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Sizing of storage tanks for roof-rainwater catchment systems

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Abstract

Rainwater harvesting has been practised for centuries. This paper assesses the potential success of rainwater catchment systems in supplying irrigation water for residential landscape. The determining factors are dependent on the rainwater supply and its distribution, the roof catchment area, and the optimal size of storage unit. In determining the landscape area which could be supported by the rainwater catchment system, a water balance spreadsheet was devised. The spreadsheet uses a recursive approach to maximize the landscape area which can be supported by a given catchment area and the design rainfall. The traditional mass curve analysis was found inadequate in determining optimal storage size because of temporal variations in rainwater supply and water demand of residential landscape. The methodology has been illustrated using residential landscape of the City of Thunder Bay, Ontario, Canada. It is demonstrated that a saving in the order of 0.73 million dollars per year can be realized by the City when the majority of households are participating in the rainwater usage for irrigation of residential landscape. Harvesting rainwater to meet or supplement garden and lawn irrigation is a simple process which is becoming a viable solution in sustaining future water resources.

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. The art and science of the rainwater harvesting is gaining impetus in both the developed and developing nations in the wake of increasing demand for the water (Hewison and Tunyavanich, 1990; Fewkes and Framton, 1993; Gould, 1995 and 1997). Canada is no exception where the need for effective water management is gaining importance as the demand for quality water continues to grow in urban centres such as the cities of Vancouver and Victoria in the Province of British Columbia (Steele, 1996). In many developed nations, one of the major usages of treated water is for irrigation of residential landscape. During summer months, such a practice 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 of the conservation efforts concerns the use of rainwater, a practice which has been used for centuries. This paper examines a way in which rainwater can be collected and utilized for irrigation of residential landscape to reduce the demand on potable water. Such an approach is not only natural but also is an environmentally friendly alternative to using potable water.

Currently, the rainwater catchment systems (RWCS) are not widely used in Canada. Most people employing such systems do so on a voluntary basis. However, the adaptation to a RWCS is an easy process for most residences. Many roof tops are designed to channel water to one or two focal points before discharging onto lawn 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. Educating Canadians to use less water for residential landscape, though ideal, is a difficult task. According to Environment Canada (1995), the average suburban landscape uses 100 m^3 of water in a vegetal growing season. It is in this vein that the use of rainwater to even supplement a portion of this amount would accrue large benefit to home owners, the municipalities, and the environment .In an effort to develop a rational procedure for estimating optimal storage size for RWCS, this paper examines the relationship between rainfall and water demand of landscape. It is in this sense that the size of such a unit will depend on the catchment area (i.e., residential roof area including garage roof area), the amount and frequency of rainfall, and the water demand of residential landscape. Other factors, such as economics and available storage sizes are also considered in the final selection of an optimal storage size.

STUDY AREA

The City of Thunder Bay 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 geographical location of Thunder Bay ensures the prevalence of an unique continental climatic in the city and its surroundings. 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 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 to this period.

METHODOLOGY AND COMPUTATIONAL PROCEDURES

The storage size for RWCS is primarily governed by relationships between the rainwater supply and landscape water demand. In sizing the storage, the consideration of rainwater supply entails the stochastic characteristics of rainfall and the roof catchment area, and the stochastic characteristics of residential landscape water demand. A brief discussion of each element of RWCS design procedure follows.

Irrigation Water Requirements of Urban Landscapes

Estimating water demand (or requirement) for a residential landscape is difficult because of a host of interacting variables. The most common variables are soil permeability, temperature, vegetation type, direct sunlight, wind, and soil nutrients status. Many species of plants exist in urban landscape with specific water demand requirements. To determine the most general water demand of a typical urban landscape, it was decided to select lawn grass as the predominant form of vegetation, since lawns are the dominant feature in urban residential landscapes in North America. 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. It is a general observation that these lawn grasses can withstand a duration of a week without water supply. In other words, it is reasonable to assume a weekly frequency of rainfall/or water supply.

The minimum amount of moisture specified by many horticultural texts for a typical urban landscape is 1 inch (2.5 cm) per week (Snyder, 1964). Other recommendations also suggest that water be applied to wet the soil to a depth of between 10 and 20 cm. This condition corresponds to approximately 2.5 to 4 cm of water (Carbeen, 1987). The variation in water demand is due to varying characteristics of soils. A rainfall of 2.5 cm is known to soak down a dry soil column to 30 cm, 20 cm, and less than 12 cm respectively in sandy soil, loamy soil, and clay soil (Snyder, 1964). For the design purposes, the mean value of say 3.2 cm [(2.5+4.0)/2] per week is assumed to be representative in this paper.

