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RESEARCH ARTICLE

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Tracking precipitation patterns across a western U.S. metropolitan area using volunteer observers: RainLog.Org

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Abstract

The southwestern United States experiences extreme hydroclimatic variability, including intense but localized monsoon thunderstorms, tropical storms, and winter storms, resulting in complex and variable patterns of precipitation over space and time. Official gauges associated with long-term monitoring networks are sparsely distributed throughout the region and are unable to capture the spatial complexity and variability of these precipitation patterns. The RainLog program, a volunteer precipitation monitoring program, was started in southern Arizona in 2005 to leverage enthusiasm among non-scientists around weather, water, and climate to address the gaps in official monitoring networks. An examination of the portion of the dataset that spans the Tucson metropolitan area illustrates the opportunities and challenges in using volunteer data to track precipitation. We compare near-complete records to an official observation to highlight how the broader RainLog network supports characterizing hydroclimatic variability over the period of record. We also examine several case study events drawn from metrics of network variability that represent different forms of hydroclimatic extremes. We find that in most cases the RainLog network captures a range of precipitation values that were notably different than the single value recorded at the official observing site, adding substantial value in recording and reconstructing past extreme precipitation events. This work highlights how volunteer citizen science precipitation monitoring networks can provide critical data for tracking precipitation variability and changes, although are only one complementary piece of coherent, long-term hydroclimatic monitoring.

KEYWORDS

citizen science, hydroclimate, precipitation monitoring

1 | INTRODUCTION

The southwestern United States is characterized by extreme variability in precipitation patterns tied to sharp topographic gradients and highly spatially variable convective thunderstorms that occur during the summer monsoon (Green and Sellers, 1964; Sheppard *et al*., 2002; Griffiths *et al*., 2009). This region is also expected to experience greater hydroclimatic variability both in the form of increasing storm intensity as well as longer dry spells and increasing drought intensity (Janssen *et al*., 2014; Prein *et al*., 2016; Gonzalez *et al*., 2018). Precipitation observations are critical to track these hydroclimatic changes. Official, long-term precipitation monitoring networks are relatively sparse across the semi-arid west (Osborn *et al*., 1979; Diamond *et al*., 2013). The resulting gaps in the sensor network often miss highly localized convective thunderstorms during the monsoon or overestimate regional totals if a highly localized storm occurs over one of the official observations. These gaps and overestimations hamper efforts by researchers, decision makers, and planners to adequately track changes in hydroclimatic variability over space and time across the Southwest (Comrie and Broyles, 2002; Syed *et al*., 2003; Garcia *et al*., 2008; Demaria *et al*., 2019).

Accurate precipitation monitoring is important for understanding flood processes (Saharia *et al*., 2017; Syed *et al*., 2003), planning and managing urban stormwater systems (Pyke *et al*., 2011; Barbosa *et al*., 2012), anticipating and managing ecosystem impacts like invasive species (Olsson *et al*., 2012), and capitalizing on precipitation for water resources management like water harvesting (An *et al*., 2015; Campisano *et al*., 2017). Engaging the public in assisting with data collection offers multiple benefits including increasing data density, as well as educational opportunities for the participants who contribute these data (Muller *et al*., 2015). "Citizen science" efforts organized around collecting environmental monitoring data have grown over the past decade in the United States. These efforts include the CoCoRAHS program (Reges *et al*., 2016), which specifically targets precipitation monitoring, as well as other efforts that focus on phenological data (Crimmins *et al*., 2017), migrating birds (Cooper *et al*., 2014), and urban heat islands (Chapman *et al*., 2016).

In Arizona, "RainLog.Org" was started in 2005 to address precipitation monitoring gaps (Rupprecht, 2009). Unique features of the RainLog network that differentiate it from other efforts include the ease of registration, no need for formal training or long-term commitment, and an ability to record and compare records on an interactive map without the need to sign up for a proprietary monitoring system or establish a reliable network connection to a personal weather station.

The variability of participation, participant training, and instrument precision, all pose significant data quality challenges for citizen science observation networks, but careful analyses can extract unique signals from these datasets. These observations are important in their ability to fill gaps in our current observational networks and constitute a valuable resource that could be used for climate service and adaptation planning activities, without significant additional resource investments (Buytaert *et al*., 2016). The value of these data to assist with planning and decision-making require that they be well understood as a standalone dataset—including opportunities and limitations for their use, especially when analysed in comparison to other official, regional datasets. Using these data in conjunction with, or in comparison to, official networks has the potential to improve our understanding of fine-scale hydroclimatic variability and our ability to respond to extremes. This, in turn, will support planning and decision making that benefit from increasing data density.

In this paper, we demonstrate the value the RainLog network adds in tracking precipitation patterns across the Tucson, Arizona metropolitan area beyond the single, official monitoring station located at Tucson International Airport. First, we compare network-wide seasonal precipitation totals from nearly complete records in the Tucson area to the official observation for Tucson over the study period. Second, we examine spatial precipitation patterns depicted by all observations in the RainLog network using four case studies that represent iconic weather events for the region (synoptic-scale low-pressure systems, tropical storms, and summer thunderstorms).

The paper is organized into the following sections. Section 2 provides a history of the development and implementation of the RainLog program. Section 3 describes the methods employed in the present study focusing on the Tucson metropolitan region. Section 4 presents and discusses the results from the study including a description of observation frequency over the study period, seasonal precipitation summaries for nearly complete gauge records, and a presentation of the case studies. Major findings and conclusions are presented in section 5.

1.1 | Data: Overview of RainLog network

The RainLog program was established in 2005 by the Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA, a National Science Foundation Science and Technology Center) at the University of Arizona (UArizona) in partnership with UArizona Cooperative Extension. The intention of the effort was to engage the general public in collecting and posting near-real time precipitation observations that could be used for drought monitoring, irrigation scheduling, and general research purposes related to hydrology and climatology across Arizona (Rupprecht, 2009). The hub of the effort was the development of the RainLog website which utilized a simple account management and mapping system where participants register a gauge and report entries each morning, ideally at 0700 LST (UTC-7), of total precipitation observed over the previous 24-hr period. Observers can flag entries (e.g., "Trace" or "Snow") and enter comments to report other conditions (e.g., storm impacts or weather observations) and set data quality flags when an observation represents a multi-day total (e.g., when reading gauge after being absent for several days). Observations then post to a database and are displayed on maps available on the front page of the website, creating a visualization of recent rainfall across the region. Maps of past days and multi-day totals can also be accessed on the site for applications like drought monitoring that require reports at longer timescales (Figure 1). A recently developed application programming interface (API) allows users to access raw RainLog data and conduct their own analyses (https://rainlog.org/help/api).

