PREDICTION OF GROUNDWATER RECHARGE RATES IN SEMI-ARID URBANIZED WATERSHEDS

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ABSTRACT: Pre-development and post-urbanization groundwater recharge rates were estimated for an 92,347 acre study area in southeastern Arizona. Recharge in semi-arid watersheds primarily takes place within ephemeral stream channels, with the majority occurring during wet years. Estimated pre-development recharge rates ranged from 0.5 to 1.5 percent of annual precipitation. Point measurements over five years from two channel and two stormwater basin monitoring sites within an urbanized area showed recharge rates of one to five feet per year in the basins and five to 12 feet per year in the channels. These data scaled to the watershed channel area indicates that existing urbanization could double channel recharge rates above pre-development rates. A three-part modeling approach was used to predict changes in groundwater recharge resulting from urbanization and proposed construction of 40 variously sized stormwater flood control basins. Data from a high-density precipitation gauge network were used to create synthetic annual records for average, wet and dry years. These daily precipitation data were used in the Automated Geospatial Watershed Assessment tool (AGWA/KINEROS2) to predict runoff, channel infiltration and basin infiltration for a smaller, heavily urbanized subwatershed (Coyote Wash) within the study area. Finally, site-specific monitoring data were used to predict the percent of modeled daily infiltration that would recharge groundwater. The rainfall/runoff/infiltration predictions generated by AGWA were then analyzed for regression relationships (precipitation-runoff; runoff-channel infiltration, and runoff-basin infiltration) and scaled up to permit their application to other watersheds in the study area. Watershed and channel areas, soil types, land cover and percent impervious surface at full build out were used with a 45-year daily precipitation record as input to the regression models. Recharge was then estimated from modeled infiltration using site-specific monitoring data. An additional 1220 afa of estimated incidental recharge resulted from the addition of 40 basins within the study area. The regression models indicate that increased annual runoff volumes associated with urbanization will not be entirely captured. Calibration efforts suggest that the regression models overpredict runoff, so the predicted increases in infiltration, recharge, and runoff to as a result of urbanization may also be overestimated.

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INTRODUCTION

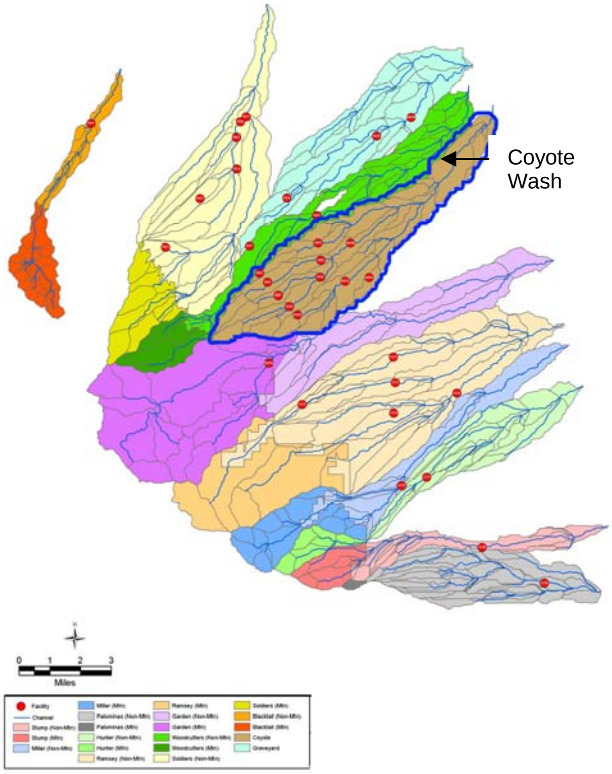


Figure 1. Study area sub-watersheds and evaluated facilities.

Urbanization may significantly alter both surface water and groundwater regimes. Roofs, pavement, and compacted soils create impervious surfaces that result in increased stormwater runoff while reducing direct groundwater recharge from the covered surface. In arid environments however, direct groundwater recharge may be negligible, with the majority of groundwater recharge occurring from mountain-front recharge and recharge from stormwater flow in ephemeral channels (Anderson et al., 1992; Lane, 1990; Keppel and Renard, 1962). Flood-control efforts in urban areas detain peak storm flows and increase the duration of stormflow in ephemeral channels and retention basins. Consequently, increased stormwater runoff in arid areas may increase incidental recharge to groundwater from stormflow in ephemeral channels and retention basins.

A 92,437-acre study area within the Upper San Pedro River watershed was evaluated for potential increased groundwater recharge from a total of 40 proposed stormwater retention/detention basins (facilities) to be located within thirteen sub-watersheds within the study area (Figure 1). The thirteen sub-watersheds drain into the San Pedro River from the west and are all located within the Sierra Vista subwatershed. Estimates of natural recharge rates from ephemeral channels within the study area range from 0.5 to to 1.9% of average annual precipitation rates using a variety of recharge estimation and in-situ monitoring methods (GSA, 2004).