Water demand is normally expressed as a weekly total (implying that weekly rainfall is tantamount to the event rainfall), it was therefore decided to work in time durations matching this time frame. That is, the rain falling on the landscape is assumed to occur as a single event and not as a series of events in lesser amounts occurring throughout the week. Such an assumption may entail drawbacks because the application of water to lawns is best suited in the form of high intensity and less frequency rather than less intensity and high frequency. It is noted that the occurrence of rainfall as a series of several small events interrupted by hot dry spells causes the watering pattern to deviate from the optimal guideline. As a result, the rainfall will not infiltrate into the root zone of vegetation. Even though a correct amount of water may have been applied to the landscape, it may prove to be insufficient. The constraints of this study did not permit such analyses. However, one could compensate for such anomalies in rainwater demand by providing a margin of safety through slight overestimation of the weekly irrigation water demand. Another method would be through the development of the frequency distribution of daily rainfall structure.

Estimation of Rainwater Supply for Irrigation of Urban Landscape

In the determination of roof rainwater supply for irrigation of an urban landscape, two components are involved. The first component is the roof rainwater supply which is governed by the characteristics of rainfall and the urban catchment. The second component concerns the storage and delivery aspect of roof rainwater supply to satisfy the weekly irrigation water demand of residential landscape. Therefore, the potential total quantity of water which is expected to be available for irrigation is a function of the catchment area, the distribution and magnitude of rainfall occurring in the season, and the efficiency of the rainwater catchment system. The interaction between these variables and the potential amount of water that can be harvested is obtained as follows.

$$S=\Sigma\ C_r * (R_w)_i/1000 * A_r \qquad (1)$$

Where, S is the total available rainwater supply (m^3) for the n number of weeks in the season, C_r is the roof runoff coefficient, R_w is the design weekly rainfall depth (mm), and A_r is the roof-catchment area (m^2). The weekly water demand of 3.2 cm is considered either fully or partially satisfied whenever rainfall occurs during the week. The weekly amount of rainwater which is either stored or supplied to residential landscape is obtained based on following considerations.

(1) If the rainfall amount is less than the weekly water demand of 3.2 cm, an additional water would be supplied to satisfy the irrigation requirement.

(2) If the rainfall equals the weekly demand of 3.2 cm, no additional water would be required.

(3) If the rainfall exceeds the 3.2 cm, the entire roof rainwater would be stored to-supplement the water demand of residential landscape in the subsequent weeks.

It is noted for brevity that detailed considerations pertaining to the effects of infiltration and runoff have not been considered in this paper.

Estimation of Rainwater Supply for the Design Rainfall

Determination of the design rainfall can be carried out in several ways. In this paper, it is determined based on the analysis of past historical rainfall records corresponding to the RWCS season (i.e., vegetal growth period). Most design rainfall amounts are determined based on frequency analysis. The probability of exceedance or non exceedance is used to determine the reliability of the system as follows.

Based on the probability of occurrence, P, the return period of an event is expressed as T=1/P. The probability that a rainfall event will occur at least once in n successive years, often called risk of failure (or simply risk in the hydrologic literature, Chow et al., 1988), is given as follows.

$$\text{Risk}=R= 1- (1- 1/T)^n \qquad (2)$$

The evaluation of risk is based upon the probability of exceedance of an event (i.e., weekly totals in this paper). When determining the reliability over a n-year period (i.e., reliability=$(1-1/T)^n$) of a RWCS, the opposite holds true in that the desired event is based on the probability of non-exceedance, because the lack of rainfall will determine the ultimate reliability of the system. It should be noted that the reliability is the complement of risk i.e., Reliability=(1-Risk) as defined by Chow et al. (1988).

Storage Sizing Procedure for Rainwater Catchment Systems

The storage unit is the link between the rainwater supply and the water demand of a landscape. The purpose of the storage tank is to hold the collected rainwater from the catchment area until it is required by landscape. The size of a storage tank is dependent on both the rainwater supply and the water demand of a landscape. In determining the storage size for a typical reservoir where demand is constant, the mass curve analysis is ideal. However, such an approach cannot be used for storage sizing of a RWCS because of varying water demand of residential landscape. In such cases, the storage size is best determined by a water budget analysis. In this approach, the rainwater supply, the water demand of landscape, and the storage volume are interactively assessed on a weekly basis. The interactions between rainwater supply and water demand are demonstrated for the set of parameters involved in design procedure of the RWCS (Table 1).

Table 1. Tabular Water Budget for the Design of RWCS.

