A Prototype Analysis for Determining the Stormwater Retention and Water Supply Benefits of Cisterns

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Abstract:

Cisterns are usually considered for their water supply benefit. This paper evaluates how effective cisterns are as flood control measures as well as water supply. It considers a problematic situation that is becoming common in the southwest – residential areas on small lots where over half the lot is impermeable. The study uses a simple mass-balance relationship with daily input of rainfall to the cistern and daily use of the water by two citrus trees. It uses the 105 years of daily rainfall measurements at the University of Arizona to calculate daily site runoff and to determine if water will be available to irrigate the trees. The cisterns were shown to be capable of reducing runoff in comparison to a site without a cistern. Likewise, the simulation showed that cisterns will provide most of the water for the trees in an average year.

One measure of smart growth from a hydrologic perspective is for post-development runoff to be maintained at pre-development levels. This simulation showed that whether runoff is maintained at pre-development levels depends on soil types and the runoff from impermeable areas not harvested by the cistern. Cisterns can reduce runoff to pre-development values for the 2 to 10 year events for soils with high runoff potential. For more permeable soils, both water harvesting in earth works and a cistern may be necessary to maintain runoff volume at pre-development levels.

In addition to assessing the benefits of water harvesting for the types of residential housing currently being built, this kind of analysis could be used to determine how to lay out developments that result in smart growth from a hydrologic perspective. Future assessments should integrate the storage capacity of earthworks into the analysis to determine the integrated benefits of cistern and earthworks water harvesting on landscape water supply and flood control.

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Introduction:

The need for flood control in a desert is an incongruous concept. How can a land short of water also be at risk for flooding? Traditionally, water supply and stormwater management have been treated as separate problems. The de-facto model for flood control, even in a desert, has been to route stormwater to major drainages as directly as possible. Drainages have been lined and bank protection has been installed. Millions of dollars have been spent to improve conveyance of stormwater in the urban Southwest: in effect treating stormwater as a waste product. Ultimately, water is routed from residential lots, where it could be used, to major drainages where it is not used.

The solution seems all too obvious – retain rainwater so that water supply needs can be met with harvested rainwater. One study showed that the amount of water delivered by Tucson Water in an average year is approximately equal to the average annual rainfall falling on Tucson (Yoklic, 2006). On an average annual basis, the argument for harvesting rainwater could not be more compelling.

The reality is more complex. Water is used year-round, while rainfall in Tucson typically occurs in two rainy seasons. In addition, annual rainfall depths vary greatly from year to year, which impacts what might be available. Pima County is increasingly trying to find ways to utilize harvested stormwater from major drainages. (Postillion et al. this proceedings), but the volume available must be known to estimate potential benefits. Empirical relationships to estimate stormwater volumes for water harvesting (Tetra Tech, 2001) show that in a good year, twice as much stormwater can be harvested as in an average year, while in a poor year, less than half the average may be harvested (Canfield et al, 2006). In effect, a four-fold difference exists between the low and high estimates.

Whether the capricious nature of rainfall make it a viable water supply lie in understanding how reasonable it is to hold water on-site until it can be used. One way to retain water on-site is to harvest it with cisterns, which have both water supply and flood control benefits. In essence, considering both flood control and water supply benefits together allows us to value both the water and the unused storage capacity of the cistern (i.e. both the water and the capacity for more water in the cistern). French (1988) evaluated the cost-effectiveness of cisterns for flood control and water supply in Las Vegas and concluded that cisterns are cost-effective when the flood control and water supply benefits are taken together.

Homeowners are motivated to install cisterns for the on-site benefits of water conservation, and on site drainage control. However, off-sit benefits, such as reduced flooding, can be just as important. Development invariably results in an increase in the amount of impermeable materials covering a residential lot. In a thought-provoking review paper, Richard McCuen (2003) argues that the first principal of smart –growth, from a hydrologic perspective, is to maintain the same runoff volumes after development.

This study considers the viability of cisterns to provide water supply for landscapes as well as water retention for flood control. Rather than consider average annual conditions, the analysis considers conditions on a daily basis using historical data. It uses 105 years of observed daily rainfall, and the expected daily water use of a typical landscape to determine whether the stormwater and water supply benefits of cisterns will be available when they are needed.

The objectives of this study were as follows:

1.) *To assess the effectiveness of cisterns as a flood control measure.* From a flood control standpoint, the flood control benefits with a cistern must be compared with baseline (natural) pre-development conditions, as well as with post-development conditions without a cistern. The desired outcome of using cisterns is to capture runoff volume from a residential development caused by an increase in the aerial extent of impervious surfaces, so that this runoff does not contribute to flooding.
2.) *To assess the effectiveness of cisterns for landscape water supply.* To ensure some capacity in the cistern for flood control, water must be used rather than retained. This analysis considered the water needs of two medium sized citrus trees, which are trees that cannot be grown in Tucson without supplemental water.

