A Methodology for using Rainwater Harvesting as a Stormwater Management BMP

J. Alex Forasté, P.E.[1] and David Hirschman[2]

[1] Senior Civil Engineer, McKee Carson, 301 East High St., Charlottesville, VA 22902; PH (434) 979-7522; email: aforaste@yahoo.com
[2] Program Director, Center for Watershed Protection, Inc., 919 2nd St., S.E., Charlottesville, VA 22902; PH (434) 293-6355; email: djh@cwp.org

ABSTRACT

Rainwater harvesting is a dynamic stormwater management tool that can be used to address multiple objectives and provide several stormwater, water and energy conservation and financial benefits. However, it is currently underutilized as a stormwater BMP. In many cases, rainwater harvesting systems are designed in isolation, instead of being incorporated as an integral component of a site's stormwater design. One major reason for this is that there is not a consistent means to account for the water quantity and quality benefits provided by rainwater harvesting. As a result, local plan reviewers and design consultants do not have a "common language" when it comes to compliance calculations and design features.

This paper presents a rainwater harvesting specification developed to account for the water quantity and quality standards in Virginia's new stormwater program. The specification provides design guidance and a spreadsheet to model various system and demand scenarios to assess system performance. These tools provide designers with a unified method to size rainwater harvesting systems to meet stormwater management requirements and plan reviewers with a consistent set of guidelines with which to assess compliance.

The objective of the spreadsheet is to put rainwater harvesting on a level playing field with other stormwater BMPs so that its use can become more widespread. By creating a common statewide specification, the multiple benefits of rainwater harvesting can become realized on a broader scale.

1. INTRODUCTION

1.1 Current Use of rainwater harvesting as a SWM BMP

Increasingly, more regions within the United States are observing installations of rainwater harvesting systems. While some states have specified policies or regulations regarding its use including Texas, North Carolina, Virginia, Washington and Hawaii, many more cities and regional authorities have created their own sets of guidelines, often in the absence of statewide policy. Of those that promote and advocate its use, rainwater harvesting is more often associated with providing an alterative water supply than it is as a stormwater management (SWM) practice. Only a handful recognize it explicitly as a stormwater BMP and grant credit for its runoff reduction and/or pollutant removal benefits. As a consequence, when systems are proposed during the planning and design stages of a development site, they are often designed in isolation and separate from the rest of the site design, instead of being incorporated as an integral component of the stormwater management plan. This has the effect of increasing costs for the owner by not fully accounting for stormwater functions and effectively duplicating on-site BMPs. This, in turn, has the effect of decreasing the adoption of rainwater harvesting because it often becomes an easy target during value engineering.

A major reason for the limited use of rainwater harvesting as a stormwater management tool is that many program managers do not know how to account for its water quantity and quality benefits. There are areas of uncertainty that make it difficult for reviewers to approve the practice as a stormwater BMP. For example, reviewers often want to have some guarantee that the storage provided will indeed be available between storm events (and not just a full tank or "dead" storage). Without a consistent method among designers and plan reviewers to quantify benefits relating site conditions, water usage, and stormwater management, and without detailed design guidance similar to what is available in most state stormwater management manuals for other BMPs, an information void exists and its adoption as a BMP limited.

The state of Virginia did not previously have a state specification or standard method of accounting for rainwater harvesting stormwater benefits (DCR 1999), however the new program includes it as a standard BMP. This is discussed further in Section 2.

1.2 Upstream benefits (water supply, water & energy conservation, financial)

Water supply: Rainwater harvesting is unique in that it is virtually the only BMP that can provide an alterative water supply for the owner of the site. Municipalities and regional water authorities must plan for and ensure adequate water supplies for their customers. In Virginia, 86% of the raw water used comes from lakes, reservoirs, rivers and other surface sources (DEQ 2008). All of this publicly supplied water is treated to a potable water standard. A significant portion however, is not used for potable purposes (see Table 1).

