
Anthropogenic Impacts on Summer Precipitation in Central Arizona, U.S.A.

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This article explores the possibility of urbanization- and irrigation-induced increases in summer precipitation totals in central Arizona. Maximum precipitation impacts are hypothesized to occur downwind of the Phoenix area in the Lower Verde basin. Results from statistical tests indicate that summer precipitation totals in the Lower Verde basin are greater than totals in nearby basins. Precipitation totals in the basin also appear to be equivalent to totals at more monsoon-impacted stations in eastern Arizona. While this research is preliminary, the results do provide encouraging evidence of the existence of anthropogenically enhanced summer precipitation in central Arizona. **Key Words:** Arizona, irrigation, Phoenix, precipitation, urbanization.

Introduction

Localized environmental impacts resulting from urban development and agricultural growth have been documented throughout the world. Increases in water scarcity, water pollution, habitat loss, air pollution, and ground subsidence are a few of the possible negative consequences associated with human activities. These and other impacts have been frequently evident in arid and semiarid regions where the stability and health of many environmental systems are tenuous. Localized anthropogenic impacts on the environment have been confirmed in arid and semiarid locales such as Cairo, Egypt (e.g., Raufer 1997; El Arabi 1999), Kuwait City, Kuwait (Shaqour 1994; Akber, Al-Awadi, and Ghoneim 2001), Phoenix, Arizona (e.g., Larson 1986; Ellis et al. 2000), Riyadh, Saudi Arabia (e.g., El-Sharif 1985; Modaihsh 1997), and Tehran, Iran (e.g., Sohrabpour et al. 1999; Karamouz et al. 2001). Additional localized impacts resulting from urban and agricultural development have been documented, including the modification of local climates (e.g., Qureshi and Khan 1994) and increases in ambient urban greenhouse-gas concentrations (e.g., Idso, Idso, and Balling 1998).

As arid and semiarid regions in many nations have experienced rapid population growth in the last several decades (Warren, Sud, and Rozanov 1996), regional-scale environmental

impacts resulting from anthropogenic activities have become increasingly important. A prime example of such an impact is the increase of precipitation around large urban centers. Increases in precipitation have been shown to occur in locations downwind of urbanized areas (Lowry 1998). The factors contributing to this human-induced change in regional precipitation patterns include the following urban development "byproducts": urban heat islands (e.g., Changnon 1968); increased surface roughness due to commercial, industrial, and residential construction (e.g., Cotton and Pielke 1995); and elevated levels of cloud condensation nuclei (e.g., Changnon 1968). In the last half-century, this precipitation phenomenon has been documented in cities throughout the United States (Landsberg 1956; Changnon 1968; Changnon, Huff, and Semonin 1971; Huff and Changnon 1973; Harnack and Landsberg 1975; Sanderson and Gorski 1978; Rosenberger and Suckling 1989), but not in arid or semiarid cities such as Phoenix, Las Vegas, Tucson, and Albuquerque.

Largely overlooked in previous investigations into urban-induced regional precipitation impacts has been the important role of large-scale agriculture. This is not altogether surprising, given that many previously examined regions do not include a substantial amount of irrigated land. Even in arid and semiarid areas where the landscape is often heavily irrigated, tracing the agriculture-based component of

downwind precipitation enhancement is often complicated by the presence of substantial topographic relief wherein terrain irregularities can mask the anthropogenic "signal." Nevertheless, extensive irrigation should theoretically have a major impact on precipitation in arid and semiarid regions. Large irrigated areas in dry regions can enhance convective precipitation due to increased moist static energy (i.e., increased potential for atmospheric instability), the generation of a mesoscale vertical circulation by the differential heating linked to heterogeneous surface properties, and increased atmospheric water vapor through increased evapotranspiration and decreased runoff (Anthes 1984).

As arid and semiarid urban centers continue to grow rapidly, the need for a holistic examination of regional environmental impacts—including changes in precipitation patterns—resulting from both urban and agricultural development is essential. An opportunity to make an initial assessment of the impact of human activities on regional precipitation patterns in arid and semiarid regions exists within the dry regions of the western United States. Specifically, the Phoenix metropolitan area in central Arizona provides a suitable case-study site for examining the role of irrigation and urbanization impacts on precipitation totals within a mesoscale context. Phoenix and its surrounding landscape have long been heavily irrigated, and dramatic growth since the mid-twentieth century has made the Phoenix area the fourteenth largest metropolitan area in the United States (U.S. Census Bureau 2001). Because the metropolitan area is bordered on several sides by mountainous terrain, an explicit consideration of topographic effects on precipitation must also be made, in conjunction with an assessment of urban and agricultural impacts.

Research Questions and Objectives

The research presented in this article centers on the development and verification of a conceptual model that addresses the impacts of urban and agricultural development on summer precipitation totals in central Arizona. Urban effects should be greatest in the summer season, resulting from decreased synoptic-scale forcing (e.g., fronts) and less concealment of meso-

scale processes (e.g., mountain-valley circulation). Our work is driven by the following research questions:

- From both theoretical and empirical perspectives, how has urban and agricultural development in the Phoenix area influenced precipitation totals during the summer season?
- Where have these impacts been most significant?