Methods:

Lot Characteristics:

The analysis considers a 1500 square foot home on a 1/8 acre lot, which is typical of the homes now being built in many of the new developments around Tucson, Arizona. Lot development dramatically changes on-site runoff characteristics. One of the more widely-used hydrologic assessment tools, *Urban Hydrology for Small Watersheds TR-55* (USDA-NRCS, 1986), suggests 65% impervious area for 1/8 acre residential lots.

When over half of a lot is covered with impermeable surface, the potential for increased offsite runoff is great. To maintain runoff volumes following development as suggested by McCuen (2003), some additional on-site storage, such as a cistern must be found. Therefore, to evaluate the benefit of cisterns for water supply and flood control the model scenario was a home a on a 1/8 acre lot (i.e. 5,400 square feet) with 1900 square feet of desert landscaping and 3500 square feet of impervious area, of which 1500 square feet is rooftop.

Rainfall Data:

Observed daily rainfall collected at the University of Arizona from 1895 to 2000 was used in this model. This105 years of observed data (~38,000 days) provides a more realistic estimate of the variability of rainfall than simulated rainfall values.

Cistern Sizing:

There are many ways of sizing a cistern, including methods that integrate sizing for water supply and flood control (e.g. Guo and Baetz, 2007). In Tucson a cistern is typically sized for a 1 to 3 inch rainfall event, which represents about 25% of the average annual rainfall in Tucson. Summer thunderstorms in Tucson can easily produce 1 to 2 inches of rain, and often within several days of each other.

With a 1500 square foot roof, a cistern with a capacity of 370 cubic feet will be required. For this exercise, cisterns were assumed to be 8 feet long, and 4 feet diameter with the bottom 6 inches in concrete and the downspout 6 inches below the top. In practice, four of these cisterns would be required to supply 350 cubic feet of storage (2600 gallons). Figure 1 shows a scenario for how cisterns might be placed on a 1/8 acre lot.

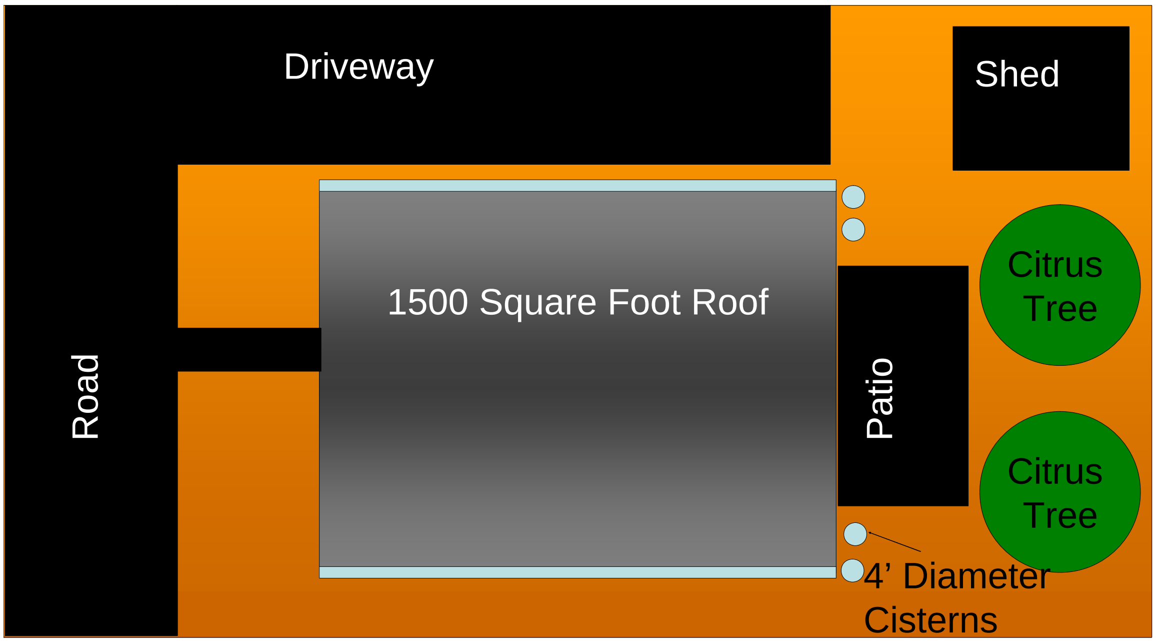

Figure 1 – A prototype layout of a 1/8 acre lot with a home with a 1500 square foot roof. The layout is approximately to scale. Water is harvested from the1500 square feet of roof. About 2000 square feet of the lot has impermeable cover that is not harvested, and about 1900 square feet remain in desert landscaping. The cisterns have a total capacity of 350 cubic feet. The two trees are mature trees with a diameter of 14 feet each.

Landscape Water Use:

A more realistic question is not whether cisterns can provide adequate retention of stormwater, but whether water will be available when it is needed for landscape irrigation. For this exercise, the water harvested was compared with the plant water requirement for citrus trees. The most common way of estimating how much water is required to grow a plant is to determine what fraction of reference crop evapotranspiration (ETo) is needed to supply the needed water.

In Arizona, the AZMET weather data collection system exists to help irrigators estimate ETo (http://ag.arizona.edu/azmet/). Daily ETo data for past eight years from the Campbell Avenue AZMET station in Tucson was used to estimate ETo. The mean ETo for a given date is shown in Figure 2.

