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RESEARCH ARTICLE

Development of an Algorithm for Sizing Storage Systems for Rainwater Harvesting

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Abstract

This paper investigates the potential of a Rain Water Catchment System (RWCS) for meeting and/or supplementing the irrigation requirements for urban residential landscapes in a Canadian situation. In a specific usage of harvested rainwater for irrigation the urban landscape, the determination of the potential landscape area is best achieved through the spreadsheet-based water balance studies. Such computer based water balance programs invoke recursive approach to maximize the landscape area that can be irrigated by the rainwater catchment system by setting the design rainfall at a desired probability level, preferably at 50% (median value). The methodology developed in this paper was applied to size the rainwater storage systems for the city of Thunder Bay, Canada. The median roof catchment area was determined as 120 m^2 and the capacity of an optimal RWCS was found to be approximately 1500 litres i.e., three tanks of 500 litres each that are commonly available in the market.

Key Words: Exceedance Probability, Frequency Analysis, Rain Water Catchment System, Rain Water Harvesting, Spread Sheet, Urban Landscape

Introduction

For centuries, rainwater has been collected and stored in ponds, cisterns, sub-surface tanks, and in the soil to support the human settlements in Asia, Africa, and Europe (UNEP, 1983; Gould, 1993; Ngigi, 1995; Li & Gong, 2002). In the recent years, small on–site rainwater harvesting systems have been successfully implemented as alternative water supply sources in some countries like Japan, Hong Kong, Singapore, and the United States (Su *et al.*, 2009). Even though Canada is endowed with immense quantity of water resources, yet the need for effective water management is imminent to meet the growing demand of quality water in urban centres such as the cities of Vancouver and Victoria in the Province of British Columbia (Steele, 1996) During summer months, one major usage of treated water is for irrigation of urban residential landscape in Canada, which is known to consume up to 60% of potable water (Steele, 1996). Such a relatively benign but wasteful practice is straining water resources and treatment plants to a degree that residents and engineers alike are seriously examining alternate ways of conserving the use of potable water. One promising alternative to conserve the potable water is harvesting the summer rains through Rainwater Catchment System (RWCS) for irrigating the residential landscape, communal fire fighting, waste disposal, street cleaning operations etc.

A rainwater harvesting system is comprised of a catchment, a system of conduits, a system of storage elements, and other appurtenances. The entire assemblage is termed as rainwater catchment system (RWCS). Many roof-tops are designed to channel water to one or two focal points before discharging onto lawns or municipal storm water system. In most cases, all that is required is a storage tank and some minor alterations to direct roof rainwater into the storage to provide an alternative source of irrigation water for residential landscape. According to Environment Canada (1995), an average suburban landscape uses 100 m^3 of water in a growing season, which can be met by installing a RWCS. It is to be noted that RWCS not only conserves the potable water but also reduces the storm water peaks by enhancing detention storage (Su *et al.*, 2009). In hydrologic sense, the most important component of a RWCS is the storage element, whose design merits considerations (Mitchell, 2007) of probabilistic features of rainfall. In a bid to develop a rational procedure for estimating optimal storage size for rainwater harvesting systems, this paper examines the relationship between rainfall and water demand for a specified usage such as landscape irrigation in the Canadian context.

Development of a Recursive Algorithm for Sizing Rainwater Storage

To determine the most general water demand of a typical urban residential landscape, the obvious choice is lawn-grass as the predominant form of vegetation, since lawns are the dominant-feature in urban residential landscapes. Incidentally, lawn-grass is also one of the most water demanding species of plants. This form of vegetation is used in the design process presented in this paper. The minimum amount of moisture specified by standard horticultural textbooks for a typical urban residential landscape is 25 mm per week (Snyder, 1964). Other recommendations also suggest that water be applied to wet the soil to a depth of between 100 and 200 mm. This condition corresponds approximately 24 to 40 mm of water (Carbeen, 1987). The variation in water demand is due to varying characteristics of soils. A rainfall of 24 mm is known to soak down a dry soil column to 300 mm, 200 mm, and less than 120 mm respectively in sandy soil, loamy soil, and clay soil (Snyder, 1964). For design purposes, the mean value of say 32 mm [(24+40)/2] per week is assumed to be representative for lawn watering demand per week.