Two main research objectives are derived from these questions: (1) to explore, through a theoretical lens, the possibility of increased summer-season precipitation in central Arizona resulting from urban and agricultural development; and (2) to verify this theoretical rationale through statistical analyses of summer-season precipitation totals in the region. Both qualitative and quantitative information produced by this research should increase the general knowledge concerning climate-induced environmental impacts in arid and semiarid urban areas. In addition, the results of this study will have implications for an improved understanding of human-environment interactions in dry regions. These include considerations regarding the effects of land-use and land-cover change on surface and near-surface moisture availability as well as climatological and ecological change in areas downwind of a large urban center. An increased understanding of regional impacts on precipitation totals may also contribute to a better discernment of synoptic-scale precipitation variability within a climate-change context.

Conceptual Model of Urban and Agricultural Impacts on Precipitation in Central Arizona

Overview of the Phoenix Area

Like many cities in the western United States, Phoenix has experienced dramatic urban growth over the past several decades. Until the middle of the twentieth century, the area was predominantly an agricultural center, with only a moderate amount of urban development (Knowles-Yáñez et al. 1999). However, over the past fifty years, urbanized Phoenix has expanded in size by nearly 700 percent (Rex 2000). Consequently, the current population

of the Phoenix metropolitan statistical area, which includes Maricopa and Pinal counties, is approximately 3.2 million (U.S. Census Bureau 2001).

This rapid urbanization has resulted in a reduction of irrigated cropland in Maricopa County by about 50 percent since 1950 (Rex 2000). A considerable amount of cropland, however, still exists in central Arizona (Figure 1). The presence of these irrigated lands and the very high rates of potential evapotranspiration—particularly during the warmest months—translate into high rates of actual evapotranspiration. Heavily irrigated lands (e.g., cotton fields and golf courses) in the Phoenix area can emit at least seven times more water vapor into the atmosphere than do equal-sized desert areas nearby.¹ Even in the region's developed, nonagricultural areas,

evidence suggests that present-day evapotranspiration rates are up to twice the rates of 150 years ago.² The development of the Phoenix area through irrigation-intensive land uses (i.e., crops, residential areas, and golf courses) has resulted in the total amount of actual evapotranspiration equaling that from a hypothetical ~1,600 km² lake situated in the middle of the region.³ If irrigated cropland to the southeast of Phoenix (Figure 1) in Pinal County is included, then the area of the hypothetical lake expands to ~2,400 km². For comparison purposes, the cumulative area of the region's canyon-located lakes is ~87 km², illustrating that irrigated and urbanized lands constitute a much larger source of atmospheric moisture in the region.

Near-surface moisture availability in the Phoenix region peaks during the summertime monsoon season (i.e., July to September). In

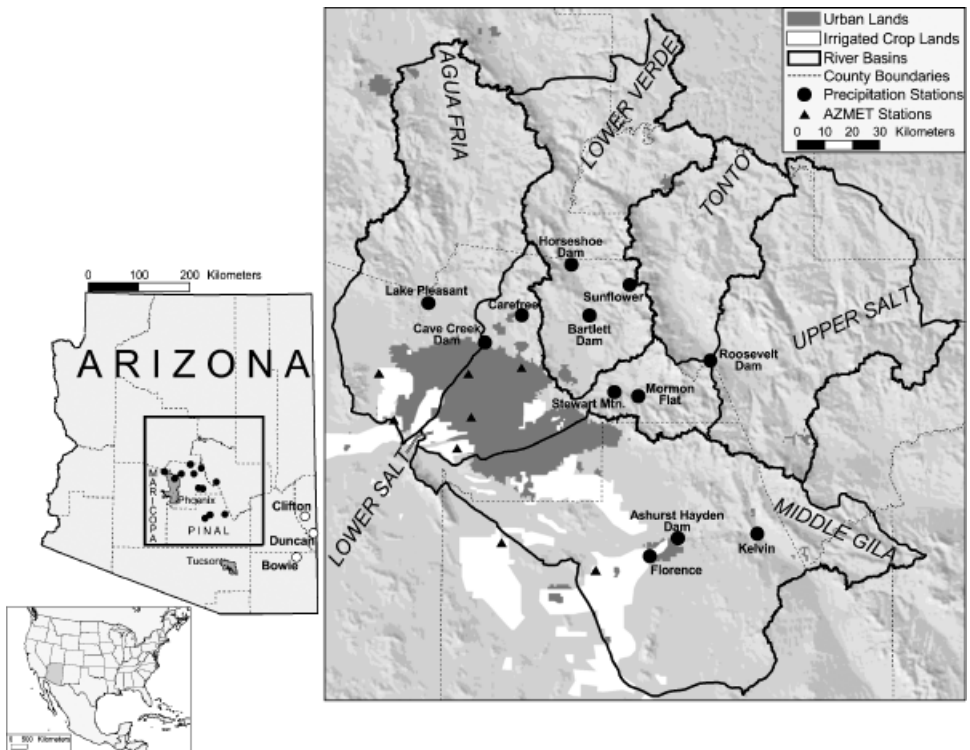


Figure 1 Map of the study region showing its location within Arizona, as well as the locations of urban lands, irrigated croplands, river basins, and meteorological stations. Urban lands were determined using satellite-measured, nighttime, light-intensity data available from the National Geophysical Data Center and land-cover information determined from a 1999 Landsat Enhanced Thematic Mapper (ETM) scene available from the Arizona Regional Image Archive. The irrigated croplands also were located using the ETM scene.

