JP2.9 # THE PHOENIX RAINFALL INDEX

Paul M. Iñiguez*
NOAA/National Weather Service, Phoenix, AZ

1. INTRODUCTION

Like many other large western cities, Phoenix has a database of daily weather observations, including precipitation, from a single observing station which is deemed as the "official" observations for the entire metropolitan area. From its inception late in the 20th century, the "official" observation station for Phoenix has been situated near the center of the city. According to the NOAA/National Climatic Data Center Website, when daily observations began in 1895, the observing station operated by the U.S. Army Signal Service was located at the corner of Center and Washington Streets in downtown Phoenix (Climate of Phoenix, 1993). In 1901, the office moved to the southwest corner of 1st Avenue and Adams Street. Relocation occurred in March 1913, when observations were recorded at the corner of 1st Avenue and Van Buren Street. Another move occurred in 1916, this time to 2nd Avenue and Van Buren Street. Eight years later, the observing station moved to 2nd Avenue and Monroe Street. The observing station finally settled into a more permanent location when it moved to the recently opened Sky Harbor Airport (KPHX) in 1935. The observing station remains on the grounds of Sky Harbor Airport to this day. A map depicting these station locations can be seen in Figure 1.

The population and area of the Phoenix Metropolitan Area (PMA) have increased significantly during the period of daily observations. According to the City of Phoenix's Website, the population of the Phoenix area in 1900 was near 28,000. Cities that would eventually fold into an endless stretch of homes, businesses, and roadways such as Apache Junction, Avondale, Gilbert, Glendale, Mesa, Peoria, Scottsdale, Sun City, and Tempe were remote and small locations if they even existed. Today, the population of the PMA is near 4.2 million (U.S. Census Bureau), and spans nearly 50 miles in all directions from the center of the urban mass (total area approximately 5000 km^2). While in 1895 precipitation records were likely representative of the area referred to as Phoenix that is clearly no longer the case. This is especially true during the summer months of July, August, and September, when precipitation is dominated by the North American Monsoon. During these three months the PMA receives roughly 40 percent of its annual precipitation primarily in the form of cold-pool driven thunderstorms. Convection of this type tends to be highly variable both spatially and temporally.

Given the large spatial coverage of the PMA, it is understandable why it is undesirable to have a single rain gage represent the "official" amount of rainfall for the entire PMA. Without question, there are many instances where the official observation station does (does not) observe precipitation while other areas of the PMA do not (do). As shown by Goodrich (2005), the single observation gage at KPHX does not adequately represent the PMA during the winter. In order to rectify this situation, a Phoenix Rainfall Index (PRI) has been created utilizing a pre-existing rain gage mesonet across the PMA. This index gives a better representation of precipitation coverage and intensity across the PMA as opposed to the single-station observation and retains the single-number value ideal for public consumption.

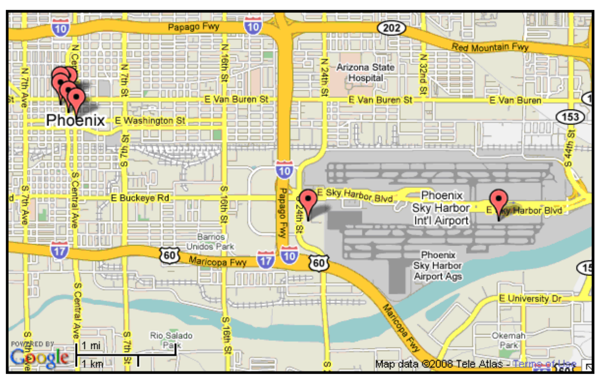

Figure 1. Historical locations of "official" KPHX observations, based on metadata from the NOAA/National Climatic Data Center. Pre-1935 station locations were near the center of Phoenix. After 1935 observations have been recorded at Phoenix Sky Harbor Airport, still considered near the city center.

