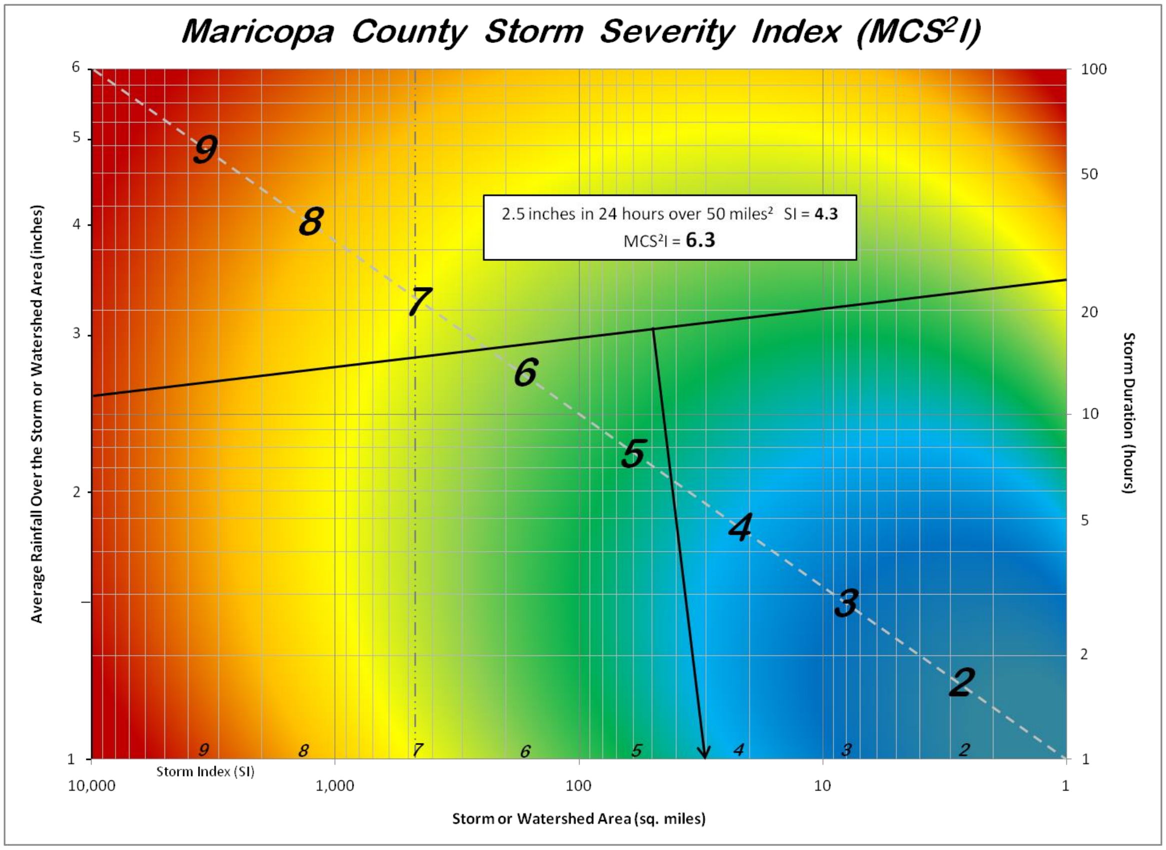
A CLASSIFICATION INDEX FOR PRECIPITATION EVENTS IN MARICOPA COUNTY, ARIZONA

By Stephen D. Waters, [1] Member, AMS



INTRODUCTION

For many years now the scientific community and the public have suffered through the use of terms like *exceedance probability* and *return period* as the primary terms used to define storm severity. These phrases are often misapplied by scientists/engineers and misunderstood by the media and the public (Glazner, White and Tomic, 1998). The term "100-year storm" describes the rarity of a storm in terms of its percent chance of occurrence in any given year, but says nothing about its areal extent or duration and to many infers a suggestion of separation ("we shouldn't have another one for a hundred years"). Also, storm return periods are almost always calculated from a point rainfall measurement, which is rarely if ever representative of the area covered by a storm. A few papers have been published on the topic of storm severity vs. rarity (Glazner, White and Tomic, 1998; Grisa, 2009), but have tended to use recurrence interval (also called return period) as an input to their classification methods, and have left out altogether any reference to the physical area of storm coverage. Examples of simplified classification methods exist in the world of hurricanes, earthquakes and tornados – why not for precipitation events?

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[1] Flood Warning Manager and Senior Hydrometeorologist, Flood Control District of Maricopa County, 2801 W. Durango St., Phoenix, AZ 85009

THEORY

The purpose of this exercise was to develop an index that would describe the severity of multiple storm types (thunderstorms, general winter storms, tropical storms), that would use three storm parameters as inputs (areal average rainfall, storm duration, and storm or watershed area) and would give similar results for storms with similar rainfall/duration properties regardless of the area covered. A note – "severity" will only apply to the precipitation as a meteorological event – runoff (flooding) generated and damage caused are determined by an additional set of inputs. A decision was made at the outset to emulate the rating of the *Richter Scale* as used for earthquakes –where a 5 is noticed but does little damage, a 7 causes significant damage and a 9 is catastrophic and rarely experienced. The method's application should range from historic storms above stream measurement points, to comparisons over given geographic areas, to forecasting using QPF values as an input. It should be easy for someone with a science background to use, give nearly identical results no matter the qualified user, and be somewhat automated using commonly available software.

DEVELOPMENT

Having chosen Microsoft® Excel® as a development platform, it took several iterations to fashion a set of axes and scales that would work in a rectangular plot area. The trials resulted in this outcome: areal average rainfall on the left, with values from 1 to 6 inches, duration on the right with values of 1 to 100 hours, and storm or watershed area on the bottom with values of 1 to 10,000 square miles. Storm severity increases with increasing rainfall and decreasing duration, so these were set opposite each other across the vertical axis. Along the bottom axis, the "Storm Index" number will increase with increasing area covered given that rainfall and duration stay the same, so the lowest value was set on the right, giving a higher index to the left. The end result is the chart shown below as Figure I:

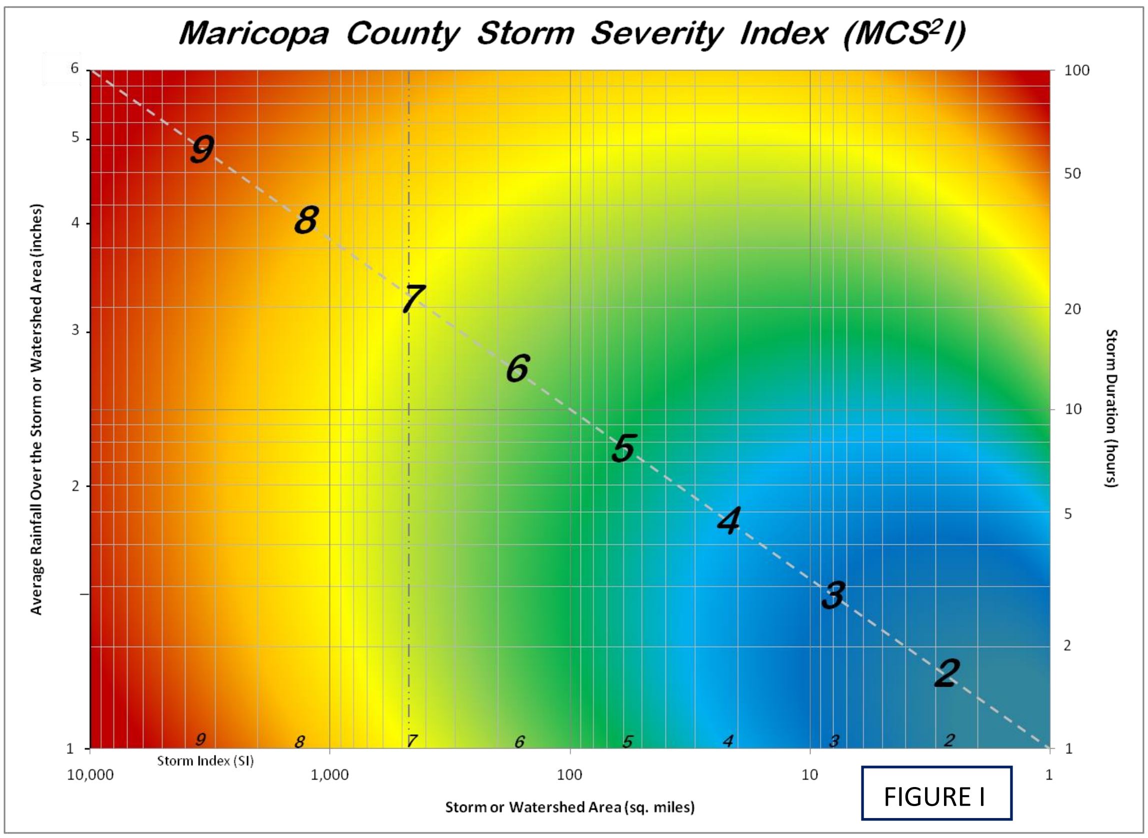
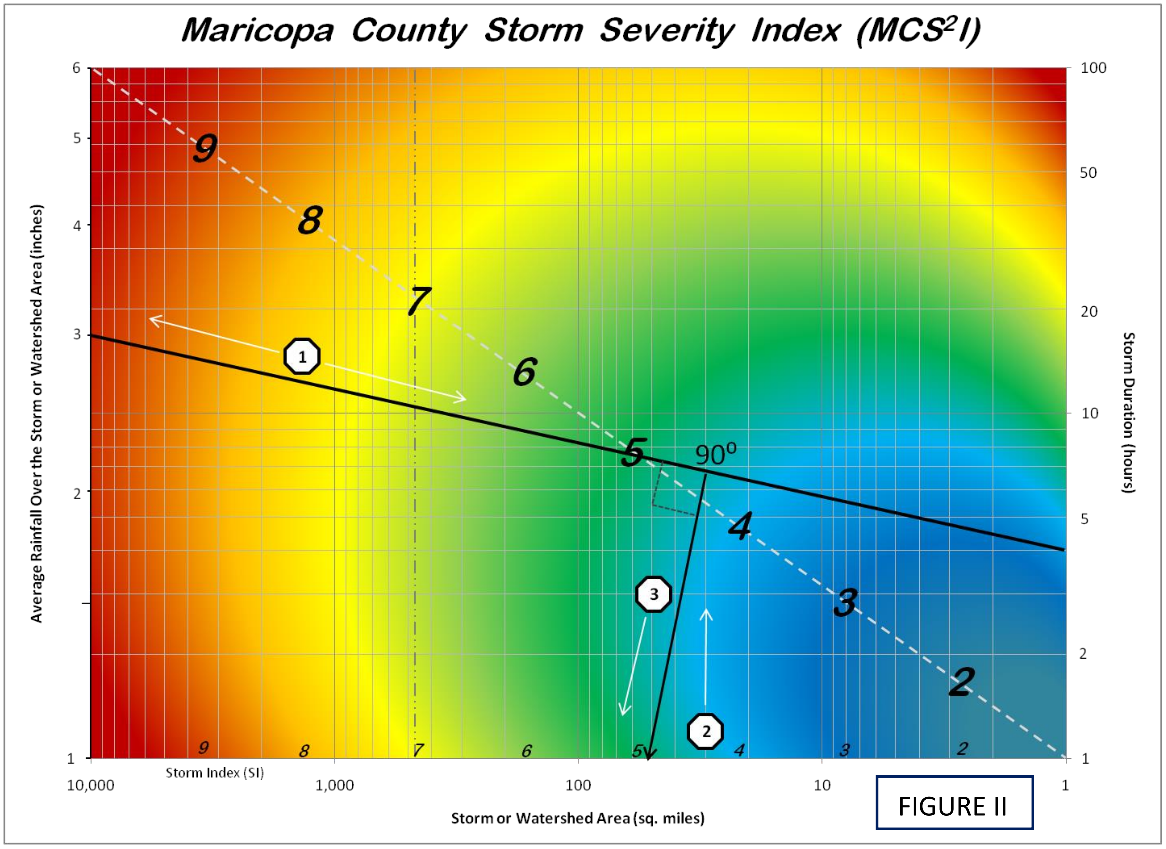


FIGURE I

HOW IT WORKS



Step 1. For the example shown in Figure II above, a line is connected from the average rainfall amount (3.0 in.) to the storm duration (4 hrs.). The average rainfall can be derived from GIS analysis of radar-rainfall estimates, satellite-rainfall estimates or a number of hand methods used to average measurements from rain gage networks.

Step 2. At a storm or watershed area of 30 mi^2, find the point of intersection with the line created in Step 1.

Step 3. From that point, a perpendicular pointer line (90^0) is drawn down to the bottom axis to estimate the Storm Index from the whole number Storm Index (≈ 4.9). The circular color hues can be followed up to the larger numbers along the diagonal line, but these are mostly added for ornamentation.

Step 4. If the storm or watershed area is greater than 467 square miles (see the Details section), then the Storm Index (SI) is equal to the Severity Index (also denoted as the Maricopa County Storm Severity Index, or MCS^2I). If not, a regression equation (Eq.1) is used to adjust SI based on the area covered. For this example: MCS^2I = **7.9**

DETAILS

Two items were considered in determining the extent of the vertical axes – local design storm depth/duration pairs and historic Maricopa County storms. In this area of central Arizona, it is exceedingly rare to see average rainfall depths greater than 6 inches in 4 days (NOAA Atlas 14), so 6 inches and 100 hours were selected as the upper bounds for the axes. For the horizontal axis, 10,000 square miles is only about 775 mi^2 larger than

Maricopa County, so this seemed a reasonable upper bound as well. The use of log scales mimics the physics of the natural world. A watershed responds more to the difference between 1 ½ inches of rain and 2 inches than to the difference between 5 ½ and 6 inches. The difference between a one and four hour storm is more significant than the difference between a 91 and 94 hour storm. Likewise, a 6 square-mile storm has more potential for severity versus a 2 square-mile storm than does a 540 square-mile storm versus a 534 square-mile storm. The perpendicular pointer was chosen so that the indicated Storm Index would increase as rainfall increased and/or duration decreased.