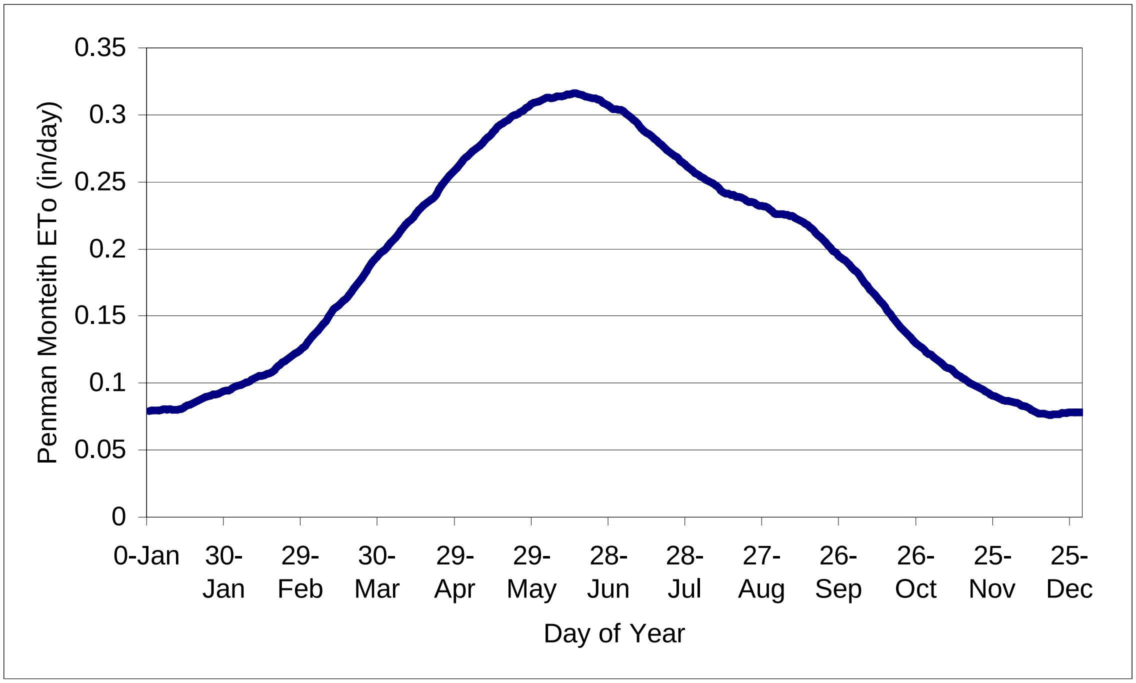

Figure 2 – Reference Evapotranspiration (ETo) at Campbell Avenue Farm in Tucson based on eight years of published estimates for daily ETo. ETo for a year is about 5.7 feet of water.

Recent observations of citrus suggest that crop coefficients are about 1.0 (Snyder and O'Connell, 2007) throughout the year which indicates that citrus trees use water at a rate approximately the same as ETo. Summing the daily ETo over a year results in about 5.7 feet of water use.

Citrus is well-suited to being irrigated from a cistern, because it is often planted in a basin that can be flooded to ensure deep watering of the root zone. Ideally, these basins will be mulched to enhance soil fertility, infiltration capacity and water-holding capacity of the soils. Such basins can also act as overflow basins if the capacity of the cistern is exceeded. In effect, the basins around a citrus tree act as water storage themselves.

Estimated Planting Area:

Mean annual rainfall in Tucson is about 12 inches (11.2 inches based on 105 years of U of Arizona data). So, assuming all roof water can be harvested, the 1f oot of rain falling on the planted area must be supplemented to meet the plant water requirements. Therefore, three of the four feet of water necessary to grow turf must be supplemental. If a rooftop is the source, three square foot of rooftop is needed for each square foot to be planted. Therefore, the 1500 square foot of roof in the prototype lot can irrigate 500 square feet of turf under ideal conditions (average rainfall, 100% irrigation efficiency). Likewise, since a citrus tree requires about 6 feet of water, five square feet of rooftop is required for each square foot of planted space.

Runoff Volume Estimates:

The runoff volume was estimated using the SCS Curve Number method. Because rainfall breakpoint data are not available for the 105 years of rainfall data from the University of Arizona, it is not possible to use a more mechanistic model, such as Green & Ampt, to estimate in storm infiltration rates.

The Curve Number approach allows for the estimate of runoff depth given a rainfall input depth. This means that rainfall intensity data are not necessary to determine infiltration losses. The Curve Number equations are as follows:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad \text{\{Equation 1a\}}$$

Where:

Q is the total depth of runoff (inches);
P is the daily rainfall depth of precipitation (inches);
0.8 is empirically derived, and is based on the assumption that initial abstractions are equal to 0.2 S;
S is the potential abstraction, numerically defined as:

$$S = \frac{1000}{CN} - 10 \qquad \text{\{Equation 1b\}}$$

Where:

CN is the Curve Number.