* *Corresponding author address:* Paul M Iñiguez, National Weather Service, PO Box 52025, Phoenix, AZ 85072; e-mail: paul.iniguez@noaa.gov

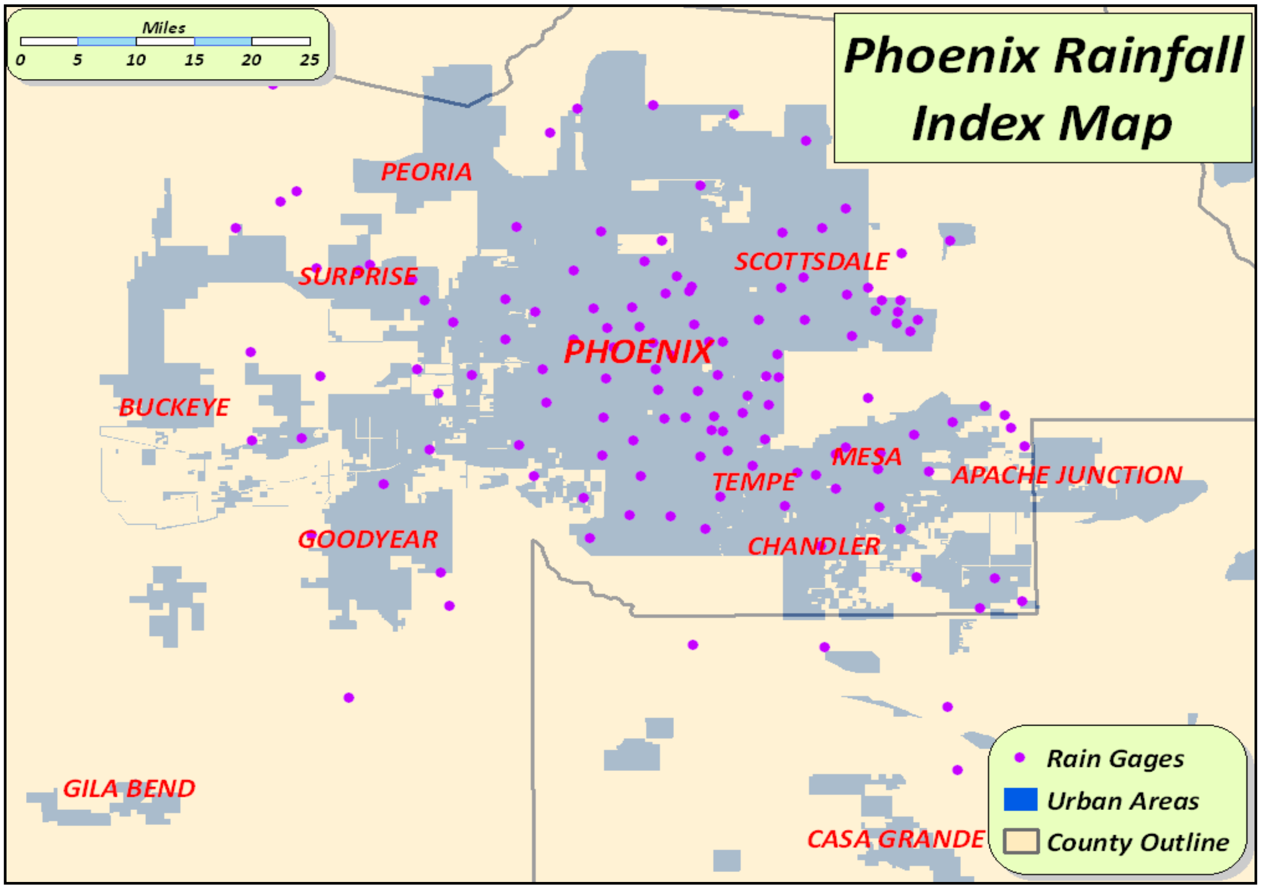

Figure 2. Location of gages (purple dots) to be used in the construction of the Phoenix Rainfall Index in relation to urban boundaries (light blue shaded regions).