Because water demand is expressed as a weekly total (implying that a weekly rainfall is tantamount to an event rainfall), it was therefore decided to develop the methodology on a weekly time frame. The storage unit is the link between the rainwater supply and water demand of the landscape. The purpose of the storage tank is to hold the collected rainwater from the roof-catchment area until it is required for the landscape. The size of storage tank is dependent on both the rainwater supply and water demand of the landscape. Therefore, the sizing of storage is best accomplished through a water balance based recursive algorithm. For the specific case of rainwater harvesting towards irrigation of an urban residential landscape, one such algorithm involving a spreadsheet computational scheme is presented below.

The design rainfall in the i^{th} week (R_i) is the rainfall-depth (mm) which is expected to occur during the week. This quantity is represented in tabular form in Column-2 of Table 1.The volume (m^3) of rainwater from roof-catchment during the i^{th} week is presented in column-3 (Table 1) and is obtained as follows.

$Q_i = R_i\ C_r\ A_r/1000.$ (1)

Where, Q is the weekly rainwater volume from roof catchment (m^3), C_r is the runoff coefficient of roof-catchment, and A_r is the area of roof-catchment (m^2). The term runoff coefficient is defined as the ratio of the runoff generated (depth or volume) due to the rainfall to the total rainfall of the event.

The volume (m^3) of the supplemental water demand for irrigation (S_i) given in column-4 (Table 1) is computed as follows.

If $[R_i\ (1\text{-}C_l)] \geq (WWD - SMS_{i-1})$ then $S_i = 0.0$
Otherwise $S_i = [WWD - R_i\ (1\text{-}C_l\ ) - SMS_{i-1}]*A_l\ /1000.$ (2)

Where, C_l is the runoff coefficient of the landscape, WWD is the weekly water demand (mm), SMS is the weekly soil-moisture storage (mm), S is the weekly supplemental water demand (m^3), and A_l is the landscape area (m^2).

The volume (m^3) of the soil-moisture storage (SMS_i) given in column-5 (Table 1) is computed as follows.

If $[WWD - R_i\ (1\text{-}C_l\ ) - SMS_{i-1}] < 0.0$ (3)
then SMS_i = Absolute value of $\{WWD - R_i\ (1\text{-}C_l\ ) - SMS_{i-1}\}$, subject to the constraints:
If $SMS_i \geq WWD$ then $SMS_i = WWD$, and $S_i = 0.0$.
If $[WWD - R_i\ (1\text{-}C_l\ ) - SMS_{i-1}] \geq 0.0$ then $SMS_i = 0.0$. (4)

The indicator value (I_i) for the failure or success of the actual storage size (ASS_i) to meet supplemental water demand in the i^{th} week is represented respectively by 1 or 0 in column-6 (Table 1) and is computed as follows. It is noted that the number 1 or 0 simply represents failure or success in the i^{th} week for later use in the computation of failure rate (P_f).

If $[ASS_i+Q_i - S_i] \leq 0.0$ then $I_i = 1$
Otherwise $I_i = 0.0$. (5)

The volume (m^3) of actual storage size (ASS_i) for rainwater harvesting given in column-7 (Table 1) is computed as follows.

If $[ASS_i+Q_i - S_i\ ] \leq 0.0$ then $ASS_i = 0.0$ (6)
Otherwise $ASS_i = [ASS_{i-1}+Q_i - S_i\ ]$.

The computation of a rainwater storage size should begin for a set of rainwater input data with SMS equal to WWD, and ASS equal to zero. In some parts of the world, especially North America, the presence of snow prior to rainfall arrival in Spring season ensures that soil moisture storage (SMS) would be at or near its maximum values.