Week (I) (1)	Design Rainfall (Rw) (2)	Available Supply (Q) (3)	Supplemented Demand (D) (4)	Ground Storage (Sg) (5)	Potential Storage (Sp) (6)	Water Deficit Signal (Dd) (7)
1 2 . . n						

The values of various columns in this table are calculated as follows.

Column (2) The design rainfall is the amount which is expected to occur during the week.

Column (3) $Q_i = (R_w)_i * C_r * A_r/1000$

Column (4) If $[(R_w)_i * (1-C_g] > [D_w - (S_g)_{i-1}]$ Then $D_i = 0.0$
Otherwise $D_i = [D_w-(R_w)_i *(1-C_g)-(S_g)_{i-1}]*A_g/1000$

Column (5) If $[D_w-(R_w)_i *(1-C_g) - (S_g)_{i-1}] < 0.0$ Then $(S_g)_i = \left|[D_w-(R_w)_i *(1-C_g)-(S_g)_{i-1}]\right|$
Otherwise $(S_g)_i = 0.0$

Column (6) If $(S_p)_{i-1}+[Q_i-D_i] < 0.0$ Then $(S_p)_i = 0.0$
Otherwise $(S_p)_i = (S_p)_{i-1}+Q_i-D_i$
Column (7) If $(S_p)_{i-1}+[Q_i-D_i] < 0.0$ Then $D_d = 1.0$
Otherwise $D_d = 0.0$

Where, A_r ,C_r ,R_w ,and S are as defined earlier. A_g is the landscape area (m^2), C_g is the landscape runoff coefficient, Q is the rainwater Supply (m^3), D_w is the weekly water demand (mm), D is the supplemented water demand (m^3), D_d is the signal with values of 1 or 0 for deficit or surplus respectively, S_g is the soil-water storage (mm), and S_p is the potential storage (m^3). 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 values of water deficit indicate 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. A 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 supply the necessary 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, and/or a reduction in the area of landscape. Determination of the optimal design involves a recursive approach 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 (P_f) for the RWCS is obtained by dividing the number of weeks during which a water deficit did occur by the total number of weeks in a rainwater harvesting season. That is, the failure rate:

$$P_f = \Sigma(D_d)_i / n \qquad (3)$$

where, $(D_d)_i$ is the occurrence of water deficit in i^{th} week, and n is the total number of weeks in a rainwater harvesting season. In the analysis of water budget 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, the rainwater cannot be rationed to satisfy the water demand in the subsequent weeks.

Table 2. Tabular design approach for optimal storage size.

Week (i) (1)	Potential Storage (Sp) (6)	Maximum (max) (8)	Minimum (min) (9)	Optimal Storage (So) (10)
1 2 : n				

In the determination of optimal storage, a technique similar to the sequent peak algorithm [Linsley et al. (1979)] could be used. This can be done either graphically or numerically. In the graphical solution, the potential storage from column (6) in Table 1 is plotted against time. An analysis of sequent peaks would determine the optimal storage. Although, the numerical approach is somewhat conceptually intractable, it saves time and effort in sizing an optimal rainwater storage. This procedure is best carried out on a computer in tabular form as outlined in Table 2 and explained as follows.

Column (8) The maximum value in column (6) from 1 to i^{th} week.
Column (9) The minimum value in column (6) from i^{th} to n^{th} week.
Column (10) $(S_o) = [(max) - (min)]_i$

The maximum value in column (10) represents the optimal storage tank size for the RWCS. A storage unit with larger volume would be able to store more water but such an excessive volume of water is not required by the residential landscape. However, a storage volume less than the optimal volume would result in periods during which the storage tank will run dry i.e., a water deficit would occur. In the determination of optimal storage, although Table 2 interacts with Table 1, it is kept separately as this table relies on the completed information in Table 1.

DATA ACQUISITION AND STATISTICAL SCREENING

In particular, three sets of meteorological records are required for the determination of the seasonal time period during which the RWCS are expected to function. 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 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, van 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. Additional details on statistical data screening procedures can be found elsewhere (Rebneris and Panu, 1996).

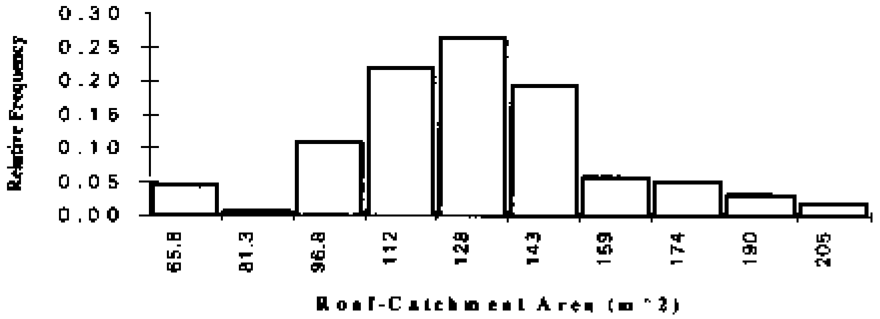

Figure 1. Relative frequency histogram of roof-catchment areas in the city of Thunder Bay.