Curve Numbers were estimated based on TR-55 *Urban Hydrology for Small Watersheds* (USDA, 1986). Curve Numbers used were as follows:

Table 1 – Curve Number Values Used in this Simulation

Condition	**CN**
Natural Desert B- Soils with moderately low runoff potential (e.g. loam soil)	82
Natural Desert C-Soils with moderately high runoff potential (e.g. sandy clay loam)	85
Natural Desert D- Soils with high runoff potential (e.g. clay loam soil)	88
Rooftops	99
Other Impervious Areas	98

The small lot in Figure 1 can be conceptualized for runoff as indicated in Figure 3. Runoff can then be estimated for pre-development conditions (3a), post-development conditions (3b) and post-development with a cistern (3c) for each day in the 105 years of observed daily rainfall. Runoff out from each fraction of the lot is calculated using equation 1.

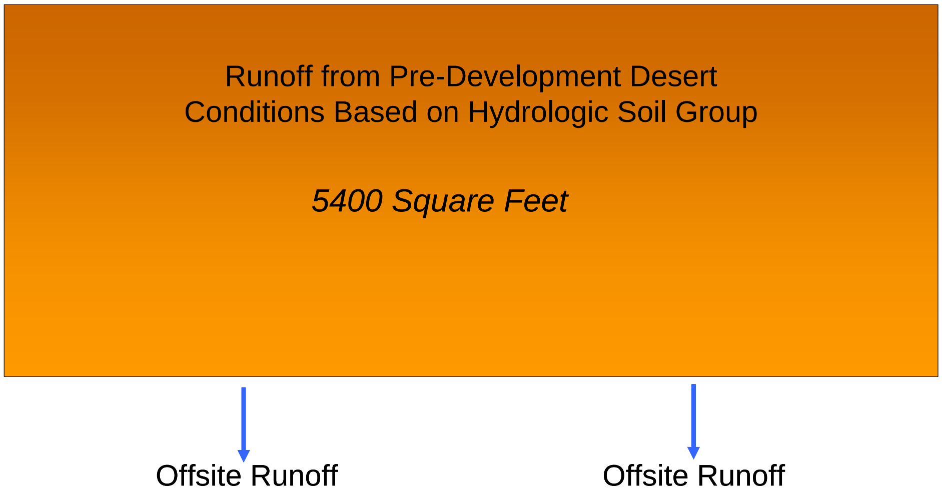

Figure 3a – Schematic of runoff conditions before development. Native soils limit runoff.

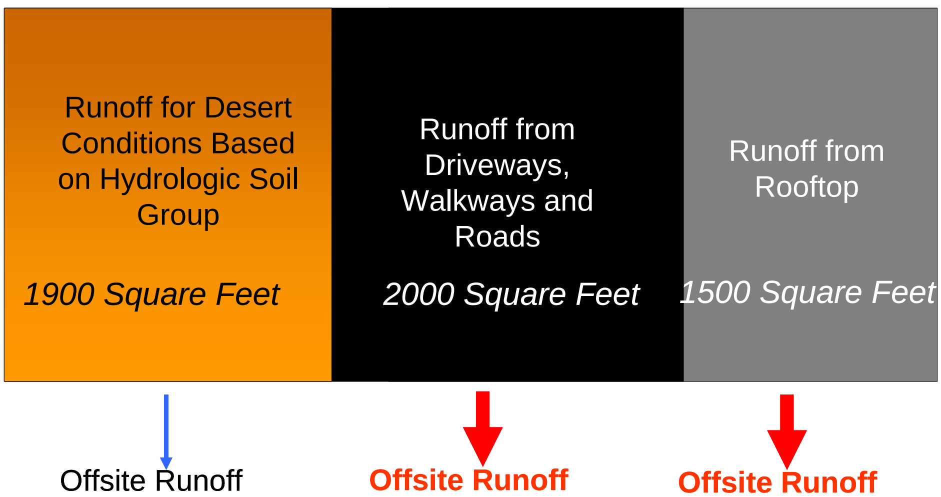

Figure 3b – Schematic of runoff conditions following development. Runoff increases because of impermeable rooftops driveways and other surfaces