The Automated Geospatial Watershed Assessment (AGWA) tool had been previously used to predict runoff, channel infiltration and basin infiltration for the 12,267-acre heavily urbanized Coyote Wash subwatershed (dark yellow area in blue limit in Figure 1) located within the study area (GSA, 2004). The AGWA model (Semmens et al., 2002) is a physically-based model which requires input of hourly rainfall data and surface characteristics such as soil hydraulic properties, land cover, and channel flow characteristics to estimate infiltration and runoff.

The Coyote Wash AGWA model predicted stormwater runoff and channel infiltration into basin-fill material (non-mountain areas - Figure 1) for both pre- and post-urbanized conditions for a series of 184 precipitation events. The precipitation events were applied using a distributed network of 89 precipitation gages across the sub-watershed and detailed mapping of the soil types, channel dimensions, and land cover for pre- and post-urbanized conditions (GSA, 2004). Existing and future impervious land surface percentages were determined for each type of zoning classification by digitizing representative areas from aerial photographs, and applying those impervious surface percentages to each zoned area (GSA, 2006). Pre- and post-urbanized scenarios were then simulated using AGWA to predict the impacts of urbanization on runoff, where post-urbanized conditions were simulated as complete buildout under existing zoning classifications.

To apply AGWA to a larger, regional-scale study would be labor-, data-, and computationally intensive. Consequently, the rainfall/runoff/infiltration predictions generated by the Coyote Wash AGWA model were analyzed for regression relationships in order to scale up to other watersheds in the study area. Scaling from the Coyote Wash sub-watershed to other watersheds within the study area assumes similarity of soil types and precipitation patterns (spatial and temporal) and channel infiltration behavior. The suite of regression equations developed from the Coyote Wash (CW) AGWA model output were applied to other study area subwatersheds to estimate runoff, infiltration, and recharge resulting from the historic 1955 to 2000 local precipitation record.

REGRESSION ANALYSIS METHODS AND RESULTS

Three classes of regression equations were developed from the CW AGWA model data to estimate: 1) runoff as a function of precipitation for different percentages of impervious surface area, 2) channel infiltration as a function inflow, and 3) facility infiltration as a function of inflow. Precipitation at the study area occurs as convective storms in summer months (June to October) and frontal storms during the rest of the year. In order to capture differences in precipitation intensity between these periods, specific regressions were developed for "summer" and "other" months. To provide runoff predictions for different levels of urbanization, runoff regressions were developed for surfaces with a wide range of percent impervious surfaces. Finally, groundwater recharge was estimated from the predicted channel infiltration by subtracting estimated evaporation from channel infiltration and also using infiltration characteristics based on in-situ monitoring.

Runoff Regressions

Approximately 75 of the Coyote Wash surfaces (model planes) representing a range of percent impervious surface areas were used for the runoff regression analysis. Planes not analyzed either contained no post-urbanization impervious surfaces or were too small.

Table 1. Precipitation-depth runoff relationships (in mm)

Equation		Description
1	$R = a*P$	Precipitation (P) runoff depth (R) for "other" months - post-urbanization scenario
2	$a = 0.6854*I^2 + 0.2895*I + 0.0875$	Predicted coefficient "a" in Equation 1 from percent impervious surface (I)
3	$r = b*P^2 + c*P$	Precipitation (P) runoff depth (r) for summer months (and other months for pre-urbanization scenario); coefficients b and c are listed in Table 2
4	$rp_{inc} = (0.7245*I)*100\%$	Predicted increase in runoff (rp_{inc}) per impervious percentage (I) when precipitation depth < 25 mm, and for high permeability t soils.
5	$rp_{inc} = (6.68*s^2 + 1.17*s + 0.054)*100\%$; $s = I*p^{-0.5}$	Predicted increase in runoff (rp_{inc}) as percent of precipitation depth (p) according to s. For low permeability soils when precipitation depth > 25 mm

Independent correlations between precipitation and runoff depths, the type of event (summer vs other months), and percent impervious surface were derived and a relationship between increased runoff and percent impervious surface was also determined. Table 1 shows five equations for predicting stormwater runoff from precipitation.

Figure 2 shows the CW AGWA model-predicted runoff vs. precipitation depth relationship for 12% impervious surface area as an example of the typical runoff response to precipitation. The model-predicted runoff showed a linear relationship with precipitation for the “other” months and a binomial relationship for “summer” months.

Table 2. Equation 3 “summer” coefficients

Impervious Percentage	B	C	R^2
0%	0.0124	-0.1012	0.8871
10-20%	0.0104	0.0969	0.9056
21-30%	0.0088	0.2185	0.8893
31-40%	0.0089	0.236	0.9449
41-50%	0.0088	0.3599	0.958
51-60%	0.0083	0.4315	0.9541
61-70%	0.0064	0.4729	0.979
75-85%	0.0047	0.6965	0.988

For the “other” months, runoff is predicted as percent of precipitation depth (Equations 1 and 2 in Table 1). For the “summer” months, the precipitation depth-runoff relationship uses two regression coefficients that vary according to the amount of impervious surface area (Equation 3 in Tables 1 and 2).

