DRAFT

MEMORANDUM

Date: September 10, 2001

To: The Honorable Chair and Members
Pima County Board of Supervisors

From: C.H. Huckelberry,
County Administrator

Re: **Climate Variability in Pima County**

Report

The attached study on *Climate Variability in Pima County* represents another remarkable collaborative effort by members of Pima County's Sonoran Desert Conservation Plan team and the science community. With Mr. David Scalero as the lead author in this initiative, the team has drafted a thoughtful and many ways ground breaking study on the potential impacts that future climate variability might have on plants, animals, people and ecosystem processes.

Placed in the context of the Sonoran Desert Conservation Plan, the study suggests measures that might be included in our habitat conservation planning and adaptive management program to respond to natural climatic variability.

Setting and Background

Pages four through eleven describe the geographic setting of Pima County, the origins of our storms, the effects of atmospheric circulations, the history of weather data collection, and climate data collection and modeling.

Climatological Variables

Pages fourteen through forty-seven describe variables such as precipitation, variability of rainfall, drought, floods, groundwater, temperature, frost and potential evapotranspiration.

Affect of Short Term Climate Variation on Species and Long Term Climate Change

Pages forty-seven through sixty describe the potential responses of over forty species of concern to short term climate variation. In addition the study reviews past trends and looks at future scenarios of climate changes in southern Arizona in order to discuss potential implications of increasing temperatures and precipitation over time.

Recommendations

In light of the variations in climate and corresponding ecological responses, the study suggests a number of strategies for minimizing the potential adverse effects of climate variability on the ability to meet species protection goals under the Sonoran Desert Conservation Plan:

- Keep wildland ecosystems as intact and functioning as possible.
- Increase redundancy of representative habitats by preserving and rehabilitating multiple sites within the reserve system.
- Represent species and special elements across environmental gradients.
- Protect climatic refugia at multiple scales.
- Implement and evaluate mitigation techniques as far in advance of "take" as possible.
- Prepare contingency plans for mid-course corrections in mitigation and minimization techniques.
- Monitor climatic variables.
- Incorporate scientific findings on biotic and abiotic responses to climatic change.
- Restore pre-settlement fire regimes in forests and woodlands.
- Restore floodplain hydraulics to help store water and reduce the destructive impacts of flood waters downstream.
- Develop and implement localized drought plans for domestic and municipal water uses.
- Plan land uses to avoid increased droughts, both inside and outside the reserve system.
- Acquire water rights (surface and groundwater) to reduce diversions of water from riparian habitats.

Conclusion

Climate Variability in Pima County is an excellent primer and will contribute to the community's understanding of this complex topic. It is exciting to see the continued innovation of staff and the science community in presenting and integrating data and information into the Sonoran Desert Conservation Planning process.

Attachment

CLIMATE VARIABILITY IN PIMA COUNTY, ARIZONA, AND ITS SIGNIFICANCE TO THE SONORAN DESERT CONSERVATION PLAN

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Acknowledgments

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The authors would also like to thank Doug Duncan, U. S. Fish and Wildlife Service, Bruce Gungle, United States Geological Survey-Water Resources Division, Dr. Ken Kingsley, SWCA, Barbara Tellman, Water Resource Research Center, and Dale Turner, National Park Service Inventory and Monitoring Program, for their reviews on this report.

1.0 Introduction

1.1 Significance of Climatic Variability

Climate is an integral part of the natural environment. Climatic properties such as temperature and precipitation influence the rates and magnitude of fundamental ecosystem processes such as net primary productivity and soil development. Over time, climate influences the amount of carbon in the soil, the range of species' distributions, and the relative abundance and type of vegetation found in a given area. Climate also indirectly influences ecosystems by changing the frequency, magnitude and spatial scale of disturbance processes like fire, flooding and disease (Swetnam and Betancourt, 1998).

Climatic variability can be examined on a time scale ranging from days to millennia (Table 1). This report examines climate and related hydrologic and biological phenomena primarily over the span of years and decades.

In many parts of this report, the terms "normal" and "average" are used to indicate frequently observed climate conditions throughout the region. However, these terms are not truly meaningful in the context of comparing climate change in the southwestern deserts. It is important to note that cycles in climate, even long term ones, are considered to be "normal" for this area. Many desert species are adapted to these cycles and need them for survival. Both floods and droughts serve as important functions in the renewal of life (Tellman personal communication, 2001). A common mistake made by newcomers is thinking that conditions observed over a span of a few years are normal to the area. During dry years people may not recognize potential flooding hazards and build within floodplains, resulting in serious consequences once wetter years arrive. Ranchers and farmers may mistake heavy rainfall years as "normal" and manage their lands accordingly, only to sustain heavy losses once drought-like conditions prevail.

1.2 Climatic Variability and the Sonoran Desert Conservation Plan

Under the Endangered Species Act, applicants for incidental take permits, such as Pima County, must take into account reasonably foreseeable threats to species, such as those circumstances which could result from floods, fires, droughts, freezes and other aspects related to variations in climate. Climate change, for instance, is one subject which has received much attention and will be considered here as an aspect of climatic variation.

Climatic variability affects nearly every facet of biological conservation planning. For instance, climatic variability can affect the feasibility of attaining biological goals and objectives stated in the Habitat Conservation Plan (HCP). Uncertainty about future climatic conditions, and the dynamic range of historic climate should therefore be considered when developing biological goals. Reserve design for individual species needs to consider climatic variability over space. Will a species be more secure from foreseeable climatic changes in a preserve that has a wide elevation gradient, or is replication in completely different watersheds, regardless of elevation variation, more desirable?

Table 1. Climatic Phenomena in southern Arizona

Time Scale	Climate Events	Hydrologic Events	Soil Phenomena	Biological Phenomena
Tens of Millennia	Glacial cycles	Changes in stream networks	Formation of petrocalcic and argillic horizons	Adaption of mammal genotypes to place
Millennia	Climate change	Arroyo filling Regional changes in water table and recharge rates, due to climate	Development of B horizon	New plant assemblages due to plant migration
Centuries	Major droughts CO_2-induced warming	Changes in rainfall-runoff relationships over regions	Formation of A horizon	Regional shifts in species ranges Stand-replacing forest fires Ecotonal shifts succession in deserts? Change in dominance of plants
Decades	El Niño events Pacific Decadal Oscillation Sunspot cycles	Changes in sinuosity and slope; Arroyo formation and fill	Soil erosion Cryptogamic crust formation Changes in soil nutrients and carbon	Changes in vegetation composition Life span of many plants Exotic species invasion Recruitment pulses Regionally synchronized fires
Years	Major winter storms Wind storms (micro-bursts)	Bankfull discharge Streambed recharge Local, natural variation in water table	Soil erosion Changes in soil moisture at deeper levels	Shifts in life cycle of annuals Fire frequency in grasslands, some forests Wind throw
Seasons	Summer monsoonal thunderstorms Foresummer drought Frost	Seasonal variation in ET and base-flow discharge	Seasonal changes in soil moisture	Seasonal growth Animal migration
Days	Daily light cycle	Rapid growth and reproduction of some cryptograms in response to rainfall.	Bioturbation	Foraging Predation

Adaptive management plans are written to provide flexibility for HCPs to respond to changed circumstances which can reasonably be anticipated. Climatic variation is one type of changed circumstance that can be anticipated. Adaptive management plans should be designed to respond to climatic variability that might be experienced during the term of the permit. Applicants for HCPs must propose minimization and mitigation measures. By considering climatic extremes, more effective minimization and mitigation strategies may be designed. Monitoring to determine whether biological goals are being met is needed to provide feedback for adaptive management. If adaptive management is to respond to climatic variability, then monitoring will need to include measurement of key variables that influence the habitat or population dynamics of covered species.

HCPs must consider changes in circumstances affecting a species or geographic area covered by an HCP, that can be reasonably anticipated by the applicant and U. S. Fish and Wildlife Service at the time of the preparation and that can be planned for. These are called "changed circumstances". In the event that additional conservation and mitigation measures are deemed necessary to respond to changed circumstances, the applicant will be expected to implement the measures specified in the HCP, but only those measures and no others.

USFWS will not require the commitment of additional land, water, or financial compensation, or additional restrictions on the use of land, water or money for a finding of an unforeseen circumstances, unless the landowner consents. If an unforeseen circumstance occurs, the wildlife agencies are limited to modifications within conserved habitat areas and the conservation program set up in the HCP. These modifications will not involve additional land, water or financial compensation, or additional restrictions.

1.3 Purpose

The purpose of this report is to explore the range of climatic variability that might be experienced over the next 30 years, and to contemplate how these variations might affect plants, animals, people and ecosystem processes. It was written for scientists, planners and the general public who are or will be involved in the development of the Sonoran Desert Conservation Plan. A general review of literary sources and computer modeling was performed to provide a general overview of climate variability in Pima County. Our focus was on water availability and temperature, since these are two of the most important climatic factors that determine species distribution over the landscape. By adding the effects of climate variation on species found within the region and the probability of climatic changes for the future, the authors hope to provide insights as to why climate variation is important in the conservation planning process and the actions that can taken to reduce the stresses that human activities have in compounding the negative effects of climate on natural environments. As a conclusion, the report provides potential measures which might be included within an HCP to respond to natural climatic variability.

2.0 Setting and Background

2.1 Geographic Setting

Pima County is situated between the subtropics and temperate climatic zones of North America. Our coniferous forests and broad-leafed deciduous riparian woodlands are part of our temperate heritage, while our desert and oak woodland vegetation is a legacy of the tropics (Brown, 1982). Pima County's position at the edge of the tropics is also reflected in the fauna, as many species are at the northern limits of their range within this region (Felger and Wilson, 1995).

Pima County is located within the Basin and Range physiographic province of the southwestern United States. The Basin and Range province is characterized by a series of broad alluvial valleys separated by linear, sharply-rising mountain ranges. Elevations in Pima County range from a low point of 660 feet west of Ajo, to a high point of 9,157 feet above mean sea level in the Santa Catalina Mountains north of Tucson (Figure 1).

The Santa Catalina, Santa Rita and Rincon Mountains, and, to a lesser degree, other ranges in the County have served as a refuge for animals and plants that would have otherwise disappeared during warm, inter-glacial periods such as that which has prevailed over the last 10,000 years. These mountain ranges, known as "sky islands," also nurture perennial streams with a unique fish fauna. During glacial periods, the floral and faunal constituents of the mountains and streams extended farther down into the valleys.

