Reliability of rainwater harvesting

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Abstract

The increased emphasis on sustainability has resulted in an effort to reduce the reliance on municipal water in favor of the use of collected rainwater. This paper addresses the reliability of rainwater collection and use for residential buildings. It describes a procedure that utilizes a water balance based on the amount of collected rainfall, household demand, and storage tank capacity. The probabilistic nature of rainfall is incorporated by establishing weekly exponential distributions based on historical data. These rainfall distributions are used in a Monte Carlo simulation along with characteristics of the residential system (catchment area, storage tank size, household demand, etc.). Results show that along with the size of catchment area, the storage tank capacity is critical in determining the reliability of the system. The procedure is illustrated with data from Portland, Oregon.
Keywords: rainwater harvesting, reliability, residential water supply.

1 Introduction

With increasing water rates, a growing number of homeowners are considering the use of rainwater to help lessen the reliance on municipal water. While the practice is more common in other countries, it is far from widespread in the U.S. In addition, water supply utilities are also looking for ways to reduce water use and forestall the need for capacity expansion. Judicious use of rainwater has the potential to address both concerns. The intent of this paper is to assess the potential use of rainwater for domestic purposes in Portland Oregon, paying particular attention to the reliability of rainwater collection.

1.1 Previous work

The use of rainwater has been addressed by a number of individuals and organizations, but usually from the practical viewpoint of design. There are a

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number of publications that emphasize overall sustainable practice with sections on rain harvesting (e.g., City of Austin [1], Barnett and Browning [2]). Others are specific to water supply (e.g., Milne [3], Pacey and Cullis [4]). Several publications are aimed specifically at developing countries, where safe distribution systems may not be in place (e.g., Fok et al. [5], Minnigh et al. [6], Schiller and Latham [7]), or where rainfall is minimal (e.g., NAS [8], Minnigh et al. [6]). Much of the published work on rain-water harvesting pertains to the practical aspects of systems, including component design, code issues, and expected water yield. The Texas Water Development Board [9] presents a step-by-step approach to estimate how much rain might be collected, along with rainfall frequency curves for several cities in the state. Few approaches have attempted to incorporate the reliability of rainfall by analyzing the variability and sequencing of rainfall on a period-to-period basis. Schiller [10] presented a method using monthly time increments and historical rainfall data.

1.2 Rainwater collection components

While there are several variations, a basic rainwater collection system incorporates the following components: (1) catchment – an impervious surface that collects rain, usually a roof, (2) collection – gutters and downspouts to direct the water from the catchment area to storage, (3) first flush diverter – a device to divert the initial fraction of rainfall, (4) storage – a reservoir that stores collected rainwater for future use, (5) overflow – a means of removing excess water from the tank, (6) conveyance – a delivery pipe from the tank to the end use, and (7) treatment – a means to improve quality to meet end use requirements.

The important components for this study are the catchment and storage. The size and surface characteristics of the catchment are important in determining the quantity of water entering the tank. Naturally, there is a linear relationship between the catchment area and the amount of rainwater collected. For every one inch of precipitation, roughly 2/3 of a gallon of water is collected per horizontal square foot of the catchment. However, some initial rain is lost through the wetting of the roof. In addition, for better water quality, the collection sys-tem is often designed to divert away from the tank the initial portion of the runoff (first flush). The storage tank is a critical determinant of the system reliability. A larger storage tank will allow for a longer water delivery period through dry months.

1.3 Portland's rainfall

Portland's precipitation averages approximately 37 inches per year, with most of it falling as rain between October and June. Daily rainfall values for Portland exist for 62 years, from which weekly averages were determined, as shown in Figure 1. The resulting table of 52 values for each of 62 years was used to determine statistical parameters, appropriate distributions, and correlation coefficients.

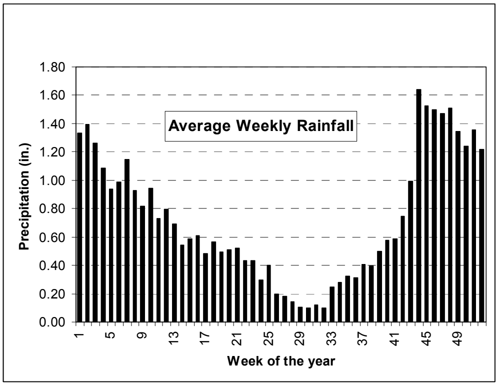

Figure 1: Histogram of weekly average rainfall amounts for Portland Oregon.