Comparison of Pre- and Post-urbanization Runoff Estimates

A comparison of runoff between the pre- and post-urbanization scenarios in the CW AGWA model was made for all the selected planes including both “summer” and “other” month data. Two relationships were observed: Equation 4 (Table 1) shows a linear relationship between runoff and percent impervious surface area at precipitation depths less than 25 mm. This relationship indicates that every 1% increase in impervious surface causes an additional 0.72% of runoff. For precipitation depths greater than 25 mm, Equation 5 (Table 1) shows that runoff is related to the increase in impervious surface times the square root of precipitation.

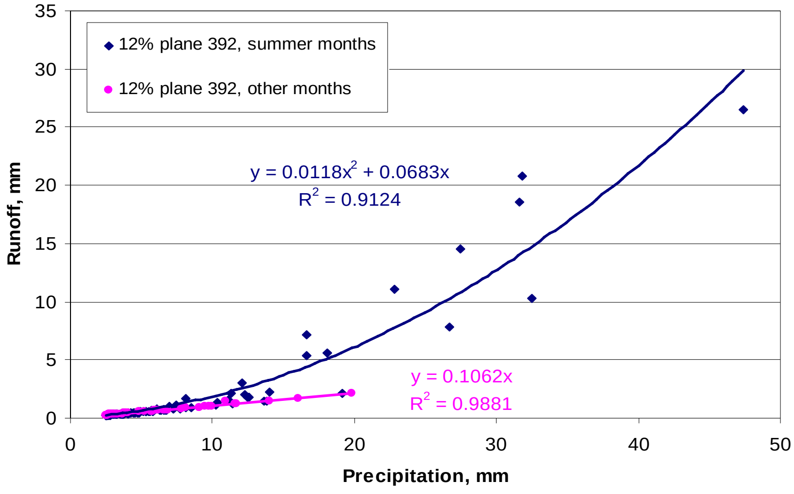


Figure 2. Example of “summer” and “other” month runoff relationships

Up-scaling of Runoff Regression Equations

Equations 1-5 (Table 1) were tested for scaling accuracy by selecting 21 contiguous planes in the Coyote Wash AGWA model to form a larger watershed (2,316 acres) and testing all of the 184 simulated precipitation events (GSA 2004). The impervious surface area percentage was then calculated for this larger watershed and regression equations 1 through 3 in Table 1 were applied to estimate runoff. Figure 3 shows that the regression equation-predicted runoff matched the Coyote Wash AGWA model-predicted runoff quite well, though with larger scatter for high runoff events. The calculated runoff with increasing impervious surface predicted by the regression equations also agreed well with the Coyote Wash AGWA-predicted values (Figure 3).

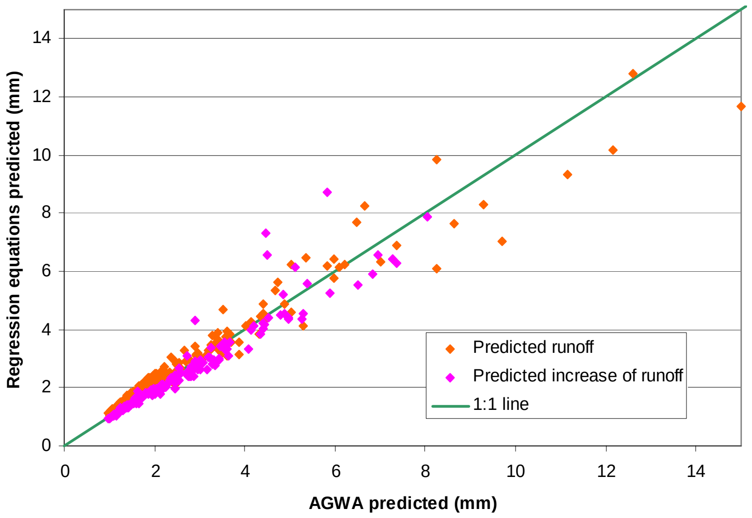


Figure 3. Regression equation-predicted vs. AGWA-predicted runoff for larger watersheds

Consequently, the regression equations derived from smaller-scale planes appear to be applicable to the larger-scale sub-watersheds.

Channel Infiltration Regressions

Predicted stormwater channel inflow and infiltration volumes were converted to inflow and infiltration depths by assuming uniform flow distribution across each channel section (cm^3/cm^2). This conversion allows comparison between different channel and contributing source areas.

Two types of regressions were developed: 1) overall channel infiltration regressions - these regression equations were applied on primary channels with one or no detention facilities; 2) divided channel infiltration regressions - applied on primary channels with more than one detention facility (See Figure 1). In this approach, the sub-watersheds were divided into areas upstream and downstream from each facility. Regression analyses were conducted separately for each of these groups of channels.