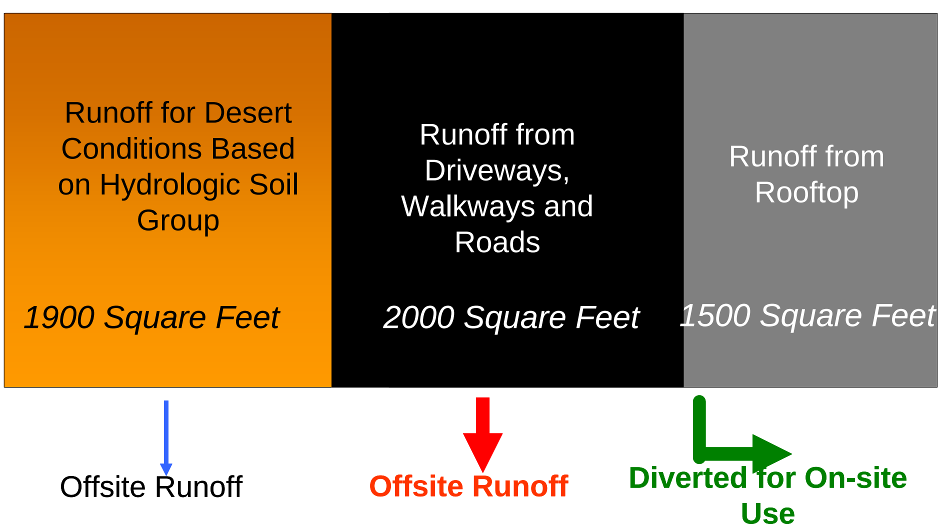

Figure 3c – Schematic of runoff conditions following development with a cistern. Rooftop water is collected and diverted to the cistern.

A Mass-Balance Approach to Cistern Volume Estimates:

For water diverted from the roof into the cistern, (runoff schematic 3c) the water in the cistern must be estimated on a daily basis to determine storage. Using a simple mass balance technique, it is possible to estimate how much water will be present in the cistern throughout the year. In basic terms it is:

For storage > 0 cubic feet and less than 350 cubic feet

For day (i) the storage is:

$$Storage(i) = Storage(i-1) + \Delta Storage \quad \text{\{Equation 2a\}}$$

$$\Delta Storage = Rain - ET \text{ (daily water use)} \quad \text{\{Equation 2b\}}$$

In other words, the volume of water in the tank depends on the water the previous day, the water used in irrigation (from Figure 2), and the water harvested off the roof.

Analytical Framework:

Calculations of both runoff and cistern storage were calculated daily. Because of the potential for storing water in both the cistern and the root zone of the citrus tree, daily deficits of water were not considered to be significant. Instead, the analysis looked at overall ability of the cisterns to harvest enough water to irrigate the trees, and to supply it when the plant needed it on average. In contrast, daily runoff values were tracked for flood control, because individual events cause floods of concern.

Results and Discussion:

Cisterns as a Flood Control Device:

The results show that cisterns have considerable flood control benefit, but that the benefit depends to some extent on soil type. Figure 4 shows the impact of the cisterns on flood control on Hydrologic Group D soils - soils with the highest runoff potential.

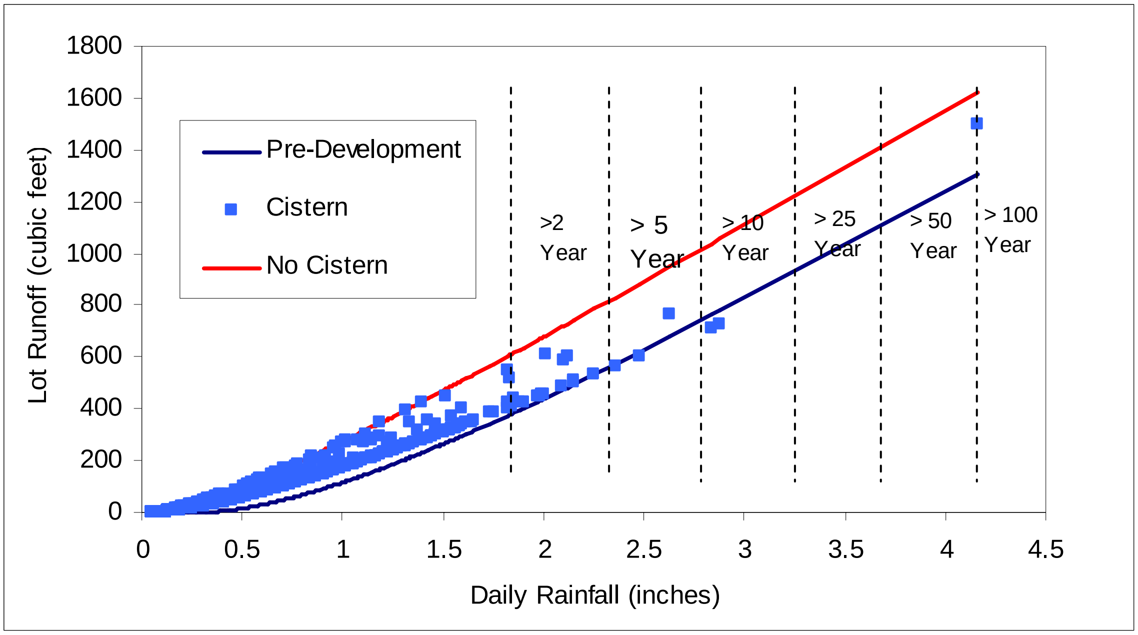

Figure 4 – Simulated lot runoff based on daily mass-balance for the prototype lot on Hydrologic Soil Group D soils. The figure shows that runoff is held to approximately pre-development rates on days where observed 2 to 10 year rainfall occurred during the last 105 years.