RSULTS AND DISCUSSION

Based on the analysis of residential lot sizes in Thunder bay, the mean residential catchment surface area was determined to be approximately 120 m^2 (Figure 1). Based on the analysis of rainfall data, the duration of rainwater collection season was defined from April 26 to October 31 (i.e., 27 weeks). A further analysis of mean weekly temperatures in the beginning of Spring and also towards the end of Fall aided in discerning the duration of residential landscape water demand season from May 17 to October 10. Additional details on various aspects of the seasonal definitions used in this paper can be found elsewhere (Rebneris and Panu, 1996).

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. The probability of exceedance was computed using the well known Weibull plotting position formula. Higher probability of exceedance of rainfall implies a lower amount of expected rainfall, and consequently a lower risk of failure. The seasonal rainfall amounts corresponding to different levels of exceedance probability are given in Table 3.

Table 3. Seasonal rainfall amounts (mm) at varying probabilities of occurrence.

Seasonal	Probability of Exceedance (%)										
	3.6	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	96.4
Rainfall (mm)	525.3	364.0	301.3	287.7	270.6	223.1	202.7	181.9	166.3	146.5	69.5

An adjustment of weekly rainfall was accomplished by determining the proportion of the seasonal rainfall (Table 3) corresponding to each week for the respective level of reliability. The weekly proportions were found by dividing the expected weekly rainfall amounts for a given reliability level by the rainfall sum of all the weeks for the same level of reliability. These proportions further represent the distribution of seasonal rainfall throughout the rainwater collection period. The patterns of distribution will vary according to the level of reliability from which they were derived. The rainfall distribution was found to be highly variable at the 90% level of reliability, whereas it was found to be less variable at the 10% level of reliability. The design rainfall comprises of two components: namely the seasonal rainfall totals based on its probability of occurrence, and the seasonal rainfall distribution (i.e., weekly rainfall values).

The design rainfall is obtained through multiplication of weekly proportions corresponding to a desired reliability of seasonal rainfall distribution by the desired seasonal rainfall probability. Various combinations of distribution reliability and rainfall probabilities can be compiled to obtain the desired amount of design rainfall. The overall importance of the rainwater catchment system is governed by the level of reliability used in the design of RWCS. For a system of high importance, a high level of reliability should be used for the rainfall and the distribution of rainfall. Conversely, for a system of less importance, a lower level of reliability would be used. The level of reliability of a RWCS unit is governed by the specified requirements of the user.

Design Procedure for Optimal Storage Size

For various computational requirements, a spreadsheet based algorithm as outlined earlier in Tables 1 and 2 was used. This algorithm relates the maximum size of landscape which can be supported by a roof catchment area for various probability of rainfall exceedances corresponding to a given level of rainfall reliability. In these tables, the collection of rainfall 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. Likewise, in the Fall, the termination of rainfall collection and 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 land scape is assumed to be zero. The weekly water demand for irrigation was assumed to be 3.2 cm.