RainLog data have been used for different activities across the region including characterizing monsoon season rainfall in local media reports (Arizona Daily Star, 2020) and local climate summaries (NOAA, 2019a), and as a data source in watershed management plans (NexGen Engineering, 2017). Dense observations in urban areas like Tucson have made RainLog a useful source of data to track fine-scale precipitation patterns important for understanding stormwater runoff (Gupta, 2020). Growing interest in rainwater harvesting across the region has also led to use of RainLog data to track local precipitation and water harvesting potential (e.g., Daly, 2014; City of Tucson, 2020).

Recruitment and training of participants has largely been informal since the establishment of the network. Marketing for the program was and continues to be conducted through media stories (e.g., Hammond, 2016), UArizona Cooperative Extension programs like the Master Gardener program (e.g., Gruenhagen, 2017), and informally through word of mouth among participants. Participants are encouraged but not required to use a standard, wedge-shaped gauge and indicate the gauge that they are using with their observations when registering. Wedge-shaped gauges were distributed through several early recruiting efforts because of their relative low cost and ease of use. This lack of standardization introduces potential errors in observations across different

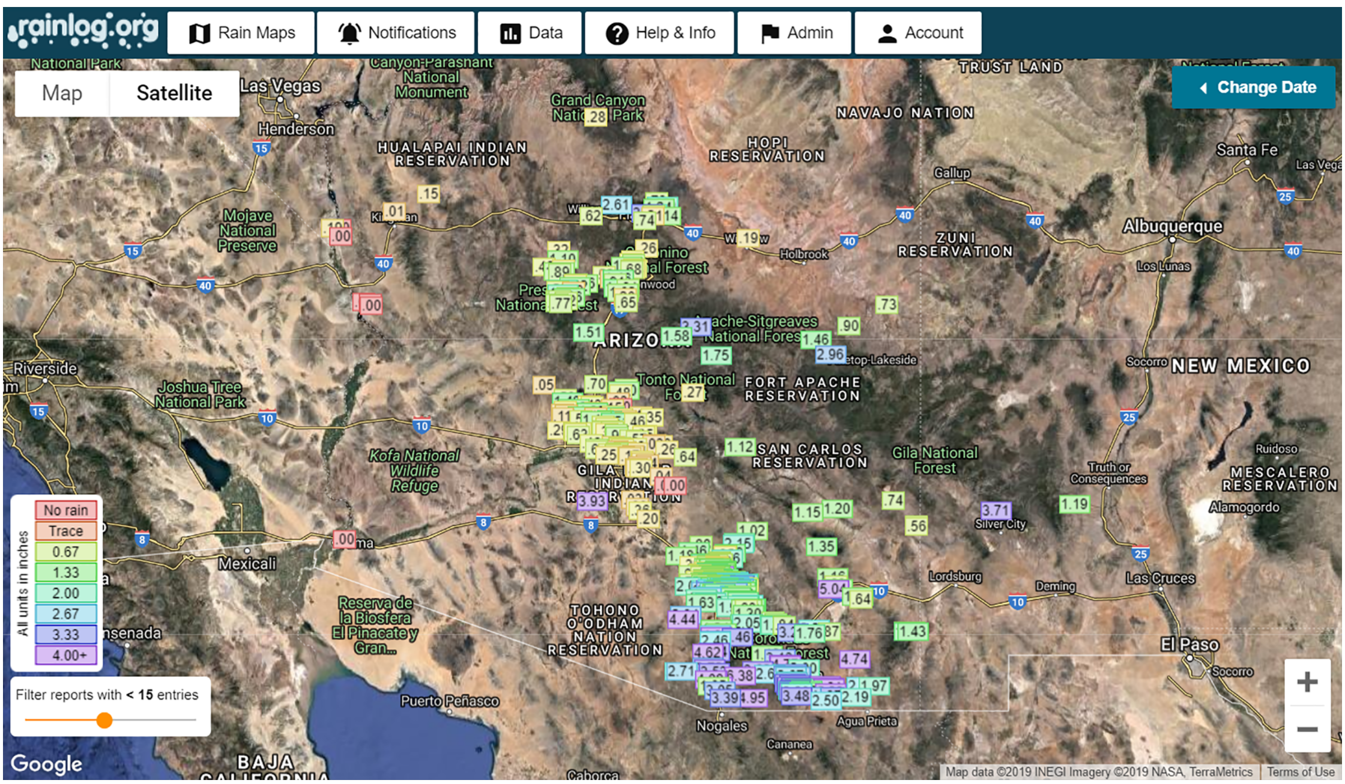


FIGURE 1 August 2019 total precipitation observations logged by RainLog participants (site displays values in inches) [Colour figure can be viewed at wileyonlinelibrary.com]

gauge types, but reduces barriers to participation and allows participants to use their existing gauges if they are already home weather enthusiasts. Previous studies have determined that differences among simple, small orifice gauges are typically small, though, and track well with standard gauges in official networks (Huff, 1955; Snow and Harley, 1988). Self-reported gauge metadata are part of each observation and stored in the database and can be used to filter data or assess potential errors related to gauge type. This informal approach yields a rich dataset of precipitation observations, but is a mix of consistent, long-term observations and records that are much more ephemeral and closer to a "crowdsourced" snapshot of precipitation events. These aspects of the network create challenges in using the data in more traditional ways (e.g., evaluating trends over time), but can be used to complement existing, sparse, official networks.

In the summer of 2005, the RainLog website came online and started accepting registrations and observations. Participants registered close to 50 gauges by the end of the year, mostly across southeast Arizona, extending from Tucson to Sierra Vista. By the end of 2018, 4,237 gauges had been registered in the RainLog system, resulting in over 2.6 million precipitation observations. Given the Arizona-centred nature of the network, 89% these gauges were located in Arizona (3,809), though several other states including Texas (35), California (33), and New Mexico (20) had numerous gauges created over the 2005–2018 period.

A challenge with many citizen science programs is retaining participants once they have registered for a program (West and Pateman, 2016). This is especially important for precipitation observations, where consistent reporting of zeros results in a complete record at a gauge location. Of the 4,237 gauges registered in RainLog, 68% submitted more than two observations. This number decreases to 35% when considering the number of gauges with 200 or more observations.

Within Arizona, most of the registered gauges with at least two observations are clustered in and near the large, metropolitan areas of Tucson and Phoenix. Seven-hundred and fifty-six gauges are registered within the city of Tucson, constituting over 26% of all gauges ($n \geq 2$ observations) in the RainLog database. This yields a gauge density of around one gauge for every square kilometre within the city of Tucson. However, some smaller towns and cities have a substantial number of registered gauges. Flagstaff, for example, has 47 gauges registered within the city limits (27 with more than 100 observations) and is only 121 km^2 in area, yielding a gauge density of around 1 gauge for every 3 km^2. These observations could be a valuable resource for smaller communities that lack extensive official precipitation monitoring networks to support local planning efforts related to flood control and water resources.