Table 1. Percent of Total Water Use that is Non-Potable

User Type	% Non-Potable
Residential	50-78
Office	86
Hotel	43

Figures represent national estimates

In residential settings, toilet flushing, clothes washing and irrigation account for 50-78% of total water usage (EPA , Frye 2009, AWWARF 1999). Office and hotel non-potable water usage, including toilet flushing, clothes washing, irrigation and cooling towers account for approximately 86% and 43%, respectively (PI 2003). By supplying an alternative non-potable water source, such as stored rainwater, a significant portion of the non-potable demand can be met on-site, thereby relieving some of the demand on potable water sources. This surrogate source of water has the potential to increase water use efficiency and partially decentralize the current highly centralized water infrastructure system that is in place in the United States.

Energy: Public water supply systems have a high embedded energy content (Kloss 2008), as it takes energy to withdraw raw water from its source, treat it, and distribute it. The vast majority of energy that is consumed by public water systems is used for distribution. Supply and conveyance consumes approximately 10%, water treatment 7% and distribution 83% (CEC 2006). Overall, the water sector consumes 3% of the electricity generated in the U.S. and water and wastewater utility consumption represents roughly 30-60% of a city's energy bill (EIA 2009)

While energy consumption per unit of publicly supplied water varies from system to system, some estimates put the value between 1,100 to 20,100 kilowatt-hours (kWh) per million gallons of water supplied (CEC 2006). Kloss (2008) estimated that by decreasing potable water demand by 1 million gallons, electricity use could be reduced by nearly 1,500 kWh and carbon dioxide emissions would be reduced by roughly 1 to 1½ tons, when fossil fuels are used for power generation. Additionally, if the water and wastewater utility sector as a whole reduced energy use by only 10%, approximately $400 million nationwide would be saved annually (EPA 2008).

Because the supply for rainwater harvesting is available on-site, the energy required to distribute the water is dramatically scaled down, as the need to transport from treatment plant to site is eliminated. While intuitively this relationship seems evident, little research appears to have been conducted in this area. One case study by Younus (2008) and the Cabell Brand Center (2009) showed that rainwater harvesting systems could supply one unit of non-potable water consuming significantly less energy than would be required to treat and transport the same amount from a publicly supplied system.

Financial: The infrastructure that supports water supply to communities including reservoirs, pump stations, storage tanks, water treatment plants, piping distribution systems and personnel represent considerable costs. According to the EPA, $334 billion will be needed for repairs and maintenance of municipal water systems (EPA 2009).

Owners of on-site rainwater harvesting systems may also realize financial benefits through decreased purchases of municipal water, and in some locations through utility fee offsets. Considering its use as a SWM tool and water rate hikes over time, an attractive payback period and future savings may be realized for the owner.

1.3 Downstream benefits (stormwater)

The connection between increased impervious surfaces from development and poorer water quality runoff is well established and documented (Schueler & Holland

2000). The higher pollutant loads and increased volume contribute significantly to the degradation of downgradient urban streams, rivers and estuaries (Burton & Pitt 2002). If designed adequately, rainwater harvesting can reduce large volumes of runoff from impervious surfaces (building rooftops) relieving some of the stressors on these water bodies. This will in turn assist to reduce sedimentation and degradation caused by erosive volumes and velocities and mitigate downstream flooding. For localities that operate on combined sewer overflow (CSO) systems, the reduced runoff volume can have the potential to decrease the incidence of wastewater treatment plant bypasses during storm events, during which times significant bacteria and nutrient loads can contribute to receiving bays and water bodies.

2. DESIGN SPECIFICATION AND SPREADSHEET TOOL

2.1 Specification

The Virginia Department of Conservation and Recreation (DCR) is currently in the process of updating its stormwater management handbook (first adopted in 1999) and adding an online Virginia Stormwater BMP Clearinghouse in conjunction with the Virginia Water Resources Research Center at Virginia Tech (http://www.vwrrc.vt.edu/SWC/index.html). The latter will house all updated BMP specifications (DCR 2009).