addition to evapotranspiration rates being high, as average daytime temperatures exceed 29°C (Sellers and Hill 1974), moisture is also advected into the region from the Gulfs of California and Mexico via the North American monsoon system circulation, resulting in frequent convective-precipitation events (Adams and Comrie 1997). The core area of the monsoon is centered over northern Mexico, with the Phoenix area situated essentially on the edge of the region of influence (Comrie and Glenn 1998). Orographic effects tend to elevate summer precipitation totals in the mountainous areas north and east of the city (Figure 1). In the early afternoon, thunderstorm activity peaks on the Mogollon Rim (Balling and Brazel 1987b; Watson, Lopez, and Holle 1994); the rim provides effective orographic forcing for vertical motion (Wallace, Maddox, and Howard 1999). Storms are thought to propagate downslope thereafter through the interaction of cloud-produced downdrafts with warm, upslope air (Watson, Lopez, and Holle 1994). As a result of the downslope propagation, precipitation in the Phoenix area is most frequent around midnight (Balling and Brazel 1987a).

Theoretical Impacts of Urbanization on Precipitation in Central Arizona

Urbanization can transform a landscape immensely, with a number of potential impacts on precipitation formation and amount. Among the urban factors influencing precipitation is surface roughness, a measure of the average vertical relief and small-scale variations of a terrain surface. Urban areas can have roughness lengths as long as 1.3 m; conversely, rural areas have roughness lengths between 0.0002 and 0.2 m (Troen and Peterson 1991). This difference can translate into increased mechanically generated turbulence (Chase et al. 1999) within urban areas and increased convergence downwind of urban areas (Cotton and Pielke 1995). The convergence has been suggested as a potential cause of increased positive vertical velocities downwind of urban areas (Hjelmfelt 1982). Those updrafts can enhance cloud formation.

Urbanization also results in increased pollutant emissions, which eventually elevate atmospheric concentrations of cloud condensation nuclei (CCN) in and near urban areas. CCN are

either emitted directly into the atmosphere or formed in the atmosphere from sulfur oxides, nitrogen oxides, and hydrocarbons through the gas-to-particle conversion process (Seinfeld and Pandis 1998). Anthropogenic activities in urban centers often increase CCN concentrations by factors of two or more over concentrations at rural locations (Hudson and Frisbie 1991). These additional CCN can have large impacts on microphysical processes within a cloud (Orville et al. 2001). For example, clouds formed primarily from anthropogenic CCN typically have more and smaller droplets than do "natural" clouds (Alkezweeny, Burrows, and Grainger 1993). In Maricopa County, anthropogenic sources emit over 350,000 metric tons of pollutants (i.e., nitrogen oxides, hydrocarbons, sulfur oxides, and particulate matter) into the atmosphere annually, making Phoenix a major source of CCN (Maricopa Association of Governments 1997; U.S. Environmental Protection Agency 2000).

In many large urban areas, the development of an urban heat island (UHI) is common. As urban areas expand, the resulting surfaces (e.g., asphalt) are more capable of storing solar energy and converting it to sensible heat than were the previous undeveloped surfaces. With more sensible heat transferred to the air, the temperature in urban areas tends to be 2–8°C higher than surrounding rural areas (Oke 1987). In Phoenix, however, the prevalence of irrigated lands and the subsequent conversion of large quantities of energy into latent heat—as opposed to sensible heat—prohibit the development of a daytime UHI (Brazel et al. 2000). Daytime temperatures are lower in the urban area than in the surrounding desert areas (Brazel et al. 2000). Therefore, the Phoenix area behaves more like a "heat sink," rather than a "heat island," during the summer season (Lougeay, Brazel, and Hubble 1996). Despite the absence of a daytime UHI, the urbanization of the Phoenix area should still promote enhanced convergence, resulting from increased surface roughness and enhanced cloud formation due to high levels of CCN.

Theoretical Impacts of Irrigation on Precipitation in Central Arizona

Central Arizona has relatively high human-related water-consumption rates. For example,

the Phoenix Active Management Area (AMA), which includes most of the Phoenix metropolitan statistical area, has over six times more water use per unit area than does the Tucson AMA (Arizona Department of Water Resources 1996), which is located less than 200 km to the south. This discrepancy is caused by extensive irrigation in the Phoenix area on both croplands and urban lands: at least 60 percent of the water consumption in the area is used for irrigation (Arizona Department of Water Resources 1996).

