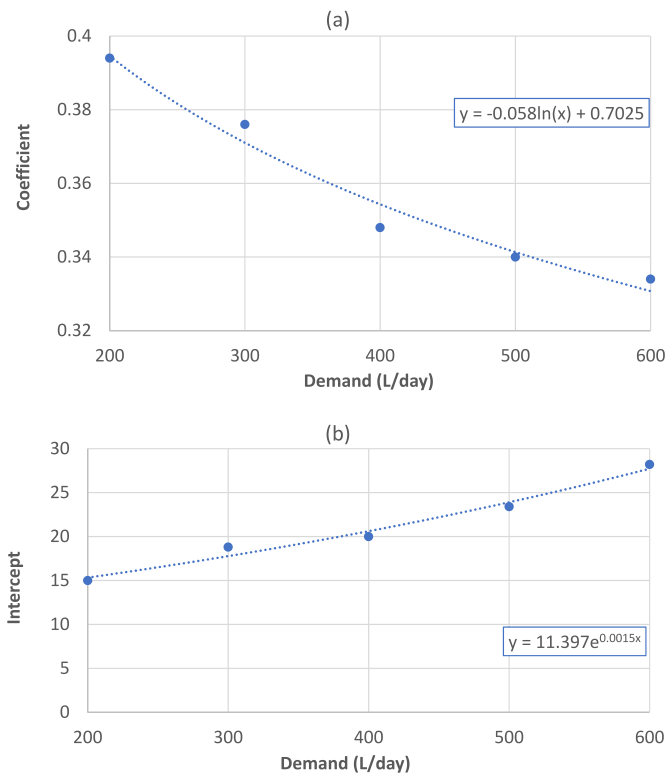

Fig. 5. Relationships of demand with optimum tank size versus roof area equations': (a) coefficients, and (b) intercepts.

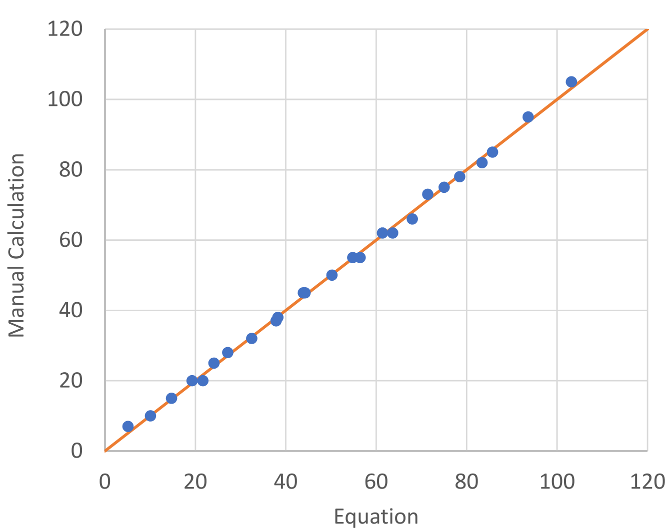

Fig. 6. Comparison of optimum size calculations through equation and manual calculation.

been promoted by many authorities. However, size optimisation is a crucial factor towards the implementation of rainwater tank, especially in urban areas where space is limited or expensive. In addition, bigger tank size will cause higher initial costs. An optimum tank size is necessary to achieve a higher benefit-cost ratio or a lower payback period of the associated costs. However, an accurate estimation of optimum tank size was not easy, often required use of specific software tool, rigorous data as well as relevant expertise. Among the methods of estimating optimum size, the daily water balance modelling approach has been widely used. Rippl method is another method which has been used by some other researchers. This paper presented details of a daily water balance model and produced series of model results on annual water savings and reliability under different input scenarios and weather conditions. From eight years' of available data, three years were selected as dry, average and wet years. It is to be noted that such shorter period data may not be fully representative, however due to the scarcity of daily rainfall data for the selected region, being a pioneer study on such analysis, shorter peroid data can be accepted to explore the issue related to weather variability. It is recommended that with the availability of longer period data, in future such analysis can be reiterated.

Daily water balance model results in regards to optimum tank size were compared with the results through Rippl method. In an earlier study, as the Rippl method was used to calculate optimum tank sizes for the city of Nablus (Palestine), for comparison, this study used the same city, same roof and tank sizes, as well as same demand. Moreover, for the current study, available daily rainfall data from the city was categorised into three distinct years; dry, average and wet. A series of water savings and reliability curves were produced for 195 different combinations of tank sizes, roof areas and weather conditions with the demand used in the earlier study. From the produced curves, the optimum tank size for a particular combination of the variables was determined through visual inspection of the set of curves. An optimum size is the one, beyond which an increase in tank size does not render any additional water savings benefit. It was found that the daily water balance model produced optimum tank sizes are much smaller than the one reported in the earlier study using Rippl method. It is concluded that while Rippl method might be effective for reservoir or detention basin design, it is not accurate for rainwater tank optimisation.

With the aim of deriving a generalised equation for the calculation of optimum tank size without using a modelling tool and having tedious calculations, this study used an earlier developed water balance model (eTank) for the calculations of optimum tank sizes for 25 different combinations of roof sizes and demands with daily rainfall data for an average year. From the results, it is clear that optimum tank size linearly varies with the roof area for a particular demand. Five such linear relationships were derived for five different demands. It was found that coefficients and intercepts of these linear equations can be correlated with logarithmic and exponential functions, wich eventually can be incorporated to a single equation having roof area and demand as independent variables for the calculation of optimum tank size. It is shown the equation calculated values are very closely matching with the manually calculated optimum sizes having an excellent correlation ($R^2 = 1.0$). It is to be noted that such equation is valid for the studied city only. It is not valid for other city/location, as the rainfall amount and pattern will be different for different cities. A future study incorporating different rainfall amounts and patterns is recommended which can endeavour to derive a universal generalised equation of optimum tank size valid for any region.

CRediT authorship contribution statement

Monzur Alam Imteaz: Conceptualization, Formal analysis, presentation, preparation of manuscript. **Sameer Shadeed:** Data collection, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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