Pima County is geologically diverse. Rock types run the gamut from acidic volcanic and intrusive rocks, to limestone, basalt, andesite and metamorphic schists. Wide, sloping, alluvial piedmonts derived from erosion of the mountains are a dominant landform. Substrate diversity on these alluvial slopes is enhanced by great variation in the type and degree of soil formation. Over time, dust accumulating on these surfaces creates distinctive subsurface zones of clay and calcium carbonate which profoundly affect the character of the vegetation. Associated with the valley floors are extensive bottom lands of deep, fine soils. Where bedrock outcrops occur in present-day valleys, sites are created for high groundwater tables to persist during long periods of aridity.

2.2 Origin of Storms

Pima County is located between the mid-latitude and subtropical atmospheric circulation regimes (Sheppard et al., 1999). The interplay between various atmospheric circulation patterns causes much of the variation in our climate. Most of the precipitation in the region is derived from three distinct sources of moisture: the North American monsoon, dissipating tropical cyclones, and frontal and cutoff low-pressure storm systems (Webb and Betancourt, 1992).

The North American monsoon is the major circulation pattern that sets the climate of the Southwestern U. S. apart from the rest of the United States. The term "monsoon" is based on its similarities to the better known Southwest Asian Monsoon. Similarities in the two circulations

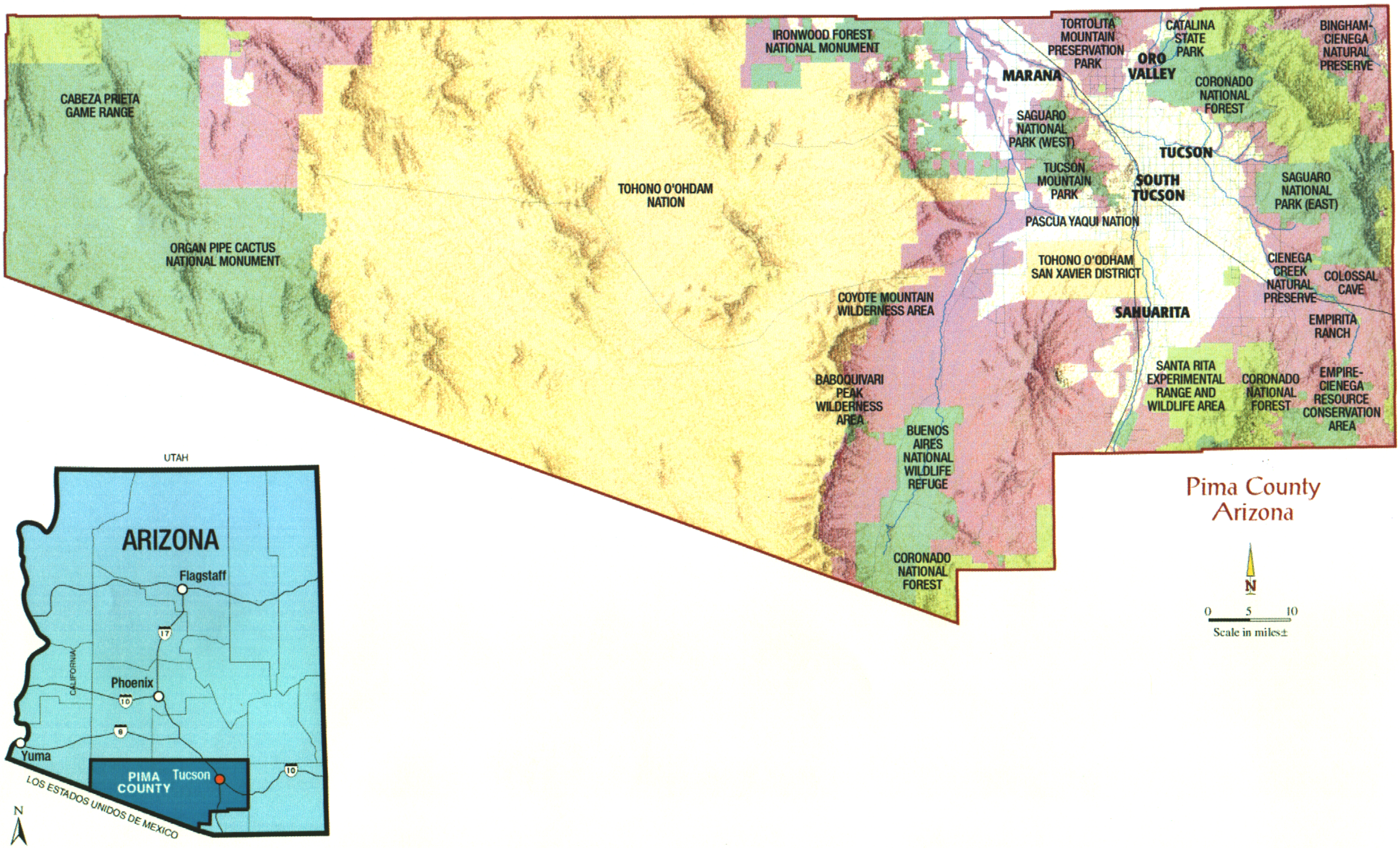


Figure 1. Site Location Map

include a shift in mid-level moisture flow from westerly to easterly, the mean diurnal low-level moisture flow changing from offshore to onshore, extremely hot and dry conditions preceding the onset of rainfall and a rapid increase in areal coverage of rainfall during the early summer (Douglas et al., 1993). The monsoon produces around half of our average annual rainfall, principally during July, August and September (Sheppard et al., 1999).

During the late summer and early fall, September through October, southern Arizona's weather is often affected by dissipating tropical cyclones. Tropical cyclones in the Pacific Ocean generally develop off the west coast of Mexico, approximately 185 miles south of the southernmost point in Baja California (Webb and Beteancourt, 1992). Most of these tropical cyclones move west-northwestward and may intensify into tropical storms or hurricanes. In many cases these storms continue moving out into the ocean, where they are dissipated by wind shear and colder water. Some tropical cyclones, however, move to the north and east, and dissipate over Mexico and the United States. These storms often cause intense precipitation and regional flooding (Webb and Betancourt, 1992). Some of Pima County's best autumn floods have resulted from these storms, including the memorable flood of October 1983, described later within this report.

Winter storms in Pima County originate from large-scale low-pressure frontal systems that follow westerly winds from the Pacific Ocean (Webb and Betancourt, 1992). These storms generally form near the Gulf of Alaska and move southward with the expansion of a low-pressure cell, called the Aleutian Low, that occurs in the North Pacific. During dry winters in Pima County, a high pressure ridge forms off the west coast and steers the westerly winds to the north, bringing rain into the Pacific Northwest. During wet winters, the high-pressure ridge is displaced westward and a low pressure trough develops over the Western United States (Webb and Betancourt, 1992). Westerly winds then tend to move along the West Coast and enter the continent as far south as San Francisco, and bringing rain to the Southwest.

When the high-pressure ridge (mentioned above) is well developed, the low-pressure systems can stagnate, forming cutoff-low-pressure systems. These systems can intensify off the coast of California before moving inland, and produce substantial rainfall once they reach Arizona (Webb and Betancourt, 1992). In autumn, these cutoff low-pressure systems may stall over warm tropical waters and steer dissipating tropical storms inland, thus producing ideal conditions for very heavy rainfall in Arizona (Hansen and Schwarz, 1981).

2.3 Effects of Atmospheric Circulations

Storms in Pima County can be affected by the El Niño-Southern Oscillation (ENSO) cycle, with opposite phases consisting of the El Niño and La Niña circulations. El Niño is an increase in sea surface temperatures in the eastern equatorial Pacific Ocean that usually results in increasing winter precipitation across Peru and the southern tier of the United States (USDC, 1998a). La Niña, associated with cooler oceanic surface temperatures in the Eastern Pacific, often results in dry winters across the southwestern United States (USDC, 1998b). Typical durations of ENSO events range from 6 to 18 months. Both El Niño and La Niña events can vary in strength (i.e., the 1987 La

Niña event was stronger than the La Niña in 1995, and the El Niño in 1997-1998 was unusually strong compared to past El Niño events).

Another important oceanic influence upon our climate is the Pacific Decadal Oscillation (PDO), which involves variations in sea surface temperatures in the North Pacific Ocean. In 1996, fisheries scientist Steven Hare coined the term "Pacific Decadal Oscillation" while researching the connection between the Pacific climate and Alaskan salmon production (JISAO, 2000). Unlike ENSO events, the PDO has been known to persist for long periods of time, with both cool and warm events lasting 20 to 30 years over the last century. Several independent studies found that two full cycles occurred during the last century: two "cool" regimes from 1890-1924 and 1947-1976, while "warm" PDO regimes occurred from 1925-1946 and 1977 to the mid-1990's (JISAO, 2000). Causes and predictability for this influence on our climate are currently unknown.

2.4 History of Weather Data Collection

The collection of written, reliable weather records in Pima County dates back to the late 1800's. The first weather station in Tucson was established at Fort Lowell in November 1866 (Glueck, 1997). The weather station with the longest record in Pima County is at the University of Arizona, where records began in 1894. Weather records typically consist of daily rainfall measurements, and minimum and maximum daily temperatures. The availability of modern, automated measuring devices has generally increased the resolution (hourly measurements are now common) and precision of measurements.

Weather stations exist in only a few locations in Pima County, and even fewer stations have long (greater than 20 years) periods of records. Table 2 and Figure 2 summarize the locations of weather stations in and near Pima County that have records longer than 20 years. Records from stations located outside of Pima County were used to more accurately model climatic data along the fringes and where records were scarce.

Because of the paucity of historic records, other sources of information are being used by researchers to extend our understanding of climatic variability back in time. Study of pollen grains found in layers of sediment can be used to indicate the types of vegetation that once existed in an area, and hence give clues to the climate that existed in periods of the past (Merideth, 2001). Other sources of information are geologic features shaped by water, such as stream channels and deposits related to past stream flows, or sand dunes, which generally correspond to prevailing winds in arid climates. Study of pack-rat middens, which consist of rodent collected vegetation over time in caves and rock shelters, can also provided information on past vegetation types (Meredith, 2001).