This increased availability of surface water through irrigation, and the subsequent increase in actual evapotranspiration rates, produce elevated atmospheric-humidity levels. During the monsoon season, absolute-humidity levels above irrigated lands throughout the Phoenix area are at least 15 percent higher (i.e., 13.3 g m^{-3} versus 11.6 g m^{-3}) than absolute-humidity levels above nonirrigated areas.⁴ In spite of the previously mentioned land-use and land-cover changes over the past half-century, dew-point temperatures in Phoenix did not change significantly from 1896 to 1984 (Brazel and Balling 1986). While this analysis was based on data from a single site and may not be characteristic of the entire Phoenix area, it can be assumed that dew-point temperatures did not decrease at a large rate over that time period. This assumption is validated by the fact that even though the amount of irrigated cropland has waned in recent decades, the preponderance of water-intensive landscaping in residential and recreational areas requires a substantial amount of irrigation. Phoenix still resembles an "oasis" (Wehmeier 1980), but its form is derived from an agricultural/urban situation, compared to the mostly agricultural situation that existed over fifty years ago.

Previous studies have suggested that the presence of irrigated lands can lead to increased precipitation totals. For example, increased irrigation in northern Texas from 1931 to 1970 has been considered to be the cause for a 25-percent increase in summer precipitation totals over and near irrigated areas in the region (Barnston and Schickedanz 1984). Enhanced evapotranspiration from irrigated areas in dry regions of the western United States may serve as a moisture and moist-static-energy source for rainfall systems at considerable distances

downwind (Segal et al. 1998). In addition to increasing atmospheric-humidity levels, irrigation can also enhance mesoscale convergence, thereby increasing the potential for cloud formation. Segal and colleagues (1989) note that the Phoenix area, with its extensive irrigated lands, has the potential for a relatively intense, nonclassical mesoscale circulation in the form of an "inland sea breeze." Consequently, irrigated land can be not only a moisture source and a trigger for increased atmospheric instability, but also a catalyst for enhanced lifting of air parcels in and downwind of the Phoenix area.

Theoretical Impacts of Urban and Agricultural Development on Precipitation in Locales Downwind of the Phoenix Area

Based on the various consequences of urban and agricultural development outlined above, anthropogenic activities in the Phoenix region should contribute to enhanced precipitation potential in central Arizona. Increased water-vapor transfer from the surface to the atmosphere and the enhancement of flow convergence are hypothesized to be the primary controls of increases in precipitation-enhancing factors.⁵ Increased water-vapor transfer to the atmosphere from large-scale irrigation should result in elevated atmospheric-moisture levels and increased convective instability (Barnston and Schickedanz 1984; Chase et al. 1999). Enhanced flow convergence, both through increased surface roughness and as a product of nonclassical mesoscale circulations, should result in more widespread lifting of air parcels in and downwind of the city.

Because of a southwesterly wind flow that prevails throughout the afternoon hours of the monsoon season in the Phoenix area (Wallace, Maddox, and Howard 1999; Stewart et al. 2002) (Figure 2), precipitation impacts should be displaced primarily to the Lower Verde basin (Figure 1). By late afternoon, the Lower Verde basin is directly downwind of the bulk of the urban and agricultural lands. In addition, the orientation of the basin does not prohibit the confluence of the regional-scale winds and local, upslope winds. Through an examination of lightning activity, King and Balling (1994) and Watson, Lopez, and Holle (1994) found an early-evening (i.e., 5:00 P.M. to 7:00 P.M.)