2 | STUDY AREA AND METHODS: ASSESSING PRECIPITATION VARIABILITY ACROSS THE TUCSON, ARIZONA METROPOLITAN REGION

To better understand some of the strengths and weaknesses of observations within the RainLog database, we focused on the area with the highest density of records: the Tucson Metropolitan area. This area in southeastern Arizona in the southwest United States has a population of over 500,000 for the city of Tucson and over 1,000,000 when including surrounding cities and town within the metropolitan statistical area (University of Arizona Economic and Business Research Center, 2019). The area sits in a valley at 750 m elevation between several mountain ranges that rise to over 2,700 m. The climate of the region is characterized as "Hot Desert" within the Köppen classification system (Beck *et al*., 2018) and experiences hot summers and temperate winters. Precipitation typically occurs in two distinct seasons with about 40% of the total precipitation occurring in the cool season (November–April) associated with synoptic-scale low-pressure systems and 60% in the warm season (May–October) associated with convective thunderstorms occurring during the summer monsoon and decaying tropical storms in the early fall (Sheppard *et al*., 2002).

Precipitation monitoring networks across the metropolitan area include a tipping bucket gauge network operated by the Pima County Flood Control District, several NOAA Cooperative observer sites, and a growing network of CoCoRaHS participants contributing observations that become part of the official Global Historical Climate Network database (Reges *et al*., 2016). The observing site at the Tucson International Airport (TIA) is used as the official report for Tucson in characterizing precipitation totals for the day and at longer timescales (seasonal to annual totals) by the media (Arizona Daily Star, 2019a), the local National Weather Service Office (NOAA, 2019a) and in characterizing and tracking local climate (Ethen, 2011).

Historical observations made at TIA from 2007 to 2018 were extracted from the RCC-ACIS (2019) database and represent midnight to midnight totals while RainLog observations typically represent 24 hr totals ending at 0700 LST. This can create issues in comparing totals on specific days when precipitation is observed after midnight, but has minimal impact in comparing totals over longer time periods. For this study, we explore how

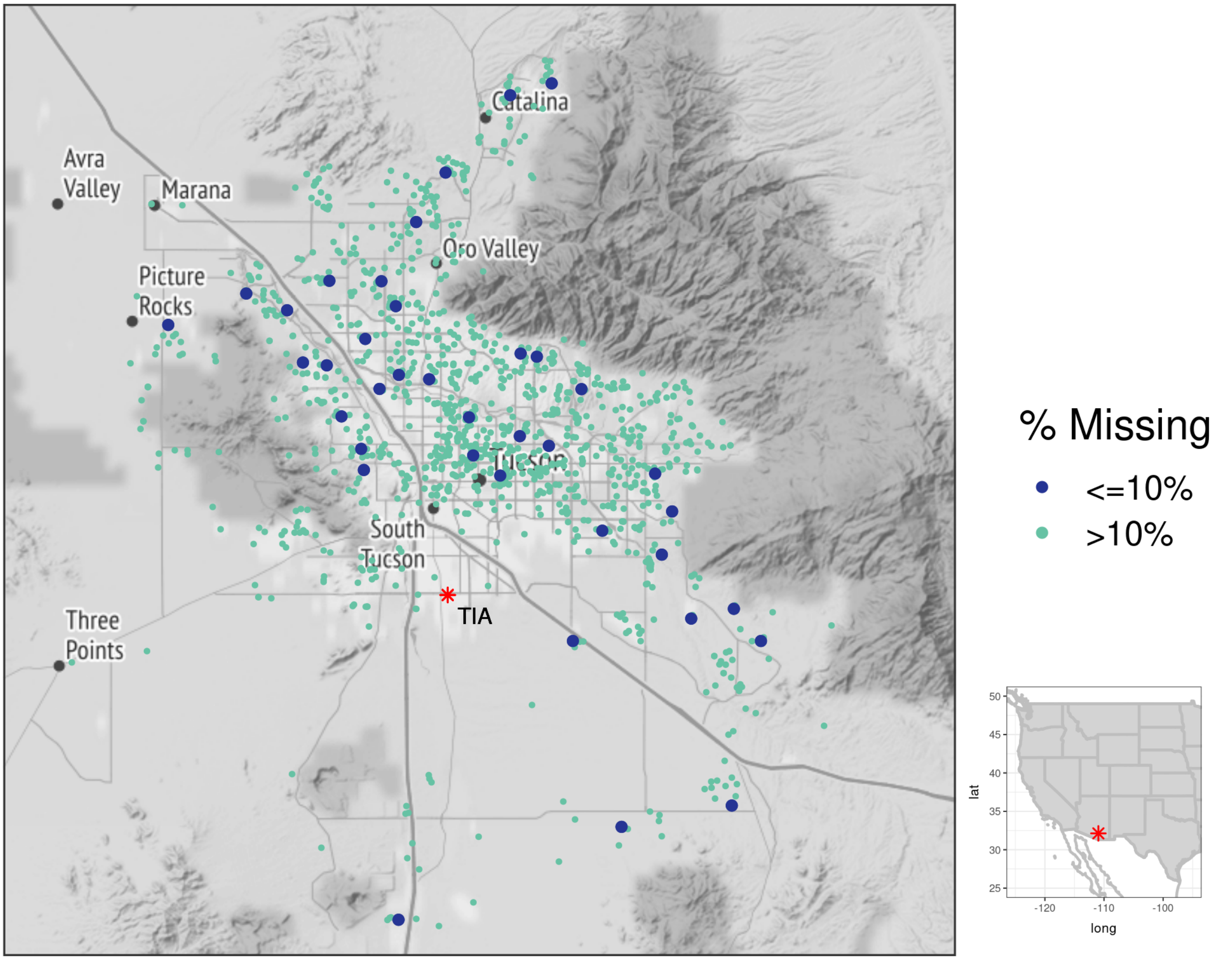


FIGURE 2 RainLog gauges in Tucson metropolitan area, Arizona in the southwestern United States. Light green dots represent gauges with more than 10% observations missing over the 2007–2018 study period, while blue dots represent gauges with near-complete records (≤10% missing). The red asterisk indicates the location of the Tucson International Airport (TIA) and official meteorological monitoring station for the region [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation patterns characterized by the RainLog network compare to and add value to the official observations collected at TIA, since it is typically used as the single location to represent Tucson weather and climate. Future work will evaluate how the RainLog network compares to other networks in the region.