As this figure shows, post-development runoff with the cistern (the prototype scenario conceptualized in Figure 3c) approximates conditions runoff from undeveloped conditions, (the runoff scenario in Figure 3a) for most storms between about 2 and 10 year return period. Because impervious surfaces cover about 3500 square feet and only 1500 square feet are routed to the cistern, 2000 square feet of impervious area will be contributing runoff. The fact that post-development runoff with the cistern is approximately the same as the undeveloped case indicates that storage in the cistern is counteracting the effects of the impervious areas. In effect, the cistern compensates for the increased runoff from the 2000 feet of impervious area not connected to the cistern by making roof less likely to contribute runoff than pre-development conditions.

The largest rainfall event in the 105 year record was a 4.16 inch rainfall on October 1, 1983 which is equal to the NOAA 14 Upper 90% rainfall estimate for the100-yr, 24 hour storm. In Pima County and the City of Tucson, retention and detention are not expected to address the impact of a 100-yr event (PCDOT&FCD and City of Tucson 1987). However, the model indicates that there was at least some capacity in the cistern that day because runoff is less than the post-development conditions without a cistern. In reality, the four day rainfall including the three days prior was 6.9 inches, which is between a 200 and 500 year event. Therefore, the model indicates the cistern would have some flood control benefit even with four day precipitation of 200 to 500 years.

For more permeable soils, such as Hydrologic Soil Group B soils, benefits will not be as good. The post-development runoff is greater than pre-development runoff for every simulation (Figure 5). In part this is because the high infiltration capacity of Hydrologic Group B soils make them a more capable storage media than the Hydrologic Group D soils.

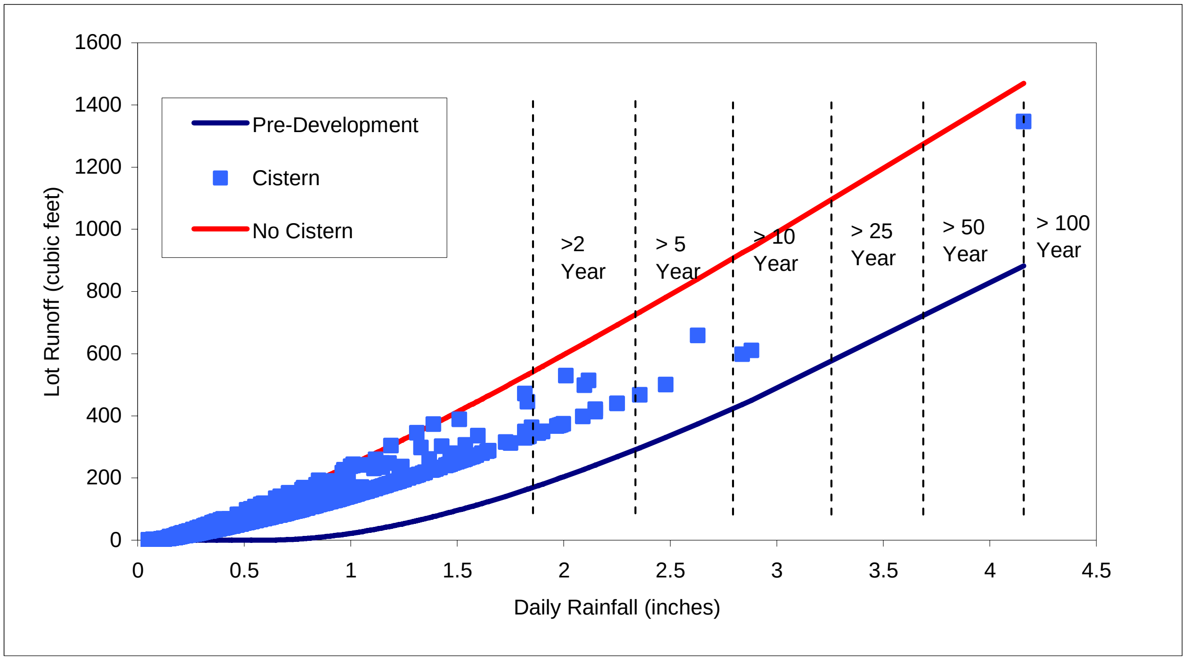

Figure 5 – Simulated lot runoff based on daily mass-balance for the prototype lot on Hydrologic Soil Group B soils. Runoff is above pre-development rates because the infiltration storage capacity of the B soils is so great. However, the cisterns significantly reduce runoff over the case without cisterns.

In effect the simulation shows that for permeable soils the conversion of 2000 feet of permeable soil to impermeable surface cannot be compensated by the installation of a cistern. Still, the evaluation indicates that cisterns sized to hold 3 inches of rainfall off a roof can also greatly reduce runoff.

This analysis did not consider water harvesting in earthworks. However, the analysis of the Hydrologic Soils Group B soils shows that post-development runoff depths cannot be reduced to pre-development depths using cisterns alone. Some other measures will need to be considered. It is highly conceivable that by diverting some of the water in the 2000 square feet of impermeable area not connected to the cistern into sunken basins runoff from the lot could be reduced to at or below pre-development runoff depths.

The results show that even on a small lot with more than 50% impervious surfaces, cisterns can limit runoff. Furthermore, cisterns can be used to maintain runoff at pre-development runoff depths - the first principle of smart growth from a hydrologic perspective.