A rainwater harvesting specification and spreadsheet were developed to support the updated program. The goal of the specification was to design a guidance tool that fit seamlessly into the broader stormwater program and framework. With this in mind, a methodology was developed to quantify the stormwater benefits of rainwater harvesting into the common currency of a runoff reduction credit. To achieve this, a spreadsheet was designed to quantify the credit (Forasté & Lawson 2009) and a specification developed to outline the procedure and provide design and plan review guidance. A broad range of topics from site integration to sizing methods and material selection are covered in this specification. A brief overview is provided below with the full text available on the BMP Clearinghouse website. The spreadsheet is discussed further in section 2.2.

Physical feasibility and site conditions are reviewed including: (a) consideration of available space, existing site constraints, building and utility setbacks, (b) site topography as it relates to roof drain slopes, elevation drops in system components, frost lines and inlet and outlet orifice inverts, (c) available head as it relates to pumping, locating the cistern, and end uses, (d) water table levels, potential flooding and buoyancy risks for underground tanks, (e) soil condition as it relates to bearing capacity and support strength, native or fill soils, soil pH in relation to tank material, (f) contributing drainage area (rooftop only), (g) roofing material and its interaction with the generally acidic rainwater considering the potential for leaching of harmful rooftop or inner tank material contaminants, and (h) vehicle loading.

The specification provides guidance on design applications and system and tank configurations. More detail is provided on these topics in the sections below. The basic system components are presented including rooftop surface, collection and conveyance system (e.g. gutter and downspouts), pre-screening and first flush diversion, storage tank, distribution system and overflow, and overflow filter path or secondary runoff reduction practice. Different tank options and materials, including their advantages and disadvantages are discussed. Design and tank sizing criteria methods are provided.

The specification also provides recommendations for regional and special case design adaptations, construction sequencing and inspection, system maintenance agreements, inspections and scheduling, community, and environmental concerns. A list of plan submittal requirements and a recommended checklist, intended for plan reviewers, is included to better ensure effectiveness of design.

2.2 Cistern Design Spreadsheet

A Cistern Design Spreadsheet (CDS) was developed to assist designers with the sizing of rainwater harvesting systems. It is considered an integral component and companion to the specification. The spreadsheet models water levels and behavior of the cistern on a daily basis, based on user defined inputs -- including geographic region, rooftop area captured, and water demands – for a 30-year rainfall record (1977 through 2007). Results are summarized in tabular and graphical output to both quantify the stormwater credit and assist the user to select an appropriate cistern size.

A relatively simple graphical user interface (GUI) is provided for user input. Here, the user selects one of four geographic regions within Virginia that best matches the design location's rainfall pattern. NRCS 24 hour rainfall depth and County zone maps are available for 17 different locations in Virginia on DCR's website and can be used to select the regional rainfall data that best matches the available spreadsheet options.

Next the user enters the rooftop capture area that will serve as the supply for the system. The remaining sections of the input tab are divided into various water demand use categories. These include irrigation, flushing toilets/urinals, laundry use, additional use (bus wash, street sweepers, etc), chilled water cooling towers and secondary runoff practice drawdown. The user may choose to use typical estimates or user-specified daily demands (gallons/day). Seasonal use can be specified for irrigation and secondary runoff reduction practices, while weekly use can be specified for indoor uses, additional daily uses and chilled water cooling towers to better model site conditions. For example, if a commercial office will utilize the rainwater to flush toilets during the week, but is closed on the weekends, a Monday through Friday timeframe can be selected.

Once inputs are entered, two results worksheets provide graphical tools and resulting performance metrics to assist the user in selecting the best sized cistern to meet design objectives. More detail on these assessments is provided in Section 4.5.

For the purposes of stormwater management, three primary spreadsheet results are of most interest: (1) cistern size associated with the required treatment volume, (2) drainage area or captured rooftop area, and (3) computed runoff reduction credit. This runoff reduction credit translates the rainwater harvesting stormwater benefits into the common currency that is utilized by all other Virginia stormwater BMPs.

3. CONCEPT OF USING RAINWATER HARVESTING AS A SWM BMP

3.1 Runoff Reduction Method

The first edition of the Virginia DCR Handbook (1999) provided measures to limit peak runoff rates for select storms and provided design guidance for water quality treatment measures to address the first one-half inch of rainfall. While peak flow rates from the post-development 2-year storms were limited to that of the pre-development condition, volumes were left largely unaddressed. The result was that "2 year" pre-development storms occurred more frequently and for longer durations under post-development conditions. This resulted in receiving channels and streams experiencing more frequent flows at high, and sometimes erosive, velocities and channel forming volumes.

