APPENDIX D: DOCUMENTATION FOR DEVELOPMENT OF STORMWATER HARVESTING FACTORS

MEMORANDUM

Planning & Development
Regional Flood Control District

DATE: October 31, 2011

TO: File **FROM:** Dave Stewart
SUBJECT: Stormwater Harvesting Factor Study

INTRODUCTION:

A simple method of estimating the reduction in stormwater runoff volume and peak discharge due to placement of stormwater harvesting basins throughout a project site was required that would provide reasonable estimates without extensive modeling effort such as routing flows through the individual stormwater harvesting basins. A modeling study was developed that could quantify the reduction in peak discharge and runoff volume from varying scales of stormwater harvesting at a subdivision with hydrologic data.

Rainfall and runoff data was collected by the USGS for the La Terraza subdivision in Sierra Vista, Arizona, from 2005 – 2008 as the subject of a thesis (Kennedy, 2007) (Figure 1) that also collected soil infiltrometer data for the urban soils and the upstream grassland watershed. The subdivision was selected for this study since it is one of the few if not only residential subdivisions near Pima County with recorded rainfall, runoff, and soil infiltration data. Runoff data collection was discontinued by the USGS in September of 2008.

Kennedy (2007) modeled the La Terraza subdivision using the physically-based USDA-ARS KINEROS2 model. For the Stormwater Harvesting Factor Study, the EPA's StormWater Management Model (SWMM) Version 5.0 (Rossman 2010), a dynamic rainfall-runoff model, was selected due to its applicability for urban drainage systems, its ability to run continuous simulations, and its ability to model Low Impact Development (LID) practices such as stormwater harvesting basins. The EPA SWMM model uses either kinematic wave or dynamic wave routing with a variety of infiltration methods and therefore was able to emulate the KINEROS2 model for La Terraza developed by Kennedy (2007).

By running the La Terraza SWMM model as a continuous simulation of the rainfall events from 2005 to 2008, the model could be validated with the observed runoff data and provide an estimate of modeled runoff error for the urban watershed. With an acceptable level of error, the model could be used to produce runoff results for a variety of stormwater harvesting scenarios and return period design storms.

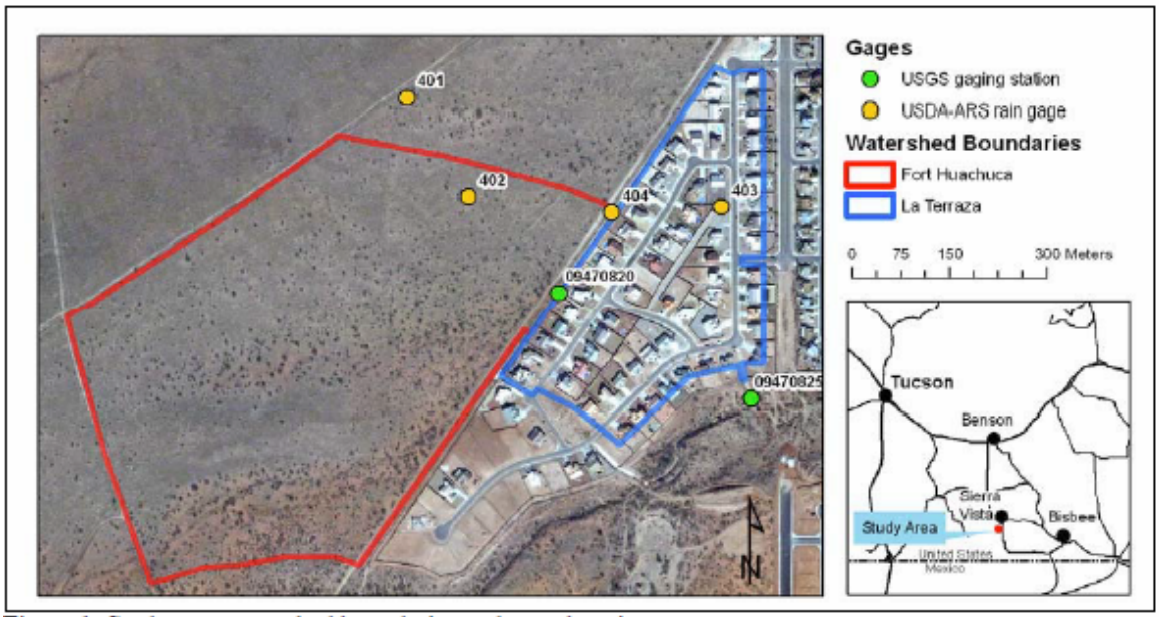

Figure 1. The location of the USGS rainfall and runoff gages near the La Terraza subdivision in Sierra Vista, Arizona (Source: Kennedy 2007).

Purpose

The purpose of this study is to:

1.) validate that the model simulates the observed runoff events,
2.) describe the method that was used to derive stormwater harvesting factors and
3.) present equations for using the stormwater harvesting factors.

METHODS:

Model Development

The La Terraza SWMM model was created by matching the subcatchments in Kennedy's KINEROS2 model (Figure 2) and using the associated data when applicable (See Table A.1 through A.4 for base model parameters). Two shallow channels were added in the SWMM model to represent the street system to prevent additional infiltration from routing flow over downstream subcatchments. SWMM subcatchments adjacent to the street drain into the street channel system and are routed to the outlet. Subcatchments not adjacent to the street system in the SWMM model follow the KINEROS2 pattern of routing flow onto downstream subcatchments.

The Green-Ampt infiltration method was used for the SWMM catchments and the saturated hydraulic conductivity (K_s) was used from Kennedy's measurement of effective K_s for La Terraza's urban soils and the upland grassland soils. Kennedy's watershed-scale value of K_s for the urban watershed (2.5 mm/hr or 0.1 in/hr) was used for all subcatchments in the urban area, and the grassland watershed-scale K_s (25 mm/hr or 1 inch/hr) was used for all subcatchments in the grassland area. The Green-Ampt suction head and initial deficit values (6.4 in and 0.15

respectively) were found from K_s using the SWMM manual and other tables that are based on Rawls (1983).