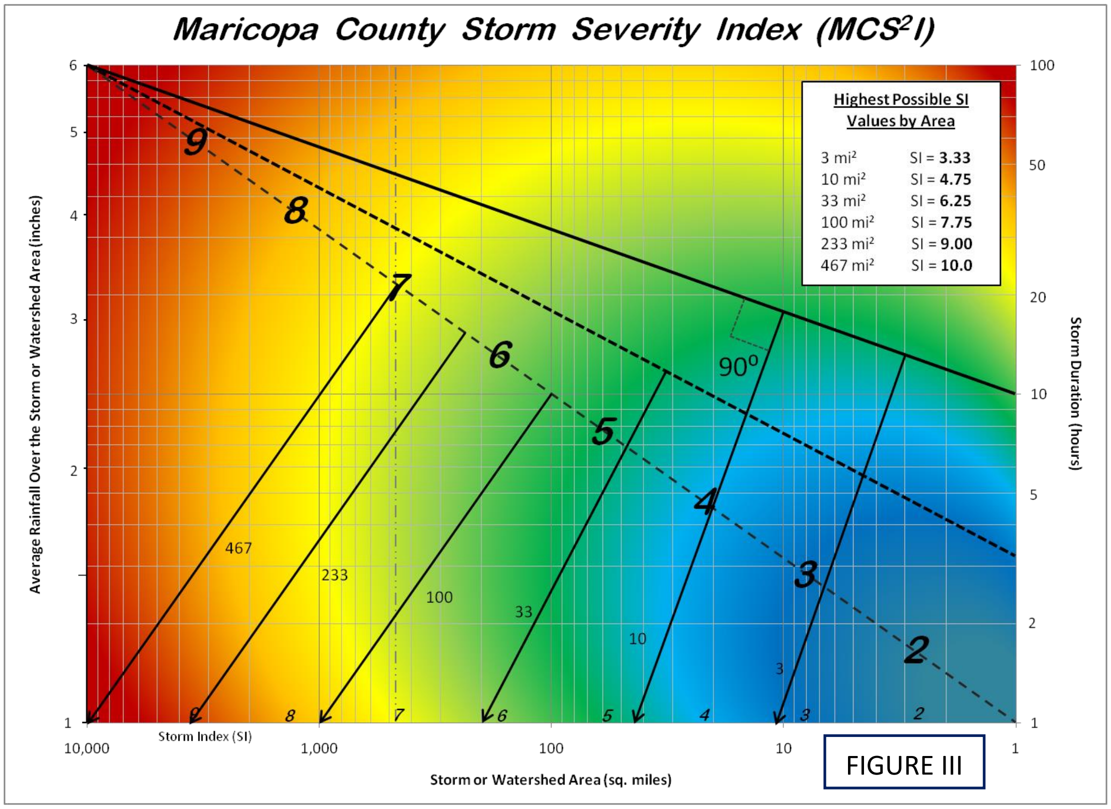


FIGURE III

To provide the severity range (1-10) for storms/watersheds of small areal extent, it was necessary to develop an adjustment to the Storm Index by "normalizing" it based on area. Figure III above begins this process by showing the maximum Storm Index for a range of areas from 3 to 467 square miles. 467 square miles is the upper bound for a Storm Index of 10 and a rainfall rate of 6 inches in 1 hour. This number would of course be altered with a change to the area scale. These numbers were then entered into Excel® as follows:

AREA (mi^2)	**Maximum Storm Index (SI)**	**10 / SI (N-factor)**
3.00	3.33	3.0000
10.00	4.75	2.1053
33.00	6.25	1.6000
100.0	7.75	1.2903
233.0	9.00	1.1111
467.0	10.0	1.0000

TABLE 1

The N-factor values, plus the corresponding Areas, Areas^2 and Areas^3 were entered into Excel's® Regression Analysis Tool. It returned a y-intercept value of 4.2097, and coefficients of -3.0244, 1.0817 and -0.1498. So the normalization equation used to adjust SI values to Severity Index values for areas less than 467 mi^2 is:

$$\mathbf{MCS^2I = SI\ [4.21 - (3.02\ logA) + (\ 1.08\ logA^2) - (0.15\ logA^3)]} \quad (1)$$

A graph of the N-factors in Table 1 vs. predicted N-factors from Equation (1) is shown below:

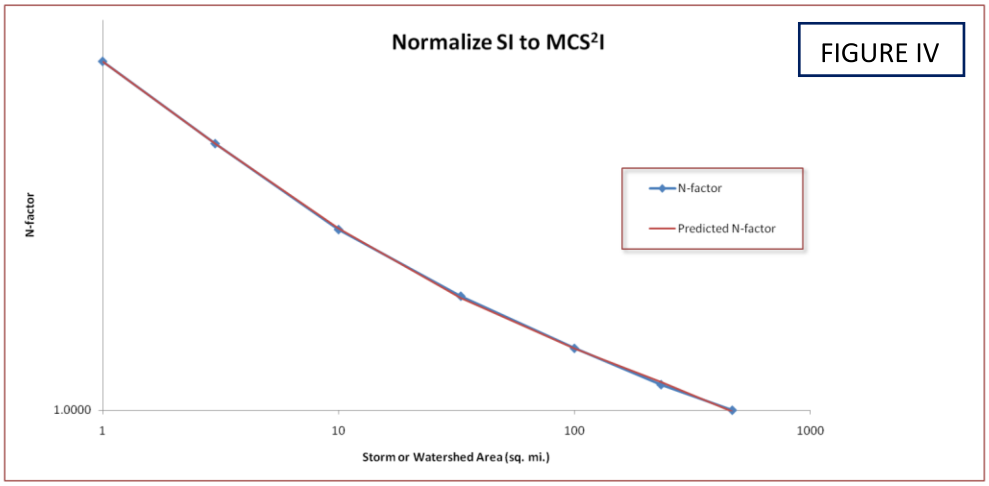


FIGURE IV

LIMITS

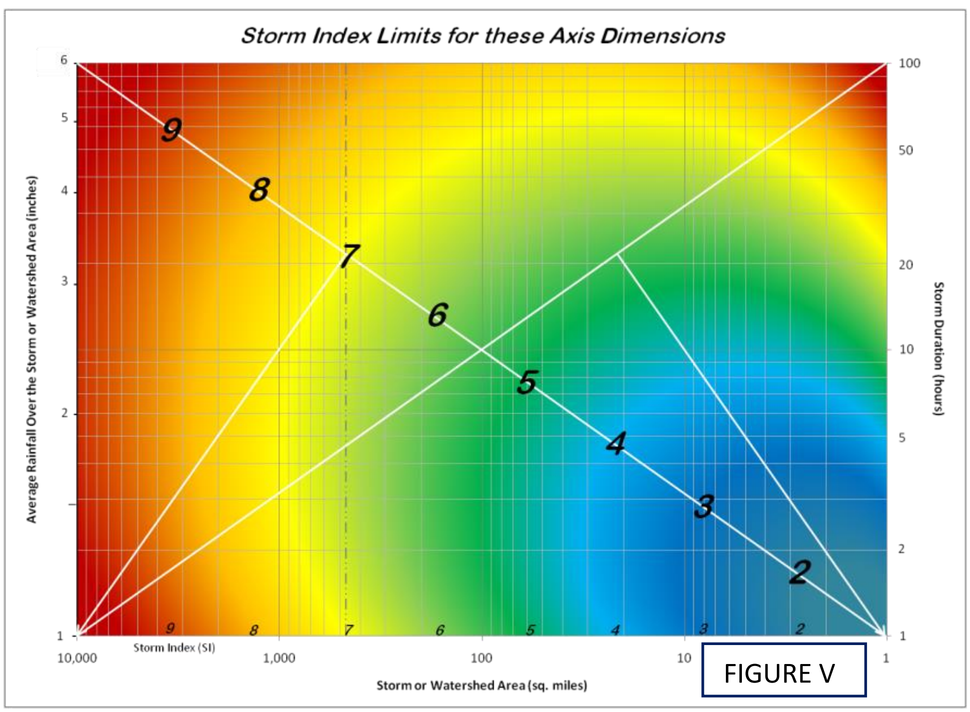


FIGURE V

The white lines on Figure V above should help in visualizing the following limitations of the method:

1. For a storm of 1 inch (min) in 100 hours (max), the smallest possible area for which the method can be applied is 22 mi^2. At 1 inch in 6 hours, that area shrinks to 2 mi^2.
2. For a storm of 6 inches (max) in 1 hour (min), the largest possible area is 467 mi^2. At 6 inches in 6 hours, the largest possible area rises to 900 mi^2.
3. 1 inch of areal rainfall over 10,000 mi^2 will always have a Storm Index of 10 and a Severity Index of 10 regardless of duration.
4. 1 inch of areal rainfall over 1 mi^2 will always have a Storm Index of 1 and a Severity Index of 2.4 regardless of duration.
5. Beyond a storm or watershed area of 467 mi^2, SI for a given rainfall depth and duration will increase with increasing area.

The storm parameters listed above (1.00"/ 10,000 mi^2; 6.00"/1 hr.) that represent the boundary conditions of the graph also represent outliers in terms of what Mother Nature produces in central Arizona. All of the historic storms analyzed in the development and testing process of this method fell well within these boundaries.

EXAMPLE STORM

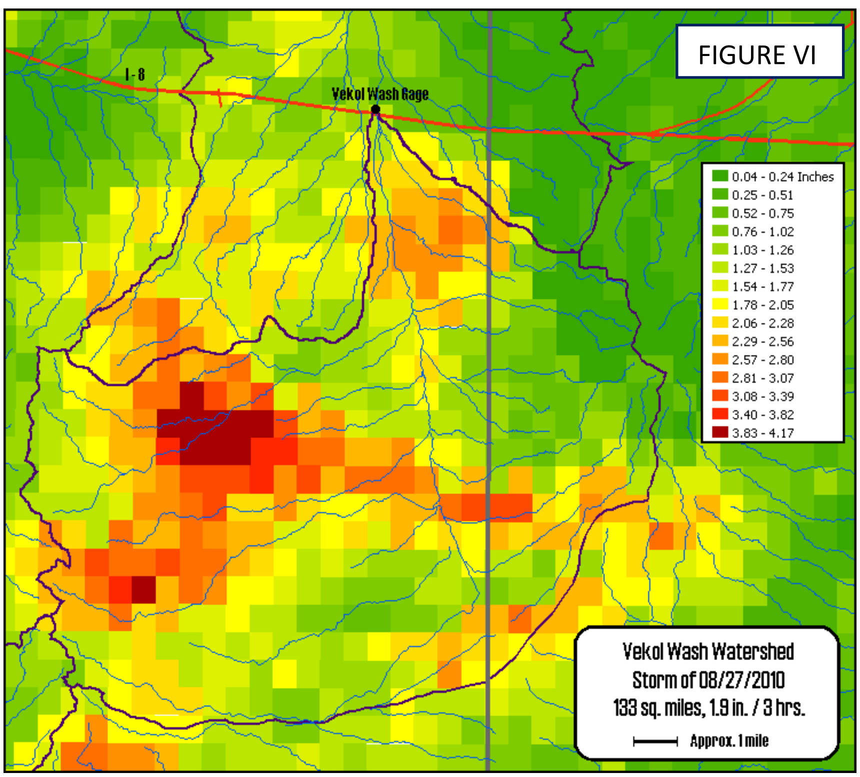
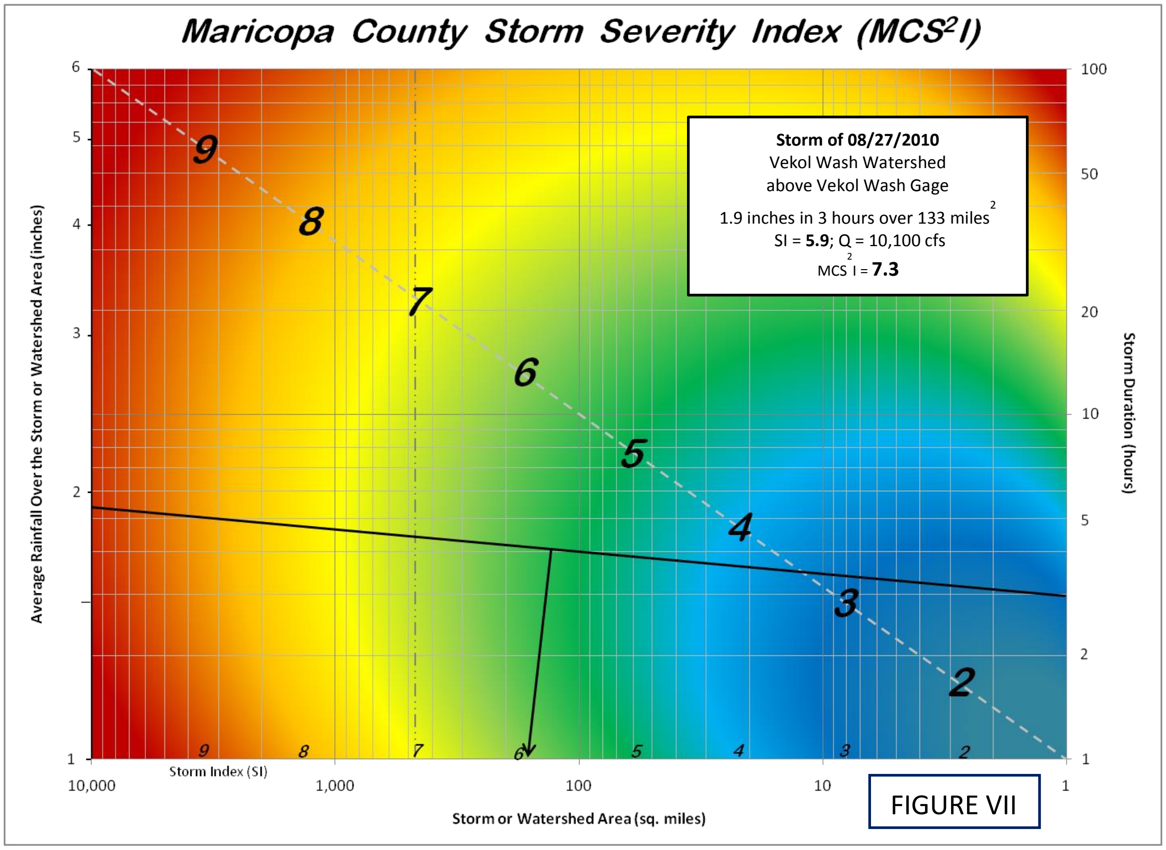


FIGURE VI

Figure VI above depicts a thunderstorm that occurred about 40 miles south of Phoenix on August 27, 2010. ArcGIS® was used to determine the average rainfall over the watershed using a coverage of locally-adjusted, gage-corrected radar rainfall estimates provided by a weather products vendor. Each colored pixel is 1km on a side and represents the mean rainfall value for that square kilometer. This storm generated a peak discharge of 10,100 cfs at the Vekol Wash stream gage – the highest in its 20-year record. It was determined that the average rainfall value for the contributing watershed (purple boundary below the gage) was 1.9 inches. A duration of 3 hours was extracted from data transmitted by the Vekol Wash rain gage.

