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EVALUATION OF HYDROLOGIC AND HYDRAULIC PROCEDURES FOR SMALL URBAN WATERSHEDS IN THE SOUTHWEST

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Abstract

Hydrologic and hydraulic design procedures developed by the Pima County Department of Transportation and Flood Control District were proposed for use by the Department of Transportation, Engineering Division of the City of Tucson, Arizona. These procedures were evaluated with respect to their reasonableness of approach and in comparison with other methods and existing data used to derive similar methodology and standards. The proposed criteria/methodology were found to be consistent with procedures used in other cities in the Southwest, and with the current state of the art in urban hydrology and hydraulic engineering practices and procedures. However, locally derived rainfall intensity-duration relationships were found to be superior to regionally based relationships, and minor modifications were suggested for channel design procedures.

INTRODUCTION

The primary objective of the evaluation was to examine the validity and reasonableness of the City of Tucson's hydrologic and hydraulic design procedures, methodology, and criteria. This objective required that we consider the City of Tucson procedures in comparison with accepted theory and standard engineering practices and in relation to accepted regional procedures and federal standards.

During the middle to latter part of the 1970's, an effort was made to develop improved procedures to predict peak rates of discharge from small watersheds in Pima County, Arizona. These efforts resulted in publication of a hydrology manual for the Pima County Department of Transportation and Flood Control District (Zeller, 1979), and Drainage and Channel Design Standards for Local Drainage for Flood Plain Management within Pima County, Arizona (Pima County, 1984). As a result of these efforts to improve procedures for Pima County, the City of Tucson is adopting similar standards and procedures based almost entirely on the Pima County standards and procedures.

However, some of these procedures were questioned by local consulting engineers, builders, developers, and their clients. In an attempt to develop the best possible standards and methodology, the City of Tucson sought independent evaluations of their proposed methodology and standards for hydrologic and hydraulic designs. This paper summarizes findings from a longer report (Lane, Ward, and Stone, 1984) describing the results of an independent evaluation of the City of Tucson's hydrologic and hydraulic design procedures and methodology.

RESULTS AND DISCUSSION

To accomplish the evaluation objectives, we performed the following tasks and analyses:

1. Analyses of rainfall intensity-duration relationships.

2. Regional flood frequency analyses.

3. Detailed hydrologic analyses using a distributed hydrologic simulation model

4. Review and evaluation of hydraulic and drainage standards.

Analyses of Rainfall Intensity-Duration Relationships

Rainfall data from the Walnut Gulch Experimental Watershed (Osborn, 1983) and from the National Weather Service station at the Tucson International Airport (Reich, 1978) were used to derive intensity-duration estimates for durations of 5 to 60 minutes, and for return periods of 2 to 100 years. These estimates were then compared with corresponding estimates from NOAA Atlas 2 (Miller et al., 1973).

Analyses of the estimates for Walnut Gulch suggested that NOAA Atlas 2 procedures underestimated the 100-year 60-minute point rainfall depths. Analyses of the estimates for the Tucson International Airport suggested that NOAA Atlas 2 procedures underestimate the 60-minute point rainfall depths for return periods longer than 10 years. There was no suggestion in the data or our analyses that NOAA Atlas 2 procedures overestimate 60-minute point rainfall depths for return periods longer than 10 years.

Comparisons of 60-minute point rainfall depths for Tucson, Arizona and Walnut Gulch are summarized in Table 1. Comparisons of 5- to 60-minute point rainfall intensities are summarized in Table 2. Based on these data and our analyses, we concluded that the City of Tucson (1977) point rainfall estimates for 5- to 60-minutes, and for return periods of 10 years and longer, are appropriate for use in hydrologic and hydraulic analyses in the vicinity of the Tucson International Airport.

Finally, we concluded that the City of Tucson rainfall intensity-duration relationships are superior to the older relationships based on NOAA Atlas 2. We recommended that the City of Tucson request the National Weather Service to revise, as appropriate, the rainfall intensity-duration estimation procedures described in NOAA Atlas 2.

Table 1.--Comparison of 60-minute point rainfall depths at Tucson, Arizona from NOAA Atlas 2, National Weather Service, Tucson Int'l Airport (TIA) Data and from the City of Tucson (1977), with data from Walnut Gulch (Osborn, 1983, Fig. 36) and NOAA Atlas 2. Data are from Lane et al. (1984), and rainfall depths are in inches.

Return Period (years)	NOAA[1] Atlas 2 Tucson	NWS[2] TIA	Reich (1978) City of Tucson (1977)	Walnut Gulch[3]	
				Osborn (1983)	NOAA Atlas 2
2	1.28	0.95	1.06	1.15	1.20
5	1.58	1.43	1.52	1.55	1.45
10	1.77	1.80	1.96	1.85	1.61
25	2.01	2.27	2.38	2.25	1.93
50	2.24	2.63	2.65	2.56	2.18
100	2.48	3.01	3.12	2.85	2.40

NOTES:

[1]NOAA Atlas 2 estimates for Tucson from Miller et al. (1973), as tabulated by Zeller (1979, p. 51).