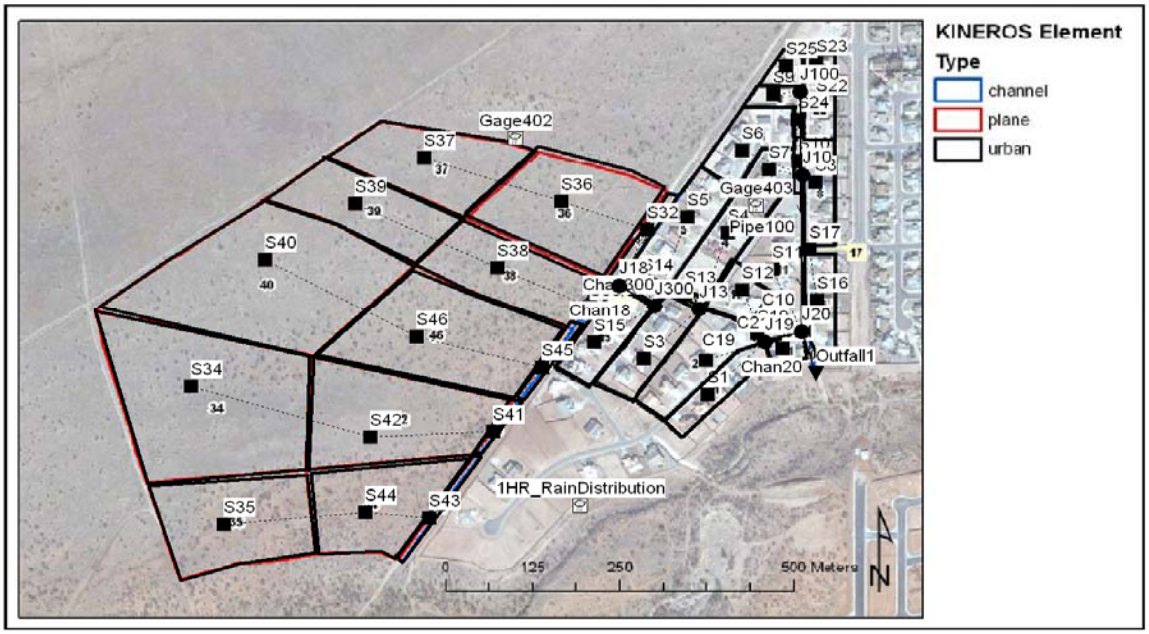

Figure 2. An image of the KINEROS2 model from Kennedy (2007) with the SWMM subcatchments created overtop with identical parameters where appropriate.

Model Validation

The rainfall from USDA Gage 402 was used for the grassland subcatchments and the rainfall from USDA Gage 403 was used for the urban subcatchments for the continuous simulation of the period from 2005 – 2008. The average monthly evapotranspiration (ET) for Sierra Vista based on data from 1991-2003 (Runyon, personal communication) was used in the SWMM continuous simulation.

The runoff data from the grassland watershed (USGS Gage 09470820) was used in the SWMM model as inflow to the urban watershed to evaluate the modeled urban runoff at the outlet compared to the data (USGS Gage 09470825). In addition, the grassland watershed was modeled and the modeled runoff from both the grassland and urban watershed were compared against the gage data.

The peak discharges for the 59 precipitation events and the overall runoff volumes were compared between the models and the runoff data. The root mean square error (RMSE) was calculated between the modeled peak discharges and the observed peak discharges as:

$$RMSE = \sqrt{\frac{\sum (Modeled - Observed)^2}{n}}$$

to provide an estimate of model error in predicting peak discharge relative to the gage data.

Stormwater Harvesting Basin Modeling

Several scales and distributions of stormwater harvesting were modeled using the SWMM model. The grassland watershed was removed from the models to provide a comparison of

runoff for only the developed area. All stormwater harvesting basins were assumed to have a depth of 1 foot. The scales of stormwater harvesting included are:

- Two percent of developed area at one foot deep (10.3% of 100-yr La Terraza urban runoff volume)
- Five percent of developed area at one foot deep (25.7% of 100-yr La Terraza urban runoff volume)
- Ten percent of developed area at one foot deep (51.4% of 100-yr La Terraza urban runoff volume)
- Sixteen percent of developed area at one foot deep (85.7% of 100-yr La Terraza urban runoff volume)

The following cases of stormwater harvesting distribution in the site were considered (Figure 3):

- Distribution Case 1 (100% Distributed): Stormwater harvesting basins are distributed equally relative to subcatchment area (i.e., 2% of each subcatchment area) for each stormwater harvesting scale.
- Distribution Case 2 (50% Distributed): Half the area of stormwater harvesting is distributed equally relative to subcatchment area and the remaining half of stormwater harvesting area designated as a basin at the outlet of the site.
- Distribution Case 3 (0% Distributed): The stormwater harvesting area is one basin at the outlet of the site, with all channels and subcatchments leading to it.

The stormwater harvesting areas were modeled in SWMM by creating new subcatchments with an area representing the scale of stormwater harvesting and 12 inches of depression storage, and the infiltration properties for compacted urban soils of the surrounding pervious areas. The area of the upstream subcatchment was reduced by the area of the new stormwater harvesting area and the impervious percent of the upstream subcatchment was increased accordingly to maintain a constant acreage of pervious and impervious areas.

The stormwater harvesting basin at the outlet for the 50% and 0 % distributed cases was modeled by creating a new subcatchment and removing the appropriate area from the surrounding subcatchments, and creating a storage unit with a storage curve and a weir one foot above the bottom. The new subcatchment receives rainfall for the basin area and routes it directly to the storage area. The modeled storage area receives drainage from all channels and subcatchments, calculates infiltration using the same parameters as the rest of the urban pervious areas, and has a storage volume equal to the area multiplied by 1 ft of depth. The modeled weir leads to the outlet of the site.

Case 1:100% Distributed **Case 2: 50% Distributed** **Case 3: 0% Distributed**

Figure 3. Example site distributions for each scale of stormwater harvesting. The hypothetical stormwater harvesting areas are shown in green and are not drawn to scale. Stormwater harvesting areas were modeled for each individual subcatchment in the 100% and 50% distributed cases.

Design Storms

The design storm used to model the stormwater harvesting basins was a 1-hour nested rainfall distribution. A 1-hour storm duration was chosen to follow the use of a 1-hour rainfall depth in the Pima County Hydrologic Procedures (PC-Hydro) and due to the small watershed area (29 acres of development), the 1-hr storm is expected to be the critical storm.

A rainfall intensity duration frequency curve was created using data from NOAA (http://hdsc.nws.noaa.gov/hdsc/pfds/index.html) for the Sierra Vista site (02-7880). The 90% confidence interval rainfall depths were selected as typically used in Pima County. A 1-hour nested rainfall distribution was created using the depth-duration-frequency method (DDF) (Haan et al., 1994). For this study, the 5-min rainfall depth was placed in the center of the storm, surrounded by the additional rainfall for the 10-min, 15-min, 30-min, and 60-min rainfall depths (Figure 4). Results were modeled for the 100-yr, 10-yr, and 2-yr return period rainfall depths.