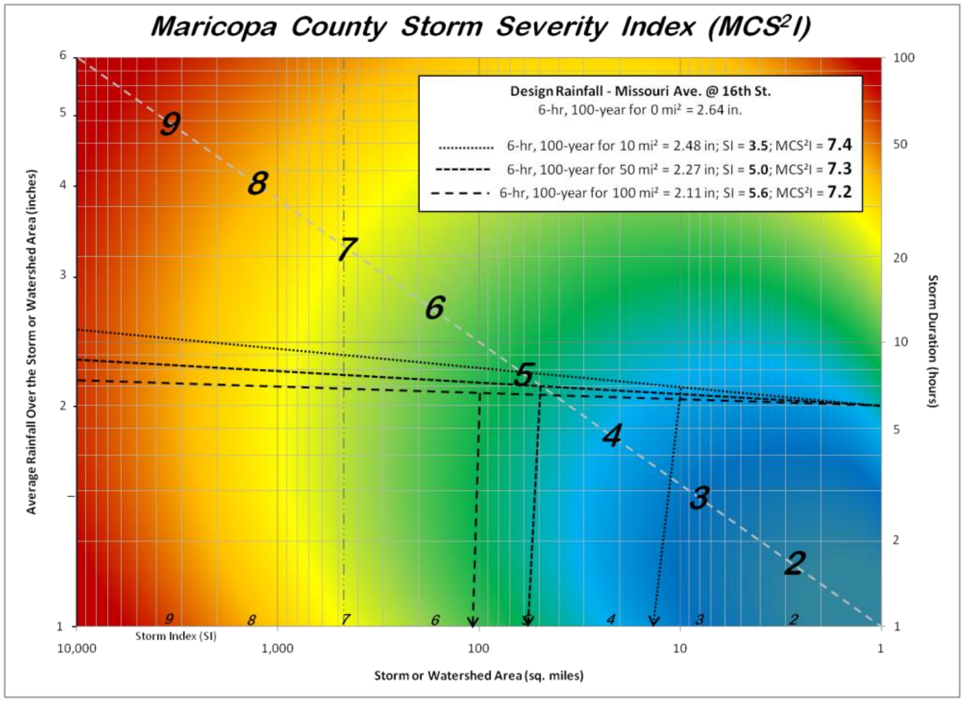


Drawing a line from 1.9 inches on the left axis (Fig. VII) to 3 hours on the right axis, extending a perpendicular pointer from the point above 133 mi^2, reading 5.9 as the Storm Index, and inputting this into Equation (1) along with the area of 133 mi^2, assigns a Severity Index of **7.3** to this storm over this watershed area.

COMPARISON TO DESIGN RAINFALL

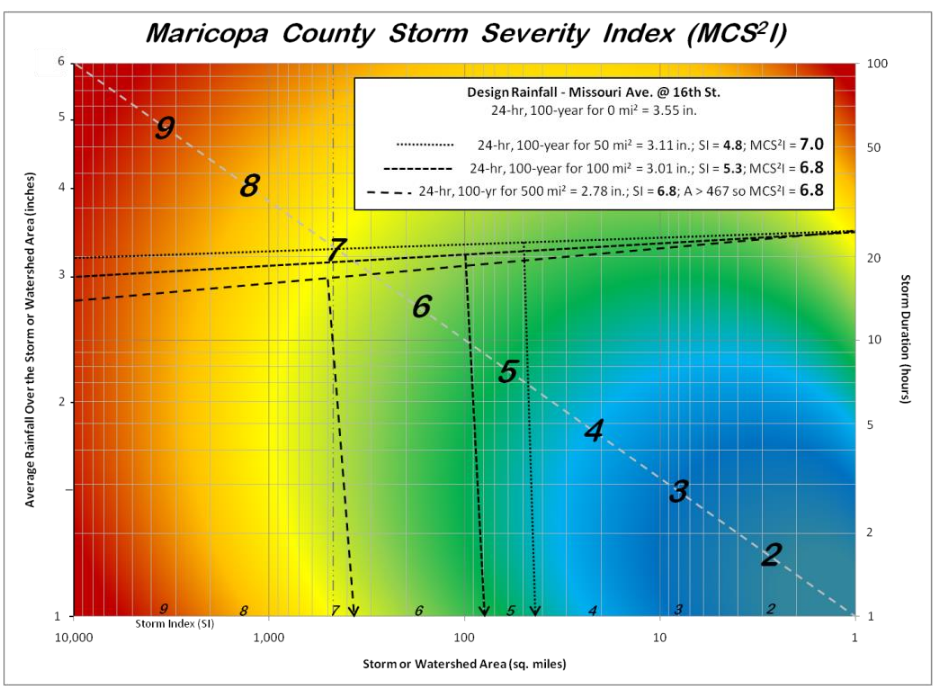
Having excluded point-rainfall exceedance probability from the input list for this methodology, we should nevertheless be able to examine design rainfall in the context of severity. We would expect the federal design standard, i.e., the 100-year storm, to score fairly high on the index. Two popular design storms in Maricopa County are the 6- and 24-hour, 100-year rainfall events, and these are used in the following example. The "point" chosen was Missouri Ave. and 16th St. in downtown Phoenix, which happens to have a rain gage. The 6-hour, 100-year rainfall value for this point from NOAA Atlas 14 is 2.64 inches. Table 2.1 in the Drainage Design Manual for Maricopa County (Gerlach, Motamedi & Loomis, 2010) lists areal reduction factors for 6-hour duration rainfall. Using this table for areas of 10, 50 and 100 square miles reduces the point value (0 mi^2) of 2.64 inches to 2.48, 2.27 and 2.11 inches respectively. Plotting these rainfall values vs. their respective areas on the MCS^2I graph (Fig. VIII) produces Storm Index numbers of 3.5, 5.0 and 5.6. Entering these into Equation (1) gives Storm Severity Index numbers of **7.4, 7.3** and **7.2**. As we would expect from the method, the severity index numbers are quite close to each other, giving an indication that a "100-year" storm, no matter the areal extent, will be consistently calculated by the Severity Index. Also, notice that the slope of the lines connecting average rainfall to duration is nearly flat. We will see in further examples that the line will in general slope down (from left to right) for severity values greater than **7** and slope up for values less than **7**.