2 Reliability analysis

2.1 Water balance

A spreadsheet program was created to account for water inflow, outflow and storage in the system. For each of the simulations several user-defined parameters were required, including: daily demand, catchment (usually roof) size, storage tank capacity, percent-age lost to first flush, and the status of the tank (full or empty) at the start of simulations. A simple water balance, shown in Equation (1), was used to deter-mine the volume stored at the end of the current week by adding weekly rainfall to the storage carried over from the previous week, and subtracting the weekly demand. The rainfall, in inches, was selected from an appropriate statistical distribution, described later.

$$S_{i+1} = S_i + (1 - flush)(I_i) - D_i = \begin{cases} 0 & \text{if } S_{i+1} < 0 \\ CAP & \text{if } S_{i+1} > CAP \\ S_{i+1} & \text{otherwise} \end{cases} \tag{1}$$

where:
S_{i+1} = storage at end of week i,
S_i = storage at beginning of week i,
flush = the fraction of a rainfall event diverted from storage tank,
I_i = inflow during week i
$= \left(\frac{1}{12}\right)\left(7.48 gal./ft.^3\right)\left(\text{roof size } in\ ft.^2\right)\left(\text{rainfall } in\ inches\right)$,
D_i = water demand during week i, and
CAP = capacity of tank.

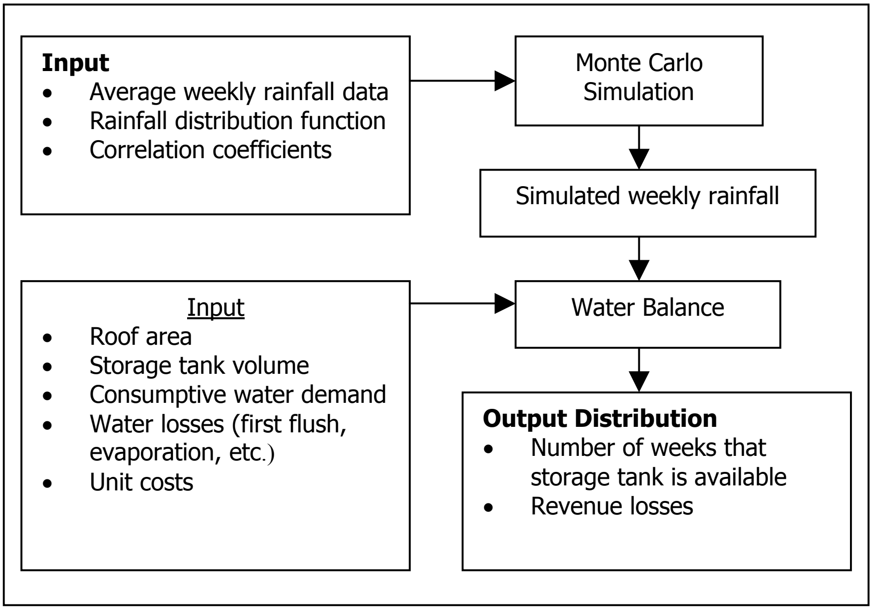

Figure 2: Diagram of the procedure.

Figure 2 shows a schematic diagram of the procedure. For each week, the spreadsheet recorded tank availability (i.e., non-zero storage at the end of the week). The water balance was conducted for 52 weeks of the year, and the total number of weeks that the tank was available for use was determined. The water balance was performed on a yearly basis, starting each new simulation with the beginning of each calendar year. This assumption corresponds to the practice of not using the tank when it is empty during the later summer and early fall months, and allowing the tank to fill during the fall. Therefore, week number one was assumed to be the first week in January, starting the water balance with a full tank.

2.2 Reliability analysis

The reliability of a rainwater collection system cannot be determined using only the weekly average rainfall. Examination of the average precipitation data for Portland indicates that when averaged over the historical record, each week of the year receives some rainfall. However, closer examination of all the data shows that in some years Portland can go several weeks during the summer months without any significant precipitation. A storage tank designed using average weekly precipitation data may not be adequate during dry summers. In order to determine the reliability of a storage tank during dry periods, the variability in rainfall must be incorporated into the water balance analysis. A stochastic component was incorporated into the analysis by defining probability distributions for each week of rainfall included in the water balance and beginning of each calendar year. This assumption corresponds to the practice of not using the tank when it is empty during the later summer and early fall months, and allowing the tank to fill during the fall. Therefore, week number one was assumed to be the first week in January, starting the water balance with a full tank.