The updated program addresses this through a runoff reduction approach, allowing water quality treatment credit for both pollutant removal rate efficiencies as well as a reduction in the total volume of stormwater leaving a site (CWP 2008). By granting credits for both, the BMP playing field is effectively leveled for rainwater harvesting. Since the practice does not have a commonly-used removal efficiency, the benefits are realized through volume reduction.

To realize stormwater compliance under the updated program, a runoff reduction spreadsheet is utilized (DCR 2009). The spreadsheet is to be used by both designers and plan reviewers, and computes pollutant load reduction and volume reduction computations. Proposed land uses, soil types, contributing drainage areas and removal rate efficiencies are used as primary input variables for each BMP.

3.2 Methods of modeling

Of the available manuals that provide guidance on cistern sizing, many utilize monthly water supply and demand estimates to determine a monthly 'budget' and appropriate tank size (Texas 2005, Watearth 2009). Rainwater supply is based on mean or median monthly rainfall data and specified capture rate efficiency. Demand is based on averaged monthly water use estimates. While this method may be appropriate and sufficient for certain applications, treating water supplies and demands as blocks of water on a monthly basis has limitations. By not incorporating seasonal and annual fluctuations, refined rainfall variability within a month, or variable water levels within the tank, systems may be over or under designed and present less accurate modeling results of water savings and system performance over time.

The method, as many designers have used it, also implicitly assumes that the tank is empty or near empty, since it is assumed that space within the tank is available to receive and store the full monthly water supply all at one time. Finally, it would be difficult to model the system, for the purposes of stormwater management, and to quantify an appropriate runoff reduction credit for the target 1" storm event, since the rainfall data is aggregated and only analyzed on a cumulative basis versus for an individual storm event.

It is for these reasons that a continuous simulation model was selected and a spreadsheet developed for the Virginia program. The spreadsheet model utilizes thirty years of daily rainfall data to simulate cistern performance over time, under varying temporal conditions, summarizing the results to quantify a credit.

3.3 System Configurations and common attributes for SWM credit

While it may be possible to treat and reuse harvested water for potable purposes, with appropriate design and treatment measures specified and with special regulatory approval, this specification focuses on non-potable uses. These uses may include flushing of toilets and urinals inside buildings, landscape irrigation, exterior washing (e.g. car washes, building facades, sidewalks, street sweepers, fire trucks, etc.), supply for chilled water cooling towers, replenishing and operation of water features and water fountains, and clothes washing, if approved by the local authority.

One or several of these uses may be employed, depending on an owner's demand needs and design objectives to create a rainwater harvesting system configuration. Several options are presented in the specification, and while various configurations may be conceived of, certain criteria must be followed in order to obtain credit for the purposes of stormwater management. These are the common attributes and a simple set of principles that all configurations share:

- Dedicated year-round drawdown for credit. While seasonal practices (such as irrigation) may be incorporated into the site design, they are not granted treatment volume credit for stormwater purposes, unless a drawdown at an equal or greater rate (or in a secondary practice) is also realized during non-seasonal periods (e.g. infiltration during nonirrigation months).
- Utilization of rainwater as a resource to reuse for on-site demand or infiltration to promote groundwater recharge.
- Only rooftop areas are to be harvested (no at grade level surfaces) and closed conveyance must be used once water reaches ground surface (to limit exposure to further contamination)
- Pollutant load reduction from site is realized only through reduction of runoff volume leaving the site.
- Reduction of peak rates and frequency of high flows is realized through reduced volume of runoff.

A key element to each system is that it must dedicate a continuous (year-round) utilization of rainwater through either (i) internal use or (ii) outdoor use and/or treatment in a secondary runoff reduction practice (e.g., infiltration, small-scale bioretention, filter strip, dry swale). While other commonalities and design attributes certainly exist, these are some of the basic principles that guide the design of each system.