All observations made within a 40 km radius of the geographic centre of the city of Tucson between 2007 and 2018 were queried from the RainLog database. This query produced 933,453 precipitation observations made at over 1,200 gauges (Figure 2). The mean elevation of these gauges is 800 m above sea level (SD = 80 m), similar to the elevation at TIA (776 m). Around 80% of these gauges were wedge-type rain gauges. The remaining gauges were a mix of simple cylinder type, funnel catch with overflow and some tipping buckets tied to home weather stations.

Observations were screened in several steps. The first data quality screen was performed using the self-reported data quality flag attached to each observation. Only observations with self-reported "Good" and "Trace" quality flags were retained for further analysis. A sort of observations in decreasing order revealed numerous erroneous entries with daily totals exceeding 254 mm and in one instance 2,463 mm. These appear to be errors with the position of the decimal point which is a common error in other volunteer networks (Daly *et al.*, 2007). Twenty-five observations with daily totals greater than 133 mm, the expected 1 in 1,000 year 24-hr total precipitation for the Tucson International Airport precipitation gauge (NOAA, 2019b), were removed from the analysis dataset.

Multiday-totals are also a known issue in volunteer precipitation monitoring networks. RainLog participants are instructed to set the observation data-quality flag on multi-day totals (accumulations observed in the gauge that represent multiple days rather than the current day's total) to "poor" and note the period the cumulative total represents in the remarks field. A word search of the "Remarks" field yielded numerous observations with the terms "cumulative" and "accumulated" in the remarks field even with the data quality field set to "good." These observations were removed along with others that had the terms "gone," "out of town," "vacation," "trip" in the remarks field. This screening yielded 538 questionable observations that were removed from the working dataset. Overall, 14,081 records (1.5%) were removed through the data quality screening steps, resulting in 919,372 observations for subsequent analyses.

3 | RESULTS AND DISCUSSION

The screened RainLog observations for the Tucson metropolitan area over the 2007–2018 period provide a large sample of observations to explore the strengths and weaknesses of the network. These include a high-density collection of observations that can portray localized heavy rain events in detail, but is limited by numerous missing observations at some gauges and short records. This analysis provides an initial characterization of the RainLog dataset to help inform how it can best be leveraged to support future monitoring and planning efforts and can serve as an example to other volunteer, hydroclimatic monitoring efforts. The following section of results and discussion details characteristics of record length at gauges, observation frequency, a comparison of near-complete records to the official TIA observation and several case study events of heavy rainfall across the Tucson region.

3.1 | Observation frequency and network characteristics

In the Tucson metropolitan area, the RainLog network has grown in registered gauges, but has also experienced increasing variability in the number of observations entered each day. Figure 3 shows the number of observations made in the Tucson area on each day over the 2007–2018 time period. The dots represent the days with the most (blue) and least (red) number of observations within a given year. The fact that there are wide swings in the number of observations each day within a year indicates that many observers are not making consistent reports, especially reports of zero precipitation, throughout the year. The minimum number of daily observations (red dots) climbed steadily from 94 in 2007 to a maximum of 217 in 2012. The maximum number of daily observations (blue dots) has steadily climbed each year to a maximum of 378 in 2018. It is not clear why the minimum number of daily observations fell from 2012 through 2017 despite the maximum number of daily observations remaining constant during this period. There was a spread of 200 observations between the minimum and maximum days in 2018 alone, with 178 observations made on April 29 and 378 on October 13.

The swings in daily observation rate can be linked to a strong bias in many observers reporting only on precipitation days, especially ones with widespread, heavy amounts. Figure 4 shows the number of daily observations versus the median precipitation observed across the whole Tucson area. The colour ramp further indicates the percentage of observations within the network that were greater than zero. The highest reporting rates are observed on days with large median precipitation amounts and a high percentage of non-zero observations. For example, the day with the most observations in the whole study period occurred on October 13, 2018 with 378 records entered, 98% with non-zero precipitation and

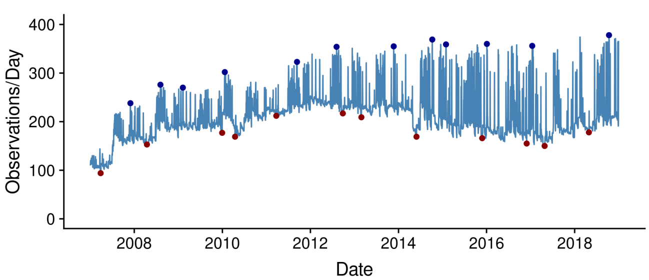


FIGURE 3 Number of observations submitted to RainLog network in Tucson metropolitan area each day from 2007 to 2018. Blue and red dots indicate day of maximum and minimum number of observations respectively in each year [Colour figure can be viewed at wileyonlinelibrary.com]

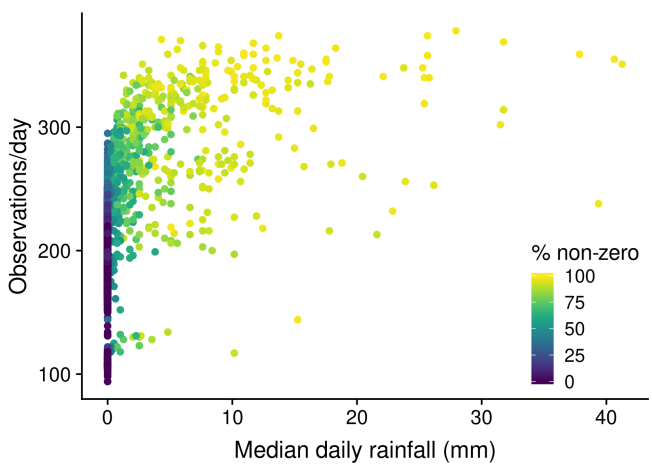
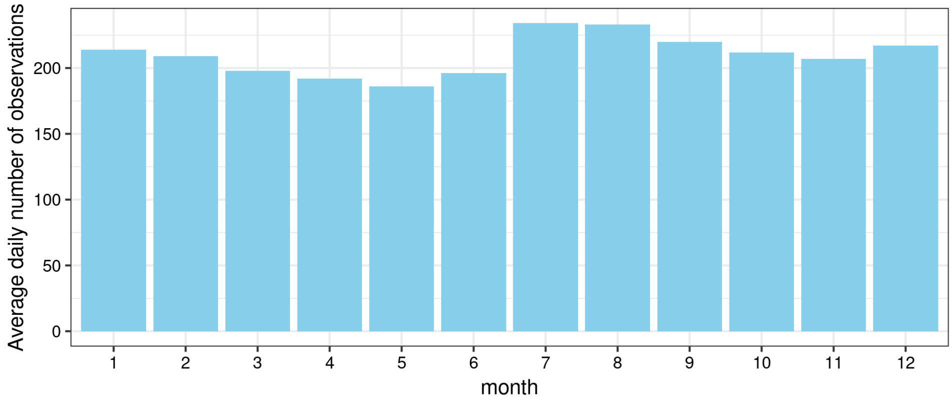


FIGURE 4 Median daily rain event size across the RainLog network versus the number of observations entered on that day. The colour scale represents the percentage of observations that were greater than zero for the day [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Average daily number of observations by month from the RainLog network in the Tucson metropolitan area (2007–2018) [Colour figure can be viewed at wileyonlinelibrary.com]



66% with precipitation amounts greater than 25 mm—an enthusiastic response to a widespread, heavy precipitation event. All days with more than 300 observations had median precipitation amounts greater than zero and more than half of the observers reporting precipitation.