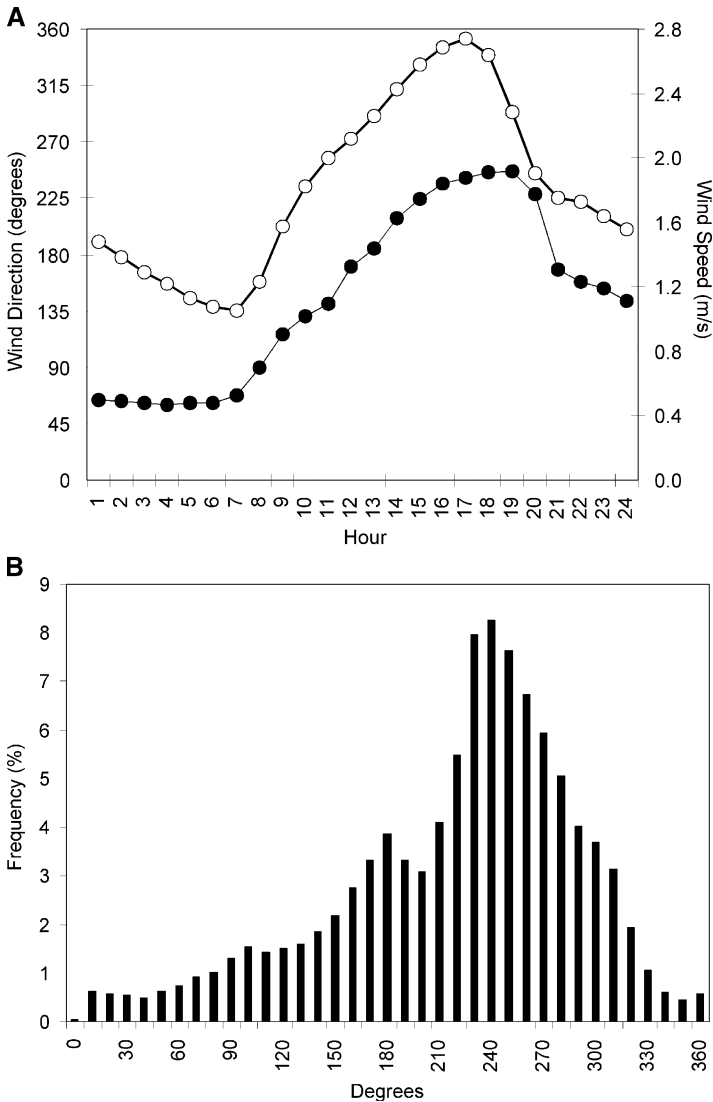


Figure 2 Near-surface wind characteristics during the monsoon season in the Phoenix area as represented by (A) diurnal variations in wind direction (—●—) and wind speed (—○—) as well as (B) relative frequencies of afternoon (1:00–6:00 P.M.) wind directions. Estimates of wind direction and wind speed are median values derived from hourly wind-speed and wind-direction data for the following AZMET stations (dates in parentheses indicate years of data availability): Laveen (1994–2001), Phoenix Encanto (1989–2002), Phoenix Greenway (1989–2001), and Scottsdale (1991–1998).

maximum in deep monsoonal convective activity to occur within the Lower Verde basin. This occurrence may result from strong, upslope moisture flow from the Phoenix area, since peak evaporation occurs in the afternoon and it takes

several hours for the resulting atmospheric moisture to travel to the basin. In addition, the interaction of this warm, moist, upslope flow with cool, downdraft air from established thunderstorm clouds should increase thunder-

storm development in the Lower Verde basin compared to that in the nearby basins. Watson, Lopez, and Holle (1994) and Maddox, McColium, and Howard (1995) note that the key factor controlling thunderstorm propagation and convective instability in central Arizona is the availability of atmospheric moisture. Consequently, the transport of Phoenix-derived water vapor to those uplands areas may be the most important cause of precipitation enhancement.

In sum, a strong theoretical rationale exists for the anthropogenic enhancement of precipitation in upland areas downwind of Phoenix, which leads to the following question:

- How do precipitation totals in the basins proximate to Phoenix conform to the supposition that the anthropogenic enhancement of precipitation totals is most severe in portions of the Lower Verde basin?

It needs to be noted that for the purposes of this article, severe impacts are manifested in relatively high precipitation totals compared to expected totals, based on a station's elevation and location in the overall monsoon-influenced region. The following methodology attempts to answer the above question.

Methodology

To verify whether higher-than-expected monsoonal precipitation—based on location and elevation—has occurred within the Lower

Verde basin, monthly precipitation data from first-order and cooperative weather stations in Arizona were obtained from the National Climatic Data Center (NCDC). Data were extracted for the period 1950–2000, which corresponds to the years of greatest urban growth in and around Phoenix. Data for the months of July, August, and September were aggregated for each year, resulting in a summer-season precipitation time series for each station.

The study area was centered on the upland areas immediately north and east of the Phoenix area. In addition to the Lower Verde basin, it included the Lower Salt, Agua Fria, and Middle Gila basins (Figure 1). The Tonto basin was excluded, as upwind precipitation transport from Phoenix would not likely be evident at such a geographically displaced distance. While several of the weather stations in the four main basins had full or nearly full fifty-one-year data records, others did not, resulting in a certain level of compromise to obtain the most spatially and temporally complete dataset with which to best address the research objectives. In the end, three stations either in or proximate to each basin, representing a range of elevations and geographical positions and having reasonably acceptable temporal data availability, were retained for analysis (Table 1). In addition to the twelve stations in the Lower Verde, Lower Salt, Agua Fria, and Middle Gila basins, three additional NCDC weather stations from the high-elevation areas of southeastern Arizona

Table 1 *Characteristics of the Meteorological Stations from which Precipitation Totals Were Obtained*

Station	Latitude (°)	Longitude (°)	Elevation (m)	Local Relief	Precipitation (mm)	N	Basin/Zone
Carefree	33.81	-111.90	760	Low	102	32	Northwestern Lower Salt
Cave Creek Dam	33.72	-112.05	490	Low	76	19	Northwestern Lower Salt
Lake Pleasant	33.85	-112.27	490	Low	85	27	Agua Fria
Bartlett Dam	33.82	-111.63	500	Low	114	51	Lower Verde
Horseshoe Dam	33.98	-111.71	615	Low	125	50	Lower Verde
Sunflower	33.92	-111.48	1,160	Moderate	181	30	Lower Verde
Mormon Flat	33.55	-111.44	550	Low	116	49	Eastern Lower Salt
Roosevelt Dam	33.67	-111.16	650	Low	115	51	Eastern Lower Salt
Stewart Mountain	33.56	-111.54	430	Low	100	50	Eastern Lower Salt
Ashurst Hayden Dam	33.09	-111.29	490	Low	83	42	Middle Gila
Florence	33.03	-111.39	460	Low	87	47	Middle Gila
Kelvin	33.10	-110.98	550	Low	119	34	Middle Gila
Bowie	32.32	-109.48	1,150	Low	135	45	"Monsoon zone" ^a
Clifton	33.05	-109.29	1,150	Low	150	49	"Monsoon zone" ^a
Duncan	32.75	-109.12	1,160	Low	133	51	"Monsoon zone" ^a

Note: N = the number of years from 1950 to 2000 with valid precipitation totals for the summer season.