4. DESIGN CRITERIA AND SIZING METHODOLOGY

4.1 Tank Configuration and Design Objectives

There are three basic tank configurations, two of which are provided in Figures 1a and 1b. The first reserves the maximum amount of storage possible in a tank for reuse purposes (Figure 1a). An emergency overflow outlet is installed near the top of the tank with only an additional volume provided above this overflow to allow for high water levels during very large, infrequent storms. The second configuration is similar to the first, however includes a small orifice below the overflow outlet to provide for more control of larger storms (Figure 1b). This configuration creates an additional volume dedicated for detention purposes to address both flood mitigation and/or channel protection. Because the smaller orifice simply limits discharge rates and does not store water above the invert, less volume is available for reuse.

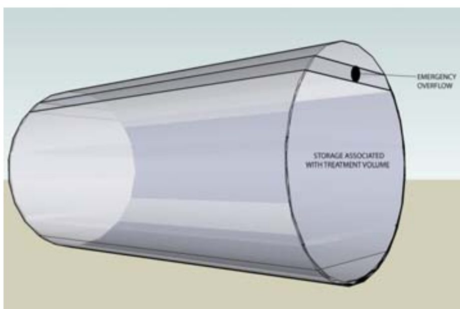

Figure 1a. Maximizes Reuse

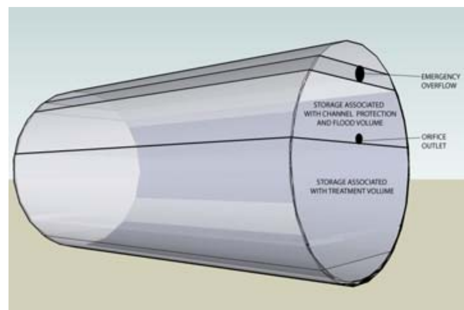

Figure 1b. Incorporates Detention

The third tank configuration is similar to the second, however maintains a constant drawdown within the system. The drawdown may be facilitated through a very small orifice in the bottom of the tank, acting as a "leaky tank" or may be pumped at a controlled daily rate to a secondary runoff reduction practice (e.g. rain garden, micro-scale infiltration, urban bioretention). The flow rate directed to the secondary runoff practice is very small and needs to be specified appropriately, as the purpose is to allow the runoff to be treated or recharged to groundwater. The tank design and controlled release rate should not be designed in such a way so that the primary function of the system becomes a detention facility.

The third configuration is useful when demand is not enough to sufficiently draw water levels in the tank down between storm events to achieve the desired treatment credit. It is also useful for sites that utilize captured rainwater for irrigation during part of the year, but have no other uses for the water during the non-irrigation season months (DCR 2009). Without an on-site infiltration/treatment or another drawdown mechanism to create a year-round drawdown, credit cannot be realized for the practice as no stormwater benefit would be realized during non-irrigation months.

4.2 Incremental Design Volumes

Cisterns are often defined by their material, size and location, above or below ground. For stormwater design purposes, it is useful to disaggregate this total volume size into four primary incremental volumes: (1) Storage for low water cut off, (2) Storage associated with Treatment volume, (3) Storage associated with Channel and Flood Protection volume, and (4) Storage dedicated to overflow and freeboard. Each of these four volumes are fixed for any one particular system and the cumulative volume defines the total size of the cistern.

The low water cutoff volume is a ‘dead’ volume that needs to be preserved for pumped systems in order to maintain proper operation of pumps preventing them from running dry. A cut off water level should be specified by the designer. The space between this cut off water level and the inside bottom of the tank defines this volume. The second incremental volume is the storage associated with the treatment volume and the only volume that addresses the target 1” storm allowing the system to obtain runoff reduction credit. This is also the only incremental volume that is able to store supply water for reuse and likewise the water level is only drawn down by that reuse. Included within this volume is the variable water level at the beginning of each precipitation event.

The third incremental volume is the storage associated with channel and flood protection. This volume is optional. As discussed in Section 4.1, the user or designer may decide to include additional capacity for storms larger than the target 1” storm, such as the 2, 10 or 100 year 24 hour event that allows the system to better handle these infrequent rainfall events through a detention facility. This volume is defined as the space between the invert of the orifice designed for routing these large events and the emergency overflow outlet invert (Figure 2).