[2]NWS Tucson Int'l Airport estimates represent the results of an independent frequency analysis of the National Weather Service, Tucson Int'l Airport data from 1943-1974, using a log-normal probability distribution and the Weibull plotting position formula $(m/(N+1))$.

[3]Walnut Gulch data represent point frequency estimates from a log-normal probability distribution and from NOAA Atlas 2.

Table. 2--Comparison of 5- to 60-minute rainfall intensities at Tucson Int'l Airport (TIA) from analysis of National Weather Service data using a log-normal probability distribution with City of Tucson (COT) estimates (Reich, 1978, City of Tucson, 1977). Data are from Lane et al. (1984), and rainfall intensities are in inches per hour.

Return Period (years)	5 min		10 min		20 min		30 min		60 min	
	TIA	COT	TIA	COT	TIA	COT	TIA	COT	TIA	COT
2	3.67	4.02	2.82	3.25	2.13	2.30	1.65	1.78	.95	1.06
5	5.08	5.25	4.08	4.30	3.21	3.21	2.54	2.53	1.43	1.52
10	6.02	6.50	4.93	5.38	3.99	4.00	3.16	3.20	1.80	1.96
25	7.26	7.51	6.12	6.56	5.10	5.02	4.00	3.96	2.27	2.38
50	8.16	8.25	6.96	7.42	5.91	5.83	4.68	4.48	2.63	2.65
100	9.10	8.84	7.80	8.13	6.78	6.45	5.38	5.10	3.01	3.12

Regional Flood Frequency Analyses

Runoff data from selected watersheds in southeastern Arizona were analyzed (using the log-normal probability distribution) to estimate flood peaks for return periods of 2 to 100 years. These flood peaks, in turn, were used to establish an approximate regional relationship between drainage area and peak discharge. This regional relationship can then be used as a benchmark to judge the reasonableness of subsequent flood peak estimates.

The 100-year flood peak estimates are summarized in Table 3. Notice that the data from High School Wash represent 8 years of record, and may result in low estimates for the 100-year flood peak in relation to the other watersheds. Analyses of the Santa Cruz River data suggest that the data are nonstationary, and annual peak discharges are increasing (e.g., Reich, 1984; Lane et al., 1984). The 100-year flood peak estimates on the Santa Cruz River at Tucson range from 30,000 cfs to over 90,000 cfs, with most estimates in excess of 50,000 cfs. Therefore, the flood peak estimates shown in Table 3 are only approximate, and subject to uncertainty.

Table. 3--Flood peaks estimated from flood frequency analysis of runoff data from selected watersheds in southeastern Arizona.

Watershed	Drainage area	Period of record	100-yr flood peak	
	(sq mi)		(cfs)	(cfs/mi^2)
High School Wash, Tucson, AZ[1]	0.9	1968-1975	1520.	1690.
Big (Enchanted Hills) Wash, Tucson, AZ	2.75	1965-1975	6820.	2480.
63.011, near Tucson, AZ	3.18	1963-1975	8000.	2520.
63.001, near Tombstone, AZ	58.	1956-1980	25000.	430.
San Pedro River at Charleston, AZ	1220.	1916-1980	35000.	30.
Santa Cruz River at Tucson, AZ[2]	2220.	1916-1983	40000.	20.

NOTES:
[1]High School Wash data represent only 8 years of record.
[2]Santa Cruz River data are from a nonstationary series, and 100-year flood peak estimates range from 30000 to over 90000 cfs.

Based on these analyses, we concluded that the historical flood series on the Santa Cruz River, at Tucson, represented a nonstationary flood series, and thus, we recommend additional analyses to develop improved estimates of the 100-year flood peak on the Santa Cruz River. We also concluded that the City of Tucson Flood Peak Estimator (modified Pima County Method) usually produced flood peak estimates consistent with flood peak estimates from regional analyses (Lane et al., 1984).

Detailed Hydrologic Analyses

The Pima County Method (Zeller, 1979) and a simplified version of it, called the City of Tucson Flood Peak Estimator (City of Tucson, 1982), and a distributed hydrologic model (Lane, 1982) were applied to a number of small watersheds in the Tucson area to provide a basis of comparison and evaluation of the Pima County Method, and thus, the City of Tucson Flood Peak Estimator.