2. ANALYSIS

2.1. Data

The Flood Control District of Maricopa County (hereafter FCDMC) is responsible for overseeing the development and implementation of comprehensive flood hazard control measures in Maricopa County. In order to monitor precipitation rates and amounts across Maricopa County, the FCDMC has installed a network of rain gages currently numbering near 300 in and around the area of interest. The tipping-bucket gages measure liquid precipitation in increments of one millimeter (approximately 0.04 inches) at a temporal resolution of five minutes. These data are made available by the FCDMC through its Web site (http://www.fcd.maricopa.gov).

From the full FCDMC network, a smaller subset of rain gages will be used to calculate the PRI for several reasons. First, in order to restrict the PRI to the PMA and not all of Maricopa County, all stations outside of a 1° x 1° box centered on downtown Phoenix will be excluded from analysis. A 1° x 1° box was chosen as it generally contains the vast majority of the PMA as it exists today and includes additional land in which the PMA may expand into during the next several decades. Second, in an effort to establish a (limited) climatology of the PRI, only stations installed prior to 1 July 1998 will be included in the analysis, thus providing a climatology based on 11 years of data (1 July 1998 through 30 June 2008). These two thresholds reduce the number of rain gages for the PRI to 132 (see Figure 2).

2.2. Index Derivation

The goal of the PRI is to indicate in a single index how widespread and intense precipitation was during a calendar day across the PMA. Despite knowledge that the diurnal precipitation pattern for the PMA exhibits a late night peak that straddles two calendar days, the PRI will be calculated on a calendar basis in order to keep the index comparable to other widely reported calendar day precipitation totals. There are two

Table 1. Monthly PRI values, average monthly values, and total annual values (all in inches).

Month	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	AVG
JAN		0.00	0.02	1.99	0.05	0.33	0.43	2.24	0.00	0.57	2.13	0.78
FEB		0.30	0.06	0.76	0.00	3.28	0.76	3.58	0.00	0.35	0.39	0.95
MAR		0.08	2.34	0.86	0.02	0.92	1.01	0.31	1.60	0.78	0.00	0.79
APR		1.08	0.00	0.80	0.06	0.15	1.17	0.24	0.00	0.14	0.00	0.36
MAY		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.03
JUN		0.03	0.17	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.02
JUL	0.32	1.46	0.04	0.60	0.79	0.43	0.34	0.22	0.72	0.44		0.54
AUG	0.34	0.45	0.31	0.33	0.01	0.85	0.13	1.55	0.96	0.12		0.51
SEP	0.39	0.64	0.00	0.00	0.75	0.05	0.50	0.05	0.76	0.02		0.32
OCT	0.54	0.00	3.08	0.02	0.26	0.33	0.80	0.30	0.19	0.00		0.55
NOV	0.25	0.00	0.22	0.10	0.40	0.82	0.67	0.00	0.00	1.55		0.40
DEC	0.41	0.00	0.00	0.67	0.26	0.22	1.62	0.00	0.20	1.18		0.46
SUM	2.25	4.04	6.24	6.13	2.60	7.38	7.43	8.50	4.44	5.15	2.84	5.70

Table 2. Monthly average PRI value and corresponding monthly average precipitation at KPHX based on 1 July 1998 through 30 June 2008 data.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
PRI	0.78	0.95	0.79	0.36	0.03	0.02	0.54	0.51	0.32	0.55	0.40	0.46	5.70
PHX	0.72	0.90	0.85	0.37	0.05	0.04	1.00	0.67	0.38	0.60	0.37	0.49	6.18

primary variables to consider in the derivation of the PRI equation, a spatial coverage term and an intensity term:

$$PRI = \begin{bmatrix} Spatial \\ Coverage \end{bmatrix} \times [Intensity] \quad (1)$$