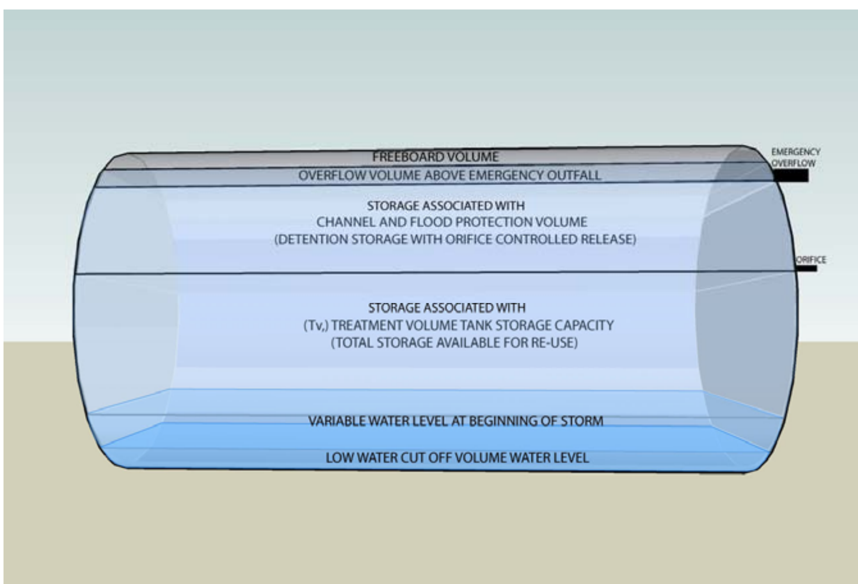

Figure 2. Incremental Design Volumes associated with tank sizing

The final and fourth incremental volume is dedicated to reserving room for overflow of large storm events in order to not inundate the system. This volume is defined as the space between the emergency overflow outlet invert and the top of the tank along the inside. Within this space is the volume associated with the high water level of the design extreme event, often chosen as the 100 year storm event, and the freeboard or additional empty space available above the water level during that event. Note that selection of the design extreme event to be modeled should also depend upon other considerations including whether gutter and roof drain capacity and minimum pre-tank filter efficiencies will sufficiently convey the extreme event.

4.3 Cistern Sizing Criteria

The Cistern Design Spreadsheet is a primary tool used to size the cistern. The volume modeled in the spreadsheet is only that associated with the low water cut off and treatment volumes (incremental volumes 1 and 2 as described above). Both the overflow volume and the storage associated with the channel and flood protection volume are not modeled in the system. These volumes along with the cut off volume are considered unusable spaces, in terms of availability for reuse.

Traditional and established routing software packages are already widely available and familiar to many designers. These packages can be used in the traditional fashion of designing detention facilities to model the Channel and Flood Protection volumes.

Once the incremental storage sizes associated with the treatment volume and low water cutoff volume have been selected, the design must be completed by adding the channel and flood protection volume (optional), and the overflow and freeboard volume to obtain the total cistern size.

4.4 Quantifying Stormwater Credit

The stormwater credit is based on the water contribution and losses the system realizes over the model period. Contributions are from precipitation and municipal backup (if included). Losses are from initial rooftop storage abstractions and losses recognized in the rooftop runoff coefficient (0.95), first flush diversion, filter efficiency, drawdown through use and overflow. It should be noted that "first flush diversion", in the context of rainwater harvesting, is different from the term "first flush" as it is normally used in the stormwater industry, and only includes the first 0.02 to 0.06 inches of rainfall; this is the portion that may include debris and is diverted by filters in order to avoid clogging. Each filter has a performance or efficiency curve associated with the rate of runoff it will effectively convey or divert from a rooftop to a cistern. The Virginia specification assumes that a minimum 95% efficiency for the 1" storm will be met. It is recommended that larger storm events be considered and that filters be selected such that 90% efficiency is realized for the 10 year storm.