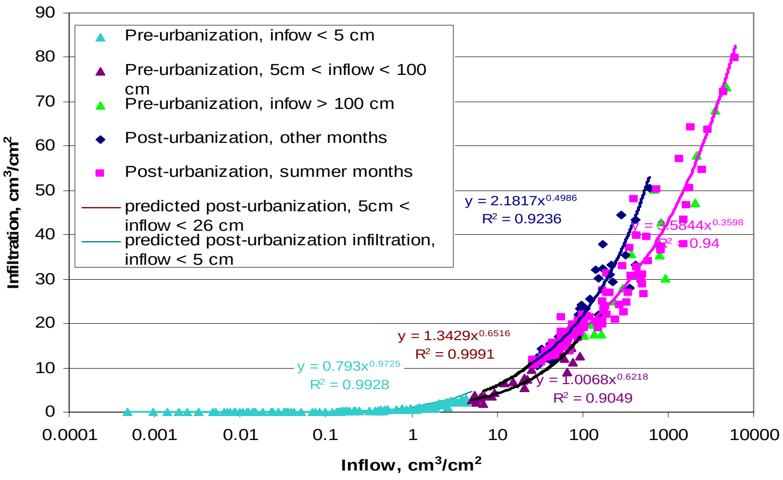


Figure 4. Model and regression predicted channel infiltration

Overall Channel Infiltration Regressions

Figure 4 shows the Coyote Wash AGWA model-predicted inflow depth vs. channel infiltration depth for all 184 precipitation events for both pre- and post-urbanization scenarios. The inflow depth-to-channel infiltration depth relationship depends on the amount of inflow, season and the degree of urbanization (percent impervious surface).

Table 3. Regression equations for overall channel infiltration

Equation		**Applicable conditions**[1]
6	$y = 0.793x^{0.9725}$ $R^2 = 0.9928$	Pre- and post-urbanization when inflow < 5 cm.
7	$y = 1.0068x^{0.6218}$ $R^2 = 0.9049$	Pre-urbanization when 5 cm < inflow < 100 cm
8	$y = 3.5844x^{0.3598}$ $R^2 = 0.94$	Pre-urbanization when inflow > 100 cm; post-urbanization summer months when inflow > 26 cm
9	$y = 2.1817x^{0.4986}$ $R^2 = 0.9236$	Post-urbanization other months when inflow > 26 cm
10	$y = 1.3429x^{0.6516}$ $R^2 = 0.9991$	Post-urbanization when inflow range from 5-26 cm

[1] X is channel inflow depth and y is channel infiltration in cm.

Five power function equations for predicting channel infiltration from channel inflow depth were identified through the regression analyses (Table 3). The pre-urbanization Coyote Wash AGWA model predictions can be adequately described for three different inflow ranges without respect to season (equations 6 to 8).

The post-urbanization scenario showed different behavior between summer and other months (equations 9 and 10). To predict channel infiltration in watersheds with smaller percentages of impervious surfaces than Coyote Wash, and hence less runoff, Equation 10 was extrapolated between Equations 9 and 6 for post-urbanization inflow less than 25 cm^3/cm^2.

Divided Channel Infiltration Regressions

Channels containing more than one detention facility were divided into upstream and downstream segments which were analyzed separately. The delayed release of stormflow from stormwater detention facilities results in delayed flow to downstream channels and facilities which ultimately increases infiltration. With these regression equations, the downstream channel inflow includes the contributing area runoff and the outflow from any upstream facility. Table 4 presents the regression equations developed from the Coyote Wash AGWA model.

Table 4. Regression equations for divided channel infiltration.

Equation #	**Pre-urbanization**[1]		**Post-urbanization**[1]		**Post-urbanization with Facilities**[1]	
11	$y = 0.9652x$	inflow < 1.5 cm^3/cm^2, upstream channel	$y = 0.9652x$	inflow < 1.5 cm3/cm2, upstream channel	$y = 0.9683x$	inflow < 1.5 cm^3/cm^2, upstream channel
12	$y = 2.9212*\ln x-0.8306$	inflow > 1.5 cm^3/cm^2, upstream channel	$y = 2.9212*\ln x-0.8306$	inflow > 1.5 cm^3/cm^2, upstream channel	$y = 2.9361*\ln x-1.3019$	inflow > 1.5 cm^3/cm^2, upstream channel
13	$y = 0.9492x$	inflow < 1.5 cm^3/cm^2, downstream channel	$y = 0.9492x$	inflow < 1.5 cm^3/cm^2, downstream channel	$y = 0.9492x$	inflow < 1.5 cm^3/cm^2, downstream channel
14	$y = 2.0828*\ln x+0.428$	inflow < 11.5 cm^3/cm^2, downstream channel	$Y = 2.3311*\ln x-0.2547$	inflow < 11.5 cm^3/cm^2, downstream channel	$y = 2.2694*\ln x-0.239$	inflow < 11.5 cm^3/cm^2, downstream channel
15	$y = 2.7873x^{0.3316}$	inflow > 11.5 cm^3/cm^2, downstream channel	$Y = 2.7943x^{0.3316}$	inflow > 11.5 cm^3/cm^2, downstream channel	$y = 2.3039x^{0.395}$	inflow > 11.5 cm^3/cm^2, downstream channel

[1] X is channel inflow depth and y is channel infiltration in cm.

Facility Infiltration Regressions

The Coyote Wash AGWA model calculated infiltration volumes for both high- and low-permeability detention facilities simulated by infiltration rates (Ksat) = 2 feet per day and 6 inches per day, respectively. The low-permeability scenario was intended to approximate clogging conditions in un-maintained facilities. Consequently, only high-permeability detention facilities were analyzed for potential enhanced recharge with regression relationships. The facility inflow and infiltration values were extracted from the Coyote Wash database and sorted by “summer” and “other” months to evaluate seasonal effects on the facilities. Inflow and infiltration volumes were then normalized by facility area to produce inflow depths and infiltration depths in order to allow comparison between different facilities. Table 5 shows the regression equations that were developed for infiltration in detention facilities with and without upstream detention facilities.