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To incorporate rainfall probability distributions, each of the 52 weekly data sets was analyzed using both Chi Squared and Kolmogorov-Smirnov tests. The exponential distribution generally provided an excellent approximation of weekly rainfall frequencies.

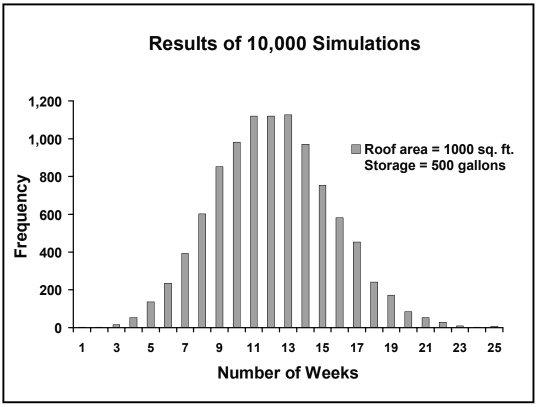

Figure 3: Frequency distribution for 10,000 simulations of tank availability for roof area of 1000 sq. ft. and tank size of 500 gallons.

2.4 Interpretation of simulation output

Monte Carlo simulations consisted of 10,000 iterations of the water balance, each based on 52 weeks of rainfall data generated from 52 exponential distributions. The output from these simulations is presented as a distribution representing the number of weeks in a calendar year that the storage tank is available for use. From these distributions, a reliability can be associated with the specific number of weeks that the tank is avail-able.

The results of one simulation for a roof area of 1,000 ft^2 and a tank size of 500 gallons are shown in Figures 3 (probability distribution) and 4 (cumulative distribution). As can be seen the results are sym-metrical, resembling a normal distribution. For a particular combination of roof area and tank size, the reliability associated with the number of weeks that water is available can be predicted. For example, there is a 90% chance that water will be available in the tank eight weeks of the year. Where as, the probability that the tank will be available 12 weeks of the year, is only 50%. At the other extreme, there is only a 10% chance that the tank will be available for 17 weeks.

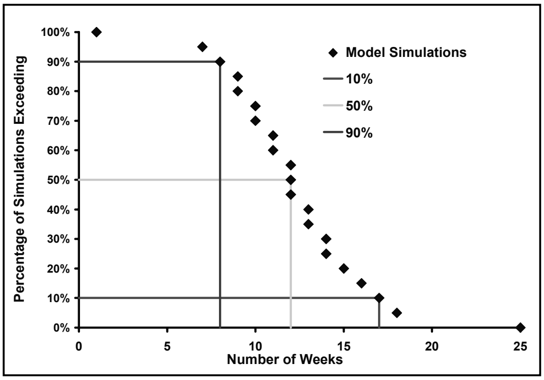

Figure 4: Cumulative distribution 10,000 simulations of tank availability for roof area of 1,000 sq. ft. and tank size of 500 gallons.

3 Results

Simulations were performed for roof sizes of 1,000, 2,000, and 3,000 sq. ft. and for tank sizes varying from 200 to 1,500 gallons. Reliability results for these combinations of roof area and storage tank volume are summarized in Figures 5, 6, and 7. Also shown in these figures is the number of weeks of available storage obtained by simply using the 62-year average rainfall for each of the 52 weeks of the year. As would be expected, for a desired reliability, as the tank size and roof size increase, the number of weeks that the tank is available for use also increases. It is interesting to note that the relationship of the “aver-age results” (those calculated from a single simulation using the 62-year average weekly values) to the reliability results, changes with different roof sizes. In particular, for the 1,000 ft^2 roof, using an average value significantly underestimates the utility of the systems for all tank sizes. For the 2,000 ft^2 roof, the "average results" show relatively good agreement with the reliability predictions. With the 3,000 ft^2 roof, the utility of the system is overestimated for smaller tank sizes using "average results," but both the "average results" and reliability predictions are in agreement for larger tank sizes. Thus, not only is there an apparent disagreement between "average results" and reliability predictions, this discrepancy is a function of both roof area and storage tank volume. This seemingly anomalous result is addressed further in the discussion section.