^aComrie and Glenn (1997).

were selected for comparative purposes. These stations are in the primary North American monsoon precipitation region, as defined by Comrie and Glenn (1998), hereafter the “monsoon zone.” Since the synoptic-scale monsoon system acting alone should cause significantly higher precipitation totals in the monsoon zone than in the Lower Verde basin, comparisons between moderately monsoon-impacted stations (i.e., Lower Verde basin) and strongly monsoon-impacted stations (i.e., “monsoon zone”) enable a lucid examination of possible human-induced increases in summer precipitation totals in the Lower Verde basin.

Each summer-precipitation time series for the three stations in the Lower Verde basin were compared with the other nine time series for stations in the Lower Salt, Agua Fria, and Middle Gila basins as well as with the three time series for stations in the monsoon zone. Only those years having valid data for both stations were used in the comparisons. Mann-Whitney *U* tests were used to test for significant ($\alpha = 0.05$) differences between pairs of stations. The Mann-Whitney *U* test is advantageous because it does not assume a normal distribution, making it suitable for very small data samples (Shaw and Wheeler 1998).

Results and Discussion

Lower Verde versus Agua Fria, Lower Salt, and Middle Gila Basins

The Lower Verde basin as a whole appears to receive more summer precipitation than do the other basins surrounding the Phoenix area (Table 2). With 22 to 73 mm more precipitation, the basin’s Sunflower station is significantly wetter than all other stations in nearby basins. These differences are certainly caused, in part, by Sunflower’s higher elevation (i.e., 490 to 730 m higher than the other stations). The differences may also be associated with increased orographic lifting induced by relatively steeper terrain in the vicinity of the station (Table 1). The Sunflower station should theoretically be one of the stations most affected by upwind anthropogenic activities. However, its anomalous topographic position does not enable clear comparisons with nearby stations. The terrain near the Sunflower station is still less than half as steep as that of the Mogollon Rim and typical “sky islands” of southern Arizona. Possible anthropogenic impacts at the Sunflower station are discussed later in the article.

The Lower Verde basin’s Bartlett Dam and Horseshoe Dam stations have higher mean

Table 2 Differences in Millimeters between Median Summer Precipitation Totals at Stations in the Lower Verde Basin and Stations in Nearby Basins and the Monsoon Zone

	Lower Verde		
	Bartlett Dam (500 m)	Horseshoe Dam (615 m)	Sunflower (1,160 m)
Agua Fria and northwestern Lower Salt			
Carefree (760 m)	+ 20 (32)	+ 17 (29)	+ 36 (13)
Cave Creek Dam (490 m)	+ 24 (19)	+ 57 (19)	+ 69 (15)
Lake Pleasant (490 m)	+ 31 (27)	+ 56 (27)	+ 71 (22)
Lower Salt			
Mormon Flat (550 m)	-14 (49)	+ 7 (49)	+ 22 (30)
Roosevelt Dam (650 m)	-4 (51)	+ 16 (50)	+ 34 (30)
Stewart Mountain (430 m)	+ 11 (50)	+ 31 (49)	+ 59 (30)
Middle Gila			
Ashurst Hayden Dam (490 m)	+ 24 (42)	+ 48 (41)	+ 73 (25)
Florence (460 m)	+ 30 (47)	+ 49 (47)	+ 66 (30)
Kelvin (550 m)	-24 (34)	-2 (34)	+ 23 (29)
“Monsoon zone” ^a			
Bowie (1,150 m)	- 34 (45)	-17 (44)	+ 16 (28)
Clifton (1,150 m)	- 45 (49)	- 24 (49)	-11 (30)
Duncan (1,160 m)	- 39 (51)	-17 (50)	+ 11 (30)

Note: Only totals from those years when both stations had valid data were used in the calculations. Positive values and negative values indicate higher and lower totals, respectively, at the Lower Verde basin stations. Bold, italicized values represent significant differences at $\alpha = 0.05$. Numbers in parentheses after these values represent the number of summers involved in the comparisons. Numbers in parentheses after the stations’ names are the stations’ elevations in meters above sea level.

^aComrie and Glenn (1997).

precipitation totals than do the three stations within the Agua Fria and northwestern Lower Salt basins. The precipitation differences between Bartlett Dam and the Cave Creek Dam and Lake Pleasant stations are much larger than expected, given that all three stations have similar elevations. Bartlett Dam's precipitation total is significantly higher than that at Cave Creek Dam. While Horseshoe Dam is 125 m higher than Cave Creek Dam and Lake Pleasant, it has nearly 60 mm more summer precipitation, which is a significant difference. Perhaps of greatest interest, though, are the relationships between the Bartlett Dam and Horseshoe Dam stations and the Carefree station in the northwestern Lower Salt basin. Even though Carefree's elevation (760 m a.s.l.) places it 260 m above Bartlett Dam and 145 m above Horseshoe Dam, the two Lower Verde basin stations do not receive less precipitation.