Another widely used technique to describe past climates is to look at the density and width of annual tree-ring growth (Merideth, 2001). Tree-ring records, which provide annual resolution, can extend the climatic record back 1000 years or more. Tree-ring records of mid-elevation forests are thought to reflect a composite of moisture availability during the growing season and temperature, as modulated by soil type and other site-specific factors (Sheppard et al., 1999). Tree rings in SW

Table 2. Location of Weather Stations

Map #	Station ID	Station Name	County	Elev. (ft)	Record (Yrs)	Begin Date	End Date
1	020080	Ajo	Pima	1800	86	05/01/1914	12/31/1999
2	020088	Ajo Well	Pima	1430	28	07/01/1948	04/30/1975
3	020204	Amado	Santa Cruz	3051	28	07/01/1948	07/31/1976
4	020287	Anvil Ranch	Pima	2750	52	07/01/1948	12/31/1999
5	020309	Apache Powder Company	Cochise	3689	68	07/01/1923	04/30/1990
6	020380	Arivaca 1 E	Pima	3620	44	01/02/1956	12/31/1999
7	020680	Benson	Cochise	3671	79	06/01/1894	05/31/1975
8	020923	Bosley Ranch	Graham	4803	19	07/01/1948	05/31/1966
9	021231	Canelo 1 NW	Santa Cruz	5010	89	01/01/1910	12/31/1999
10	021306	Casa Grande	Pinal	1462	99	06/01/1898	12/31/1999
11	021314	Casa Grande Natl Mon.	Pinal	1419	79	03/01/1906	12/31/1999
12	021330	Cascabel	Pinal	3145	31	04/01/1969	12/31/1999
13	022140	Coronado Natl Mon.	Cochise	5242	40	02/25/1960	12/31/1999
14	022159	Cortaro 3 SW	Pima	2270	29	07/01/1948	09/30/1976
15	022430	Dateland	Yuma	449	17	04/01/1952	10/31/1968
16	022434	Dateland Whitewing Ranch	Yuma	545	28	06/01/1972	12/31/1999
17	022797	Elgin 5 N	Santa Cruz	4905	59	10/01/1912	01/31/1970
18	022807	Eloy 4 NE	Pinal	1545	49	05/25/1951	12/31/1999
19	022902	Fairbank 1 S	Cochise	3852	65	07/02/1909	03/31/1973
20	023120	Fort Huachuca	Cochise	4665	51	02/01/1900	12/31/1981
21	023393	Gila Bend	Maricopa	735	105	12/01/1892	12/31/1999
22	023398	Gila Bend Aviation	Maricopa	722	19	07/01/1948	12/31/1966
23	023981	Helvetia Santa Rita Ranch	Pima	4304	35	06/01/1916	04/30/1950
24	024675	Kitt Peak	Pima	6790	40	09/01/1960	12/31/1999
25	024698	Klondyke 3 SE	Graham	3612	26	09/01/1953	04/30/1978
26	025274	Maricopa 9 SSW	Pinal	1401	58	06/01/1898	12/31/1958
27	025627	Mohawk	Yuma	541	52	07/01/1900	05/31/1951
28	025908	N Lazy H Ranch	Pima	3050	44	07/01/1948	12/31/1991
29	025921	Nogales	Santa Cruz	3812	36	07/01/1948	06/30/1983
30	025922	Nogales Old Nogales	Santa Cruz	3904	48	12/01/1892	06/30/1948
31	025924	Nogales 6 N	Santa Cruz	3560	48	10/01/1952	12/31/1999
32	026116	Oracle	Pinal	4603	54	01/01/1893	03/31/1949
33	026119	Oracle 2 SE	Pinal	4510	50	02/25/1950	12/31/1999
34	026132	Organ Pipe Cactus N M	Pima	1678	52	07/01/1948	12/31/1999
35	026202	Palisade Ranger Stn.	Pima	7956	17	01/01/1965	09/30/1981
36	026280	Patagonia #2	Santa Cruz	4042	57	07/01/1921	12/31/1977
37	026282	Patagonia #2	Santa Cruz	4190	22	01/01/1978	12/31/1999
38	026506	Picacho Reservoir	Pinal	1512	28	01/01/1956	08/31/1983
39	027036	Redington	Pima	2940	51	07/01/1948	12/31/1999
40	027058	Red Rock 6 SW	Pima	1880	53	01/01/1893	10/31/1973
41	027326	Ruby 4 NW	Santa Cruz	3983	36	04/01/1895	12/31/1955

Table 2. Location of Weather Stations

Map #	Station ID	Station Name	County	Elev. (ft)	Record (Yrs)	Begin Date	End Date
42	027330	Helmet Peak Ruby Star R	Pima	3642	33	02/01/1950	10/1719/83
43	027355	Sabino Canyon	Pima	2640	35	07/01/1948	09/30/1982
44	027403	Sahuarita 2 NW	Pima	2690	17	02/14/1956	08/31/1972
45	027530	San Manuel	Pinal	3460	46	06/01/1954	12/31/1999
46	027555	San Rafael Ranch	Santa Cruz	4744	53	12/01/1892	03/31/1968
47	027583	Santa Margarita	Pima	3934	34	06/01/1917	11/30/1950
48	027593	Santa Rita Exp Range	Pima	4300	50	05/01/1950	12/31/1999
49	027600	Santa Rosa School	Pima	1841	19	09/23/1959	06/30/1977
50	027619	Sasabe	Pima	3590	41	02/12/1959	12/31/1999
51	027622	Sasabe 7 NW	Pima	3825	50	12/01/1950	12/31/1999
52	027726	Sells	Pima	2345	29	07/02/1948	12/31/1999
53	027751	Sentinel	Maricopa	689	31	01/01/1899	03/31/1960
54	027880	Sierra Vista	Cochise	4600	18	03/01/1982	12/31/1999
55	027915	Silver Bell	Pima	2740	37	02/11/1906	04/30/1974
56	028619	Tombstone	Cochise	4610	104	07/01/1893	12/31/1999
57	028795	Tucson 17 NW	Pima	2561	18	05/01/1982	12/31/1999
58	028796	Tucson UA Exp Farm	Pima	2330	50	02/11/1949	12/31/1999
59	028800	Tucson Magnetic Obsy	Pima	2526	46	07/01/1948	03/31/1994
60	028815	Tucson UA	Pima	2478	106	09/01/1894	12/31/1999
61	028817	Tucson U of Ariz #1	Pima	2315	18	05/01/1982	12/31/1999
62	028820	Tucson WSO	Pima	2549	52	07/01/1948	12/31/1999
63	028865	Tumacocori Natl Mon.	Santa Cruz	3267	52	07/01/1948	12/31/1999
64	029382	Willow Springs Ranch	Pinal	3691	29	04/06/1949	12/31/1978
65	029420	Winkelman 6 S	Pinal	2080	30	02/22/1942	05/31/1980
66	029562	Y Lightning Ranch	Cochise	4590	61	01/01/1939	12/31/1999

* Shaded stations are located outside Pima County

Legend

Map #	Provided by the Pima County Technical Services, Geographic Information Systems
Station ID	Provided by the National Weather Service Cooperative Network
Station Name	Provided by the National Climatic Data Center
County	County in which station is located; stations outside of county used for data gaps and fringe areas
Elevation	Elevation above sea level
Record	Number of years during which records were kept
Begin Date	Beginning date of record
End date	Ending date of record

Weather Station Locations

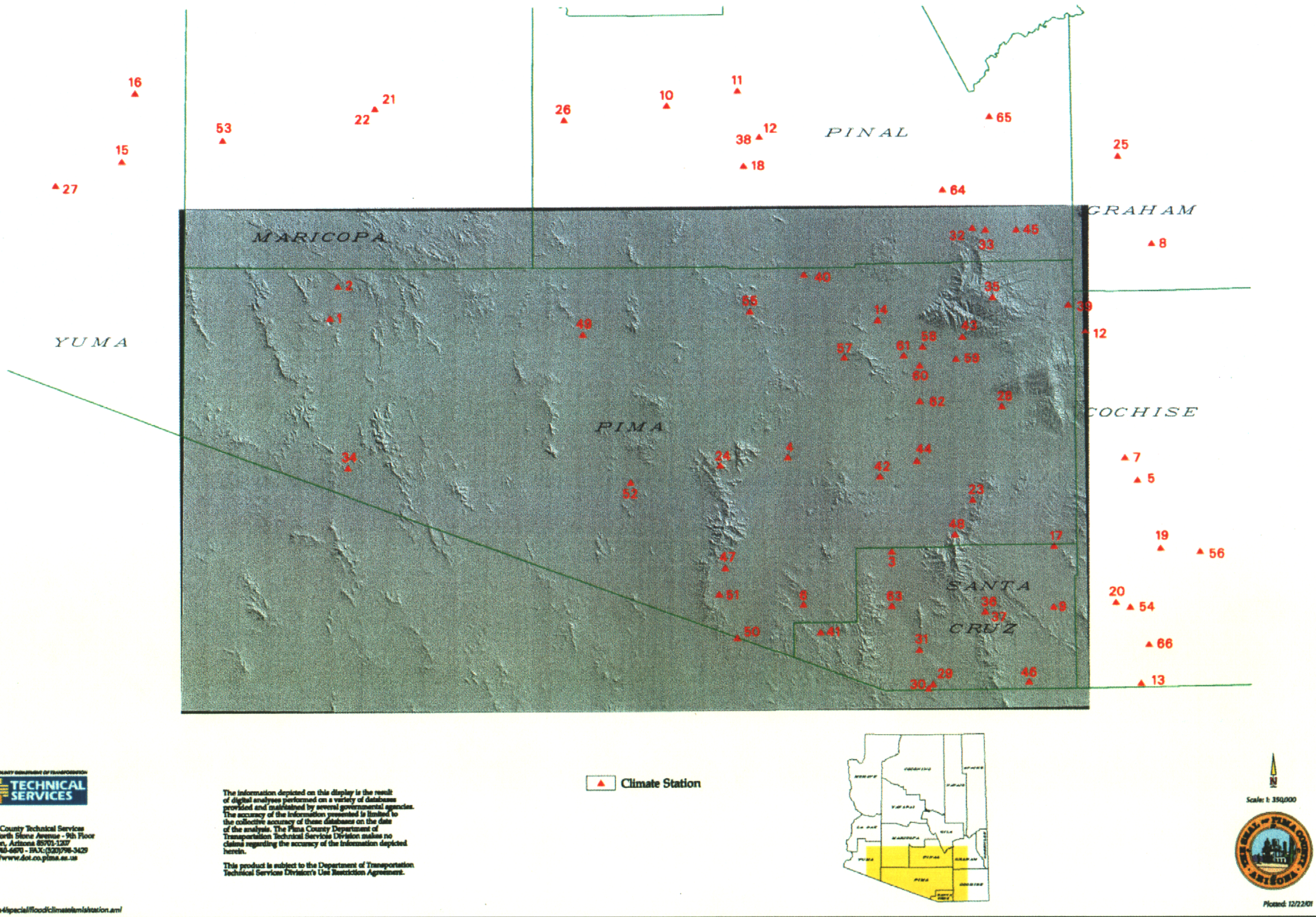


Figure 2. Location of Weather Stations

conifers, which are the easiest and most commonly dated, actually provide a record of winter versus summer and fall rains. In most years, the foresummer drought produces a "false" growth ring, which is distinct from the annual growth ring, and thus allow the researcher to separate the two wet seasons (Gungle personal communication, 2001).