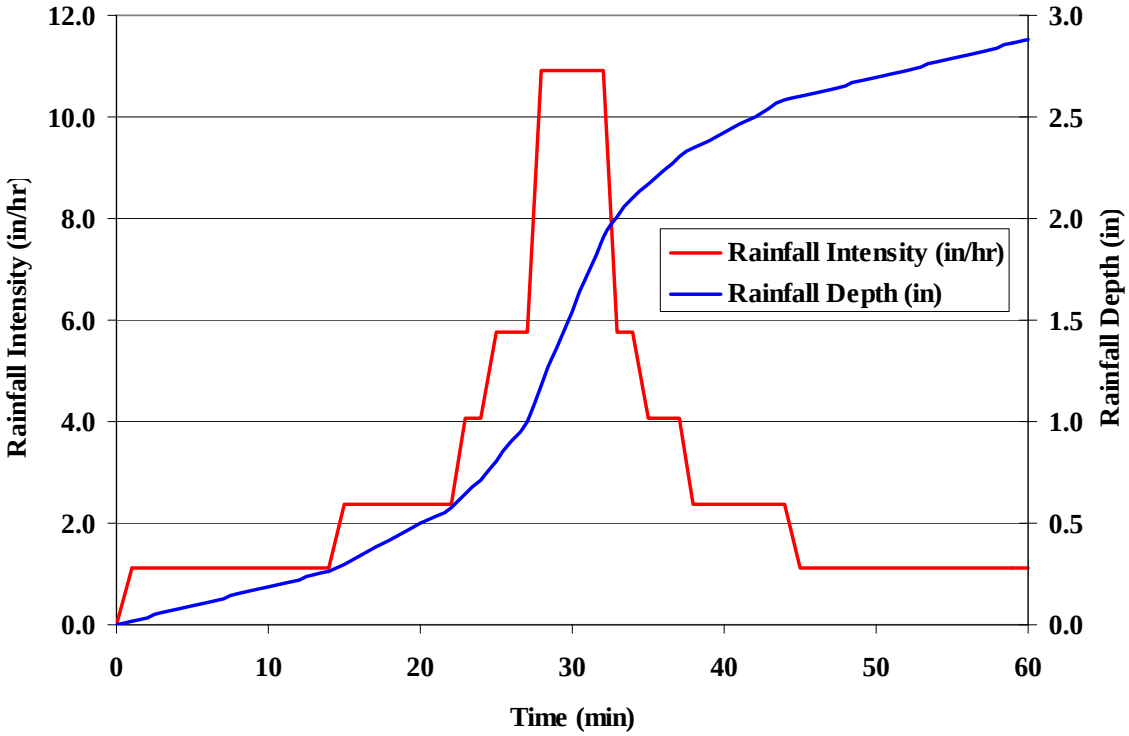

Figure 4. Nested 1-hr rainfall distribution using 1% annual chance rainfall depths.

Additional Watershed Configurations

Two additional watershed configurations were considered by rearranging some of the La Terraza subcatchments. A watershed with a shortened flow path was considered by attaching all subcatchments directly to the outlet without any channel systems. A watershed with longer flow paths than La Terraza was considered by moving the eastern half of the La Terraza subcatchments upstream of the channel system of the western half, and multiplying all channel lengths by a factor of two. In the additional cases, the

watershed area remains the same and only the length of flow path and order of subcatchments are different.

RESULTS:

Model Validation Results

The SWMM model had a root mean square error (RMSE) of 4.6 cfs when predicting the urban peak discharges (grassland runoff data was used as inflow) and 79% of the variation in peak discharge was explained ($R^2 = 0.79$) (Figure 5). The La Terraza SWMM model will only be modeling urban runoff for this study. Fifty nine peak discharges were compared for the period from 2005 – 2008. A larger error is associated with the larger observed peak discharge events, particularly the seven events that recorded a peak discharge of 25 cfs. When the urban and grassland watersheds are both modeled, the RMSE is 8.5 cfs and R^2 is 0.59.

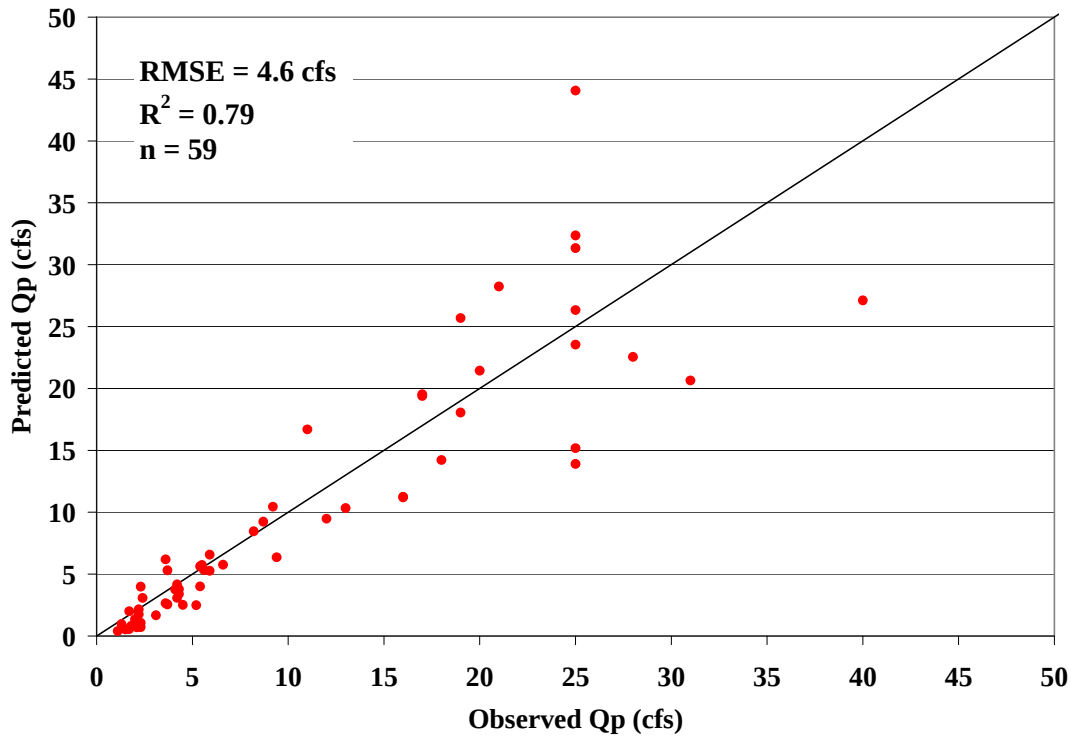

Figure 5. The comparison of modeled peak discharges to observed peak discharges from modeling the urban watershed and using the observed grassland runoff data.

When the urban runoff was modeled and the observed grassland runoff data was introduced into the model, the modeled cumulative runoff volume was 43.1 ac-ft or 27% higher compared to the observed cumulative runoff volume of 33.9 ac-ft (Figure 6). When the grassland and urban watersheds are modeled, the cumulative runoff volume is 40.5 ac-ft or 19% higher (there was virtually no modeled runoff from the grassland watershed). The modeled urban runoff volume is higher than the observed volume and therefore it is a conservative estimate.