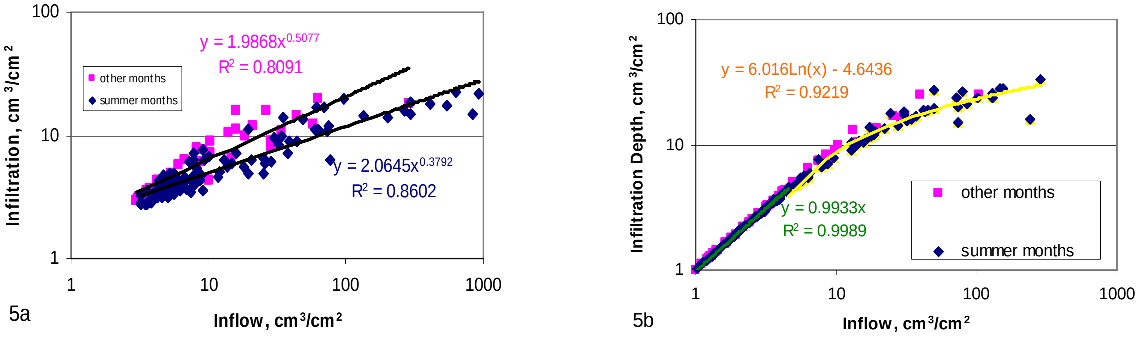
Table 5. Infiltration-inflow regression equations for detention facilities.

No Upstream Facilities[1]			**Upstream Facilities[1]**		
Equation		**Applicable Conditions**	**Equation**		**Applicable Conditions**
1	$y = x$	inflow < 3 cm^3/cm^2	1	$y = x$	inflow < 3 cm^3/cm^2
2	$y = 2.0645x^{0.3792}$	inflow > 3 cm^3/cm^2; summer months	2	$y = 0.9933x$	inflow < 4.5 cm^3/cm^2
3	$y = 1.9868x^{0.5077}$	inflow > 3 cm^3/cm^2; other months	3	$y = 6.016\mathrm{Ln}(x) - 4.6436$	inflow > 4.5 cm^3/cm^2

[1] y is infiltration in cm, x is inflow in cm.

Figures 5a and 5b show the detention facility regression analyses. Figure 5a shows a seasonal effect on the inflow-infiltration relationship for detention facilities without upstream facilities.

This effect reflects the fact that high-volume, short-duration storms (i.e., summer thunderstorms) contribute significant and rapid inflow that passes through a detention facility faster than do long-duration storms (i.e., other storms) of equal inflow volume.



Figures 5a and 5b. Inflow vs. Infiltration, Detention facilities without (5a) and with upstream facilities (5b).

Figure 5b shows that detention facilities downstream of other detention facilities exhibit seasonal divergence in their inflow-infiltration relationship. In this case, the upstream detention facility effectively modulates large storm pulses in the summer months, thereby increasing the stormflow duration at the downstream facility. In addition, the presence of an upstream facility increases the magnitude of inflow-infiltration curve (Figure 5a vs. Figure 5b), indicating enhanced infiltration.

APPLICATION OF THE REGRESSION EQUATIONS TO THE STUDY AREA

Study Area Runoff Estimates

The daily precipitation depths recorded from 1955-2000 at the Sierra Vista/Fort Huachuca National Weather Service station were used to calculate the daily stormwater runoff and channel and detention facility infiltration values for each of the study area watersheds over the 46-year record. Prior to use in the regression equations, daily precipitation values were modifed to account for spatial variability across individual watersheds using an areal reduction factor (Osborn, et al 1980). Areal reduction factors decrease the precipitation depth as the watershed area increases and varied between 0.74 and 0.92 for the different study area watersheds. Average annual predicted runoff and infiltration values were then determined from the daily values. Predicted stormwater runoff volumes for both pre- and post-urbanization are listed in Table 6.

It should be noted that the Coyote Wash AGWA model regression relationships were used to estimate runoff from basin-fill (non-mountain areas) at each sub-watershed (Table 6). For mountain (bedrock) areas, the regression equations are not applicable. Consequently, the SCS curve-number method (USDA, 1986) in conjunction with areal reduction factors was used to estimate mountain area runoff rates. Since the focus of this paper is on the Coyote Wash AGWA model regression relationships, mountain runoff estimates are not discussed in detail. Nevertheless, mountain runoff estimates were subject to calibration and are included in total runoff and channel and facility infiltration calculations. A detailed description of the mountain area runoff estimates is provided in GSA, (2006).