2.5 Climatic Data Collection and Modeling

Climatic data for this report was obtained through the Western Regional Climatic Center (WRCC) and the National Climatic Data Center (NCDC). Most of the data from the WRCC are already manipulated and accessible as monthly means, daily extreme temperatures, number of heating days, fall freeze probability and freeze free probability. NCDC data was obtained and manipulated for all stations not listed by the WRCC.[1] All data for this report are being stored using Microsoft Access and manipulated using Excel Spreadsheets. Spatial representations of average seasonal precipitation were prepared by Dr. Joel Michaelson (Figures 7, 9, 15 and 16). These models use a regression of precipitation against elevation. Elevations are based upon a 30 meter digital elevation model. All relevant climate data for the U.S. and Mexico collected by the National Weather Service and archived at the National Climatic Data Center were used for these analyses.

The Pima County Flood Control District (PCFCD) has its own rain gauge network, called the ALERT system, which it uses for the purposes of providing flood warnings to the Tucson area. ALERT stands for Automated Local Evaluation in Real Time. The network comprises approximately 65 precipitation gauges throughout Eastern Pima County, 25 of which also report stream flow (Figure 3). Four of the gauges located along the mountain ranges provide complete weather data, including temperature, wind speed and direction, relative humidity and barometric pressure.

The ALERT system provides precipitation, stream flow and weather transmissions from a field gauge to an office database, which then translates the transmissions into usable data for the PCFCD hydrologists and other users (i.e., National Weather Service, Pima County Emergency Management, etc.). The time from measurement by the gauge to translation by the database is almost instantaneous. Figure 4 exhibits a typical rain gauge setup and transmission relay to the PCFCD office. All of the data are stored by the database, which periodically archives old data onto backup disks. The data are primarily used by PCFCD hydrologists to predict when and where flooding will occur, so they can direct road closures and evacuations as necessary. The data may also be used retroactively, to document flood hazard areas and assist with future planning efforts for floodplain areas. ALERT system data were not used for modeling by Dr. Michaelson because of the relatively short record at each station (most stations were installed after 1987). Although not used specifically for this report, ALERT system data could be useful for future climatological and biological monitoring for the Sonoran Desert Conservation Plan.

[1] Temperature data were not available through the NCDC for many of the stations. The designation "NA", meaning not available, is used in these cases.

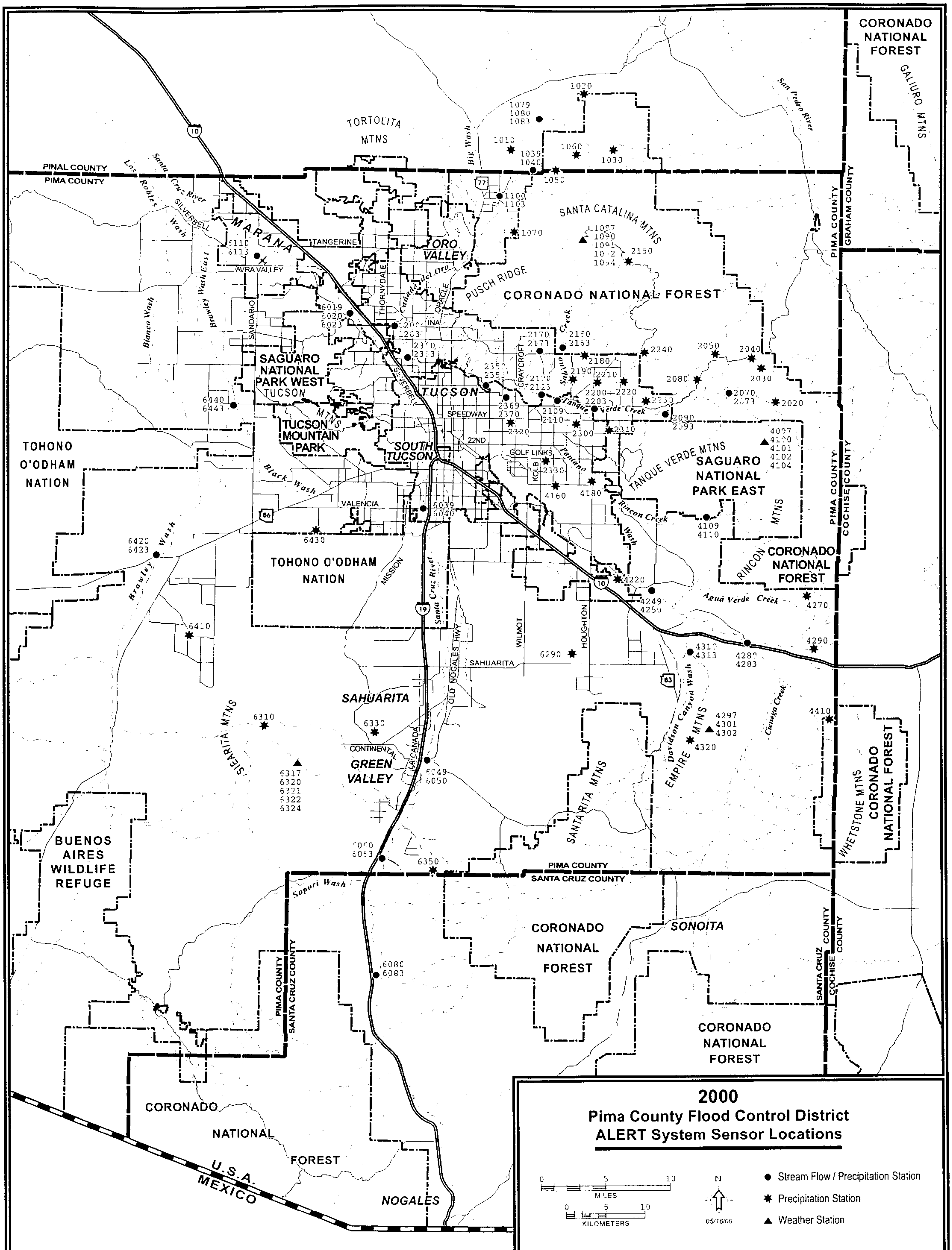


Figure 3. ALERT Gauge Locations in Pima County

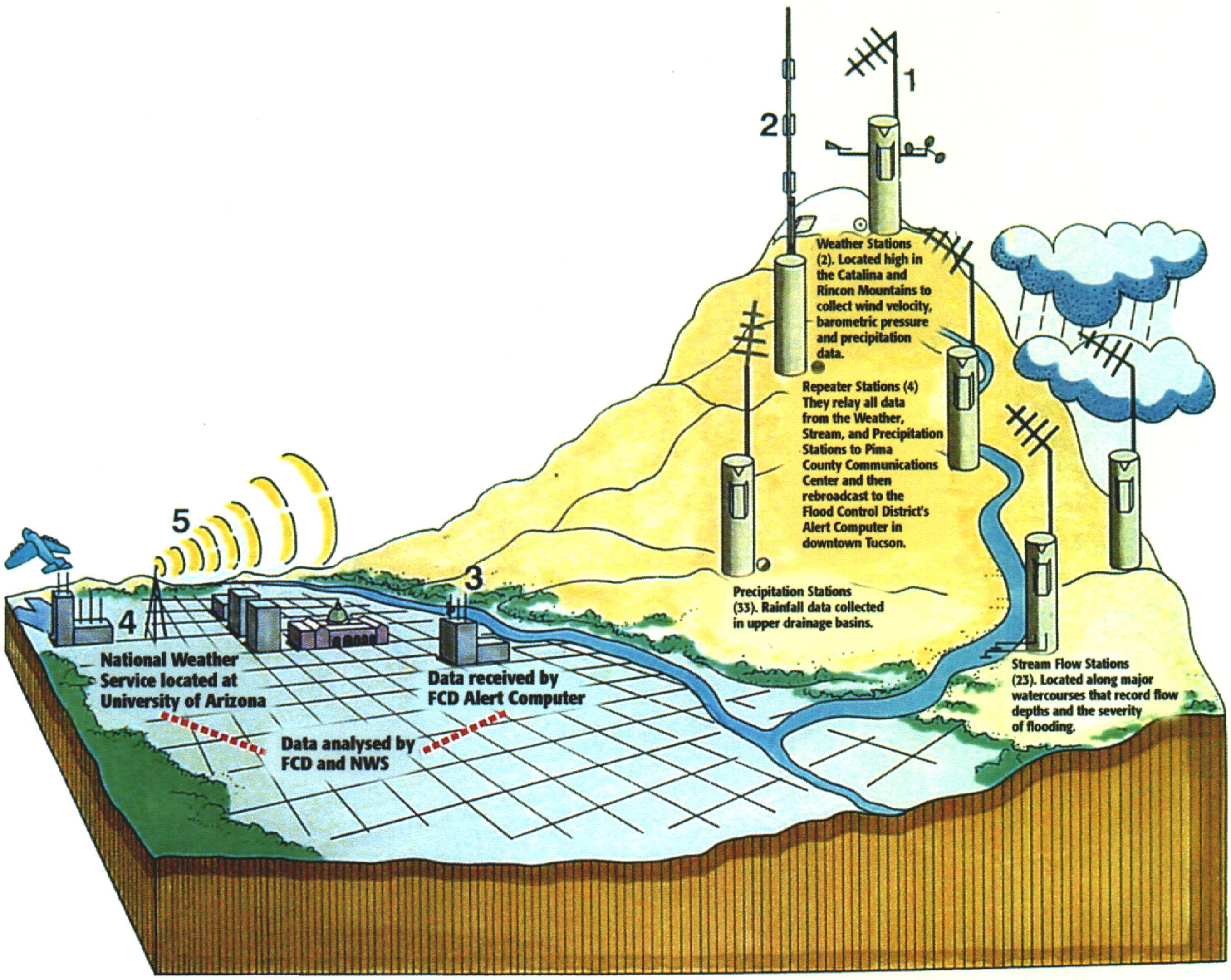


Figure 4. ALERT Gauge and Transmission Relay Schematic

3.0 Climatological Variables

3.1 Precipitation

In Pima County, half of the rainfall occurs during the summer monsoonal period, usually July and August. September, October and November are typically dry. The amount of winter rainfall is highly variable, but generally occurs from December to March. The late spring and foresummer aridity (April through June) generally corresponds with high temperatures, making the duration of the arid foresummer a key biological constraint. The summer monsoonal rains reduce water stress during the hottest portion of the growing season, which is one reason why the Sonoran Desert is more biologically diverse than the Mohave Desert, which is dominated by winter rainfall alone, and the Chihuahuan Desert, which receives mostly summer rainfall.