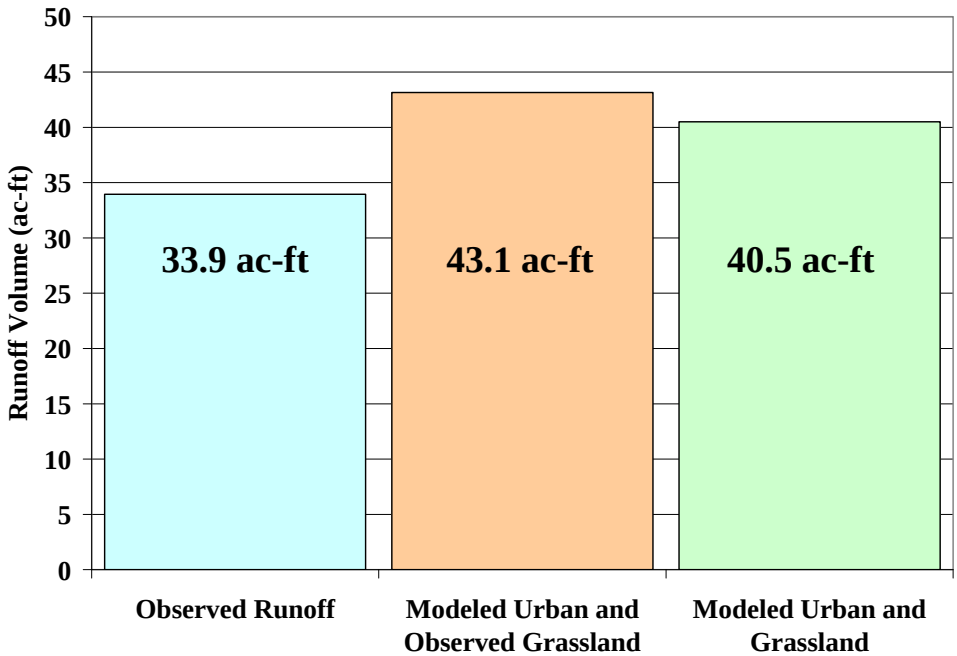

Figure 6. Modeled cumulative runoff volume compared with runoff data for La Terraza from 2005 – 2008.

Stormwater Harvesting Basin Modeling Results

i. *Peak Discharge Reduction relative to Scale and Distribution,*

The reduction in peak discharge for the 100-yr, 10-yr, and 2-yr storms are shown below by scale and distribution of stormwater harvesting (Tables 1, 2, and 3). The overall stormwater harvesting volume (V_{BAS}) divided by the runoff volume ($V_{POST\text{-}RP}$) (i.e. $V_{BAS}/V_{POST\text{-}RP}$)or X_{RP} is a useful metric for stormwater harvesting because it is independent of a specific basin geometry (there may be a variety of areas and depths), and the effectiveness in reducing peak discharge is dependent on the runoff volume from the watershed. Figure 7 shows the reduction in 100-yr hydrograph for the 100% distributed case at varying scales of stormwater harvesting (X_{RP}).

Table 1. Reduction in 100-yr peak discharge (197.2 cfs) by stormwater harvesting scale and distribution.

	Catchment Area			
	2.0%	**5.0%**	**10.0%**	**16.7%**
X_{100yr} (V_{BAS} / $V_{POST\text{-}100yr}$)	**10.3%**	**25.7%**	**51.4%**	**85.7%**
0% Distributed, Reduction in Qp_{100yr}	0.9%	21.9%	58.9%	93.0%
50% Distributed, Reduction in Qp_{100yr}	0.0%	11.9%	49.5%	84.9%
100% Distributed, Reduction in Qp_{100yr}	0.4%	22.2%	54.8%	88.9%

Table 2. Reduction in 10-yr peak discharge (115.0 cfs) by stormwater harvesting scale and distribution.

	Catchment Area		
	2.0%	**5.0%**	**10.0%**
X_{10yr} ($V_{BAS}/V_{POST\text{-}10yr}$)	**17.5%**	**43.8%**	**87.6%**
0% Distributed, Reduction in Qp_{10yr}	6.2%	44.6%	92.1%
50% Distributed, Reduction in Qp_{10yr}	2.5%	35.8%	84.7%
100% Distributed, Reduction in Qp_{10yr}	9.7%	48.4%	89.2%

Table 3. Reduction in 2-yr peak discharge (59.2 cfs) by stormwater harvesting scale and distribution.

	Catchment Area		
	2.0%	**5.0%**	**10.0%**
X_{2yr} ($V_{BAS}/V_{POST\text{-}2yr}$)	**31.9%**	**79.7%**	**159.4%**
0% Distributed, Reduction in Qp2yr	22.6%	80.7%	100%
50% Distributed, Reduction in Qp2yr	14.7%	74.1%	100%
100% Distributed, Reduction in Qp2yr	35.4%	82.4%	100%

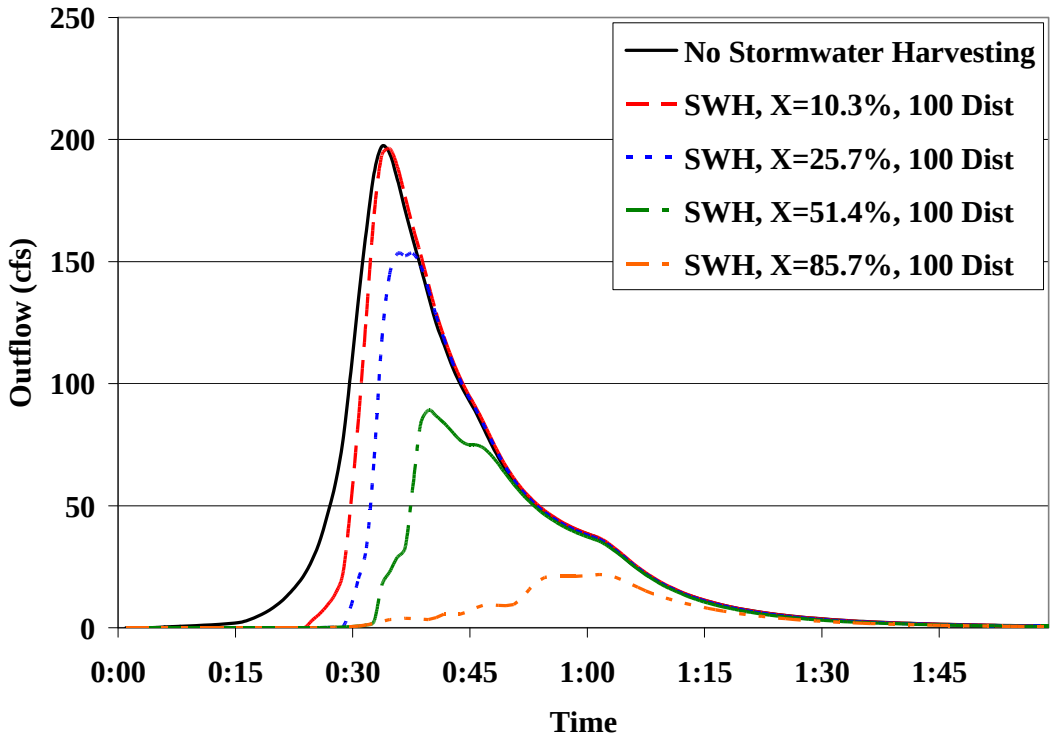

Figure 7. The effect of stormwater harvesting scale on the modeled 100-yr hydrograph.

The scale of stormwater harvesting has a large impact on the modeled peak discharge for all return periods due to different volumes of depression storage; however, the model did not show as large of a difference due to the distribution of stormwater harvesting within the site. The stormwater harvesting basins were modeled as depression storage and therefore any benefits from the attenuation of runoff by upstream basins may not be fully represented in the model.

The modeled differences in peak discharge reduction due to the distribution of stormwater harvesting may be attributed to whether the stormwater harvesting is in areas that will utilize all of the volume or be able to "catch" all of the runoff they receive. The 0% distributed case provides the most reduction in some simulations since no flow is able to bypass the stormwater harvesting because all channels and subcatchments are directed to the large stormwater harvesting area, and all volume of stormwater harvesting at the outlet is utilized before it overflows.