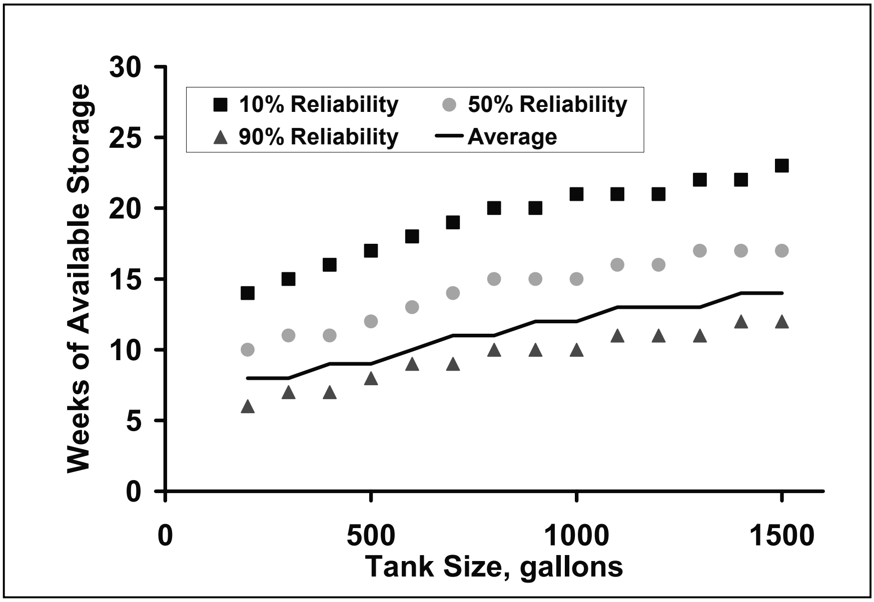

Figure 5: Reliability results for a 1,000 sq. ft. roof area.

4 Discussion

4.1 Reliability

As can be seen from Figure 5, for a specified number of available weeks (a horizontal line on the figure), the reliability increases with tank size. Likewise, for increasing roof size (Figures 5, 6, and 7), the reliability increases. However, when comparing the results using average values to the median results (50% reliability), a different trend is apparent. The effect of the difference is most dramatically seen in Figure 7, where for a small tank (200 gallons), the calculation using weekly average rainfall amounts yields an available supply for 34 weeks, whereas the median simulation result yields only 26 weeks. In contrast, for a large tank, the two approaches yield about the same result. One can draw the conclusion that, for Portland's rainfall data, the average and median results are not significantly different for large roofs and large tanks, but they are for small tanks.

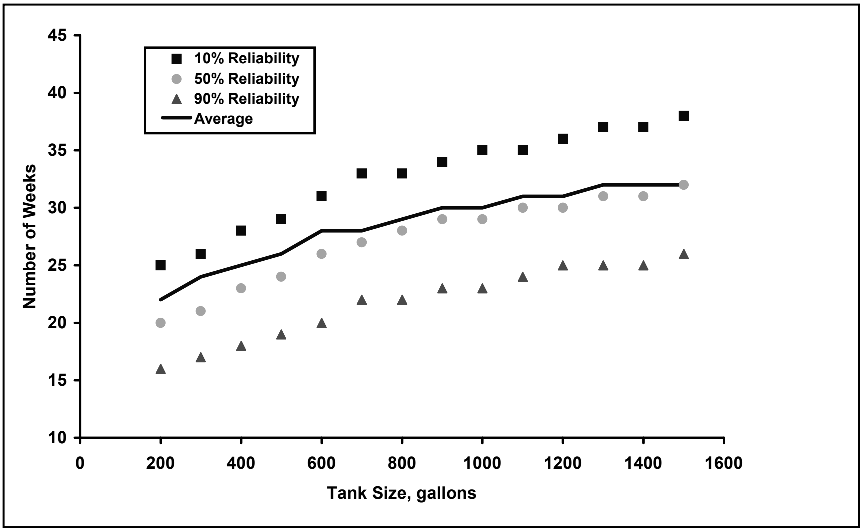

Figure 6: Reliability results for a 2,000 sq. ft. roof area.