A simple calculation of what percent of the 132 gages in the PRI network received measurable rainfall will be used to define the spatial coverage term:

$$\begin{bmatrix} Spatial \\ Coverage \end{bmatrix} = \frac{\begin{bmatrix} Number\ of\ Gages \\ w/Measureable\ Rainfall \end{bmatrix}}{[Total\ Number\ of\ Gages]} \quad (2)$$

The intensity term will be defined by the average rainfall per gage in the network:

$$[Intensity] = \frac{\begin{bmatrix} Total\ Measured \\ Precipitation \end{bmatrix}}{[Total\ Number\ of\ Gages]} \quad (3)$$

Combining equations (1), (2), and (3) yields the equation for the PRI (4). Units for the PRI are inches gage^{-1}, indicative that the PRI is an averaging index. The PRI is reported in inches as this is the unit in which the public is accustomed to receiving precipitation data.

$$PRI = \frac{\begin{bmatrix} Number\ of\ Gages \\ w/Measureable\ Rainfall \end{bmatrix} \times \begin{bmatrix} Total\ Measured \\ Precipitation \end{bmatrix}}{\begin{bmatrix} Total\ Number \\ of\ Gages \end{bmatrix}^2} \quad (4)$$

2.3. PRI Climatology

In order for the PRI to be truly useful, a descriptive climatology and set of records of the index must be created to provide a point of reference. Utilizing daily precipitation data for each of the 132 gages in the sub-network, the PRI was calculated for each day from 1 July 1998 through 30 June 2008. From the daily PRI data, monthly values were calculated (Table 1). Overall the monthly PRI values closely resemble the monthly averages at KPHX with both having peaks in February, July, and October and troughs in May-June, September, and December (Table 2). Differences noted in the PRI values include a more bell-shaped distribution during winter (December-March) and a more muted spike with the onset of the North American Monsoon in July. Annual totals are comparable.

Normal daily values for the PRI were calculated in a manner nearly identical to the method utilized by the NOAA/National Climatic Data Center. This process involves a sophisticated interpolation method (cubic spline) of the daily average PRI values by month (Greville, 1970).

Table 3. Daily normal PRI values (inches).

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.02	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01
2	0.02	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01
3	0.02	0.03	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.01
4	0.02	0.03	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.01
5	0.02	0.03	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.01
6	0.02	0.03	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.01
7	0.02	0.03	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.01	0.01
8	0.02	0.03	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.01	0.01
9	0.02	0.03	0.03	0.01	0.00	0.00	0.01	0.02	0.01	0.02	0.01	0.01
10	0.02	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
11	0.02	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
12	0.02	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
13	0.02	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
14	0.02	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
15	0.03	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
16	0.03	0.03	0.03	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01
17	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.02
18	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.02
19	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.02
20	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.01	0.01	0.02	0.01	0.02
21	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.01	0.01	0.02	0.01	0.02
22	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.01	0.01	0.02	0.01	0.02
23	0.03	0.03	0.02	0.01	0.00	0.00	0.02	0.01	0.01	0.02	0.01	0.02
24	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
25	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
26	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
27	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
28	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
29	0.03	0.03	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
30	0.03		0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.02
31	0.03		0.02		0.00		0.02	0.01		0.02		0.02

This interpolation method ensures that the all twelve data points are included in the resultant function. Daily interpolated values are then rounded to the nearest hundredth of an inch (Table 3). Realistically, daily normal precipitation values hold little value individually as the notion that a “normal” amount of rain should fall on a specific day is absurd. The utility of daily normal values arises in their aggregation over time, allowing comparison of observed precipitation to normal precipitation values.

Given the relatively short dataset the PRI is based on, individual daily record/extreme values have not been computed. However, the greatest daily PRI values for each month have been compiled for informative/inquisitive purposes (Table 4). The associated KPHX values have also been included for comparison.

Table 4. Greatest daily PRI for each month (1 July 1998 through 30 June 2008) and corresponding observed precipitation from KPHX (inches).