In general, the summer rains control the annual grass production that supports the livestock industry. Winter rains help increase soil moisture and influence woody plant growth (Swetnam and Betancourt, 1998) and provide important annual plant resources.

Precipitation generally increases with elevation, about 4-5 inches for every 1000-foot gain (Lowe 1985). This generalization appears to hold true when looking at rainfall totals for Pima County and the surrounding areas (Figure 5). Our wettest station, Palisade Ranger Station at 7,960 feet above mean sea level, receives an average rainfall of 31.2 inches. Our driest station, Ajo Well at 1,790 feet, receives an average of less than 8.0 inches per year. Average monthly rainfall totals for all stations are displayed in Table 3; lowest annual rainfall totals are displayed in Table 4.

Average annual rainfall generally increases from west to east (Figure 6). Weather stations along valleys in the west show yearly precipitation totals ranging from 7.8 to 9.7 inches, while those in the east (Tucson Basin) have totals ranging from 9.8 inches to 13.2 inches. This difference in rainfall totals might be attributed to higher elevations in the east (approximately 500 to 700 feet higher in the valleys) and the close proximity of high elevation mountain ranges to one another, thus producing heavier storm activity during the summer monsoon season.

Summer rainfall included the months of June to October (Figure 7). The Altar Valley, Empire-Cienega and upper Santa Cruz watershed receive as much precipitation as the lower portions of the Santa Catalina and Rincon Mountains. The northeastern portion of the county only receives slightly more rainfall than Western Pima County (Table 5). A comparison of summer rainfall to elevation indicates an approximate one inch increase for every 400 foot gain in elevation (Figure 8). The winter rainfall season, defined as November through March (Figure 9, Table 6), represents rain that falls when evaporation rates and plant water needs are low. Winter precipitation in Pima County is not affected by elevation as much as summer rainfall, as indicated by an estimate of one inch increase for every 800 foot gain in elevation (Figure 10). Note that a portion of Avra Valley near the Tucson Mountains has much less rainfall than the surrounding areas, which could suggest that an orographic effect is potentially occurring in this area (Figure 9).

Figure 5. Comparison of Mean Annual Rainfall to Elevation

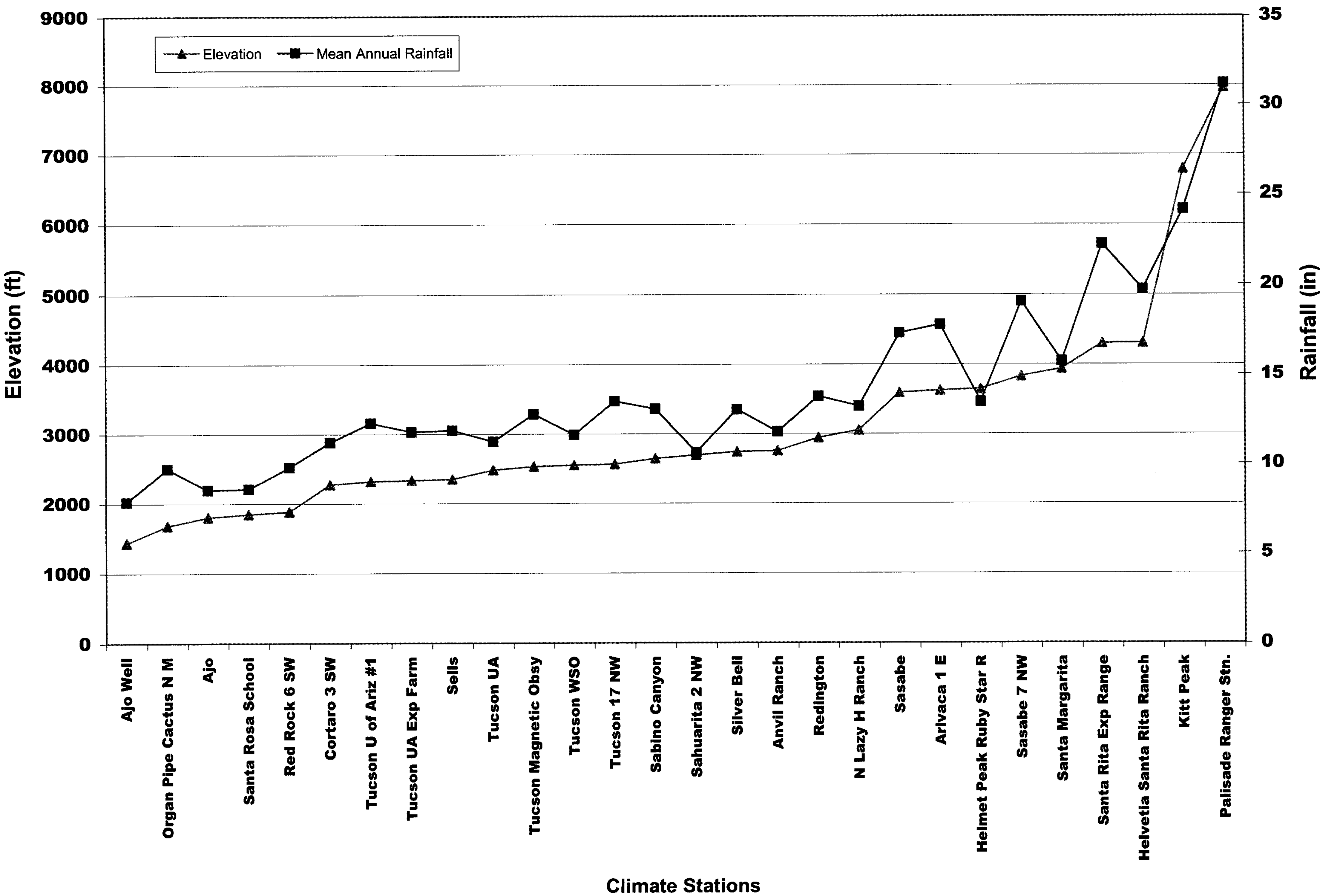


Table 3. Average Monthly Precipitation and Measure of Variability (shaded areas are outside Pima County)