The extent of modeled peak discharge reduction by the 100% distributed case depends on whether the basin at each subcatchment has enough volume to capture the runoff peak and therefore reduce hydrograph flow rates from all portions of the watershed before they "add up" into a larger peak hydrograph at the outlet.

The 50% distributed case provides less reduction in modeled peak discharge because the "half-size" stormwater harvesting at the subcatchments often retain the front of the hydrograph but do not "reach" the peak, and the sharp peaked hydrographs leaving the subcatchments "add up" to a peak discharge at the outlet higher than the other distributions of stormwater harvesting. A more detailed model that represents the attenuation effects of the stormwater harvesting basins may find a greater benefit from the distribution of stormwater harvesting throughout the site; however, this model was not able to find a significant trend in peak discharge reduction due to the distribution of stormwater harvesting in the site.

ii. *Peak Discharge Reduction relative to Return Period*

The reduction in peak discharge was plotted relative to the stormwater harvesting volume divided by runoff volume (X_{RP}) metric for all return periods (Figure 8). The value of X for the 2-yr event above 100% was represented as one point with peak reduction equal to 100% because it is assumed that when the stormwater harvesting volume is equal to or greater than the runoff volume no runoff will leave and the reduction in 2-yr peak discharge will be 100%. Most variability in modeled peak discharge reduction or "stormwater harvesting factor" (H_{RP}) is explained by a linear regression with X_{RP} for all return periods (R^2 = 0.97). Therefore, values for H_{RP} were developed based on $X_{RP} = V_{BAS} / V_{POST\text{-}RP}$ and may be applied to different return periods by using the appropriate return period runoff volume.

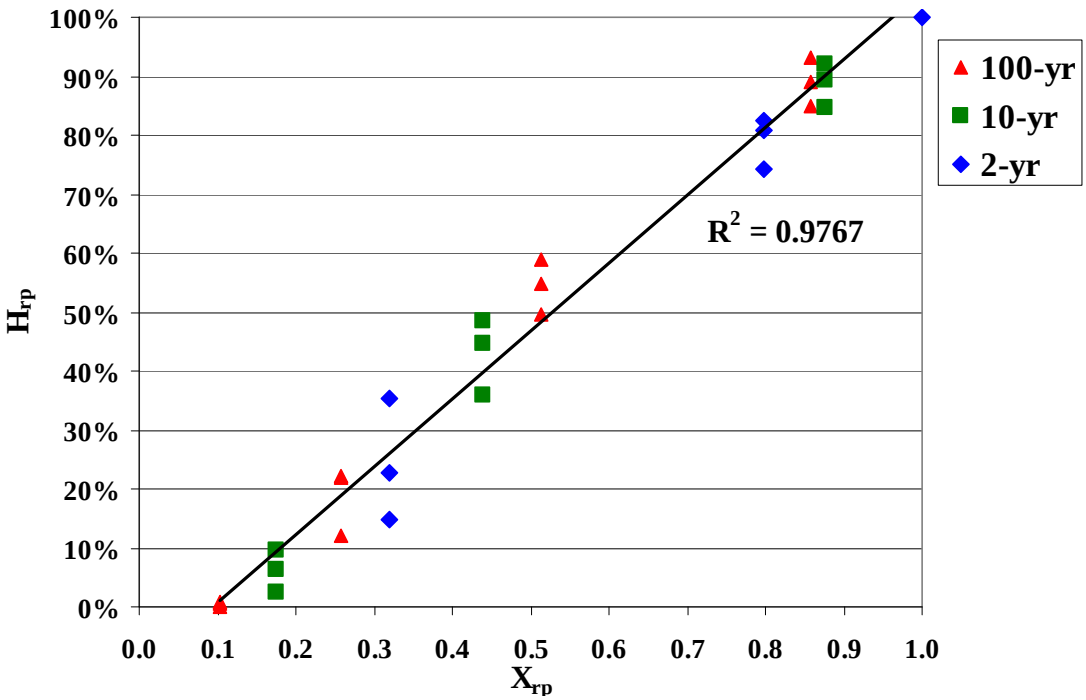

Figure 8. Reduction in return period peak discharge (H_{RP}) at varying scales of stormwater harvesting (X_{RP}) for the 100-yr, 10-yr and 2-yr hydrographs.

iii. *Reduction in Peak Discharge relative to Watershed Configuration*

The modeled 100-yr peak discharges from the watershed configurations were 197.2 cfs from the base model (the actual arrangement of La Terraza), 225.1 cfs from the shorter flow path model, and 159.7 cfs from the longer flow path model (Figure 9). The peak discharge reductions or stormwater harvesting factors (H_{RP}) for the three distributions by watershed configuration and ratio of basin volume to runoff volume (X_{RP}) are shown in Table 4.

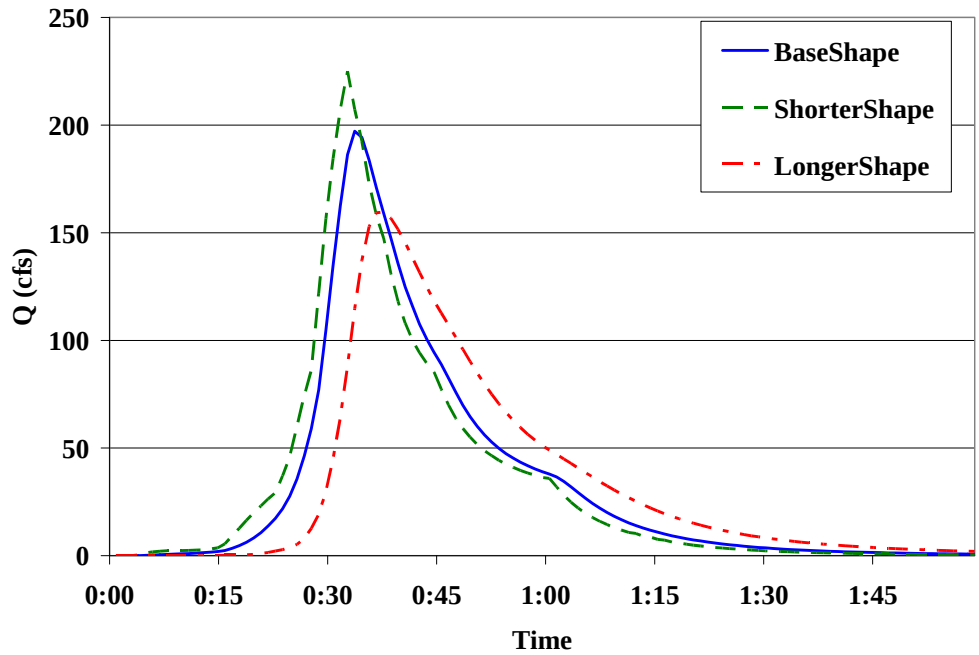

Figure 9. The modeled 100-yr hydrographs for the different watershed configurations based on La Terraza.