Table 6. Estimated annual average stormwater runoff estimates for non-mountain areas by watershed

Study Area	Watershed Name	Area (acres)	Areal Reduction Factor	Percent Impervious Area	Estimated Runoff (acre-feet)			
					Pre-Urbanization	Post-Urbanization	Percent Increase Over Pre-urbanzation	Increase in Runoff as Percent of Precipitation
Cochise County	Garden	7636	0.82	16.6%	777.6	1740.6	124%	13%
	Hunter	5457	0.84	6.5%	586.7	836.5	43%	5%
	Miller	4367	0.88	7.5%	521.5	735	41%	5%
	Palominas	6609	0.83	7.3%	691.5	995.2	44%	5%
	Ramsey	16841	0.74	10.3%	1359.2	3168.8	133%	12%
	Stump	2832	0.92	6.9%	373.5	516.6	38%	5%
Sierra Vista/Fort Huachuca	Blacktail	1424	0.95	1.0%	201.6	234.8	16%	2%
	Coyote	12267	0.76	30.6%	1052.7	3607.9	243%	23%
	Graveyard	9054	0.8	6.6%	872.1	1342.7	54%	5%
	Lewis	3694	0.865	14.3%	424.2	834.2	97%	11%
	Soldiers	12451	0.77	8.7%	1100.5	1892.2	72%	7%
	Woodcutters	7207	0.82	25.4%	733.9	2064.2	181%	19%
	Unknown	2599	0.9	11.7%	326.2	574.8	76%	9%
Total/Average		**92437**		**11.8%**	**9021**	**18543**	**89.4%**	**9.1%**

In general, for the watersheds in Table 6, post-urbanization runoff increases with increasing percent impervious area, which is consistent with the regression analyses (Table 1). Ramsey Canyon is one exception to that rule, with a 133% increase in runoff resulting from only 10.2% impervious surface area. Because the regression equations in Table 1 are applied to a range of impervious area percentages, stormwater runoff for watersheds with impervious percentages in the low part of the range may be overestimated. The average predicted increase from pre- to post-urbanization for the entire study area is 89.4%.

Runoff leaving the study area watersheds after channel and detention facility infiltration were abstracted was used as a calibration index. The total average annual estimated runoff to the San Pedro River from six of the study area's pre-urbanized watersheds was 6,487 afa. This value equals roughly 52% of the annual average non-baseflow stream discharge between the USGS streamgaging stations at Charleston and Palominas between 1950 and 2002 (USGS, 2006). Although these six watersheds comprise only about 22% of the total contributing watershed area between Charleston and Palominas, they do contain the highest mountains within that area. Assuming that the percent of annual average runoff attributable to a discrete subwatershed should be roughly equal to the ratio of the subwatershed area to the entire watershed area upstream of the confluence suggests that predicted runoff is overestimated by a factor of approximately two.

Study Area Channel and Detention Facility Infiltration Estimates

Average Annual Channel Infiltration

Table 7 shows the predicted ephemeral channel infiltration results for the pre- and post-urbanization scenarios both with and without detention facilities. For watersheds with detention facilities, the watershed channels were divided into upstream and downstream channels with the detention facility as the dividing point. Inflow into the downstream channels was calculated as runoff from downstream contributing areas plus the outflow from the upstream detention facility. The outflow from the channel into the next facility (or San Pedro River) was then calculated as channel inflow minus infiltration.

Table 7. Estimated average annual channel infiltration by watershed (acre-feet).

Study Area	**Watershed Name**	**Channel Area (acres)**	**Estimated Channel Infiltration (without facilities unless otherwise noted)**				
			Pre-Urbanization	**Post-Urbanization**	**Post-Urbanization with Facilities**	**Increase from Pre- to Post-Urbanization**	**Percent Increase from Pre- to Post-Urbanization**
Cochise County	Garden	76	352	722	664	371	105%
	Hunter	43	190	306	292	116	61%
	Miller	47	237	340	316	103	43%
	Palominas	33	159	283	249	124	78%
	Ramsey	125	510	1184	1097	674	132%
	Stump	32	146	218	192	72	49%
Sierra Vista/Fort Huachuca	Blacktail	19	147	151	147	3	2%
	Coyote	139	842	1910	1842	1068	127%
	Graveyard	95	445	619	564	174	39%
	Lewis	17	160	291	260	130	81%
	Soldiers	86	765	1183	877	418	55%
	Woodcutters	64	564	1111	1021	547	97%
	Unknown	22	121	230	217	109	90%
Total/Average			**4638**	**8547**	**7738**	**3910**	**84%**

The estimated pre-urbanized annual channel infiltration is 4,638 acre-feet. Channel infiltration is estimated to increase by 84% (3,910 afa) to 8,547 afa as a result of urbanization only. The predicted increase in channel infiltration amounts to 21% of the predicted increase in runoff from pre- to post-urbanization (Table 6). This indicates that 79% of the increased runoff will flow out of the study area under post-urbanization without detention facilities. Adding 40 detention facilities into the study area watersheds result in a predicted decrease of 809 afa of channel infiltration under the post-urbanization scenario. This decrease results from detention and infiltration in the facilities which decreases the inflow into the downstream channels. However, with facilities, the overall infiltration (including both channel (Table 7) and facility (Table 8) infiltration) increases, as discussed below.