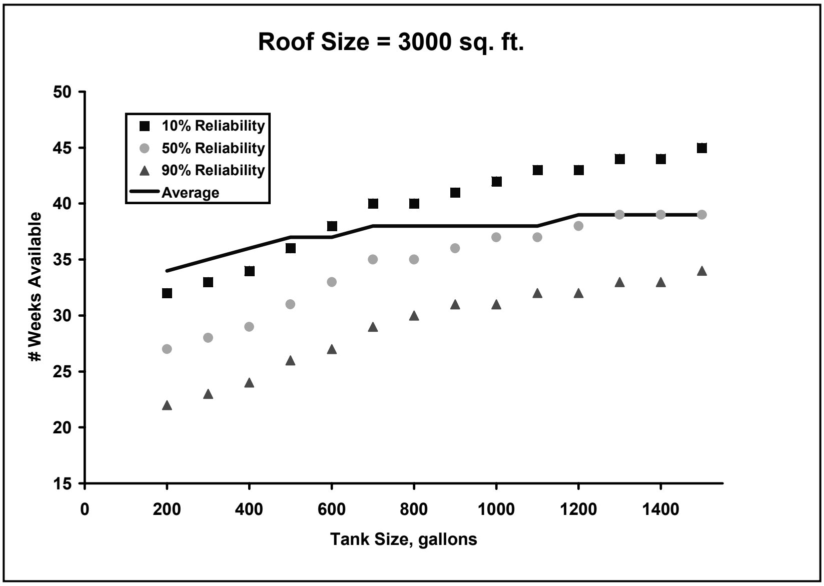

Figure 7: Reliability results for a 3,000 sq. ft. roof area.

These results can be explained by the fact that the mean value for the heavily skewed exponential distribution of precipitation values is higher than the median value. While it is true that the median value is not used as an input value (as the mean is), many more of the input values that are selected from the input distribution tend to be closer to the lower, median value. During the dry summer months when rainfall is low, mean values do not represent a likely sequence of low rainfall; a sequence of values quite likely at, or close to zero. For a small tank, the mean values (larger relative to the values close to the median) have a more pronounced effect on filling a tank, particularly a small tank. For example, for week 25, which leads into the dryer summer weeks, the average weekly rainfall of 0.4 inches will fill a 500-gallon tank to almost 85% of its capacity. The median value only provides only about 59% of the tank capacity. Note that for each of these calculations, 15% is subtracted for first flush.

4.2 Water savings

The simulation procedure is likely to underestimate the amount of water that can be utilized by a rain harvesting system. Because the computational routine is set up with weekly increments, the maximum amount of water that can be provided on a weekly basis is equal to the capacity of the tank. In reality, even though it may not rain continuously and water may not be used continuously, the tank is not emptied and filled only once a week, as is done in the routine. Therefore, depending on rainfall and demand, the amount of water available for use over a week's time could exceed the tank volume. For example, for a 1,000-gallon tank, the procedure can utilize at most 1,000 gallons a week. Yet if the problem is addressed on a daily basis, it is theoretically conceivable that the tank could refill every day, allowing the use of up to 7,000 gallons a week. This scenario assumes a 3,000 sq. ft. roof and 0.8 inches of rainfall a day, seven days in a row. This rainfall is higher than normal for Portland. However, when picking a rainier-than-average week (week 48) and the median value from that week (1966), the daily rainfall values of 0.03, 0.04, trace, 0.19, 0.27, 0.21, and 0.18 inches yield a usable volume of over 1,350 gallons, higher than the 1,000 gallons the procedure would have determined. This calculation assumes the first three daily values never reach the tank and the others are reduced by the first flush amount of 15 percent. There are many weeks during the historical record that have far greater weekly rainfalls. The continuous-use scenario assumes that the user takes advantage of the system daily; for example it is connected permanently to the household supply, allowing use of the municipal water if the tank goes dry during a day. A procedure using daily time increments is an area for further research.

5 Summary and conclusions

This study assessed the reliability of residential rainwater harvesting systems to supply water for different catchment areas and storage volumes. In particular, the procedure determines the number of weeks that such a system is available to supply a given demand. Results of the approach show that for rainfall patterns similar to those seen in Portland Oregon, combinations of roof/tank sizes from 1,000 sq. ft./500 gallons to 3,000 sq. ft./1,500 gallons have a 50% probability of reducing annual municipal water use by 8,000 to 27,000 gallons, respectively, for each system installed.

Several conclusions can be drawn from the study:

- Median (50% reliability) storage availability can not be predicted based on average weekly rainfall data,
- Reliability analysis gives a more complete picture of the effects of roof area and storage tank size on performance of rainwater harvesting systems, and
- Rainwater harvesting can reduce water use.

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