Table 4. Stormwater harvesting factors (H_{RP}), longest flow path length (Lc), peak discharge (Qp), and 100-yr hydrograph volume divided by peak discharge (V/Qp) for each watershed configuration and distribution.

Watershed Configuration	Distribution	Lc (ft)	Qp (cfs)	V/Qp	Average Hrp			
					X = 10.2%	X = 25.5%	X = 51.1%	X = 85.7%
Short	0%	177	225.1	1093.8	3.1%	22.0%	61.4%	91.7%
	50%				0.9%	11.9%	53.2%	86.0%
	100%				1.3%	19.9%	57.1%	90.0%
Base (La Terraza)	0%	1224	197.2	1229.9	0.9%	21.9%	58.9%	93.0%
	50%				0.0%	11.9%	49.5%	84.9%
	100%				0.4%	22.2%	54.8%	88.9%
Long	0%	4046	159.7	1528.7	0.7%	19.8%	54.9%	92.3%
	50%				0.5%	11.0%	43.3%	83.8%
	100%				1.9%	14.9%	51.9%	88.3%

The stormwater harvesting factors (H_{RP}) or peak discharge reduction for the three different watershed configurations were compared to the hydrograph volume relative to the peak (V/Qp) (Figure 10). The hydrograph volume (ft^3) divided by the peak (cfs) (V/Qp) (in seconds) is an arbitrary metric that could account for many watershed variables that affect the hydrograph shape such as the watershed length of flow path and slope that are used in hydrologic calculations. Figure 10 shows that at lower scales of stormwater harvesting (X = 10.2%), H_{RP} is essentially constant with about 1% difference due to hydrograph shape, and H_{RP} varies at a maximum of 5% at the X = 52.1% scale of

stormwater harvesting. At scales of stormwater harvesting closer to X = 50%, H_{RP} tends to decrease with flatter hydrographs since there is more volume to retain before "reaching" the peak of the hydrograph. Because the length of watershed flow path affects the hydrograph shape, plotting H_{RP} by length of watershed flow path finds the same trend based on scale of stormwater harvesting. Essentially, Figure 10 shows that reduction in peak discharge varies more due to hydrograph shape at scales of stormwater harvesting closer to the peak of the hydrograph (i.e. X=50%).

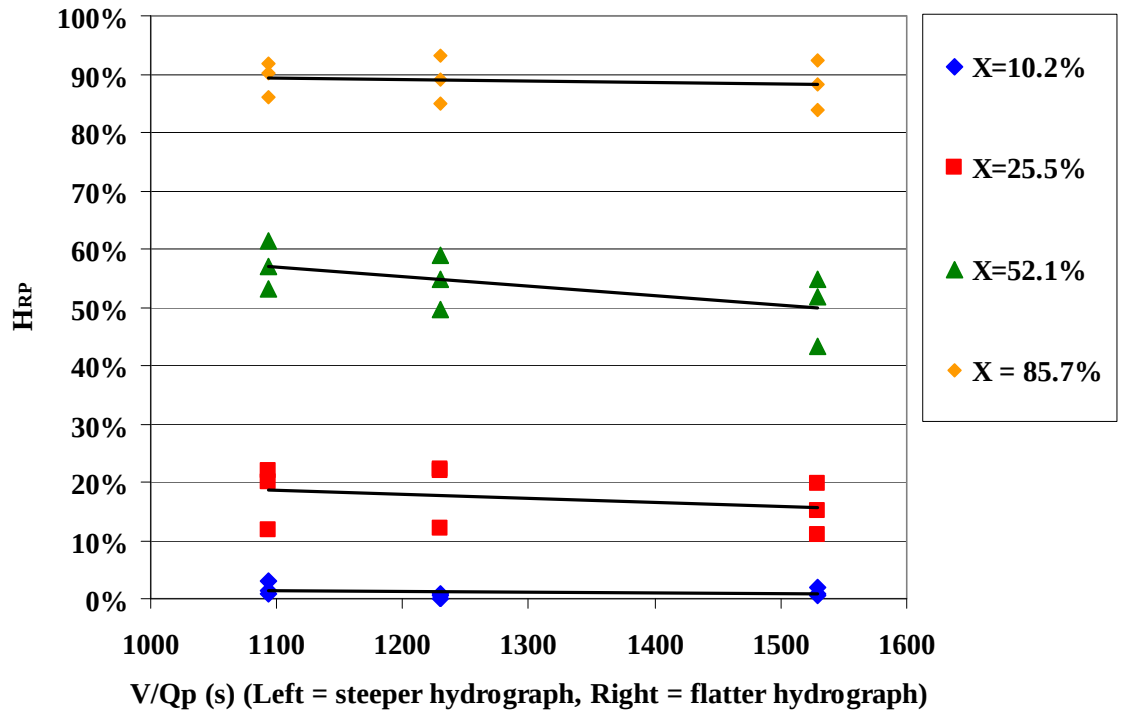

Figure 10. Variability in stormwater harvesting factors (H_{RP}) relative to hydrograph shape (V/Qp) at differing scales of stormwater harvesting (X_{RP}).

iv. *Evaluation of Stormwater Harvesting Factors for Peak Reduction*

Using the root mean square error of H_{RP} relative to the mean value as a measure of variability for the values in Table 4, the peak reduction varies due to hydrograph shape and distribution of stormwater harvesting by about 0.9% at lower scales of stormwater harvesting (X=10%), increases to about 5.0% at scales of stormwater harvesting closer to X = 25% and X=50%, and then drops to about 3.1% at higher scales of stormwater harvesting (X=85.7%) based on the modeling results.

A polynomial equation fits the values of H_{RP} slightly better than a linear equation due to the curvature from increasing reduction in peak discharge as more stormwater is captured near the peak of the hydrograph, and then the slight decreasing of peak

reduction at X greater than 50%. The order of the polynomial equation was chosen because it particularly provides a better fit for the data points in the X = 0.10 to X = 0.40 range which is expected to be used frequently (Figure 11), and the higher order polynomial tends to pass through the peak reduction at the middle of the watershed conditions at most scales. The values of H_{RP} based on this equation are shown in Table 5. This equation and table of values can be updated as more data on peak reduction due to stormwater harvesting becomes available.