Since the reporting rate is tied to precipitation events, there is also a distinct seasonality in the number of observations that closely matches Tucson's seasonal-transitional climate (Sheppard *et al*., 2002). The highest daily average number of observations occurs in July and August, at the height of the summer monsoon, closely followed by December and January, align with winter storm activity (Figure 5). Observation activity drops off slightly during the dry months of April through May when precipitation events are less frequent. The observation frequency in those months is supported by a subset of observers entering zeroes into the record on days without precipitation. Observer bias towards reporting during precipitation events and especially during the monsoon offers the opportunity to characterize fine-scale precipitation patterns associated with summer thunderstorms but produces a challenge in using any of the locations for long-term climate monitoring. We examine gauges with near-complete records first and then network-wide variability to capitalize on different aspects of the dataset in characterizing precipitation patterns across the Tucson metropolitan areas.

3.2 | Using gauges with near-complete records to characterize regional precipitation variability

We evaluate 39 gauges with less than 10% missing reports for the 2007–2018 period. As shown in Figure 2, these gauges are relatively evenly distributed across the Tucson metropolitan area. These gauges represent observers who joined near when the network was established and have maintained near-complete records up to present. There are other gauges with near-complete records, but for shorter periods within the study period. Figure 6a shows the range of yearly average RainLog observations (boxplot) relative to the yearly average at TIA (asterisk) for the November–April cool season and the May–October warm season. Both the median of RainLog observations and the TIA cool season precipitation for 2007–2018 are below the 1981–2010 "Climate Normals" period value of 110 mm. The upper end of the third quartile on the cool season boxplot is at the climate normal indicating that 75% (25%) of RainLog participants observed below (above) average precipitation over this period. Overall, the TIA 2007–2018 average total precipitation value of 79 mm was on the dry side of all RainLog observations, falling in the lowest quartile.

The median of warm season (May–October) RainLog observations is close to the TIA normal, as is the 2007–2018 TIA average seasonal total precipitation. The interquartile range of RainLog observations is larger for the warm season, extending tens of millimetres above and below the median value, indicating a larger spread of observed values (even when normalized by the median value for each season). This season is characterized by convective thunderstorms that drive locally heavy and spatially variable rainfall patterns. The RainLog network also generally observed average precipitation values higher than the airport over the study period, substantially so in the cool season.

The distribution of seasonal total precipitation from RainLog network gauges relative to the total at TIA for each year in the 2007–2018 study period is shown in Figure 6b. In general, this period was characterized by below-average cool season precipitation and large interannual variability in warm season precipitation. Cool season precipitation totals had much less spread across the RainLog network as would be expected, but notably the TIA total was in the lowest quartile in eight of the 12 years of the study period. The official observation was consistently drier and poorly represented the winter

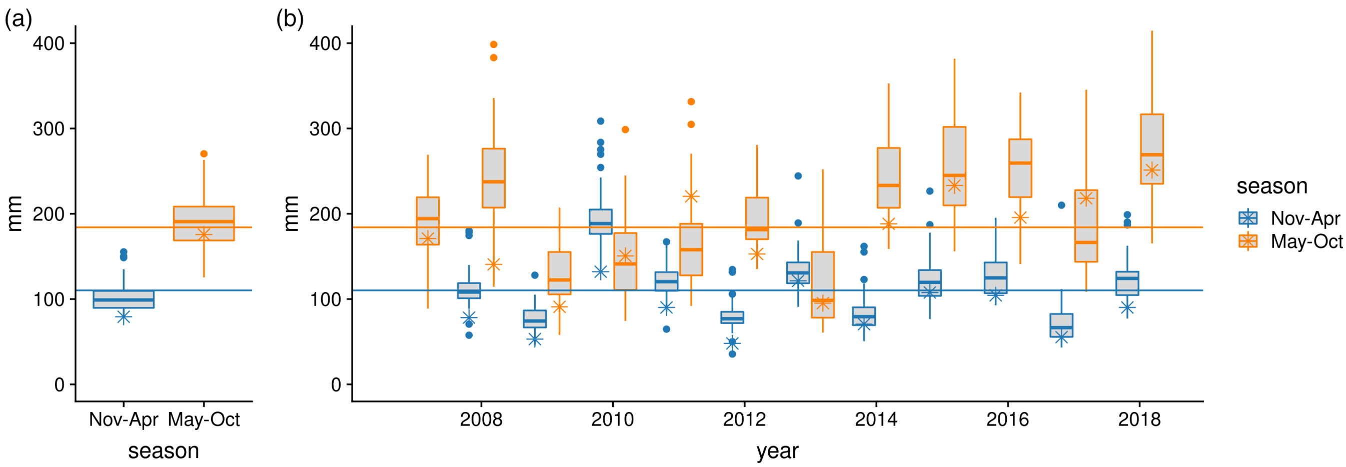


FIGURE 6 Distribution of seasonal total precipitation for entire study period (a) and for each year from May–October 2007 through May–October 2018 from RainLog gauges with near-complete records ($n = 39$) (b). Precipitation totals from TIA are represented with an asterisk. The orange and blue horizontal lines represent the average total seasonal precipitation (1981–2010 Climate Normals period) at TIA for the May–October and November–April seasons, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

season precipitation total for the Tucson metro area over the study period.

Warm season precipitation variability was high across the RainLog network with interquartile ranges spanning almost 100 mm in some years (e.g., 2013). In contrast with the cool season, there was not a consistent wet or dry bias of TIA values relative to the RainLog network median. There were seven warm seasons below the network median and five above (Figure 6b). There were only five warm seasons, though, where the TIA value was within the interquartile range of the RainLog network. The 2013 warm season was the closest to the median, but also the year with the highest spread among network values. The spread in interquartile ranges and extremes shows that in most summers the range of variability is still tens of millimetres regardless of if the TIA observation is close to the network median. Some RainLog observers are capturing precipitation totals ranging from half to sometimes twice as much as the amount observed at the official station at TIA.