Estimated Annual Detention Facility Infiltration

The estimated annual infiltration into high permeability (Ksat = 2 feet/day) detention facilities is presented in Table 8. To calculate detention facility daily inflows and outflows, the stormwater inflow into the facility was calculated as the outflow from the upstream channels and contributing areas. The outflow from the facility was calculated as the inflow minus infiltration into the facility, which was then routed into the downstream channel or planes. The total annual detention-facility infiltration is estimated at 2,955 acre feet (Table 8). Consequently, the addition of 40 detention facilities into the post-urbanization scenario results in a predicted average annual increase in channel (-809 afa) plus facility (2,955 afa) infiltration of 2,146 acre feet. As to individual facilities, the detention facility with the lowest inflow (CC4), showed the highest estimated infiltration efficiency (infiltration as a percent of inflow) because of its large holding capacity relative to the small inflow volume. By contrast, detention facility SV14 has the lowest estimated infiltration efficiency because it is relatively small for the inflow volume. Downstream facilities (i.e. CC3, CC5, CC9, FH6 expanded, SV9, and SV12) are also more efficient than other facilities because they their downstream positions result in longer storm-flow duration and less “flashy” flood flows, thus improving infiltration efficiency.

Study Area Groundwater Recharge Estimates

Incidental groundwater recharge was predicted from the average annual estimated channel and facility infiltration for each watershed by two methods: 1) Recharge Factor: applying an average field-based groundwater recharge factor (39% for channels, 31% for facilities) developed in GSA (2004) to the average annual predicted channel and facility infiltration; and 2) Monthly Evapotranspiration (ET): subtracting an estimated average monthly evaporation loss from the predicted average monthly channel and facility infiltration depths. Evaporation losses were assumed to be equivalent to 60% of the estimated monthly reference crop evapotranspiration recorded for the study area (Scott, 2003). Tables 9 and 10 present the estimated average annual incidental groundwater recharge for each of the two methods, respectively.

The predicted average annual incidental groundwater recharge rates for the pre-urbanized study area range from 1,896 to 3,487 acre-feet for the recharge factor and ET methods, respectively. Likewise, increases in estimated average annual groundwater recharge resulting from urbanization alone range from 1,418 to 3,396 acre-feet for the recharge factor and ET methods, respectively. It is likely that the recharge factor estimate (GSA 2004) more accurately reflects actual recharge rates. However, the short monitoring period and limited data set (five years at four sites) merited the use of an independent (ET) estimation method.

Table 8. Estimated annual average infiltration in detention facilities where Ksat = 2 ft/day (25 mm/hr)

Detention Facility	**Subwatershed Location**	**Facility Area (acres)**	**Inflow (afa)**	**Inflow/ Area (ft)**	**Infiltration (afa)**	**infiltration/ inflow**
CC1	Ramsey	5.2	268	51	46	17%
CC2	Ramsey	18.5	301	16	92	31%
CC3	Ramsey	5.2	260	50	80.6	31%
CC4	Ramsey	2.6	9	4	8	86%
CC5	Ramsey	17.2	259	15	134	52%
CC6	Miller	8.0	492	61	65	13%
CC7	Hunter	5.2	189	36	37	20%
CC8	Stump	8.0	442	55	66	15%
CC9	Palominas	4.1	112	27	41	37%
CC10	Palominas	8.0	302	38	63	21%
CC11	Ramsey	13.8	664	48	120	18%
CC12	Ramsey	8.0	272	34	59	22%
FH1	Blacktail	8.0	391	49	35	9%
FH2	Soldiers	2.6	218	84	39	18%
FH2A	Soldiers	2.4	180	75	48	27%
FH2B	Soldiers	1.7	132	77	26	20%
FH4	Soldiers	7.9	242	31	183	76%
FH5 expanded	Soldiers	4.7	448	95	332	74%
FH6 expanded	Soldiers	8.0	165	21	80	49%
FH7	Soldiers	20.2	924	46	313	34%
FH8	Graveyard	3.6	109	30	35	32%
FH9	Graveyard	5.2	156	30	35	22%
FH10	Graveyard	8.0	386	48	85	22%
SV1	WoodCutters	5.8	36	6	17	48%
SV2	WoodCutters	26.4	613	23	80	13%
SV3	WoodCutters	18.4	1100	60	277	25%
SV4	Coyote	2.2	117	54	23	20%
SV5	Coyote	12.1	41	3	18	45%
SV6	Coyote	5.1	156	31	59	38%
SV7	Coyote	5.1	37	7	13	33%
SV8	Coyote	11.7	76	6	17	23%
SV9	Coyote	7.7	192	25	76	40%
SV10	Coyote	5.0	272	55	53	19%
SV11	Coyote	7.8	33	4	17	52%
SV12	Coyote	6.0	279	47	83	30%
SV16	Coyote	2.7	76	28	23	30%
Rostron	Coyote	1.8	142	77	26	19%
SV13	Lewis	7.6	306	40	74	24%
SV15	Unknown	2.3	199	86	32	16%
SV14	Garden	13.8	426	31	43	10%
Total/Average			**11022**	**1607**	**2955**	**31%**

Table 9. Predicted incidental groundwater recharge (afa) estimated by recharge factor method.