FIGURE VIII



In another design rainfall example, the 24-hour, 100-year rainfall value for our point at Missouri Ave. and 16th St. from NOAA Atlas 14 is 3.55 inches. Table 2.2 in the Drainage Design Manual for Maricopa County lists areal reduction factors for 24-hour duration rainfall. Using this table for areas of 50, 100 and 500 square miles reduces the point value (0 mi^2) of 3.55 inches to 3.11, 3.01 and 2.78 inches respectively. Plotting these rainfall values vs. their respective areas on the MCS^2I graph (Fig. IX) produces Storm Index numbers of 4.8, 5.3 and 6.8. Entering these into Equation (1) gives Storm Severity Index numbers of **7.0, 6.8** and **6.8**. Again as expected, the severity index numbers are quite close to each other, and the slopes of the lines are reasonably flat.

FIGURE IX



STORMS OF EQUAL SEVERITY

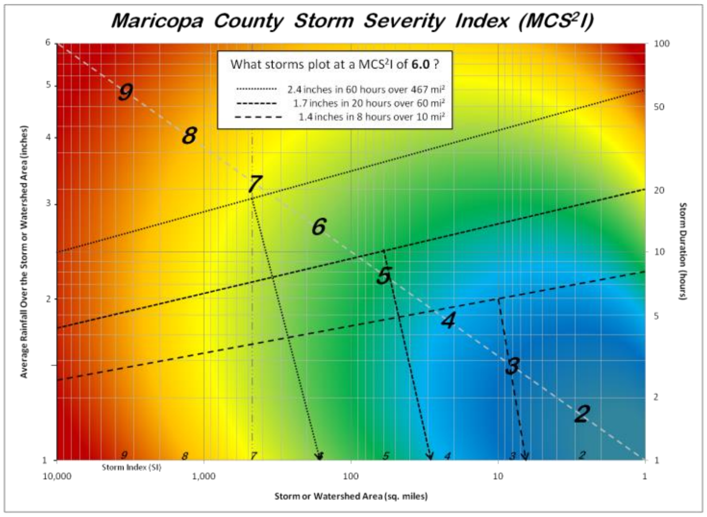


FIGURE X

In Figure X at left, three pairs of average rainfalls and durations are plotted. All of the pairs will compute to a Severity Index of **6.0** when entered into Equation (1). Because the Severity Index is less than **7**, the lines slope up from left to right.

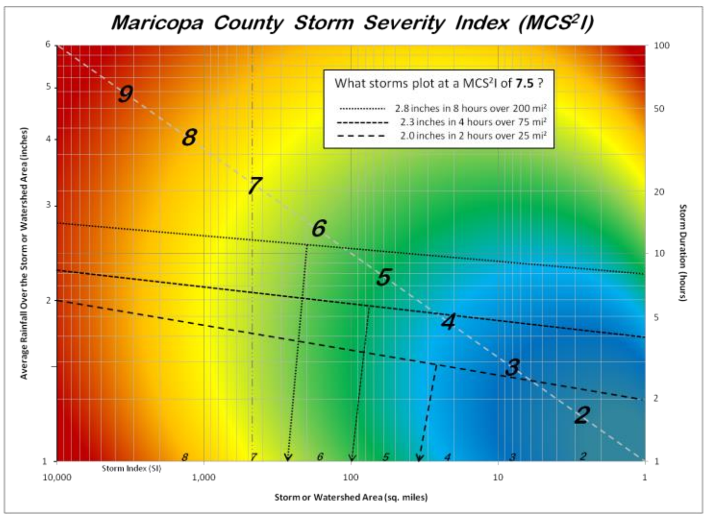


FIGURE XI

In Figure XI at left, three pairs of average rainfalls and durations are plotted. All of the pairs will compute to a Severity Index of **7.5** when entered into Equation (1). Because the Severity Index is slightly more than **7**, the lines are close to horizontal but slope down slightly from left to right.

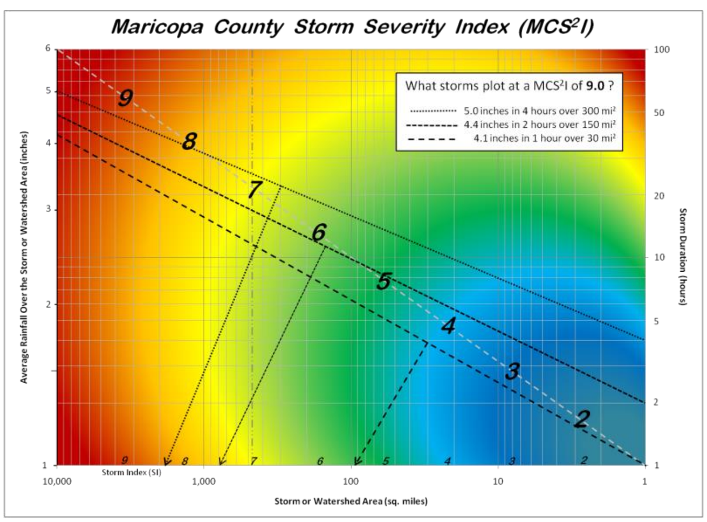
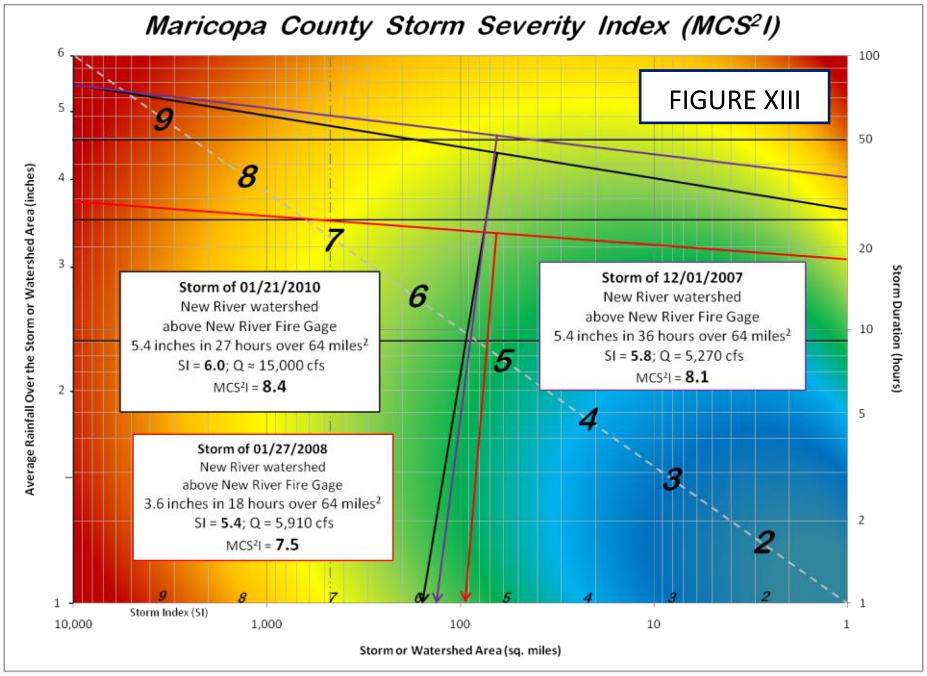


FIGURE XII

In Figure XII at left, three pairs of average rainfalls and durations are plotted. All of the pairs will compute to a Severity Index of **9.0** when entered into Equation (1). Because the Severity Index is more than **7**, the lines slope down from left to right.