Cisterns as a Source of Landscape Water:

The results showed that cisterns could be a primary source of water for 300 square feet of citrus trees, but on average supplemental water would be required to prevent the trees from becoming drought-stressed.

Figure 6 shows the how much water was harvested. On average, about 1100 cubic feet of water was harvested (8,200 gallons) in a year. If the cistern collected every drop of rainfall that fell on the roof, we would anticipate that 1400 cubic feet of water would be harvested. However, losses are attributed to overtopping of the cistern in larger rainfall events, and the 0.1 inch of each rainfall which is lost to evaporation and other sources during the event.

On average the 1100 cubic feet harvested fell short of the supplemental water required to grow two citrus trees, which was 1400 cubic feet (10,500 gallons).

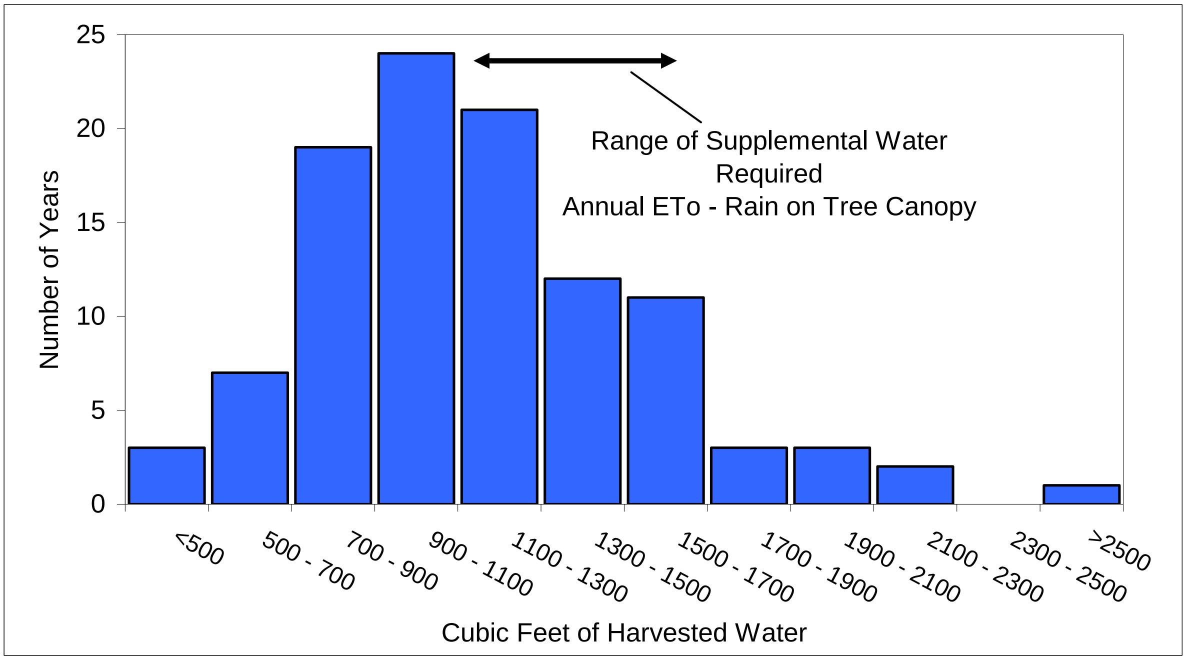

Figure 6 – Histogram of annual volume of water harvested for the 105 years of simulation. The cistern will supply the majority of water in most years, though some supplemental water may be required during the drier hotter times of the year.

However, for most of the year, harvested water can supply the water required to grow fruit trees (Figure 6). On average, from July through March harvested water will satisfy the water requirement. The largest deficit between harvested water and water demand occurs in the late spring.