Table 1. Tabular Water Budget for the Design of RWCS

Week (i)	Design Rainfall (R)	Roof Rainwater Volume (Q)	Supplemental Water Demand (S)	Soil Moisture Storage (SMS)	Indicator Surplus/Deficit (1/0) (I)	Actual Storage Size (ASS)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1						
2						
:						
n						

The value (0 or 1) in column-6 indicates whether the water demand has been met or not. Due to the occurrence of insufficient rainfall, a water deficit would happen and consequently the storage tank would run dry. Knowledge on the frequency of water deficit occurrences would be helpful. First, an occurrence of a water deficit evidently signals that the system has failed to provide the necessary supplemental water demand. The occurrence of this condition suggests that the design parameters must be altered for optimal storage size. Such alterations may involve a decrease in the level of rainfall reliability, an increase in the catchment surface area, and/or a reduction in the area of landscape. Determination of the optimal design involves a recursive algorithm, as described earlier, which is best achieved on a computer. Secondly, for fixed values of various parameters, the number of occurrences of water deficit would indicate the likelihood of number of weeks during which the system would fail. The failure rate of the RWCS is obtained by dividing the number of weeks during which a water deficit did occur by the total number of weeks (n) in a rainwater collection season. That is,

Failure rate of the RWCS = P_f =Total number of failures / n (7)

In the water balance analysis pertaining to the occurrence of a weekly water deficit, the following considerations are invoked. 1) The water must be supplied from rainwater storage to residential landscape during weeks of insufficient rainfall. 2) For an inadequate volume of rainwater in storage (ASS), the rainwater cannot be rationed to satisfy the water demand in the subsequent weeks.

For determination of the optimal storage size, one can proceed either graphically or numerically. In a graphical solution, the actual storage size (ASS) from column (7) in Table 1 is plotted against time. An analysis of such a plot based on sequent peaks (Linsley & Franzini, 1979) would determine the optimal storage size. One can also obtain the optimal storage size for the RWCS (i.e., the maximum value between the successive peaks and troughs) based on sequent peaks in column-7 in Table 1. A storage unit with larger volume would be able to store more water but such an excessive volume of water may not be required by the urban residential landscape. However, a storage unit less than the optimal volume would result in periods during which the storage tank will run dry i.e., a water deficit would occur.

Study Area

The City of Thunder Bay, Ontario (Canada) was selected for the rainwater collection study because of easy access to relevant data sources. Thunder Bay is located at the Northwest tip of Lake Superior and lies at an altitude of 183 m above sea level. For its approximately 114,000 inhabitants, it is a relatively spread out city occupying an area of 323.5 km^2. There are approximately 46,900 houses in the city of which 68.2% are single dwellings. This percentage of home ownership is 10% higher than the national average, and also represents the fourth highest in Canada (TB-2002, 1994). The cities and towns with a large percentage of home ownership would benefit more with the rainwater usage because tenants are unlikely to participate in such water conservation practices. The City lies in an unique climatic region and normally has the continental climate. However, the proximity of Lake Superior has a moderating effect on the temperatures as well as adding moisture to the otherwise dry air. The winters are long and cold, and last nearly 6 months. Despite this, the city has a record of sunshine in Ontario, averaging 2,200 hours annually. The regional climatic factors determine the seasonal length during which the rainwater catchment systems (RWCS) are expected to be operational. The RWCS are normally designed for a period during which the average temperatures are well above freezing. The growing season in Thunder Bay region is short (90 to 112 days) and therefore, the need for residential irrigation water is limited only to this period.

In particular, three sets of meteorological records are required for the determination of the seasonal time period during which the RWCS are expected to be functional. The first data set is used in determining the length of the supply season (i.e., the period during which precipitation occurs as rainfall). In turn, this requires the determination of the first day and the last day of the presence of snow on ground. The second data set is used as a check to ascertain that the mean daily temperature during the rainwater supply season is above freezing. In turn, such an observation helps in discerning the likelihood of excessive ice build up that may damage the storage tank. The final data set is used to determine the start and end dates of the growing season. The analysis of minimum daily temperatures above freezing defines the start and end dates of the growing season and in turn the water demand period of the residential landscape.