Station ID	Station Name	Average Precipitation (inches)													Std. Error
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
020080	Ajo	0.71	0.62	0.77	0.28	0.10	0.07	1.20	1.96	0.85	0.54	0.57	0.85	8.52	2.87
020088	Ajo Well	0.50	0.47	0.61	0.24	0.05	0.06	1.12	2.08	0.82	0.65	0.51	0.73	7.84	2.49
020204	Amado	0.76	0.61	0.61	0.19	0.05	0.27	3.56	2.96	1.50	0.65	0.49	1.03	12.68	3.30
020287	Anvil Ranch	0.78	0.70	0.69	0.27	0.18	0.26	2.58	2.47	1.44	0.84	0.50	1.05	11.76	4.34
020309	Apache Powder Company	0.76	0.67	0.50	0.29	0.17	0.57	3.20	3.10	1.63	0.90	0.53	0.87	13.19	3.88
020380	Arivaca 1 E	1.15	1.10	1.03	0.29	0.20	0.41	4.08	3.86	1.81	1.27	0.92	1.64	17.76	4.54
020680	Benson	0.68	0.74	0.51	0.23	0.10	0.37	2.69	2.79	1.32	0.62	0.57	0.71	11.33	3.16
020923	Bosley Ranch	1.27	0.77	1.20	0.42	0.15	0.43	2.85	2.82	1.44	0.90	0.76	1.33	14.34	3.90
021231	Canelo 1 NW	1.24	1.19	0.94	0.44	0.20	0.70	4.42	4.07	1.70	0.96	0.84	1.41	18.11	4.11
021306	Casa Grande	0.73	0.81	0.76	0.29	0.12	0.17	1.03	1.52	0.80	0.52	0.72	0.98	8.45	2.90
021314	Casa Grande Natl Mon.	0.89	0.85	0.92	0.33	0.15	0.14	1.10	1.28	0.79	0.71	0.74	1.19	9.09	3.31
021330	Cascabel	1.20	1.19	0.95	0.30	0.37	0.37	2.35	2.75	1.49	1.15	0.68	1.21	14.01	3.72
022140	Coronado Natl Mon.	1.73	1.46	1.18	0.39	0.26	0.51	4.53	3.91	1.99	1.32	1.01	2.19	20.48	5.17
022159	Cortaro 3 SW	0.74	0.79	0.81	0.40	0.07	0.28	2.26	2.05	1.07	0.87	0.71	1.14	11.19	3.30
022430	Dateland	0.32	0.38	0.13	0.08	0.00	0.05	0.17	0.57	0.26	0.48	0.13	0.61	3.18	1.76
022434	Dateland Whitewing Ranch	0.57	0.51	0.60	0.14	0.06	0.01	0.41	0.76	0.47	0.39	0.31	0.63	4.86	2.99
022797	Elgin 5 N	0.91	0.90	0.58	0.27	0.11	0.58	3.57	3.66	1.64	0.72	0.58	1.10	14.62	3.76
022807	Eloy 4 NE	0.92	0.86	1.03	0.27	0.19	0.10	1.11	1.68	0.83	0.85	0.74	1.16	9.74	3.68
022902	Fairbank 1 S	0.58	0.60	0.29	0.25	0.09	0.56	3.23	2.83	1.28	0.54	0.54	0.76	11.55	3.16
023120	Fort Huachuca	1.10	0.97	0.79	0.28	0.24	0.52	3.86	3.46	1.72	0.88	0.74	1.08	15.64	3.99
023393	Gila Bend	0.60	0.61	0.64	0.21	0.12	0.05	0.75	1.03	0.52	0.39	0.49	0.70	6.11	2.97
023398	Gila Bend Aviation	0.68	0.43	0.42	0.15	0.05	0.03	0.73	1.30	0.45	0.50	0.32	0.56	5.62	2.36
023981	Helvetia Santa Rita Ranch	1.58	1.72	1.14	0.52	0.28	0.67	4.05	4.15	2.19	0.68	1.22	1.52	19.72	5.41
024675	Kitt Peak	1.80	1.68	1.81	0.56	0.42	0.38	4.49	4.84	2.47	1.53	1.30	2.88	24.16	8.35
024698	Klondyke 3 SE	1.09	1.03	1.22	0.43	0.17	0.63	2.62	2.13	1.75	1.23	0.92	1.65	14.87	3.88
025274	Maricopa 9 SSW	0.62	0.69	0.52	0.31	0.12	0.12	1.14	1.20	0.76	0.42	0.56	0.88	7.34	3.28
025627	Mohawk	0.38	0.45	0.33	0.17	0.02	0.06	0.38	0.84	0.47	0.25	0.23	0.67	4.25	3.55
025908	N Lazy H Ranch	1.16	0.96	0.97	0.36	0.17	0.25	2.53	2.50	1.34	1.03	0.71	1.22	13.20	3.62
025921	Nogales	1.05	0.78	0.95	0.26	0.14	0.40	4.71	3.59	1.60	1.12	0.63	1.34	16.57	4.13
025922	Nogales Old Nogales	0.94	0.94	0.71	0.31	0.14	0.47	3.67	4.17	1.75	0.65	0.80	1.15	15.70	4.42
025924	Nogales 6 N	1.15	0.90	0.92	0.36	0.24	0.39	4.52	4.15	1.61	1.26	0.67	1.49	17.66	4.85
026116	Oracle	2.01	1.92	1.58	0.80	0.31	0.44	2.56	3.28	1.63	0.90	1.65	2.30	19.38	4.40
026119	Oracle 2 SE	2.16	2.16	2.26	0.87	0.46	0.37	3.22	3.77	1.88	1.62	1.57	2.39	22.66	5.56
026132	Organ Pipe Cactus N M	0.84	0.70	0.87	0.22	0.11	0.07	1.42	2.00	0.95	0.75	0.59	1.19	9.71	3.65

Table 3. Average Monthly Precipitation and Measure of Variability (shaded areas are outside Pima County)

Station ID	Station Name	Average Precipitation (inches)													Std. Error
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
026202	Palisade Ranger Stn.	2.76	2.88	2.55	0.89	0.67	0.57	5.07	4.11	3.39	2.16	2.30	3.85	31.20	3.56
026282	Patagonia #2	1.12	1.02	0.77	0.34	0.14	0.46	4.27	4.07	1.93	1.03	0.75	1.35	17.25	3.85
026506	Picacho Reservoir	0.93	0.79	0.95	0.26	0.24	0.11	0.92	1.42	0.65	0.87	0.72	1.31	9.17	3.30
027036	Redington	1.24	0.98	1.11	0.33	0.25	0.24	2.73	2.41	1.30	1.05	0.74	1.38	13.76	3.97
027058	Red Rock 6 SW	0.67	0.69	0.80	0.30	0.12	0.25	1.45	1.82	1.06	0.64	0.88	1.11	9.79	2.95
027326	Ruby 4 NW	1.78	1.25	0.93	0.47	0.14	0.62	4.36	4.64	1.76	0.71	1.07	1.21	18.94	5.96
027330	Helmet Peak Ruby Star R	0.85	0.74	0.80	0.23	0.14	0.36	3.64	2.58	1.36	1.00	0.78	0.97	13.45	4.61
027335	Sabino Canyon	1.27	0.90	1.08	0.43	0.20	0.29	2.33	2.37	1.22	1.02	0.76	1.18	13.05	3.37
027403	Sahuarita 2 NW	0.50	0.47	0.50	0.21	0.06	0.26	2.57	2.12	1.43	0.66	0.63	1.21	10.62	2.84
027530	San Manuel	1.18	1.14	1.09	0.35	0.34	0.28	2.51	2.73	1.38	1.03	0.76	1.26	14.05	3.58
027555	San Rafael Ranch	0.98	0.95	0.88	0.39	0.11	0.66	4.80	4.04	1.76	0.79	0.68	1.23	17.27	3.62
027583	Santa Margarita	0.99	1.61	0.76	0.28	0.06	0.45	3.41	3.68	1.91	0.58	0.75	1.24	15.72	5.54
027593	Santa Rita Exp Range	1.63	1.45	1.56	0.66	0.24	0.65	4.88	4.33	2.18	1.55	1.12	1.98	22.23	5.88
027600	Santa Rosa School	0.36	0.43	0.48	0.11	0.11	0.12	1.61	1.96	1.03	0.60	0.55	1.21	8.57	1.51
027619	Sasabe	1.31	1.38	1.10	0.38	0.17	0.26	3.61	3.38	1.87	1.03	0.89	1.93	17.31	4.92
027622	Sasabe 7 NW	1.37	1.11	1.42	0.50	0.19	0.34	3.86	4.08	1.81	1.35	0.98	2.04	19.05	5.54
027726	Sells	0.79	0.53	0.75	0.26	0.07	0.13	2.71	2.60	1.24	0.99	0.56	1.23	11.86	3.06
027751	Sentinel	0.56	0.41	0.38	0.21	0.03	0.13	0.61	1.03	0.26	0.25	0.29	0.47	4.63	2.68
027880	Sierra Vista	1.07	0.67	0.48	0.42	0.32	0.30	3.13	4.05	1.51	0.93	0.44	1.27	14.59	5.56
027915	Silver Bell	0.76	0.84	0.86	0.28	0.13	0.30	2.06	2.78	1.45	1.37	0.77	1.42	13.02	3.43
028619	Tombstone	0.88	0.76	0.64	0.26	0.21	0.49	3.45	3.35	1.54	0.78	0.62	0.94	13.92	3.39
028795	Tucson 17 NW	0.98	1.12	1.04	0.35	0.25	0.25	2.23	2.84	1.37	0.98	0.76	1.31	13.48	5.19
028796	Tucson UA Exp Farm	1.02	0.91	0.87	0.39	0.17	0.21	2.10	2.09	1.14	0.92	0.71	1.25	11.78	3.31
028800	Tucson Magnetic Obsy	1.29	0.94	1.09	0.35	0.23	0.26	2.05	2.24	1.23	1.03	0.77	1.29	12.77	4.13
028815	Tucson UA	0.90	0.85	0.76	0.39	0.18	0.25	2.07	2.15	1.17	0.73	0.78	1.00	11.23	3.37
028817	Tucson U of Ariz #1	0.98	1.10	0.94	0.36	0.22	0.11	1.76	2.62	1.34	0.84	0.73	1.26	12.26	4.14
028820	Tucson WSO	0.90	0.75	0.73	0.31	0.18	0.22	2.32	2.30	1.40	0.88	0.61	1.01	11.61	3.22
028865	Tumacacori Natl Mon.	1.08	0.89	0.85	0.31	0.17	0.41	3.94	3.78	1.54	0.99	0.66	1.36	15.98	5.40
029382	Willow Springs Ranch	1.25	1.02	1.08	0.59	0.25	0.33	2.53	2.58	1.23	1.28	1.03	1.92	15.09	3.90
029420	Winkelman 6 S	1.25	1.06	1.06	0.38	0.28	0.31	1.95	2.62	1.48	1.25	0.86	1.41	13.91	4.25
029562	Y Lightning Ranch	0.86	0.57	0.55	0.18	0.13	0.61	3.44	3.47	1.54	0.96	0.60	1.18	14.09	3.98

Table 4. Lowest Annual Rainfall by Station
Descending Order

Station ID	Station Name	Lowest Annual Rainfall (in)
026202	Palisade Ranger Stn.	26.00
024675	Kitt Peak	14.93
023981	Helvetia Santa Rita Ranch	13.47
026116	Oracle	12.96
026119	Oracle 2 SE	12.34
027619	Sasabe	11.31
027555	San Rafael Ranch	10.82
027593	Santa Rita Exp Range	10.51
027326	Ruby 4 NW	10.12
021231	Canelo 1 NW	10.06
022140	Coronado Natl Mon.	9.97
025922	Nogales Old Nogales	9.79
026282	Patagonia #2	9.54
025921	Nogales	9.33
028795	Tucson 17 NW	9.22
025924	Nogales 6 N	9.16
027880	Sierra Vista	9.09
021330	Cascabel	8.92
028619	Tombstone	8.82
024698	Klondyke 3 SE	8.43
020380	Arivaca 1 E	8.28
027915	Silver Bell	8.23
027622	Sasabe 7 NW	8.15
027600	Santa Rosa School	7.86
027530	San Manuel	7.77
027403	Sahuarita 2 NW	7.60
028865	Tumacocori Natl Mon.	7.49
029382	Willow Springs Ranch	7.46
023120	Fort Huachuca	7.21
020923	Bosley Ranch	6.94
025908	N Lazy H Ranch	6.82
027726	Sells	6.76
027583	Santa Margarita	6.67
029562	Y Lightning Ranch	6.57
027355	Sabino Canyon	6.36
022159	Cortaro 3 SW	6.27
028817	Tucson U of Ariz #1	6.25
020204	Amado	6.03
028815	Tucson UA	5.72
020680	Benson	5.66
020309	Apache Powder Company	5.61
028800	Tucson Magnetic Obsy	5.59
028796	Tucson UA Exp Farm	5.58
029420	Winkelman 6 S	5.55
027036	Redington	5.48
022807	Eloy 4 NE	5.41
022797	Elgin 5 N	5.38
028820	Tucson WSO	5.34
027330	Helmet Peak Ruby Star R	5.21
026506	Picacho Reservoir	4.98
022902	Fairbank 1 S	4.82
020287	Anvil Ranch	4.26
021306	Casa Grande	3.84
027058	Red Rock 6 SW	3.71
021314	Casa Grande Natl Mon.	3.56
020080	Ajo	3.46
026132	Organ Pipe Cactus N M	3.38
025274	Maricopa 9 SSW	3.11
020088	Ajo Well	2.03
023393	Gila Bend	2.02
022434	Dateland Whitewing Ranch	1.56
025627	Mohawk	1.55
027751	Sentinel	1.41
023398	Gila Bend Aviation	1.30
022430	Dateland	0.58