Implicit in this, is that a filter will be installed on all systems and the conveyance system (gutters, roof drains, etc.) will be sized to sufficiently convey all of the 1" storm. The remaining precipitation that is effectively conveyed from the rooftop to the tank is then added to the water level that existed in the cistern the previous day, with all of the total demands subtracted on a daily basis. If overflow occurs, the volume is recorded. If the tank runs dry (reaches cut off volume level), due to minimal or no rainfall and continued use, then the volume is fixed at the low level and a dry frequency day recorded. The full or partial daily demand that is met under both conditions is then quantified and recorded in terms of gallons/day.

The treatment volume is the total volume of rainfall, for storms of 1” and less that leaves the rooftop (following losses represented in the runoff coefficient of 0.95). The runoff reduction volume, or the amount of stored water reused on site, is calculated by subtracting the first flush diversion and overflow volumes from this treatment volume. The percent runoff reduction credit relates the removal volume to the total target storm event, by dividing the runoff reduction volume by the treatment volume.

4.5 Results for Storms of 1” or less

There are two worksheets provided in the Cistern Design Spreadsheet to display the results. One of these worksheets is provided specifically to report the stormwater credit and summarizes the runoff volume that the tank can capture and use for drawdown for all precipitation events of 1” or less. Metrics reported in this worksheet include runoff reduction volumes, runoff reduction credit, overflow volume and frequency from storms of 1” or less and dry frequency. The results are reported for various cistern storage capacities associated with the treatment volume in tabular format. A chart is also provided to graphically represent the runoff reduction credit and overflow frequencies versus varying tank sizes. This is an especially useful graphic as it reveals informative relationships that may not otherwise be especially evident in tabular format. A range of cistern sizes tends to emerge as the optimal range informing the designer where a small increase or decrease in tank size can have a significant impact on runoff reduction credit, overflow frequency or system cost. Figure 3 provides an example of this relationship.

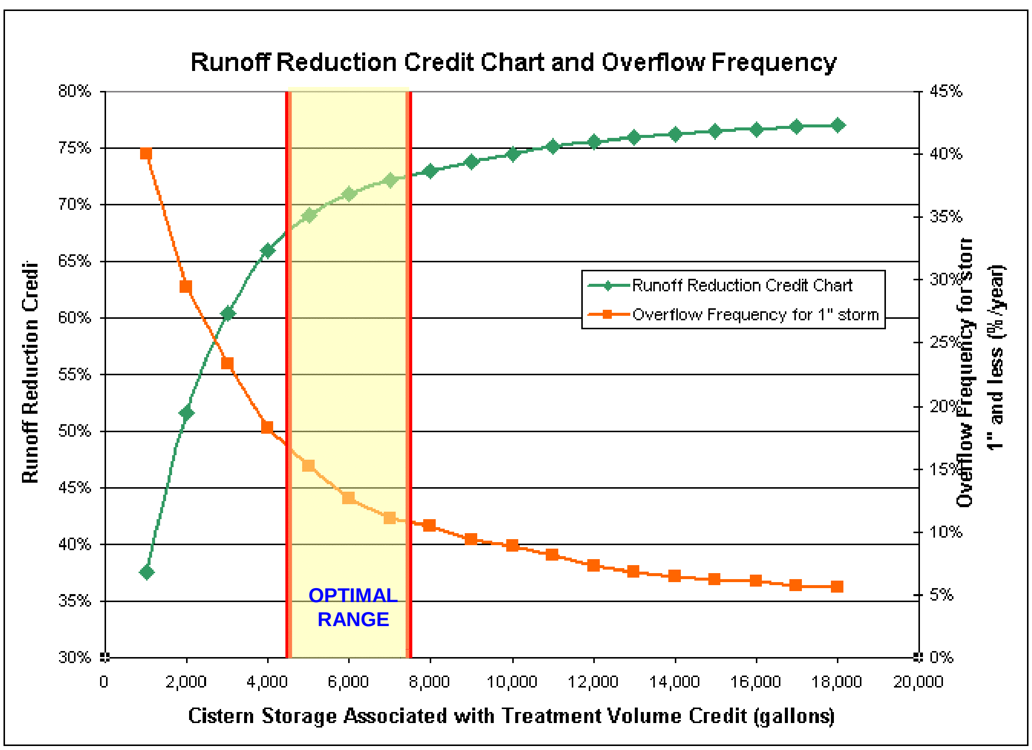

Figure 3. Runoff Reduction Credit chart and Optimal Size Range

To the left of the optimal range, a small increase in size reveals that a significant increase in runoff reduction credit would result for relatively little additional cost. Conversely, to the right of the optimal range, even a significant increase in cistern size would result in little additional stormwater credit while adding significant cost.