ANALYSIS OF HISTORIC STORMS



Analysis of historic storms is somewhat constrained in that we (FCDMC) only have locally-adjusted, gage-corrected radar rainfall estimates on-file back to August 2005. Nevertheless, Figure XIII above shows plots for three storms that occurred over the 64 mi² New River watershed above our gage site named New River Fire. The storms represented by the black and purple lines had the same average rainfall amounts (5.4 inches), but different durations (27 and 36 hours). Both scored Severity Index values greater than **8**. During the 01/21/2010 storm, one rain gage in the upper watershed recorded point rainfall measurements of 7.32 inches in 24 hours and 8.43 inches in 48 hours (Waters, 2010). The lesser storm represented by the red line (3.6 inches in 18 hours) scored a value of **7.5**.

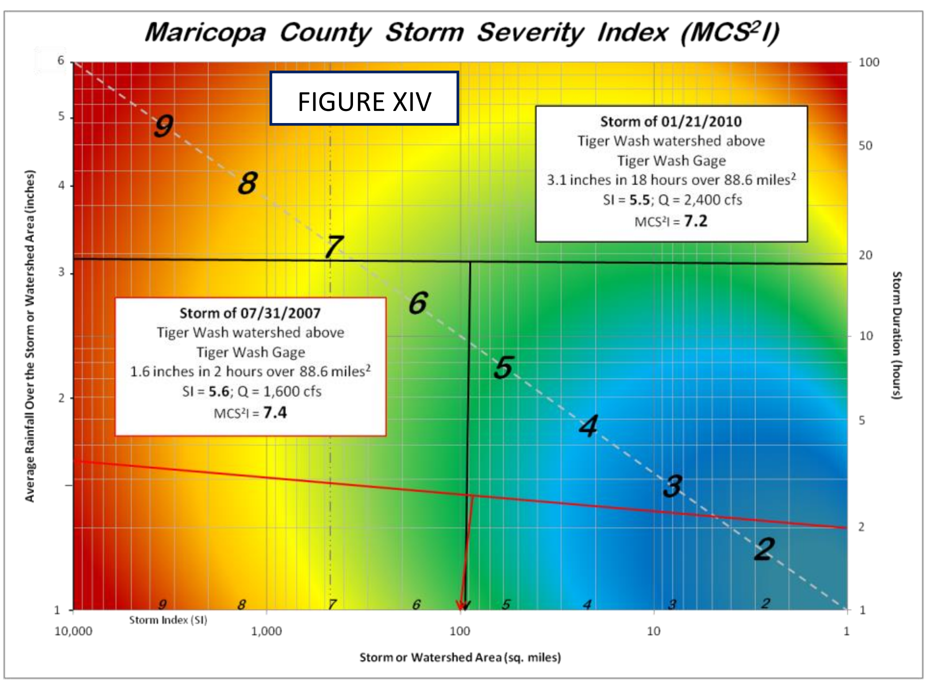


Figure XIV above shows plots for two storms that occurred over the 87 mi^2 Tiger Wash watershed above our appropriately named gage – Tiger Wash. These two storms have fundamentally different rainfall/duration pairs (one summer and one winter storm), yet plot to similar Storm and Severity Index values. Notice that the measured peak discharges are similar as well.

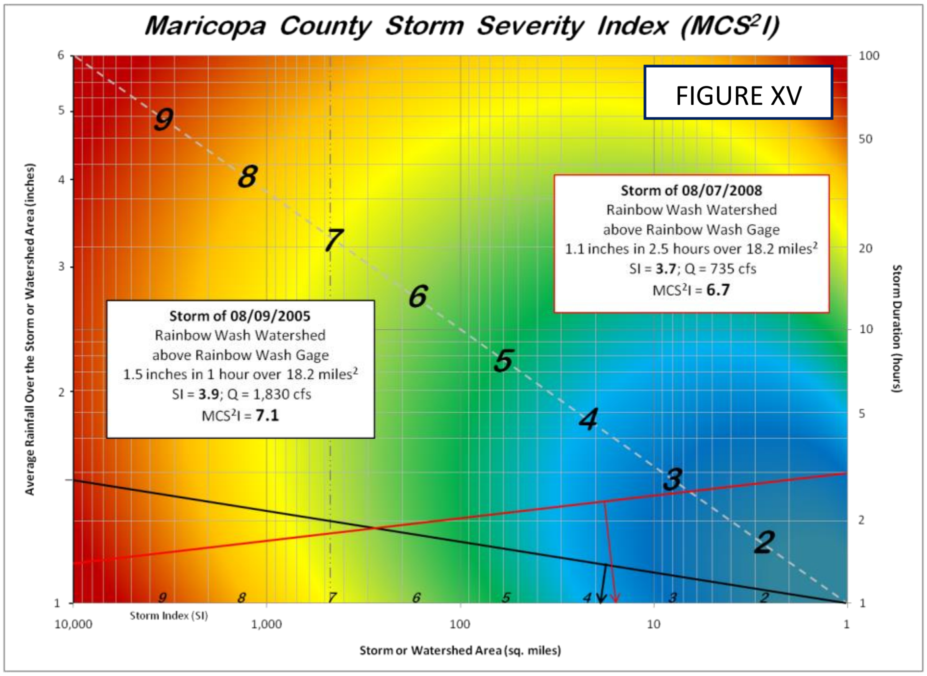
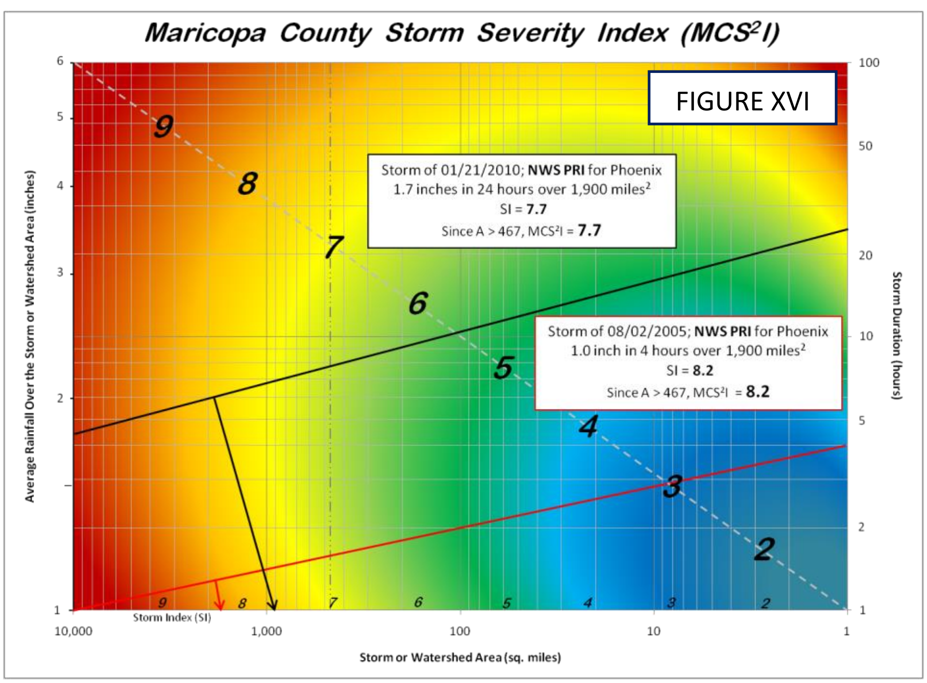


Figure XV above shows plots for two storms that occurred over the 18 mi^2 Rainbow Wash watershed above our again, appropriately named gage – Rainbow Wash. This watershed is small enough that it rarely responds to the generally longer duration winter storms. Both storms are of relatively short duration and low average rainfall amounts, yet generated significant peak discharges.