Elevation differences complicate most comparisons between the Lower Verde stations and the eastern Lower Salt stations, but the comparisons do reveal that Bartlett Dam and Horseshoe Dam seem to receive anomalously high precipitation totals. Mean precipitation values for Bartlett Dam and Horseshoe Dam were expected to be significantly larger than those for Stewart Mountain, given that Stewart Mountain is at a slightly lower elevation. Nonetheless, only Horseshoe Dam's total is significantly larger. While the Mann-Whitney *U* tests do not reveal statistically significant differences between Bartlett Dam and Horseshoe Dam and the Mormon Flat and Roosevelt Dam stations, the minimal differences in mean precipitation totals between these stations are intriguing. Based solely on topography, the typical summer precipitation total at Bartlett Dam should be noticeably less than precipitation at Roosevelt Dam, which is approximately 150 m higher in elevation. However, the fifty-one-year medians differ by only 4 mm. Similarly, precipitation at Horseshoe Dam (615 m a.s.l.) should be slightly less than that at Roosevelt Dam (650 m a.s.l.), using only topographic features as a guideline. In reality, Horseshoe Dam receives approximately 16 mm more summer precipitation than does Roosevelt Dam.

Similar results hold for the comparisons of the Lower Verde and Middle Gila basin stations. Bartlett Dam and Horseshoe Dam

receive significantly more precipitation during the monsoon season than do the Ashurst Hayden Dam and Florence stations, which are slightly lower in elevation than Bartlett Dam. Bartlett Dam (500 m a.s.l.) has slightly less summer precipitation than does Kelvin (550 m a.s.l.), while the precipitation total at Horseshoe Dam (615 m a.s.l.) equals that at Kelvin. It is not completely unexpected that Kelvin's precipitation totals equal or exceed the totals at stations in the Lower Verde basin, since Kelvin is located deeper within the monsoon region and its precipitation totals may also be increased by upwind agricultural areas. Valley winds can transport moisture from the irrigated croplands in the lower part of the basin (Figure 1) to higher-elevation areas, where impacts on precipitation should be most substantial. Similar to the Lower Verde basin, the far eastern portion of the Middle Gila basin is situated under a region of elevated convective activity during the early evening (Watson, Lopez, and Holle 1994). It remains to be seen how important those irrigated lands are in the precipitation-enhancement process.

Lower Verde versus Monsoon Zone

Stations in the Lower Verde basin, while being generally wetter than stations in nearby basins, receive relatively equal amounts of summer precipitation, as do stations located well to the southeast within the core monsoon region. Those monsoon-zone stations—Bowie, Clifton, and Duncan—all have elevations within 10 m of the Sunflower station (1160 m a.s.l.) in the Lower Verde basin, placing them at much higher elevations than Bartlett Dam (~650 m lower) and Horseshoe Dam (~540 m lower). Despite being on the periphery of the core monsoon region and having an elevation equivalent to that of the three monsoon-zone stations, Sunflower actually receives significantly more precipitation than do the Bowie and Duncan stations. At the present time, it is not possible to entirely associate this difference with anthropogenic activities in the Phoenix area, because, as mentioned previously, enhanced orographic lifting may occur at Sunflower.

Despite the monsoon-zone stations being markedly higher in elevation than both the Bartlett Dam and Horseshoe Dam basins, they do not always receive significantly more precipitation. Although Bartlett Dam receives

significantly less precipitation than do the monsoon-zone stations, Horseshoe Dam's mean summer precipitation total essentially equals totals at Bowie and Duncan. Clifton is the only monsoon-zone station that receives significantly more (24 to 45 mm) precipitation than do Bartlett Dam and Horseshoe Dam.

Conclusions

Anthropogenic activities in the Phoenix area appear to have positively affected summer precipitation totals in downwind areas, especially in the Lower Verde basin. The Phoenix-based mechanisms contributing to this enhancement of precipitation may include: (1) increased surface-to-atmosphere transfer of water vapor resulting from extensive irrigation, (2) increased flow convergence resulting from the "rough" urban landscape and irrigation-induced circulations, and (3) increased pollution-derived CCN resulting from pollutant-generating activities, such as motor-vehicle usage. It is suspected that increased atmospheric-humidity levels and increased flow convergence are the dominant controls of the precipitation enhancement, and that the primary impacts should be detected at locations primarily downwind, due to a persistent regional-scale circulation. Consequently, the Lower Verde basin, which is situated northeast of Phoenix, has a higher propensity for convective-cloud development, resulting primarily from increased air parcel lifting and atmospheric instability. Those clouds should also have higher moisture contents than do the background monsoon-related clouds.