Note: Shaded stations are located outside of Pima County

Figure 6. Comparison of Mean Annual Precipitation from West to East

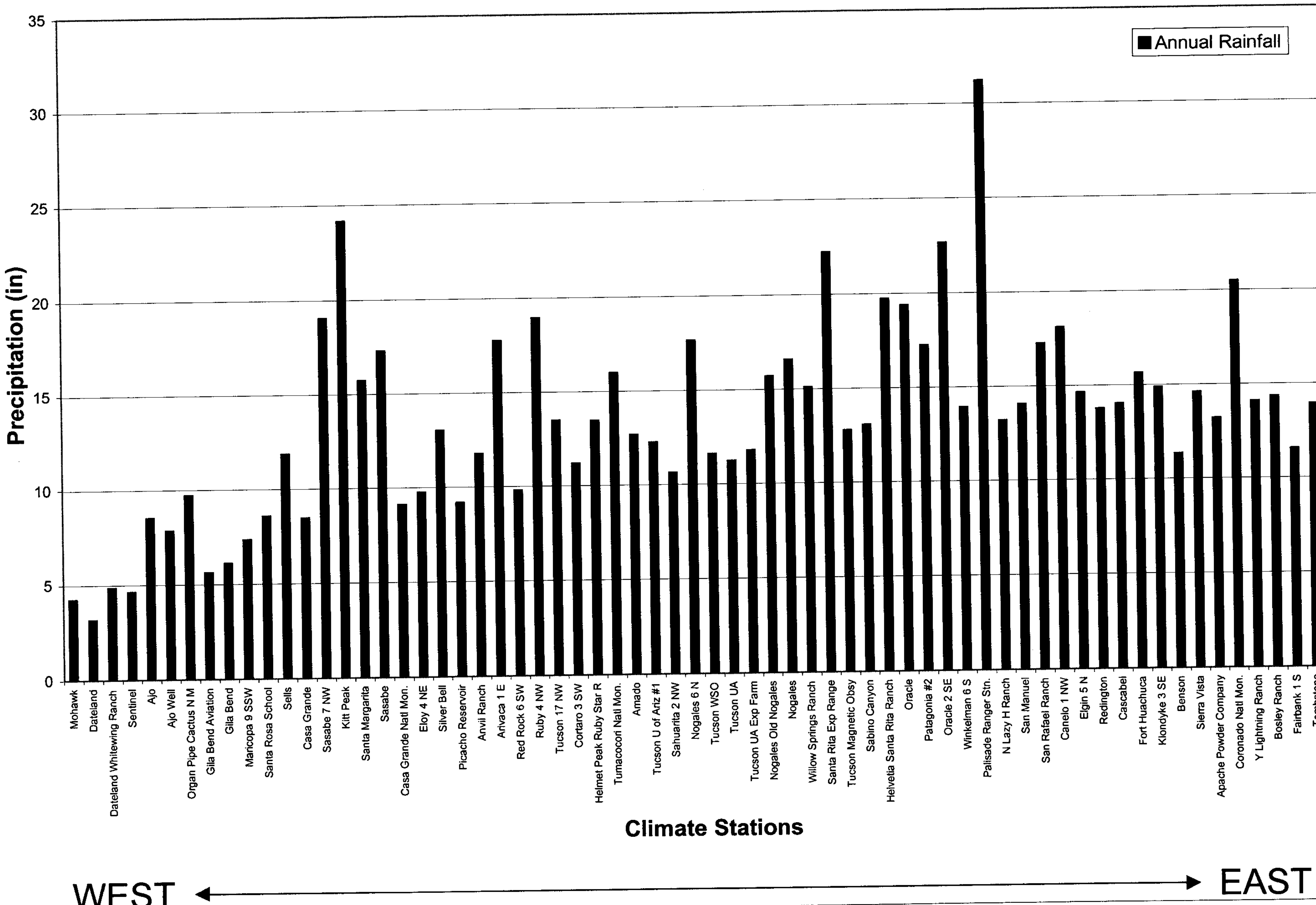


Figure 7

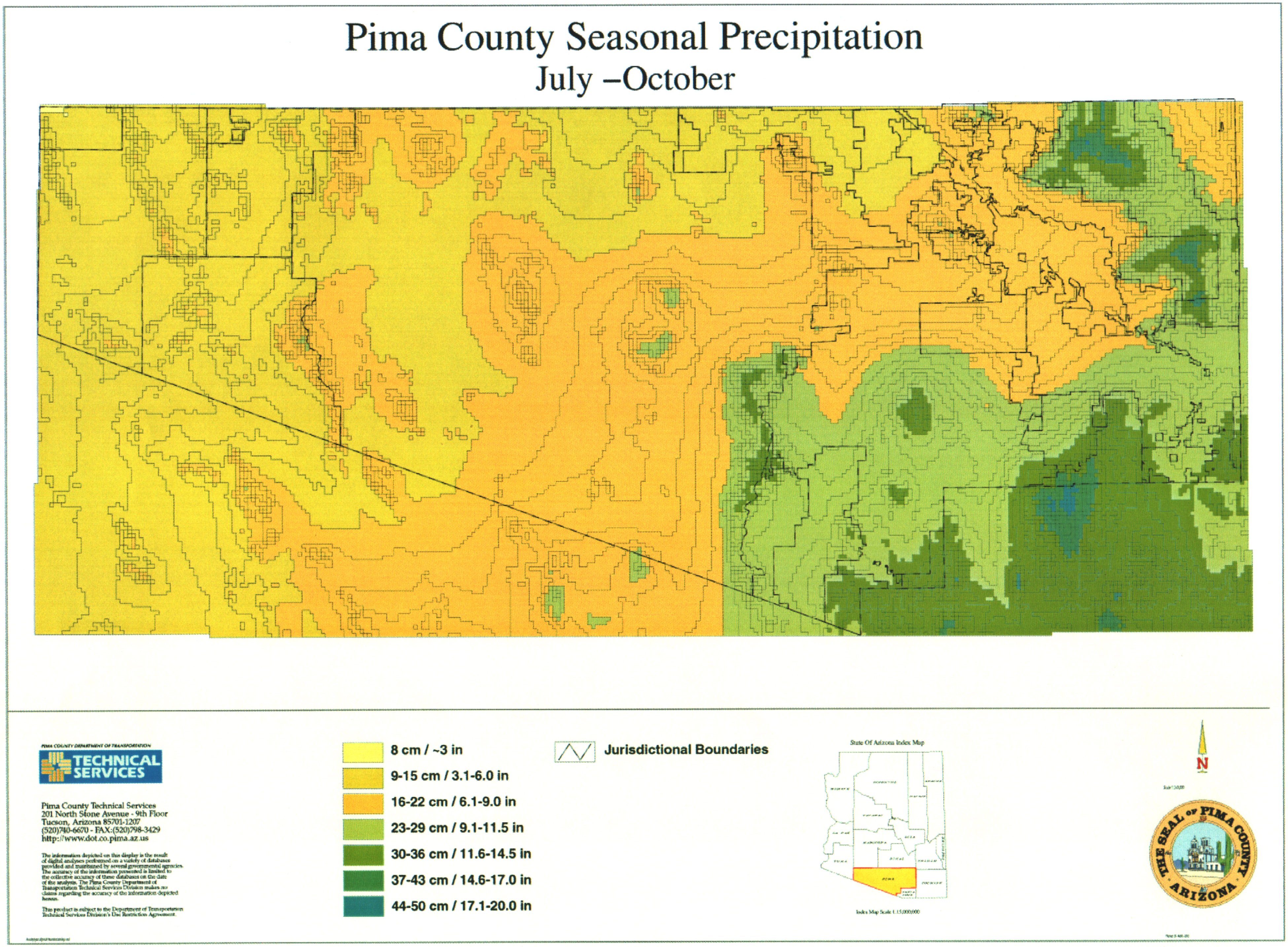


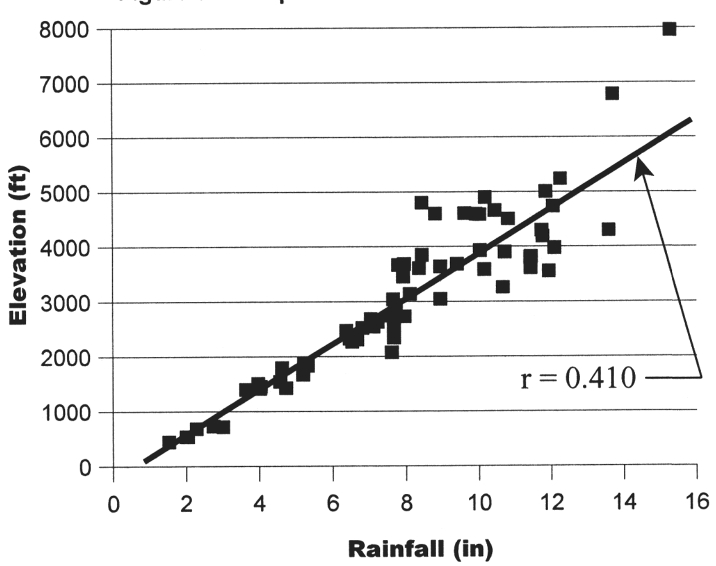
Figure 7. Distribution of Summer Rainfall

Table 5. Mean Summer Rainfall by Station (June-October)

Descending Order (Shaded Stations are Outside Pima County)