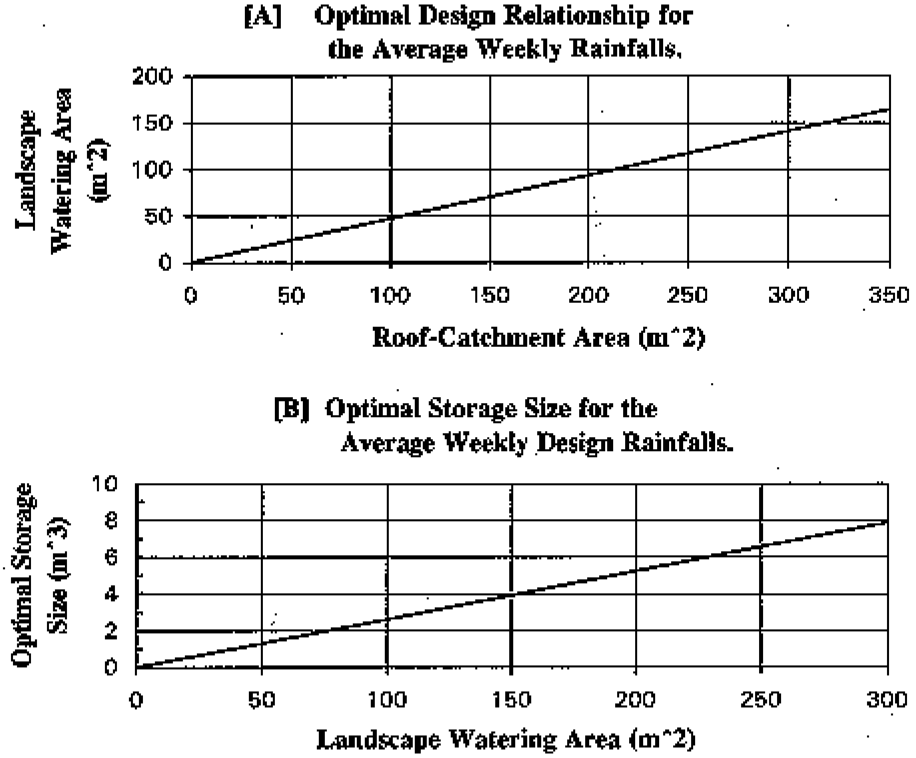

Figure 2. [a] Relationship Between Roof Catchment and landscape Watering Area at the 90% Rainfall Reliability, and [b] Relationship Between Storage Volume and landscape Watering Area at Different Rainfall Reliability.

Relationships between roof catchment and landscape area at various reliabilities of rainfall were developed similar to the relationship exhibited in Figure 2a. Based on such relationships, the optimal storage size was obtained for various levels of rainfall reliability as shown in Figure 2b. From this relationship, it is clear that storage size alone is not sufficient to provide water for irrigating a landscape, therefore one needs to work interactively with Figures 2a and 2b. Designing the storage size to meet a high level of rainfall reliability entails an inherent drawback because, any excess amount of rainwater than the minimum amount for a specified level of reliability will be wasted. This excess rainwater could have been used to support a portion of a landscape for a given period of time. In essence, the design based on specified levels of reliability is not indicative of the occurrence of actual amount of rainfall. Therefore, such a relationship merely indicates potentially the maximum area of landscape that may theoretically be supported for a given level of rainfall reliability. A household may desire to collect as much rainwater as possible to supply the need of a residential landscape. If the system falls short for a period of time, then the grass may be allowed to brown, or else the household may revert to municipal water supply. In such analyses, therefore, there is a need for considerations of the likelihood of occurrence of rainfall in a given week.

Designing Storage Size For An Expected Rainfall

To design storage size based on the amount of rainfall which has a greater likelihood of occurrence is discussed. Such weekly totals of rainfall during the season were obtained by multiplying the weekly rainfall properties for a given level of rainfall reliability by the seasonal rainfall amount at the same level of rainfall reliability. The expected amount of rainfall corresponding to the probability of exceedance can be represented in a graphical format for each week. The integration of the area below the curve defining the graphical solution will provide the average amount of rainfall which is expected to occur during a week.

For the expected average weekly rainfall values, as the design rainfall, in the spreadsheet based algorithm outlined earlier in Tables 1 and 2 and using the relationships between roof catchment area and the landscape area, a relationship between landscape and storage size was obtained. Based on the sequent peak analysis, an optimal storage size for an ideal roof catchment area of 120 m^2 for a typical single dwelling in the City of Thunder Bay has been determined to be 1.23 m^3 (1230 litres).

Benefits of Rainwater Harvesting in the City of Thunder Bay

Incentives for implementing RWCS to meet partial landscape watering requirements by the residents of Thunder Bay have been estimated to be 1.4 million m^3 (or approximately $ 0.7 million) annually. In addition, a minimum cost saving of approximately $ 40,000 annually is estimated until the cross-connections between storm water and sewage water are corrected in some parts of the city.

CONCLUSIONS

The utility of rainwater collection system for irrigation of the residential landscape is dependent on the collection of rainfall to meet the water demand of vegetation. Due to the stochastic nature of rainfall, the estimation of expected rainfall quantile represents the complexity in RWCS design.

The implementation of RWCS would not replace the dependence of households on traditional water sources, however, such a dependence would be significantly reduced. For a typical residence in Thunder Bay with a catchment area of 120 m^2, the potential rainwater that can be harvested in a season is approximately 28 m^3. A saving of $14.65 each season on the water bill is expected from the use of 28 m^3 rainwater to supplement landscape irrigation requirements. Further, a saving of $3.40 per household is expected from the reduced loading of the municipal sewage treatment plant. A total saving of 0.73 million dollars per year is expected for the City of Thunder Bay when the majority of households are participating in the rainwater usage for irrigation of residential landscape. 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.

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