The results of several statistical analyses support the notion that portions of the Lower Verde basin may receive anthropogenically enhanced precipitation during the summer season. The significantly higher precipitation totals at lower-elevation stations in the Lower Verde basin compared to precipitation totals in the neighboring basins are particularly revealing, since topography would otherwise dictate that the lower-elevation stations should receive less monsoonal rainfall. In addition, it seems that stations in the Lower Verde basin receive as much precipitation as do the more monsoon-impacted stations in southeastern Arizona. In fact, the Sunflower station, which is at a relatively high elevation, is significantly wetter

than two of the three monsoon-zone stations considered in this article. This difference, however, may be caused mostly by enhanced orographic lifting within the Lower Verde basin, rather than by anthropogenic precipitation enhancement.

Substantially more research is needed to fully verify the occurrence of elevated summer-precipitation totals in the Lower Verde basin and possibly in other regions in central Arizona. The complex topography of the study region and the presence of multiple synoptic types (e.g., monsoon and summer "dry" [Davis and Walker 1992]) greatly complicate efforts to uncover an anthropogenic signal in precipitation totals. Therefore, future work certainly should involve the examination of anthropogenic influences on precipitation totals within explicit spatial, topographical, and synoptic-climatological contexts. This might involve development of predictive and/or inferential precipitation models stratified by synoptic type. These models would not only illustrate the varying importance of spatiotopographic factors but also highlight certain locales that may be the most anthropogenically impacted. Useful results might also be obtained using spatially continuous precipitation estimates derived from satellite data, either alone or in conjunction with other geospatial datasets. If precipitation enhancement is present, then the factors most responsible for the enhancement need to be identified. Historical ecological changes linked to precipitation enhancement could be uncovered using dendroclimatological techniques, and a long-term trajectory of the anthropogenic signature could be developed given projected land-use and land-cover change rates. Such information is critical to the assessment of ecological and climatic changes. ■

Notes

¹ Irrigated areas include turf and cropland. Brown (2001) presents actual evapotranspiration values for turf. Erie and colleagues (1982) present consumptive use estimates. Actual evapotranspiration was assumed to be 75 percent of consumptive use. Therefore, actual evapotranspiration for cotton fields and turf was 561 mm and 471 mm, respectively. Actual evapotranspiration for desert areas, which was 64 mm, was assumed to equal precipitation, since soil-moisture storage should be

negligible after the extremely dry months of May and June. The precipitation value was the average of totals from 1989 to 2002 at six Arizona Meteorological Network (AZMET) stations (Coolidge, Litchfield, Maricopa, Phoenix Encanto, Phoenix Greenway, and Waddell) located throughout the Phoenix area.

² This difference was estimated using present-day land-use and land-cover (LULC) data for the urbanized portion of the Central Arizona-Phoenix Long-Term Ecological Research (CAP-LTER) study region (Stefanov, Ramsey, and Christensen 2001), while also assuming that only a desert landscape was present in 1850. The following lists the LULC classes and their respective area proportions and estimated actual evapotranspiration totals (mm) per monsoon season:

- Xeric Residential (0.37, 64)
- Commercial/Industrial (0.29, 64)
- Mesic Residential (0.12, 476)
- Canals (0.11, 64)
- Asphalt and Concrete (0.08, 64)
- Cultivated Grass (0.02, 476)
- Water (0.01, 664)

An actual evapotranspiration total (476 mm) was available only for the turf-based classes (i.e., mesic residential and cultivated grass). This total was obtained from Brown (2001). The potential evapotranspiration total (664 mm) was used as the actual evapotranspiration total for the water class, while the precipitation total (64 mm) was used as the actual evapotranspiration total for the nonirrigated classes (i.e., xeric residential, commercial/industrial, canals, and asphalt and concrete).

³ The hypothetical water-surface coverage was based on the assumption that the proportions of actual evapotranspiration to potential evapotranspiration for irrigated crops and urbanized Phoenix were 0.85 and 0.30, respectively. Thus, the total area of the lake was 85 percent of the irrigated crop area plus 30 percent of the urbanized area. The actual evapotranspiration value for irrigated crops was 186 mm month⁻¹. Endnote 2 presents the proportions of the various LULC classes in urbanized Phoenix. The composite actual evapotranspiration estimate for urbanized Phoenix was 46 mm month⁻¹. The potential evapotranspiration value was 221 mm month⁻¹.

⁴ Saffell and Ellis (2002) determined that the Coolidge, Maricopa, Phoenix Encanto, and Phoenix Greenway AZMET stations were located in or proximate to irrigated areas, and that the Litchfield and Waddell AZMET stations were located in rural, quasidesert areas. Relative humidity and dry-bulb temperature data from 1989 to 2002 for all stations were used to calculate absolute humidity. Coolidge and Waddell had the highest (14.8 g m⁻³)

and lowest (11.0 g m⁻³) average absolute-humidity values, respectively.

⁵ Since results from recent research (Rosenfeld 2000) have shown that the increase of a cloud's precipitation potential by anthropogenic CCN is a debatable impact, this article downplays possible precipitation-enhancing effects of Phoenix's CCN emissions.

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