Month	PRI	Date	KPHX
JAN	1.32	27 JAN 2008	0.87
FEB	1.54	13 FEB 2003	1.42
MAR	1.39	11 MAR 2006	1.40
APR	1.14	2 APR 2004	0.68
MAY	0.15	23 MAY 2008	0.12
JUN	0.06	28 JUN 2000	0.01
JUL	0.58	14 JUL 1999	1.24
AUG	1.00	2 AUG 2005	0.59
SEP	0.50	2 SEP 2006	0.45
OCT	0.76	27 OCT 2000	0.98
NOV	1.55	30 NOV 2007	1.23
DEC	0.69	29 DEC 2004	0.45

2.4. Applicability

Figure 3 displays the average spatial coverage term, ***S***, by month of the PRI for all non-zero PRI days. Not surprisingly, the spatial coverage is highest in February when precipitation is exclusively delivered through large-scale synoptic systems. ***S*** displays a minimum from May through September, months that are characterized by excessive heat leading to precipitation events that are strongly convective driven.

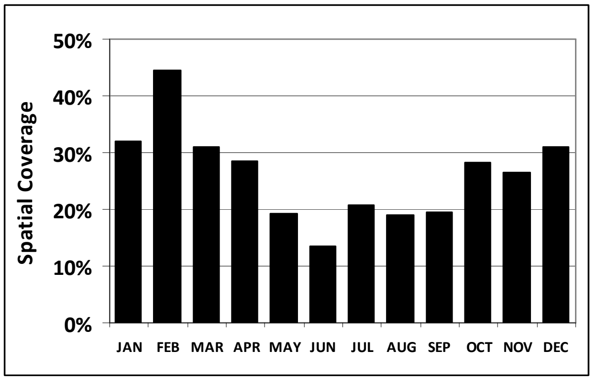

Figure 3. Average spatial coverage term, ***S***, of the PRI by month for non-zero PRI days.

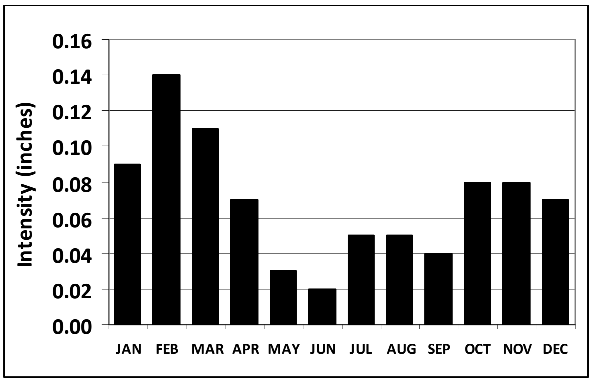

Figure 4. Average intensity term, ***I***, of the PRI by month for non-zero PRI days.

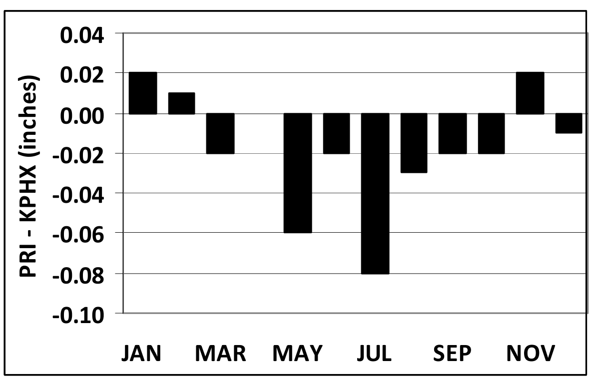

Figure 5. PRI minus KPHX average per month when the spatial term (***S***) of the PRI equation (Eqn. 3) is greater than or equal to 0.07 (the long-term mean). KPHX represents an over-estimation of precipitation across the city for most months with the difference strongest in May and July.

The average intensity, ***I***, of the PRI by month indicates that, like ***S***, intensity is greatest when precipitation is primarily from large-scale synoptic systems (Fig. 4).