3.3 | Characterizing precipitation patterns using network-wide metrics

Few observers in the RainLog program have consistent, long-term records with few missing observations, complicating efforts to utilize the network to characterize changes in precipitation at specific locations over time, as discussed in the previous section. However, the observer bias to report only on precipitation days creates a larger and more dispersed sampling of precipitation across the Tucson metropolitan area. To examine how the network can capture precipitation extremes on these days, we first calculated the daily median rainfall (DMR) and daily interquartile rainfall range (IQR) for all precipitation observations across the network on each day. The number of observations contributing to these metrics varies on each day (Figure 3), but can provide simple characterizations of network-wide precipitation patterns. Figure 7a shows the DMR across the RainLog network for each day in the study period. There is a pronounced seasonality in DMR tied to the seasonal-transitional climate of the Tucson metropolitan area where winter storms drive widespread precipitation events in the cool season (November–April) and convective storms during the summer monsoon produce locally heavy precipitation amounts. The median daily rainfall is zero when more than half of the network is reporting zero rainfall, but often is above 10 mm in both seasons of each year. Overall, the summer season (May–October) has slightly higher median daily rainfall (2.5 mm) over the study period than the cool season (November–April at 1.8 mm). In contrast, Figure 7b shows the daily interquartile range (IQR) of precipitation observations across the network. The IQR has consistently higher values in the summer versus the winter, which is to be expected, given the network's ability to capture highly localized thunderstorm events across the Tucson area. The IQR is a useful metric to characterize the variability of observations on a given day and can be used as a proxy for spatial variability.

Three case study days that represent high values of area-wide precipitation (quantified by DMR), large spatial variability (quantified by IQR), or both (blue dots in Figure 7 and Table 1) are examined to demonstrate how these non-standard metrics can leverage data across the RainLog network. These events occur in different seasons

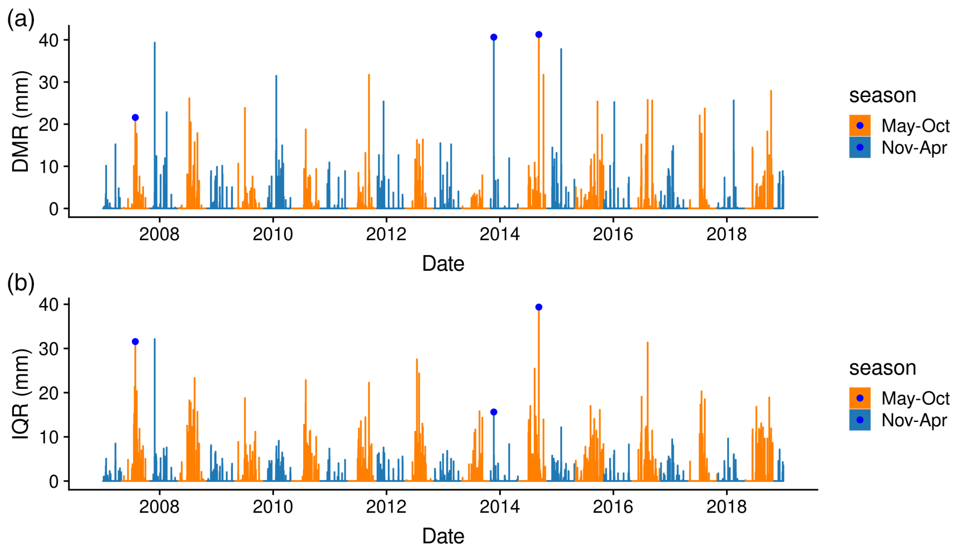


FIGURE 7 Daily median rainfall (a) and interquartile range (b) of rainfall observations each day across RainLog network in Tucson metropolitan area, 2007–2018. Dots represent days represented in Table 1 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Network-wide metrics of precipitation observations for the Tucson metro area on three case study days

Date	Number of observations	Largest observation (mm)	Observations of 0 mm	Observations >25.4 mm	DMR (mm)	IQR (mm)	Observations of "Trace"
Jul 28, 2007	213	97.8	14	98	21.6	31.6	3
Nov 22, 2013	355	82.6	5	310	40.6	15.6	0
Sep 8, 2014	351	115.6	6	248	41.3	39.4	1

and represent fundamentally different types of meteorological mechanisms (i.e., dissipating tropical storms, frontal-type storms, and convective monsoon thunderstorms) that can produce precipitation extremes across the Southwest (Hirschboeck, 1988; Webb and Betancourt, 1992).

3.3.1 | Tropical system (September 8, 2014)

The highest DMR value occurred on September 8, 2014, which was also the highest daily IQR value during the period of record. This widespread, heavy rain event associated with decaying tropical storm Norbert primarily impacted Baja California in Mexico and also initiated a deep plume of moisture to move north over much of southern Arizona. Record rainfall fell over Phoenix, triggering widespread flash flooding (NOAA, 2019c) with this event. Widespread heavy rain fell across the Tucson metro area through the morning, triggering leading to flash flooding that claimed the life of a motorist trapped in a flooded urban wash (Arizona Daily Star, 2019b). The TIA recorded 46.7 mm on September 8, which was a record for the day, while the RainLog network observed 150 values more than double this value.

Figure 8 shows observations of widespread precipitation across the entire Tucson metro area. A band of greater than 50 mm observations extends from the northern metro area to the centre of town where widespread flash flooding occurred. The western part of Tucson, which is only ~12 km away from TIA, observed much less rainfall with most observations less than 10 mm. This high variability in observations is reflected in the high interquartile range value for the day (39.4 mm). There were 351 observations submitted on September 8, the third highest number of observations on single day for the Tucson area in the study period (Table 1). Of these observations, 248 were greater than 25.4 mm. The largest observation was 115.6 mm, which would be between a 1 in 200 to 1 in 500 year event for a 24-hr rainfall event based on the Tucson long-term record (NOAA, 2019b). There were six observations of zero precipitation and one trace observation during this event, which are most likely errant reports given how widespread the heavy precipitation was across the area. Tropical storms and associated moisture like the conditions observed on September 8, 2014 can drive widespread flooding events in the late summer and early fall across the southwest United States (Hirschboeck, 1991; Wood and Ritchie, 2013). The RainLog network captured precipitation extremes of locally heavy rainfall and sharp spatial gradients in amounts across the Tucson area that were not adequately represented using official networks alone.