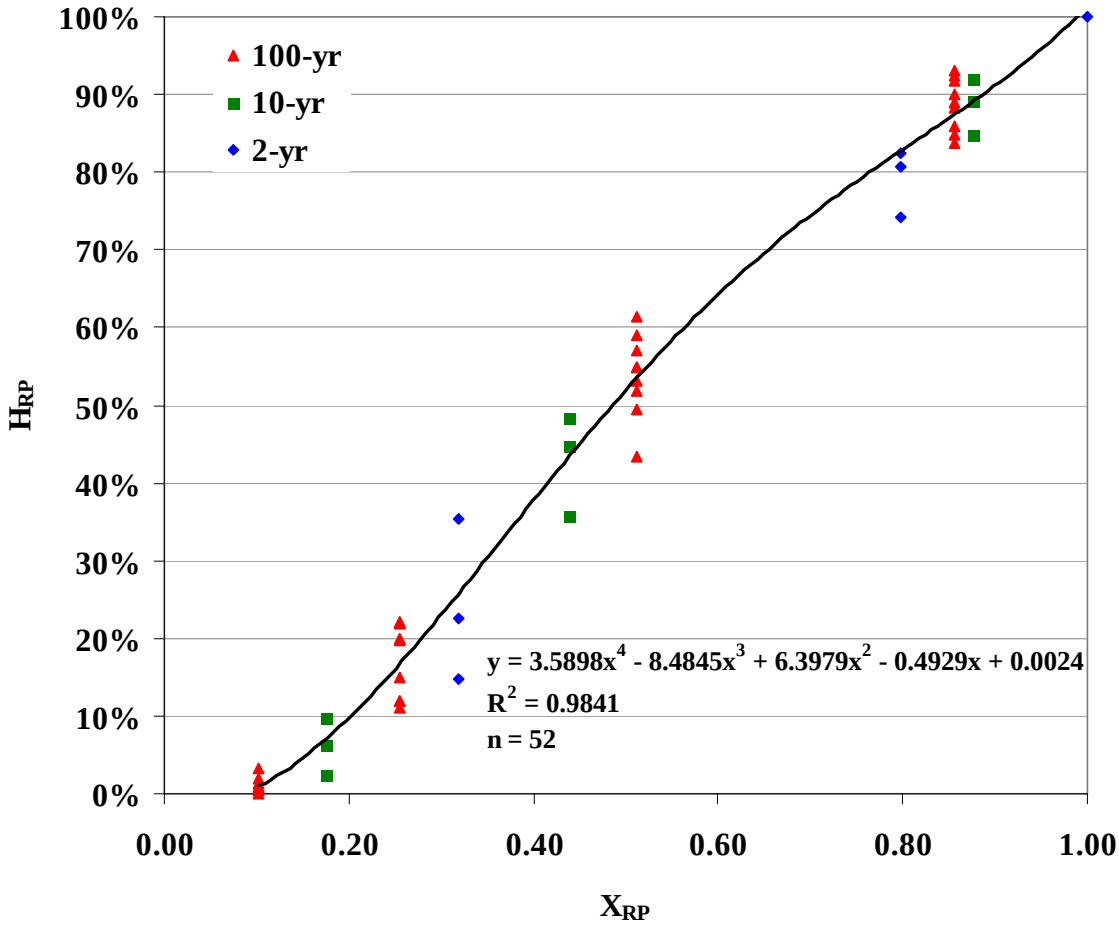

Figure 11. Best fit equation to stormwater harvesting factors (H_{RP}) relative to scale of stormwater harvesting (X_{RP}) for three different watershed configurations, three different distributions of stormwater harvesting, and three different return periods.

Table 5. Table of stormwater harvesting factors based on volume of stormwater harvesting to return period runoff volume.

X_{rp}	H_{rp}	X_{rp}	H_{rp}	X_{rp}	H_{rp}
< 0.10	0.000	0.40	0.378	0.71	0.753
0.10	0.009	0.41	0.392	0.72	0.762
0.11	0.015	0.42	0.407	0.73	0.771
0.12	0.021	0.43	0.422	0.74	0.779
0.13	0.029	0.44	0.436	0.75	0.788
0.14	0.037	0.45	0.450	0.76	0.796
0.15	0.046	0.46	0.464	0.77	0.805
0.16	0.055	0.47	0.478	0.78	0.813
0.17	0.065	0.48	0.492	0.79	0.821
0.18	0.075	0.49	0.506	0.80	0.829
0.19	0.086	0.50	0.519	0.81	0.837
0.20	0.098	0.51	0.532	0.82	0.845
0.21	0.109	0.52	0.546	0.83	0.853
0.22	0.122	0.53	0.558	0.84	0.861
0.23	0.134	0.54	0.571	0.85	0.869
0.24	0.147	0.55	0.584	0.86	0.877
0.25	0.160	0.56	0.596	0.87	0.886
0.26	0.174	0.57	0.608	0.88	0.894
0.27	0.188	0.58	0.620	0.89	0.903
0.28	0.202	0.59	0.631	0.90	0.911
0.29	0.216	0.60	0.642	0.91	0.920
0.30	0.230	0.61	0.654	0.92	0.929
0.31	0.245	0.62	0.665	0.93	0.938
0.32	0.259	0.63	0.675	0.94	0.948
0.33	0.274	0.64	0.686	0.95	0.958
0.34	0.289	0.65	0.696	0.96	0.968
0.35	0.304	0.66	0.706	0.97	0.979
0.36	0.319	0.67	0.716	0.98	0.989
0.37	0.333	0.68	0.725	≥0.99	1.000
0.38	0.348	0.69	0.735		
0.39	0.363	0.70	0.744		

v. *Volume Reduction from Stormwater Harvesting*

The runoff volume reduction due to stormwater harvesting in the SWMM models was found to be relatively close to the total volume of stormwater harvesting despite the modeled Green-Ampt infiltration in stormwater harvesting basins. The additional infiltration due to stormwater harvesting in the model was relatively insignificant due to the use of a relatively low saturated hydraulic conductivity that was measured for the compacted urban soils, and the short duration of the storm event based on a 1-hour

rainfall distribution.

Stormwater Harvesting Equations

Equations needed to be developed for a simple and accurate way of using the stormwater harvesting factors for peak reduction. Since the factors are designed to account for the total volume of stormwater harvesting within the drainage area, the total area of the site that drains to stormwater harvesting basins must be found in order to evaluate the effectiveness in peak reduction. The site area that passes through a stormwater harvesting basin (A_S) should be divided by the total drainage area (A_T) to determine the effectiveness of the stormwater harvesting as:

$$\eta_A = A_S / A_T \qquad (1)$$

It is assumed that the small watersheds used with PC-Hydro will display a linear relationship between the fraction of the area diverted to stormwater harvesting (η_A) and the reduction in peak discharge due to stormwater harvesting (H_{RP}). Therefore, it is assumed that a watershed with all of the area draining to stormwater harvesting basins produces the full peak discharge reduction from the stormwater harvesting factor (H_{RP}), while a site with half of the area draining to stormwater harvesting is assumed to produce half the effectiveness in reducing the peak discharge from H_{RP}. The accuracy of this assumption is dependent upon the site layout and the uniformity of runoff production within the area. For cases where the assumption of a linear relationship may not be accurate (such as an unequal distribution of impervious area), the assumption may be avoided by generating PC-Hydro calculations and calculating peak discharges for watershed areas diverted to stormwater harvesting ($\eta_A = 1.0$) and areas not diverted to stormwater harvesting ($\eta_A = 0$) separately.

The reduced return period peak discharge ($Q_{SWH\text{-}RP}$) due to stormwater harvesting can be calculated based on the post-developed peak discharge ($Q_{POST\text{-}RP}$), return period stormwater harvesting factor, and η_A as:

$$Q_{SWH\text{-}RP} = Q_{POST\text{-}RP}\,(1 - \eta_A\, H_{RP}) \qquad (2)$$

Where H_{RP} is taken from Table 5 based on the volume of stormwater harvesting and return period runoff volume. When a hydrograph is required for routing (i.e. designing a detention basin), the reduced runoff volume can be calculated by simply removing the stormwater harvesting volume as:

$$V_{SWH\text{-}RP} = V_{POST\text{-}RP} - V_{BAS} \qquad (3)$$

In addition, a spreadsheet is available that will modify a PC-Hydro hydrograph based on the reduced peak discharge and runoff volume due to stormwater harvesting.