The Pima County Method is a synthesis of the Soil Conservation Service (SCS) runoff equation, the kinematic wave equations for time of concentration, the National Weather Service NOAA Atlas 2 and the rational formula. As such, it incorporates the soil-cover complexes of the SCS equation, the time of concentration-intensity relationship from the kinematic equations, and thus, the peak discharge-area-intensity relationship from the rational formula. The Pima County method was developed to reflect the hydrologic impacts of urbanization through factors known to affect the volume of runoff and peak discharge. These factors include the amount of impervious area, the degree of changes in flow length, hydraulic roughness and changes in drainage patterns.

The distributed model (Lane, 1982), used for comparison and evaluation purposes with the Pima County Method, uses the SCS equation to compute runoff delivered to the stream channel network. Flow routing in the channels is based on transmission loss equations and a double-triangle hydrograph approximation to relate runoff volume and peak discharge. The distributed model method was derived for natural (nonurban) watersheds, and uses rainfall data distributed over the entire watershed area. In general, the distributed model can be used on larger watersheds, and emphasizes channel processes more than the Pima County Method.

A brief comparison of the two methods is summarized in Table 4. The Pima County Method is a handbook method designed for repeatable applications in flood peak estimation on small urban and suburban watersheds. The distributed model method was developed for watershed research, and is not supported by a user's manual or handbook. Moreover, the distributed model requires more judgment and experience for applications than does the Pima County Method. Although the procedures are quite different, they have enough in common with respect to prediction of peak discharge, that the distributed model can be used to judge the accuracy and applicability of the Pima County Method.

Computed values of the 100-year flood peak, from both methods for six small watersheds, are shown in Table 5. Notice that the estimated flood peaks are quite comparable from both methods, and differ by less than 15% in all cases. Also, the Carmack Wash and Finger Rock Wash watersheds represent small watersheds with much of their drainage areas in the Santa Catalina Mountains. Examples 1 and 2 represent "foothills" watersheds in natural and suburban development. Example 6, Big

(Enchanted Hills) Wash, represents a natural watershed in the Tucson Mountains area with desert brush cover. Example 7, High School Wash, represents a moderately urbanized watershed with about 29% of the drainage area as impervious areas. Thus, these six watersheds represent natural and urban areas, mountains and foothills areas, and an urbanized watershed on the Tucson valley floor.

Table. 4--Comparison of the Pima County Method (Zeller, 1979) and the distributed model method (Lane, 1982).

Item	Pima County method (PC)	Distributed Model method (DM)	Comments
Region of application	Pima County[1]	Seimarid rangelands	Both emphasize thunderstorm rainfall.
Runoff volume	SCS Equation	SCS Equation and transmission losses	DM incorporates transmission losses.
Peak rate	Rainfall depth and intensity. Watershed features.	Rainfall depth and an assumed hydrograph shape. Watershed features.	PC has variable T_c,[2] and DM has constant T_c.
Emphasis	Flood peaks on natural and urbanized watersheds. Handbook approach.	Runoff volume and peak rates on natural watersheds. Transmission losses. Research model.	DM designed to allow distributed raingage data as input and simulate partial area runoff.
Documentation/application	Handbook, Zeller (1979).	Journal article, Lane (1982)	PC method more repeatable, and requires less judgment.

[1]The Pima County Method was developed specifically for Pima County, but is applicable to much wider geographical areas where the rainfall-runoff model (SCS Equation) is appropriate.

[2]T_c = time of concentration. Both methods compute T_c as a function of watershed characteristics, and the Pima County Method computes T_c as a function of rainfall intensity as well.

The correspondence of 100-year flood peak estimates from the two methods suggest that the Pima County Method is in close agreement with the distributed model method, and in approximate agreement with available measured data (Table 3 herein, and Appendix D in Lane et al., 1984). From these and similar analyses, we concluded that the Pima County Method, the City of Tucson Flood Peak Estimator, and the distributed model all produce similar flood peak estimates, given the same basic input data on soils, topography, and rainfall intensity. Moreover, all three methods produced flood peak estimates in agreement with observed flood data on small watersheds (less than 10 mi^2) in southeastern Arizona.

Table. 5--Comparison of 100-year flood peak estimates for selected small watersheds in the Tucson area using the Pima County Method (PC) and the distributed model (DM) method with rainfall data from NOAA Atlas 2 (Miller et al., 1973). All watersheds are in Pima County, and are in or near Tucson, Arizona.

Watershed location	Drainage area	100-year flood peak (PC)	100-year flood peak (DM)	Method with largest peak
	(sq mi)	(cfs)		(%)
Carmack Wash at Hardy Rd	3.0	5570.	5130.	PC(+7.9)
Finger Rock at Skyline Dr	4.4	5550.	6230.	DM(-12.3)
Zeller (1979) Example 1, Natural foothills	1.8	1824.	1940.	DM(-6.4)
Zeller (1979) Example 2, Foothills CR-1	1.8	2404.	2290.	PC(+4.7)
Zeller (1979), Example 6, Big (Enchanted Hills) Wash near Mission Road	2.75	4064.	4340.	DM(-6.8)
Zeller (1979), Example 7, High School Wash at Cherry Avenue	0.9	1777.	1520.	PC(+14.5)

NOTE: Values in parentheses in the last column are a percent difference term calculated as ((QPC-QDM)/(QPC)) times 100 where QPC is the peak discharge using the PC method, and QDM is the peak discharge using the DM method. All differences in computed peak discharge are less than 15%.