4.6 Results for All Storm Events

A second results worksheet is provided to analyze overall system results for all precipitation events, not limited to the target 1" storm. This sheet is not intended to relay stormwater benefits, but rather to better inform the designer addressing other potential design objectives. Results include demand met in terms of total volume per year and percent, dry frequency, overflow days and frequency for the entire time period, and mean overflow volume per year for various storage sizes. Charts are provided to graphically represent percent demand met, overflow frequency, and percent dry frequency versus varying tank sizes. Plotting the different measures versus a range of sizes again reveals a trend of diminishing returns and optimal ranges (Figure 4).

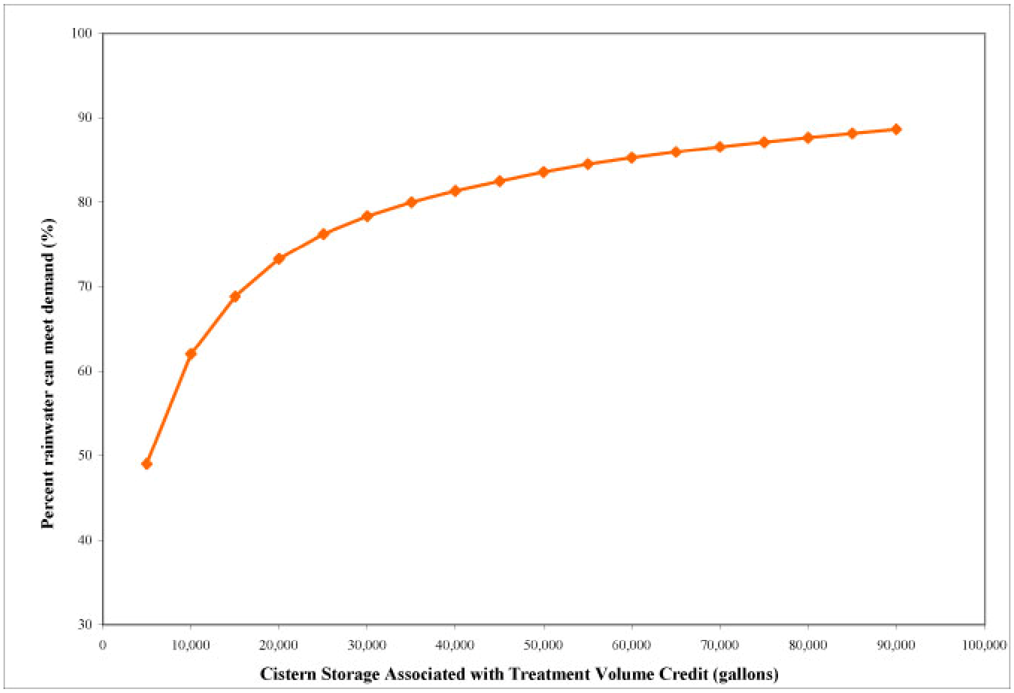

Figure 4. Percent of Demand Met by Rainwater for Various Cistern Sizes

Any one of the resulting metrics or a combination may prove to be of valuable assistance to the designer allowing them to meet any particular design objective they may have. For instance, if the objective is to provide an alternative water source available for use during potential droughts and associated water restriction periods, dry frequency may become important. If a cistern size is dry for a substantial portion of time, this can inform the user that they should consider capturing more rooftop area if available, decrease the demand on the system or decrease the size of the tank.

If the objective is to maximize water reuse, the percent of demand met by rainwater may become most important. The results can inform the user to increase tank size, increase captured rooftop area or add additional rooftops from neighboring buildings to achieve a desired reuse percentage from rainwater.

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