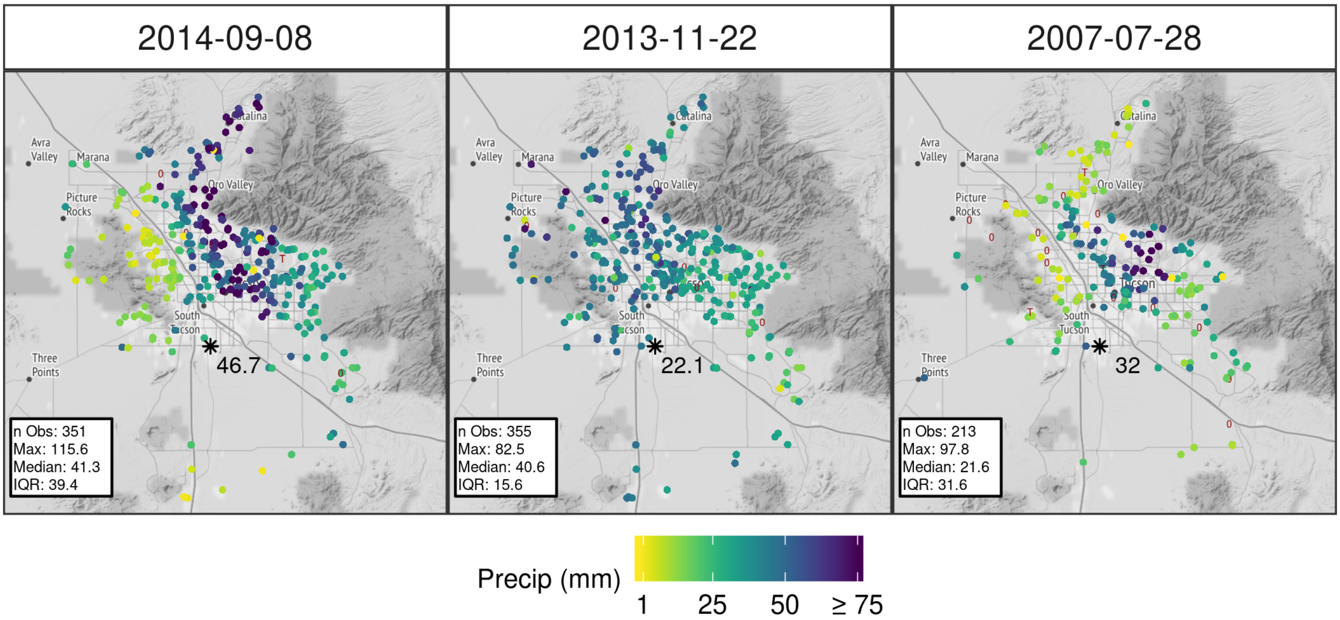


FIGURE 8 Daily total precipitation observations across RainLog network in the Tucson metropolitan area for three case study days. The asterisk and numeric value represent the daily total precipitation observation at TIA [Colour figure can be viewed at wileyonlinelibrary.com]

3.3.2 | Synoptic-scale low-pressure system (November 22, 2013)

The second highest DMR (40.6 mm) occurred on November 22, 2013. This cool-season event was driven by a slow-moving upper-level low-pressure system that funnelled large amounts of subtropical moisture into southern Arizona supporting long-duration, widespread heavy precipitation (ISU, 2019; NOAA, 2019d). Precipitation amounts recorded across the RainLog network were relatively uniform (IQR of 15.6 mm) in comparison to the other case study days, as would be expected with a cool season, frontal-type weather system (Figure 8). The number of heavy rainfall observations was higher with this event though, with 87% (310 of 355 total observations) greater than or equal to 25.4 mm. The heaviest rainfall again occurred from northwest to central Tucson with lower amounts in far eastern parts of the metro area. The observation of 22.1 mm at TIA was in the lower quartile of observations across the network and about half the DMR for day. There were five observations of zero precipitation and these are suspect on a day with such uniform coverage of precipitation.

3.3.3 | Summer monsoon thunderstorm (July 28, 2007)

The day with the third highest IQR (31.6 mm) (Figure 7) had only a modest DMR (21.6 mm) and is a good example of a highly localized, heavy rain event that is difficult to capture with a sparse observation network. The dense set of observations provided by the RainLog network, even in its early days with fewer overall observers, captured an intense summer monsoon thunderstorm event that primarily impacted north-central Tucson (Figure 8). Eight observations of greater than 75 mm (max 97.8 mm) occurred in an area with a radius of less than 3 km. The extreme gradient in precipitation is also evident on the map with areas in both eastern and western parts of the Tucson metro area observing less than 10 mm. TIA observed 32 mm with this event which is higher than the DMR of 21.6 mm, but substantially lower than the heaviest amounts observed in the northern part of the metro area. Less than half of the network (98 of 213 observations) recorded precipitation amounts of greater than or equal to 25.4 mm (Table 1) with most observers in western parts of Tucson observing 10 mm or less. A volunteer network like RainLog is particularly powerful at capturing highly localized events like this one when observers are somewhat evenly distributed like they are across the Tucson area.

There are also 14 observations of zero precipitation and 3 "Trace" observations which are possible given the localized nature of convective thunderstorms. Still, it is difficult to assess whether these observations are erroneous and an inherent challenge in using data collected from a volunteer network. Rupprecht (2009)