Finally, Lane et al. (1984) examined procedures used to estimate peak discharge in a number of other southwestern cities. The Pima County Method was found to be comparable to, or better than, methods used in Albuquerque, NM; Denver, CO; El Paso, TX; Los Angeles, CA; Phoenix, AZ; and Ventura County, CA in most respects except rainfall frequency data. We recommended that City of Tucson rainfall intensity-duration data be used in place of NOAA Atlas 2 data. With this modification, the Pima County Method and (under appropriate conditions, including watershed size limits, i.e., 2.0 sq mi or less) the City of Tucson Flood Peak Estimator will be considerably enhanced.

Review of Hydraulic and Drainage Standards

The City of Tucson proposes to adopt drainage and channel design standards developed by Pima County (Pima County, 1984). The Pima County standards adequately cover most of the major design problems with the exception of storm sewer design and detailed roadway drainage. The following paragraphs review specific factors in the Pima County guidelines.

Freeboard. The freeboard equation presented is appropirate in terms of mean flow velocity. However, we suggested modifying the freeboard equation to produce 2.0 ft, rather than 1.0 ft, as the minimum freeboard in design of conveyance channels.

Setbacks. The setbacks are 50 to 300 feet, depending upon the size of the channel. We concluded that these setback limits appear to be reasonable, but in view of the 1983 floods in Pima County, perhaps could be modified if analysis of channel erosion-meandering patterns suggest larger setbacks are appropriate. We suggested this as an appropriate area for further study using state-of-the-art channel dynamics-morphology models.

Encroachment. The 0.1 ft change in water surface elevation is conservative (in that modifications should not cause a larger change). However, it is not a practical limit in that water surfaces in general cannot be determined with this precision. Therefore, we would suggest that the standards require no change in water surface elevation as a result of encroachment.

Criteria and standards for right-of-ways, channel side slopes, bend radius, transitions, and confluences appear reasonable if the upper limit of 30 degrees for entrance transition angle is lowered to about 11 degrees (1:5 flare). Design criteria for channel stabilization should be based on the 100-year flow depth, except that the equilibrium slope may be based on the 2-year flow. Finally, we recommended a detailed review and appropriate modification of the roadway drainage guidelines. Additional details are given in Appendix F of Lane et al. (1984).

SUMMARY AND COMMENTS

Summary

The Pima County Method and the City of Tucson Flood Peak Estimator appear to be reasonable and state-of-the-art procedures with respect to current engineering practices used in several cities in the Southwest. The Pima County hydraulic and drainage procedures are also reasonable with respect to scientific, regional, and acceptable engineering practices criteria. However, we recommended using the City of Tucson rainfall intensity-duration relationship, as it is based upon a longer period of record, and is superior to the older procedures described in NOAA Atlas 2. We also recommended that the City of Tucson adopt the Pima County Drainage and Channel Design Standards for Local Drainage after they are reviewed and modifications (as a result of our review and the proposed review) completed.

Comments

Pima County, through its development of the Hydrology Manual for Engineering Design and Flood Plain Management within Pima County, Arizona (Zeller, 1979) and the Pima County Drainage and Channel Design Standards for Local Drainage (Pima County, 1984) has improved hydrologic and hydraulic methodology applicable in, and available to, the City of Tucson.

The City of Tucson has adopted, or is in the process of adopting, slightly modified versons of the Pima County hydrologic and hydraulic methodology and standards. However, as a result of questions raised by consulting engineers, builders, developers, and their clients, the City of Tucson sought an independent evaluation of their existing and proposed standards. The floods of October, 1983, subsequent flood frequency analyses suggesting increasing peak discharges on the Santa Cruz River, and the independent evaluations reported by Lane et al. (1984) and summarized herein, suggest that the present and proposed standards are acceptable, but need to be strengthened in certain areas. Specifically, the City of Tucson rainfall intensity-duration relationship (resulting in higher intensities and larger flood peaks) is superior to the relationship described in NOAA Atlas 2. Recent flood peaks on the Santa Cruz River are increasing, and estimates of the 100-year flood are being revised upward.

Therefore, we conclude that the City of Tucson and Pima County have made significant progress in standardizing procedures, but should continue to develop improved methodology and standards for hydrologic and hydraulic designs.

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development of the Hydrology Manual and Drainage and Channel Design Standards, has improved hydrologic methodology and hydraulic design standards applicable on small watersheds in the Southwest.

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