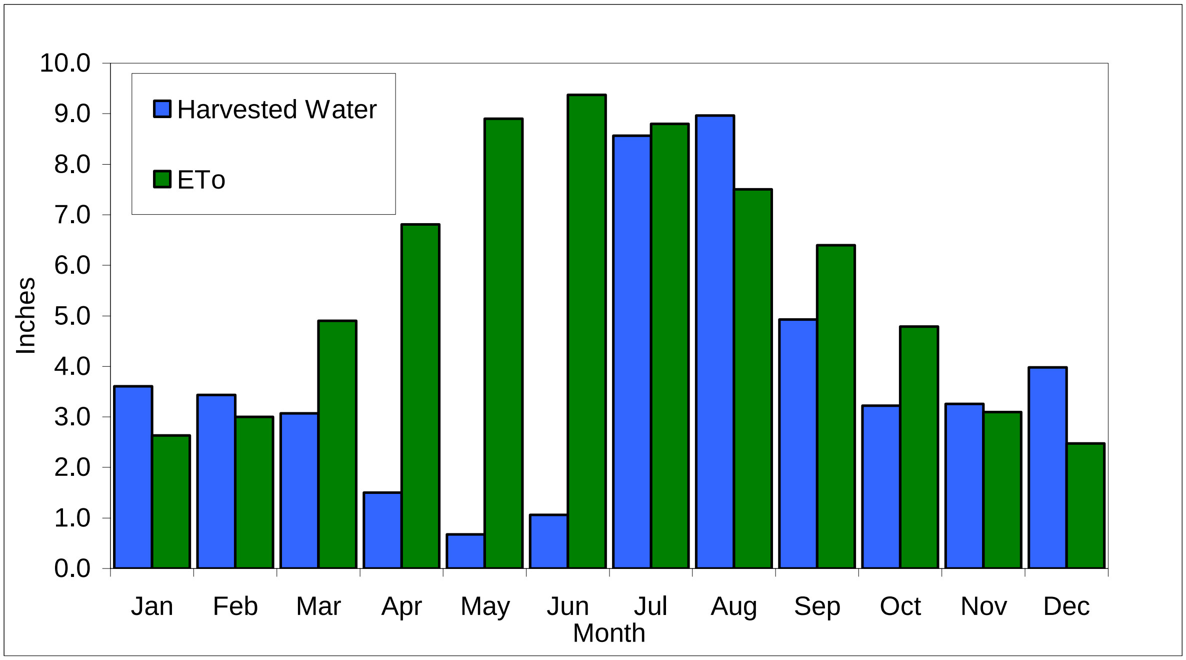

Figure 7 – Average Monthly Evapotranspiration (ETo) and Harvested Water for the 105 years of mass-balance simulation.

The shortfall could be addressed by planting less area, or building a larger cistern. However, an alternative would be to irrigate with an alternative water supply in the late spring. Because citrus are deep-rooted trees, one or two deep irrigations in the late spring would satisfy the shortfall.

Conclusions:

This analysis shows that cisterns can provide significant flood control and water supply benefits. This prototype scenario used a particularly problematic situation from a flood control perspective (i.e. impermeable cover over more than half the site) to show that cisterns can be effective, even when the site conditions have been significantly modified.

Likewise, the simulation showed that harvested water could be used to grow citrus trees most of the year in most years. Furthermore, because tree crops are deep-rooted, the sunken basin surrounding the tree acts as secondary storage capacity when a cistern overflows.

One measure for smart growth from a hydrologic perspective is for post-development runoff to be maintained at pre-development levels. This simulation showed that whether runoff is maintained at pre-development levels depends on soil types and the runoff from impermeable areas not harvested by the cistern. Cisterns can reduce runoff to pre-development values for the 2 to 10 year events for soils with high runoff potential. For more permeable soils, both water harvesting in earth works and a cistern may be necessary to maintain runoff volume at pre-development levels.

This kind of analysis has the potential to determine how runoff can be reduced and vegetation restored even with high density growth. While this scenario used lot characteristics common in new developments around Tucson, the methodology could be used to asses alternative lot layouts that aim to have less of an impact on the runoff characteristics of a watershed than the current practices. It would be helpful to integrate the water harvesting potential of earthworks into the simulation, though this is a more complicated step, because determining the storage capacity of earthworks is more complicated than estimating the volume of a cistern.

Acknowledgements:

Catlow Shipek provided useful comments in the editing of the manuscript. Barbara Rose provided suggestions for the formulation of the exercise in its original form in 2005.

References:

Canfield, H.E., Postillion, F., Fonseca, J and Chavez, K. 2006 *A Preliminary ssessment of the Multipurpose Benefit to Water Harvesting at Regional Detention/Retention Facilities in Pima County*. Presentation at Southwest Regional ARCSA, Tucson, AZ, Oct 27 & 28, 2006

French, R.H. 1988. Cisterns for Water Conservation and Flood Control. *Journal of Water Resources Planning and Management*, Vol.114, No. 5, 565-577

Guo, Y and Baetz. B.M. 2007. Sizing of Rainwater Storage Units for Green Building Applications *Journal of Hydrologic Engineering*, Vol. 12, No. 2, 197–205

McCuen, R.H., 2003. Smart Growth: Hydrologic Perspective, *Journal of Professional Issues in Engineering Education and Practice*, Vol. 129, No. 3, 151-154

PCDOT&FCD and City of Tucson. 1987. Stormwater Detention/Retention Manual.

Postillion, F, Canfield, H.E., Fonseca, J and Chavez, K. (this proceedings) Multipurpose benefits of regional detention/retention facilities in Pima County**,**

Snyder, R.L and O'Connell, N.V. 2007. Crop Coefficients for Microsprinkler-Irrigated, Clean-Cultivated, Mature Citrus in an Arid Climate *Journal of Irrigation and Drainage Engineering*, Vol. 133, No. 1, 43–52

Tetra-Tech. 2001. *Summary Report: Water Yield Analysis for the Ajo Way Stormwater Detention Facility (Yield calculated using equations 5, 6, 7 & 8.)*

USDA-NRCS .1986. *Urban Hydrology for Small Watersheds TR-55*.

Yoklic, M. *Water Harvesting Potential in an Arid City: A Quantity Assessment for Tucson, Arizona.* Presentation at Southwest Regional ARCSA, Tucson, AZ, Oct 27 & 28, 2006