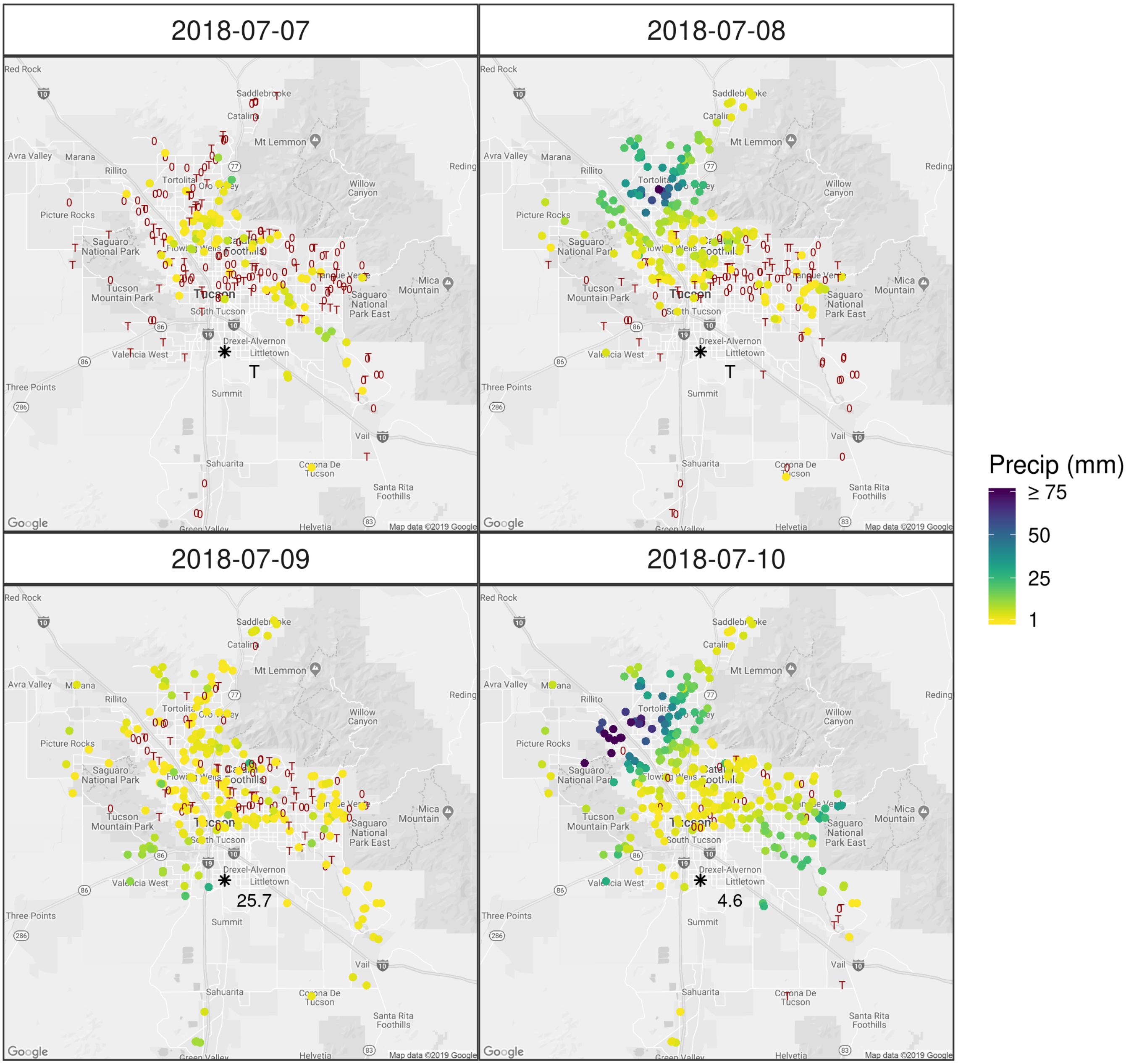


FIGURE 9 Daily total precipitation observations from RainLog network across Tucson metropolitan area from July 7, 2018 to July 10, 2018 [Colour figure can be viewed at wileyonlinelibrary.com]

noted in her analysis of the RainLog network that some observers consistently entered their observations 1 day off of expected due to confusion with the data entry protocol. Examining the day before and after events of interest can lend some insight into whether or not an observation was entered on the wrong day in some instances. Leveraging the density of the observations could also be used to examine the spatial pattern further to identify outliers with respect to nearest neighbours or remote-sensing products.

3.4 | Tracking the evolution of heavy precipitation patterns across Tucson, July 2018

The dense network of observers captures localized, intense thunderstorm events as demonstrated with the July 2007 event above. Precipitation on these days is capable of producing high impact flooding events, especially across urban areas like Tucson that rely in part on roadways and urban washes as their stormwater conveyance systems. Multiple days of heavy rainfall in one location can exacerbate flash flooding potential, so having a dense network of observers track the temporal evolution of precipitation patterns can be useful in characterizing high impact weather events. Even though few RainLog observers have complete records through time, their contributions in the summer season, peaking to over 350 observations on several days in 2018 (Figure 3), provide a detailed depiction of high impact rainfall across the Tucson metro area. We illustrate this by using RainLog to track the evolution of precipitation patterns at the beginning of monsoon storm activity in summer 2018. Figure 9 shows daily precipitation observations across the Tucson area from July 7 through July 10. A high impact flash flooding event occurred over northwest Tucson on July 10 that caused the derailment of a cargo train on a major rail line and led to the closure of several nearby roads (Marana AZ, 2019). Extreme precipitation amounts of over 75 mm were recorded by seven RainLog observers within one mile of the derailment site on July 10. Comments submitted with observations in this area noted that most of the rain fell in the early afternoon in less than an hour. This was a highly localized event with most of the network observing light amounts or no precipitation at all on July 10. The official observation for the day was 4.6 mm at TIA, 16 times smaller than the heaviest RainLog reports. This area also observed heavy rain earlier in the preceding week which may have exacerbated flash flooding potential. A localized thunderstorm brought light precipitation to this area on July 7, and a much heavier thunderstorm occurred on July 8 with several observations above 60 mm (max 88.9 mm). Gauges in and around the epicentre of flash flooding impacts observed 100–125 mm of precipitation over this 4 day period up to and including July 10. This 4 day total is around 80% of the long-term average precipitation total of 154 mm at TIA for the entire monsoon (June 15–September 30). Over this same time period TIA recorded a total of 30.3 mm with trace observations on the 7 and 8, over 25 mm on July 9 (a day when northwest Tucson largely observed no precipitation) and 4.6 mm on July 10. The RainLog network provides a dataset that allows for reconstruction and analysis of the localized extreme precipitation that created this high impact flooding event, which could be beneficial for future planning efforts.

4 | CONCLUSIONS

Volunteer observations can constitute a valuable data source for monitoring hydroclimate across the Tucson Metropolitan Area and characterizing extreme precipitation events. These observations present challenges such as short records and missing data, but can be analysed to leverage the strength of the sheer number of observations on high impact weather days that elicit a strong response of participants to log observations. Networks like RainLog are ideally used to complement long-term, official monitoring networks supported by agencies that can ensure the quality and continuity of their stations and observations. These official networks serve as anchor points against which more ephemeral observations that emerge from volunteer efforts can be compared and used to characterize spatial patterns across areas in between official gauges. Innovations and improvements in data access (e.g., open application programming interfaces-API) and platforms to contribute data (e.g., smartphone apps, home weather stations) have made it easier to integrate data from different climate monitoring networks to build better data visualization and decision support systems (Muller *et al.*, 2015). The characterizations of the strengths and potential challenges in using volunteer data like RainLog will hopefully encourage practitioners to consider using citizen science datasets for development of climate services, but with proper expectations and careful use. Future work will provide a more detailed comparison of RainLog against other monitoring networks to assess potential data quality issues and to examine how multiple networks together (both volunteer and those in official networks) can be used to study fine-scale hydroclimatic variability. Volunteers are still in the end volunteers who provide valuable contributions in terms of their observations, but cannot be expected to maintain long-term records over decades with few missing observations. They are only one complementary piece of coherent, long-term hydroclimatic monitoring.

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