CONCLUSIONS:

The effects of stormwater harvesting were evaluated using a SWMM model to simulate rainfall and runoff events at La Terraza. This evaluation found that the volume of the basin (V_{BAS}) divided by the volume of the event ($V_{POST\text{-}RP}$) provides a good metric for peak discharge reduction for various stormwater harvesting conditions. Factors were developed from the model results that can be used to quantify the impact of stormwater harvesting on flood peaks. Equations were presented for use with the stormwater harvesting factors to estimate the effectiveness in flood peak reduction for a given site.

References

Haan, C.T., Barfield, B.J., Hayes, J.C. 1994. Design Hydrology and Sedimentology for Small Catchments, Academic Press.

Kennedy, J.R. 2007. Changes in Storm Runoff with Urbanization: the Role of Pervious Areas in a Semi-Arid Environment, Master's thesis, University of Arizona, Department of Hydrology and Water Resources.

Rawls, W. J., Brakensiek, D. L., and Miller, N. 1983. "Green-Ampt Infiltration Parameters from Soils Data." *Journal of Hydraulic Engineering,* ASCE. 109(1):62-71.

Rossman, L.A. Revised 2010. Stortmwater Management Model Version 5.0 User's Manual. U.S. Environmental Protection Agency.

Runyon, T., Fort Huachuca U.S. Army Garrison, personal communication, August 2011. Fort Huachuca Climate Data Station Reports and Russell Scott's Evapotranspiration Data (USDA-ARS).

Table A-1. Base La Terraza SWMM Model subcatchment parameters.

SUBCATCHMENTS Name	Watershed	Outlet	Total Area (ac)	Pcnt. Imperv	Width	Pcnt. Slope	N-Imperv	N-Perv	S-Imperv	S-Perv	PctZero	RouteTo	PctRouted
S1	**Urban**	J19	1.46	43	587.9	2.0	0.013	0.130	0.018	0.079	14	PERVIOUS	67.4
S2		J19	2.98	27	581.1	0.2	0.013	0.130	0.018	0.079	6	PERVIOUS	77.8
S3		J13	2.46	29	539.6	0.2	0.013	0.130	0.018	0.079	7	PERVIOUS	75.9
S4		J13	2.46	25	628.9	0.5	0.013	0.130	0.018	0.079	7	PERVIOUS	72.0
S5		J300	2.72	29	602.2	6.8	0.013	0.130	0.018	0.079	7	PERVIOUS	75.9
S6		J10	2.14	30	458.4	3.7	0.013	0.130	0.018	0.079	7	PERVIOUS	76.7
S7		J10	0.98	29	198.0	0.5	0.013	0.130	0.018	0.079	7	PERVIOUS	75.9
S8		J10	1.64	44	532.2	5.0	0.013	0.130	0.018	0.079	11	PERVIOUS	75.0
S9		J100	0.56	22	103.6	2.0	0.013	0.130	0.018	0.079	4	PERVIOUS	81.8
S10		J10	0.20	12	268.1	5.7	0.013	0.130	0.018	0.079	0	PERVIOUS	100.0
S11		J20	3.44	21	829.8	2.0	0.013	0.130	0.018	0.079	6	PERVIOUS	71.4
S12		J19	1.23	21	259.1	3.0	0.013	0.130	0.018	0.079	6	PERVIOUS	71.4
S13		J13	0.13	22	178.9	3.0	0.013	0.130	0.018	0.079	0	PERVIOUS	100.0
S14		J300	0.46	30	101.0	5.0	0.013	0.130	0.018	0.079	9	PERVIOUS	70.0
S15		J300	2.23	30	506.6	3.0	0.013	0.130	0.018	0.079	7	PERVIOUS	76.7
S16		J20	1.55	48	503.2	5.0	0.013	0.130	0.018	0.079	16	PERVIOUS	66.7
S17		S16	0.03	100	42.8	0.5	0.013	0.130	0.018	0.079	100	PERVIOUS	0.0
S19		J19	0.06	61	24.3	0.8	0.013	0.130	0.018	0.079	0	PERVIOUS	100.0
S21		J20	0.44	45	178.9	2.0	0.013	0.130	0.079	0.004	0	PERVIOUS	73.3
S22		J100	0.95	45	307.6	2.0	0.013	0.130	0.018	0.079	9	PERVIOUS	80.0
S23		J100	0.35	32	113.8	2.0	0.013	0.130	0.018	0.079	9	PERVIOUS	71.9
S24		J100	0.13	13	157.5	4.3	0.013	0.130	0.018	0.079	0	PERVIOUS	100.0
S25		J100	0.56	27	162.2	2.0	0.013	0.130	0.018	0.079	6	PERVIOUS	77.8
S34	**Grassland**	S42	14.47	0	710.6	4.1	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S35		S44	7.28	0	452.0	3.2	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S36		S32	8.31	0	537.3	4.3	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S37		S36	5.78	0	344.2	4.3	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S38		S33	5.89	0	341.4	4.1	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S39		S38	5.21	0	303.4	4.9	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S40		S46	14.75	0	712.3	4.9	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S42		S41	8.77	0	436.1	3.5	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S44		s43	6.57	0	480.9	1.7	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S46		S45	10.35	0	515.3	3.2	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S43		s41	0.14	0	9.8	1.7	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S41		S45	0.07	0	9.8	1.3	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S45		S33	0.10	0	9.8	1.0	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S32		J18	0.12	0	9.8	2.1	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0
S33		J18	0.07	0	9.8	1.5	0.013	0.130	0.018	0.079	0	PERVIOUS	0.0

Table A-2. Base La Terraza SWMM Model conduit parameters.

CONDUITS Name	Inlet Node	Outlet Node	Length	Manning N
C10	J10	J20	846.2	0.025
C19	J13	J19	315.0	0.025
C21	J19	J20	223.6	0.025
Chan18	J18	J300	210.0	0.030
Chan20	J20	Outfall1	203.4	0.014
Chan300	J300	J13	304.5	0.025
Pipe100	J100	J20	700.0	0.020

Table A-3. La Terraza SWMM Model cross section variables.

XSECTIONS Link	Shape	Geom1	Geom2	Geom3	Geom4	Barrels
Chan20	TRAPEZOIDAL	6	10	0.5	0.5	1
Pipe100	CIRCULAR	2	0	0	0	1
Chan300	RECT_OPEN	3	24	0	0	1
Chan18	TRAPEZOIDAL	5	5	0.25	0.25	1
C19	RECT_OPEN	3	24	0	0	1
C21	RECT_OPEN	3	24	0	0	1
C10	RECT_OPEN	3	24	0	0	1

Table A-4. La Terraza SWMM Model junction variables.

JUNCTIONS Name	Invert Elev.	Max. Depth
J20	4683	5
J100	4684	6
J300	4697	5
J18	4700	5
J13	4692	5
J19	4686	5
J10	4688	5