Climatic records used in this paper have been collected for the meteorological station located at the Thunder Bay Airport. Data sets for this station from 1942 to 1991 (50-year) were readily available. The data sets were checked for completeness, homogeneity, trend, and randomness. For such tests, one may use one of the existing statistical tests such as mass analysis, double-mass analysis, von Neumann ratio test, cumulative deviations, likelihood ratio test, and the run test. The homogeneity of rainfall records is commonly checked by mass and double-mass analyses. Due to lack of suitable precipitation records of nearby meteorological stations, the double mass analysis was not used.

Because many stations have had missing data gaps, a "piece-wise" approach was used to test individual blocks of the data, and gaps filled appropriately.

Application of Methodology

Based on the analysis of residential lot sizes in the City of Thunder Bay, the median residential roof-catchment surface area was determined to be approximately 120 m^2 (Rebneris & Panu, 1996). The analysis of rainfall data indicated that the duration of rainwater harvesting season is to be from April 26 to October 31 (i.e., 27 weeks). A further analysis of mean weekly temperatures in the beginning of Spring season and also towards the end of Fall season aided in discerning the duration of residential landscape water demand season from May 17 to October 10.

Determination of Design Rainfall

The frequency analysis of weekly rainfall data from April 26 to October 31 (i.e., 27 weeks) for Thunder Bay was conducted to determine the probability of exceedance of a given weekly rainfall value using the well known Weibull plotting position formula. Frequency curves for each of 27 weeks were developed using 50 years of weekly rainfall data sets. From each of these curves, weekly rainfall values corresponding to various probabilities of exceedance (4%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%) were obtained. A compromise value of the exceedance probability can be taken at 50% i.e., the median value, which falls within the realm of common design practices. The median value has another advantage in that it represents a central value thus ensuring a near probability free distribution analysis of rainfall data. Therefore, the design rainfall was taken as the median value of the week, which means there are 27 values of rainfall corresponding to weeks in succession. For the city of Thunderbay, these values were determined as 5.4, 4.8, 6.4, 5.4, 10.2, 11.6……2.7, 2.7 mm for successive weeks.

Determination of Optimal Storage Size

For various computational requirements, a spreadsheet based algorithm as outlined earlier in Table 1 was used. This algorithm relates the maximum size of landscape which can be irrigated by a roof-catchment area for a weekly rainfall values corresponding to a desired probability of exceedance (50% in the present case). In this algorithm, the rainfall collection commences in the first week of the season beginning on April 26 and the water demand for irrigation begins in the third week of the season beginning on May 10. During this period, therefore, the soil moisture storage can be considered at or near its full capacity. Likewise in the fall season, the rainwater harvesting process terminates as the water demand for irrigation ceases on the last day (October 10) in the 24th week of the season. For computational brevity, the runoff coefficient of the urban residential landscape is assumed to be zero. The weekly water demand for irrigation was assumed to be 32 mm. As the probability of exceedance of the design rainfall decreases, the landscape area, which can be irrigated, increases and vice versa. A specific case pertaining to sizing a rainwater storage system for the weekly-expected (median) value of rainfall was carried out and the weekly values 5.4, 4.8, 6.4, 5.4, 10.2, 11.6……, 2.7 mm were used as inputs. Using the spreadsheet algorithm as discussed above and plugging the above median values of weekly rainfall, Table 1 was filled. The values in column 7 in Table 1 were plotted graphically as shown in Figure 1 as a representation of sequent peak analysis.