To demonstrate the usefulness of the PRI, an analysis of PRI versus KPHX data was performed. It was found that ***S*** throughout the dataset displayed a Poisson distribution with a mean (λ) of 0.07. For all days when ***S*** $\geq$ 0.07, the difference between the PRI and KPHX was calculated and averaged by month (Fig. 5). It was found that on average KPHX represents an over-estimation of precipitation across the PMA, with the strongest differences noted in May, when rain can be widespread (synoptically driven) but exhibit strong convective activity within the larger system, and July, when early monsoon-season thunderstorms can be sporadic due to the relatively dry boundary layer. Overall Fig. 5 demonstrates that, due to the aerial averaging, the PRI tends to mute convective rainfall while accentuating widespread synoptic rainfall events in the winter. This supports the goal of the PRI – to better represent precipitation across the entire PMA as opposed to the current single-gage method.

To showcase the applicability of the PRI, two brief examples are provided. The first example is from a convective rainfall event on 22 July 1998. On this date, KPHX observed 1.02” of rain. However, the PRI was only 0.01”. A spatial interpolation of the rainfall data from all 132 gages indicates that this rainfall was isolated, thus KPHX was not representative of a majority of the PMA (Fig. 6). A second convective event on 24 August 2006 demonstrates when KPHX “misses” rain. On this date, there was somewhat widespread and heavy precipitation across the PMA, stretching from the north-central PMA to the southeast (Fig. 7). KPHX observed 0.01” while the PRI was 0.31”. Clearly the KPHX observation under-represented precipitation for this event.

2.5. Dissemination

All data related to the PRI, including normals, extremes, and historical data, will be made readily available at no charge through the NOAA/National Weather Service Phoenix, AZ office’s Website (http://www.wrh.noaa.gov/psr/PRI/). The PRI will be calculated on a daily basis and posted to the Website shortly after 12 AM LST. Dissemination procedures are expected to be in place by June 2009. Through time additional tools will likely be developed, including mapping features.