Study Area	Watershed Name	Pre-Urbanization		Post-Urbanization without Facilities		Post-Urbanization with Facilities, Ksat = 2 feet/day	
		Channel Infiltration	Channel Recharge	Total Recharge	Increase in Recharge	Total Recharge	Increase in Recharge Over Post-Urbanization
Cochise County	Garden	575	224	262	38	272	10
	Hunter	190	74	119	45	125	6
	Miller	237	92	133	40	144	11
	Palominas	159	62	110	48	129	19
	Ramsey	510	199	462	263	595	133
	Stump	146	57	85	28	95	10
Sierra Vista/Fort Huachuca	Blacktail	147	57	59	1	68	9
	Coyote	842	328	745	417	845	100
	Graveyard	445	174	241	68	268	26
	Lewis	160	63	113	51	125	11
	Soldiers	765	298	461	163	659	197
	Woodcutters	564	220	433	213	514	81
	Unknown	121	47	90	43	95	5
Total		**4861**	**1896**	**3314**	**1418**	**3934**	**620**

The addition of 40 proposed high-permeability detention facilities result in a predicted increase of 620 afa (recharge factor) to 1,659 afa (ET) of additional groundwater recharge using the two different methods. If the predicted increase in annual groundwater recharge from the two methods is averaged, urbanization alone results in 2,407 acre-feet of increased recharge from the pre-urbanized scenario, while the predicted average annual recharge benefit from high-permeability detention facilities is 1,140 acre feet. Although the stormwater runoff calibration exercise indicates that runoff was overestimated by a factor of two or more, overprediction of channel infiltration and groundwater recharge may be less significant because error in stormwater runoff estimation occurs primarily at high flows where channel infiltration is already limited.

Table 10. Predicted incidental groundwater recharge (in acre-feet) estimated by ET method.

Study Area	Watershed Name	Pre-Urbanization		Post-Urbanization without Facilities		Post-Urbanization with Facilities, Ksat = 2 feet/day	
		Channel Infiltration	Channel Recharge	Total Recharge	Increase in Recharge	Total Recharge	Increase in Recharge Over Post-Urbanization
Cochise County	Garden	575	470	524	53	543	20
	Hunter	190	118	219	101	233	14
	Miller	237	156	247	91	275	28
	Palominas	159	100	211	111	259	48
	Ramsey	510	309	910	601	1223	313
	Stump	146	92	155	63	182	27
Sierra Vista/Fort	Blacktail	147	112	115	3	135	20
	Coyote	842	600	1674	1074	1908	235
	Graveyard	445	285	442	157	514	72
	Lewis	160	125	250	124	277	28
	Soldiers	765	600	996	396	1636	639
	Woodcutters	564	437	958	521	1159	201
	Unknown	121	81	182	101	196	15
Total		**4861**	**3487**	**6883**	**3396**	**8542**	**1659**

CONCLUSIONS

Thirteen watersheds within the Upper San Pedro River basin were evaluated to estimate the potential for increased groundwater recharge from urbanization and the addition of 40 potential stormwater retention/detention facilities. A highly detailed stormwater runoff and channel infiltration model had been previously prepared for one of the watersheds (Coyote Wash AGWA model) to predict stormwater runoff and channel infiltration. The Coyote Wash AGWA model output was analyzed to develop a series of regression equations for predicting stormwater runoff and channel and facility infiltration in watersheds within study area. Five equations were developed and tested for predicting runoff, or increase in runoff (from pre- to post-urbanization), based on precipitation depth and percent impervious area. Ten additional equations were developed to predict the amount of channel infiltration from the predicted runoff and three equations to predict detention facility infiltration.

The regression equations were then used to predict stormwater runoff and channel infiltration for pre- and post-urbanized conditions both with and without the 40 potential detention facilities. Input data included the 45-year daily precipitation record from the Sierra Vista/Fort Huachuca National Weather Service station, watershed and channel dimensions, and percentage of impervious surface areas for post-urbanized conditions for each subwatershed. Daily stormwater runoff and channel and detention facility infiltration predictions were summarized by year and average annual values calculated for the 45-year period. The predicted average annual stormwater runoff within the thirteen watersheds was approximately 9,000 and 18,500 acre-feet for the pre- and post-urbanization scenarios, respectively. Calibration efforts suggest that these values overestimate runoff by a factor of approximately two.

Predicted average annual channel infiltration ranged from roughly 4,600 to 8,500 acre-feet for the pre- and post-urbanization scenarios, respectively, without detention facilities. The addition of 40 detention facilities is predicted to decrease channel infiltration but increase overall channel plus facility infiltration by approximately 2,150 afa. Incidental groundwater recharge was predicted by applying either a recharge factor to infiltration or subtracting the amount of estimated channel evapotranspiration from the estimated channel and facility infiltration. The predicted average annual increase of groundwater recharge from pre- to post-urbanization is 2,407 acre-feet. Adding the 40 facilities increased the predicted groundwater recharge by 1,140 afa. Although the stormwater runoff leaving the study area may be overestimated by a factor of two or more, predicted increases in channel infiltration and groundwater recharge may have less error because stormwater runoff error occurs primarily at high flows where channel infiltration is already limited.

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