The Phoenix Rainfall Index (PRI) (Iñiguez, 2009) is an experimental product developed and made available by the National Weather Service Phoenix Forecast Office. The PRI is a mathematical average of approximately 125 rain gages that cover 1,900 square miles of the Maricopa County urban center. Index data are available on the Phoenix NWS website back to 2005. The highest recorded summer and winter storm values are plotted on Figure XVI, giving a comparison to the previous examples that used watersheds. The rainfall values don't seem severe, but the area covered is quite large, so the storms score high on the Severity Index. Many of our urban stream gages experienced record peak discharges during the storm of 08/02/2005.

APPLICATION TO OTHER GEOGRAPHIC AREAS

Figures XIII and IX demonstrated that rainfall/duration pairs for 6- and 24-hour, 100-year storms in central Maricopa County plot as nearly horizontal lines across the graph. This method could easily be applied to other geographic areas by an adjustment to the average rainfall scale based on local design rainfall. For example, a Precipitation Frequency Estimates table from NOAA Atlas 14 for a point in central Ohio (N 40.275°, W 82.619°) lists a 6-hr., 100-yr. value of 4.32 inches and a 24-hr., 100-yr value of 5.62 inches. These values are approximately 1.6 times larger than the values used to develop the Maricopa County 1.0-6.0 inch average rainfall scale (2.64" and 3.55"). Multiplying 1.6 times 6.0 gives an average rainfall scale maximum of 9.6 inches, which if applied to the chart should produce similar results and cover the range of storms experienced in central Ohio.

CONCLUSIONS

TABLE 2

Summary of Storm Ratings

Storm	Location	Above	Discharge (cfs)	Ave. Rainfall (in.)	Max. Measured Rainfall (in.)	Duration (hours)	Area (mi^2)	SI	MCS^2I
Jul. 18, 2015	Wickenburg	Morristown	15,600	1.97	5.00	3.0	461.0	7.2	**7.3**
Sep. 8, 2014	Urban Phoneix	N/A	N/A	2.51	5.12	6.0	1,953.0	8.8	**8.8**
Aug. 19, 2014	New River	Carefree Highway	39,300	3.07	4.69	4.5	152.0	6.7	**8.1**
	Skunk Creek	Carefree Highway	18,700	2.66	3.46	5.0	49.0	5.3	**7.7**
Aug. 12, 2014	S. Phoenix, Laveen	N/A	N/A	3.31	2.94	2.0	50.4	5.7	**8.3**
Jul. 31, 2012	Anthem	Carefree Highway	6,500	1.53	5.02	1.5	19.2	4.0	**7.2**
Dec. 29, 2010	NRSCCC	USCOE Dams	N/A	1.30	1.81	16.0	459.0	6.3	**6.3**
Aug. 27, 2010	Vekol Wash	Vekol Wash Gage	10,100	1.90	3.83	3.0	133.0	6.3	**7.3**
Jan. 21, 2010	New River	New R. Fire Gage	≈15,000	5.40	7.56	27.0	64.0	6.6	**8.4**
	Cave Creek	Spur Cross Gage	13,560	4.40	5.75	27.0	72.0	6.3	**7.8**
	Tiger Wash	Tiger Wash Gage	2,400	3.10	5.75	18.0	88.6	5.8	**7.2**
	Urban Phoenix	N/A	N/A	1.70	3.98	24.0	1,900.0	7.8	**7.7**
	NRSCCC	USCOE Dams	N/A	4.20	7.56	27.0	459.0	7.8	**7.4**
	Sols Wash	Matthie Gage	690	2.50	3.27	21.0	113.0	5.4	**6.6**
Aug. 25, 2008	Sols Wash	Matthie Gage	645	1.30	2.91	2.5	113.0	5.8	**7.1**
Aug. 7, 2008	Rainbow Wash	Rainbow Wash Gage	735	1.10	1.14	2.5	18.2	3.6	**6.7**
Jul. 10, 2008	Buckhorn-Mesa	N/A	N/A	1.70	2.72	2.0	31.0	4.7	**7.2**
Jan. 27, 2008	New River	New R. Fire Gage	5,910	3.60	4.40	18.0	64.0	5.8	**7.5**
Dec. 1, 2007	New River	New R. Fire Gage	5,270	5.40	6.10	36.0	64.0	6.1	**8.1**
	Cave Creek	Spur Cross Gage	6,630	4.00	6.06	36.0	72.0	5.7	**7.1**
Jul. 31, 2007	Cave Creek	Spur Cross Gage	3,425	1.10	2.68	2.5	72.0	5.1	**7.0**
	Tiger Wash	Tiger Wash Gage	1,600	1.60	1.69	2.0	88.6	5.6	**7.4**
Aug. 10, 2005	Vekol Wash	Vekol Wash Gage	2,150	1.50	0.79	1.0	133.0	6.1	**7.3**
Aug. 9, 2005	Rainbow Wash	Rainbow Wash Gage	1,830	1.50	1.89	1.0	18.2	3.9	**7.1**
Aug. 2, 2005	Urban Phoenix	N/A	N/A	1.00	2.64	4.0	1,900.0	8.2	**8.2**

Table 2 above presents the results of all storms analyzed using this method. Storms with less than 1 inch of average areal coverage were excluded, both because it is the lower limit of the method and because storms with lesser rainfall amounts generate little if any runoff from small to medium sized watersheds. MCS^2I values ranged from **6.3** to **8.8**, average rainfall values from 1.0 to 5.4 inches, durations from 1 to 36 hours, and areas from 18 to 1,953 square miles.

The purpose of this exercise was to develop an index that would in simplified terms describe the severity of multiple storm types, that would use three storm parameters as inputs (areal average rainfall, storm duration, and storm or watershed area) and that would give similar results for storms with similar rainfall/duration values regardless of the area covered. This was accomplished using an Excel® chart and an equation to normalize the index. The range of Severity Index values derived from historic storm data fits nicely with the concept of the *Richter Scale*, where **6's** will get our attention, **7's** will likely require some type of response from emergency personnel, and **8's** and above will certainly require a response as life and property are at risk. The Severity Index will be applied to future storms in Maricopa County and used as a basis for comparison for particular watersheds or geographic areas, and in our forecast products to assign expected response to predicted storms. It is hoped that other agencies within the county, and even the state and the nation, might also adopt the use of this method as a means to quickly and simply communicate the concept of storm severity to the general public.

A template file for developing the MCS^2I, which includes the chart, lines and equation solver, is available for download from the Flood Control District of Maricopa County website.

ACKNOWLEDGEMENTS

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