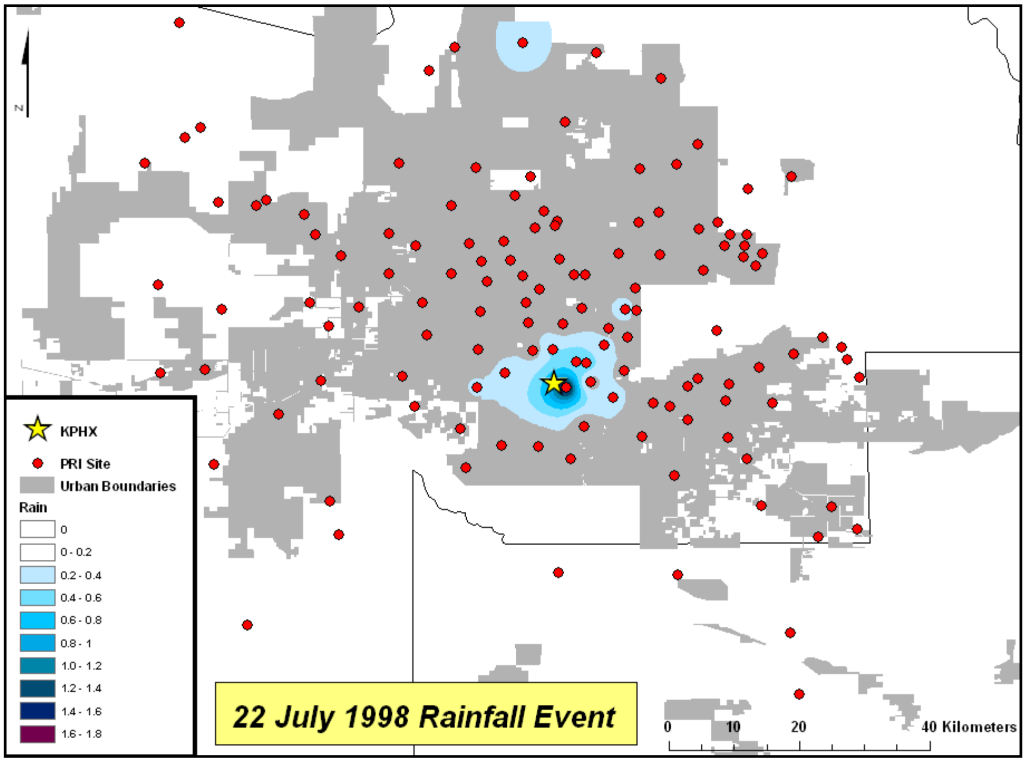

Figure 6. 22 July 1998 convective rain event. In this example, KPHX observed 1.02" while the PRI was 0.01". It is clear that precipitation, while of moderate intensity, was very isolated.

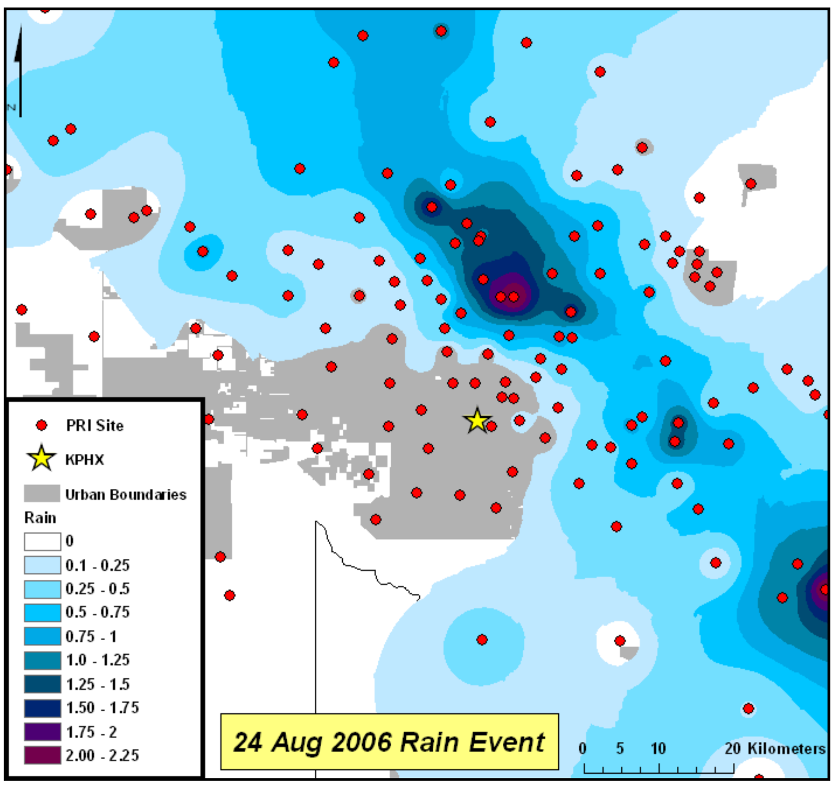

Figure 7. 24 August 2006 convective rain event. In this example, KPHX observed 0.01" of rain while the PRI was 0.31". Obviously precipitation was more widespread and heavy than the KPHX observation would indicate.

3. CONCLUSION

It has become obvious that using a single observation station to represent precipitation for a large city such as the PMA, which covers 5000 km^2, has become inadequate. Given the existence of a relatively high density precipitation network across the PMA, a precipitation index was created which better conveys the spatial coverage and intensity of precipitation across the city. It was found that the Phoenix Rainfall Index (PRI) correlates well with observations at the official observation station for the PMA (Phoenix Sky Harbor Airport – KPHX). Data for the PRI, including normals, historical values, monthly extremes, and daily values, will be disseminated to the local weather and climate enterprise at no additional charge through the NOAA/National Weather Service Phoenix, AZ office's Website.

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