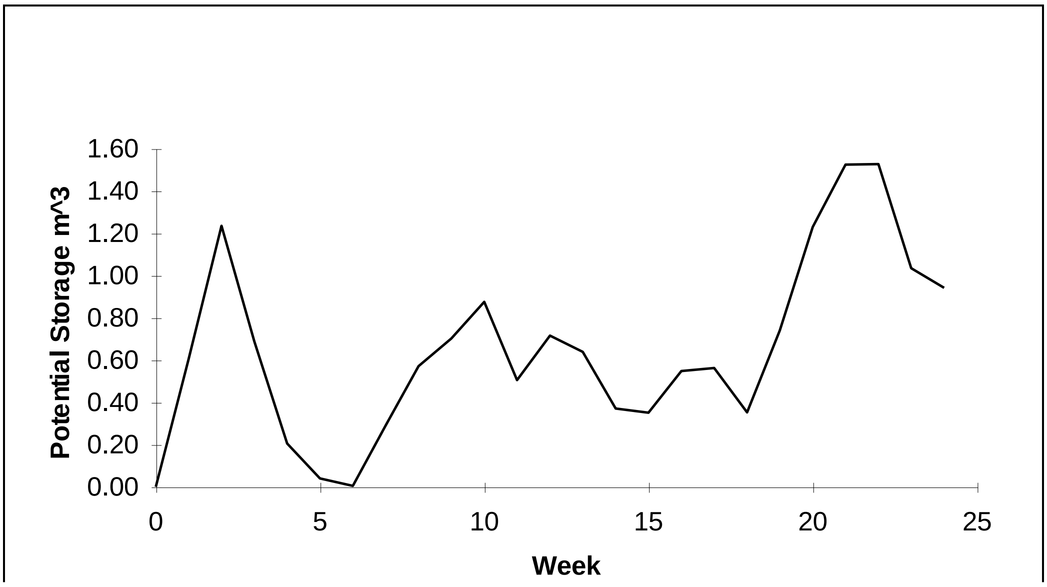

Figure 1. Graphical Display of the Storage Volume Depicting Sequent Peak Analysis

The optimal storage size using sequent peak analysis as described above was obtained as 1.23 m^3 (1230 litres), which corresponds to a roof- catchment area of 120 m^2 for a typical single dwelling in the City of Thunder Bay.

Additional Benefits of RWCS

Incentives for implementing the RWCS for irrigation by residents of Thunder Bay can be demonstrated by evaluating the amount of water saved. Thunder Bay water costs (year 2000) are based on the quantities of water which are purchased. The first block of 28 m^3 costs $0.9458 /$m^3$, the second block which is any amount in excess of 28 m^3 costs $0.2952 /$m^3$. There is an access charge applied to every 3 month billing period of $11, and a sewage tax of 65% is charged on the total amount. So a home which uses 200 m^3 of water in a billing period will pay,

[28($0.9458) + 172($0.2952) + $11] * 1.65 = $145.62

If a residence with a catchment area of about 120 m^2 is capable of harvesting 28 m^3 of rainwater (based on a mean seasonal precipitation of 235 mm) over a season and putting it to use, the cost savings would be approximately $13.65. This is assuming the lower water rate, and neglecting the access charge. If all of the 46,900 homes in Thunder Bay were to participate then over 1.4 million m^3 of water and $682,500 could be saved annually. Further, a saving of about $3.40 per household is expected from the reduced loading of the municipal treatment plant. If an estimated 11,000 homes which currently discharge rainwater to combined sewers were to implement RWCS, a minimum net savings of about $37,400 could be realized by the city each year. Therefore there is a cost benefit for the city to encourage the use of RWCS. Such savings do not include any of the anticipated environmental benefits. Additionally, there would be other benefits such as the reduction in chemicals and energy used in the water treatment processes, the reduction in pollutants discharge to receiving waters, and a decrease in peak loads and flow rates in city mains.

Conclusions

A recursive algorithm for obtaining rainwater storage size for weekly rainfall input and lawn watering requirement has been developed. For a typical residence in Thunder Bay with a roof-catchment area of 120 m^2, the potential rainwater that can be harvested in a season is approximately 28 m^3. The water can be harvested by providing the storage elements of 1230 litres, i.e. rounded as 1500 litres to correspond with 3 containers of 500 litres each, which are commonly available in the market.

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