Station ID	Station Name	Elev. (ft)	Summer Rainfall (in)
026202	Palisade Ranger Stn.	7956	15.30
024675	Kitt Peak	6790	13.71
027593	Santa Rita Exp Range	4300	13.59
022140	Coronado Natl Mon.	5242	12.26
027326	Ruby 4 NW	3983	12.09
027555	San Rafael Ranch	4744	12.05
025924	Nogales 6 N	3560	11.93
021231	Canelo 1 NW	5010	11.85
026282	Patagonia #2	4190	11.76
023981	Helvetia Santa Rita Ranch	4304	11.74
027622	Sasabe 7 NW	3825	11.44
020380	Arivaca 1 E	3620	11.43
025921	Nogales	3812	11.42
026119	Oracle 2 SE	4510	10.81
025922	Nogales Old Nogales	3904	10.71
028865	Tumacocori Natl Mon.	3267	10.66
023120	Fort Huachuca	4665	10.44
022797	Elgin 5 N	4905	10.17
027619	Sasabe	3590	10.15
027583	Santa Margarita	3934	10.03
029562	Y Lightning Ranch	4590	10.02
027880	Sierra Vista	4600	9.92
028619	Tombstone	4610	9.61
020309	Apache Powder Company	3689	9.40
027330	Helmet Peak Ruby Star R	3642	8.94
020204	Amado	3051	8.94
026116	Oracle	4603	8.81
022902	Fairbank 1 S	3852	8.44
020923	Bosley Ranch	4803	8.44
024698	Klondyke 3 SE	3612	8.36
021330	Cascabel	3145	8.11
027915	Silver Bell	2740	7.96
029382	Willow Springs Ranch	3691	7.95
027530	San Manuel	3460	7.93
020680	Benson	3671	7.79
027036	Redington	2940	7.73
027726	Sells	2345	7.67
028795	Tucson 17 NW	2561	7.67
025908	N Lazy H Ranch	3050	7.65
029420	Winkelman 6 S	2080	7.61
020287	Anvil Ranch	2750	7.59
027355	Sabino Canyon	2640	7.23
028820	Tucson WSO	2549	7.12
027403	Sahuarita 2 NW	2690	7.04
028800	Tucson Magnetic Obsy	2526	6.81
028817	Tucson U of Ariz #1	2315	6.67
022159	Cortaro 3 SW	2270	6.53
028796	Tucson UA Exp Farm	2330	6.46
028815	Tucson UA	2478	6.37
027600	Santa Rosa School	1841	5.32
027058	Red Rock 6 SW	1880	5.22
026132	Organ Pipe Cactus N M	1678	5.19
020088	Ajo Well	1430	4.73
020080	Ajo	1800	4.62
022807	Eloy 4 NE	1545	4.57
021306	Casa Grande	1462	4.04
021314	Casa Grande Natl Mon.	1419	4.02
026506	Picacho Reservoir	1512	3.97
025274	Maricopa 9 SSW	1401	3.64
023398	Gila Bend Aviation	722	3.01
023393	Gila Bend	735	2.74
027751	Sentinel	689	2.28
022434	Dateland Whitewing Ranch	545	2.04
025627	Mohawk	541	2.00
022430	Dateland	449	1.53

Figure 8. Comparison of Summer Rainfall to Elevation



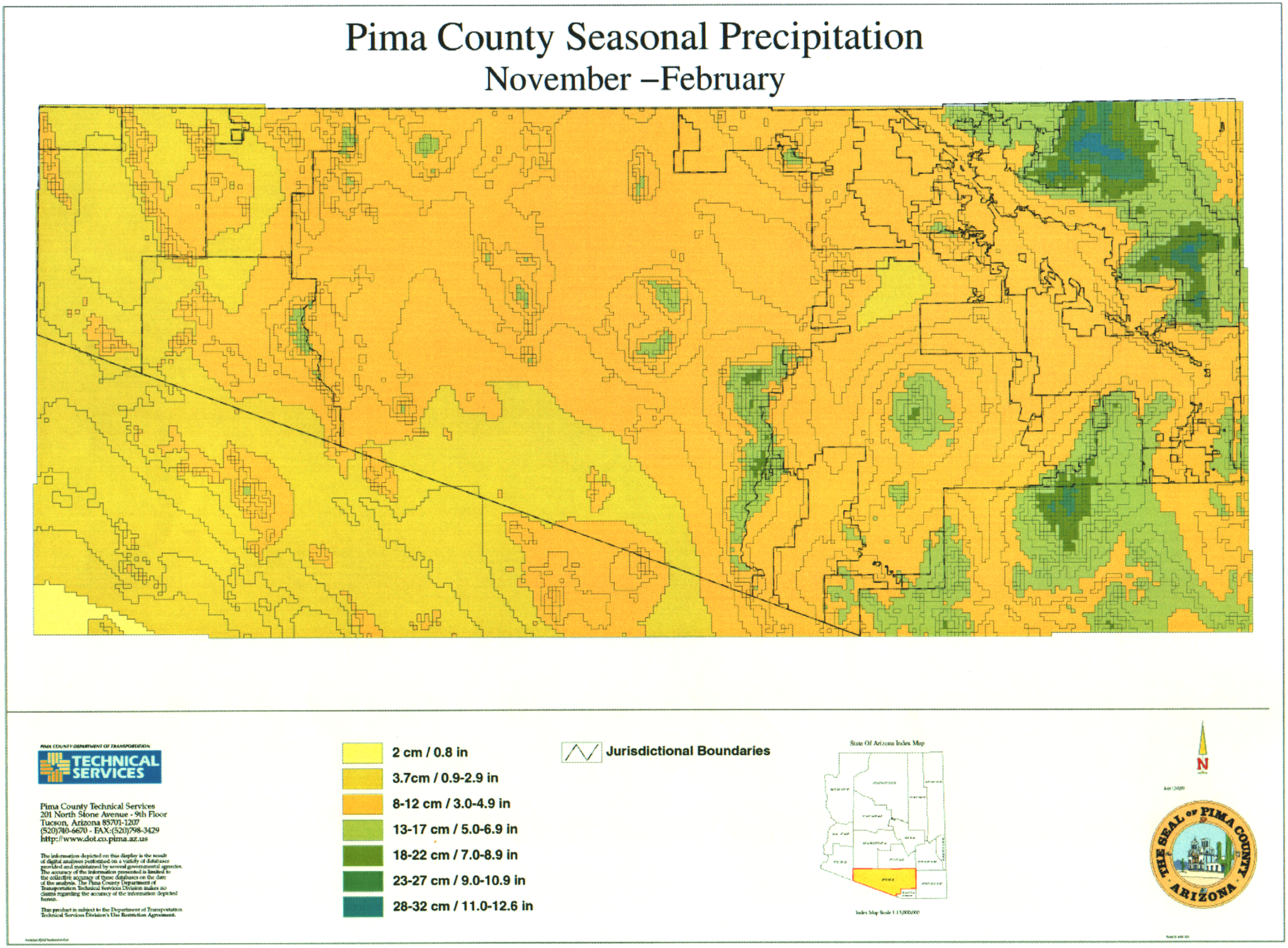


Figure 9. Lowest Minimum Temperature

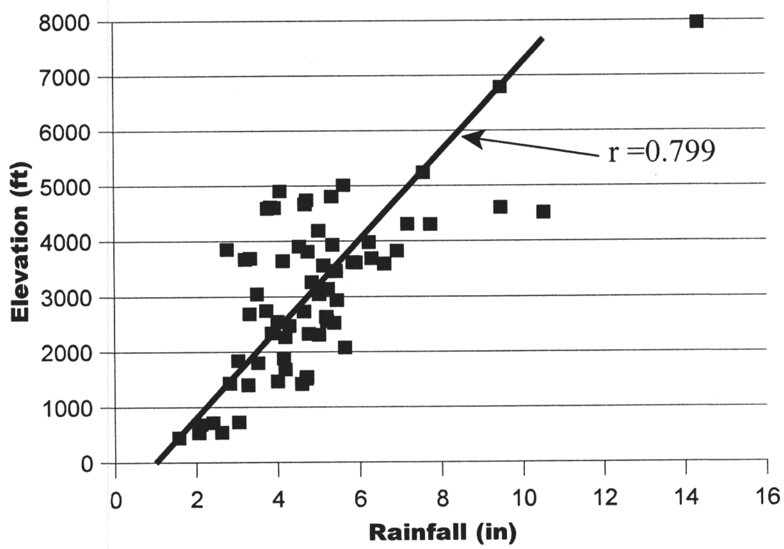
Figure 9

Table 6. Mean Winter Rainfall by Station (November-March)

Descending Order (Shaded Stations are Outside Pima County)

Station ID	Station Name	Elev. (ft)	Winter Rainfall (in)
026202	Palisade Ranger Stn.	7956	14.34
026119	Oracle 2 SE	4510	10.52
024675	Kitt Peak	6790	9.47
026116	Oracle	4603	9.46
027593	Santa Rita Exp Range	4300	7.74
022140	Coronado Natl Mon.	5242	7.57
023981	Helvetia Santa Rita Ranch	4304	7.18
027622	Sasabe 7 NW	3825	6.92
027619	Sasabe	3590	6.61
029382	Willow Springs Ranch	3691	6.30
027326	Ruby 4 NW	3983	6.24
024698	Klondyke 3 SE	3612	5.91
020380	Arivaca 1 E	3620	5.84
029420	Winkelman 6 S	2080	5.64
021231	Canelo 1 NW	5010	5.62
027036	Redington	2940	5.45
027530	San Manuel	3460	5.43
028800	Tucson Magnetic Obsy	2526	5.38
027583	Santa Margarita	3934	5.35
020923	Bosley Ranch	4803	5.33
021330	Cascabel	3145	5.23
028795	Tucson 17 NW	2561	5.21
027355	Sabino Canyon	2640	5.19
025924	Nogales 6 N	3560	5.13
025908	N Lazy H Ranch	3050	5.02
028817	Tucson U of Ariz #1	2315	5.01
026282	Patagonia #2	4190	5.01
028865	Tumacocori Natl Mon.	3267	4.84
028796	Tucson UA Exp Farm	2330	4.76
025921	Nogales	3812	4.75
027555	San Rafael Ranch	4744	4.72
022807	Eloy 4 NE	1545	4.71
026506	Picacho Reservoir	1512	4.70
023120	Fort Huachuca	4665	4.68
027915	Silver Bell	2740	4.65
021314	Casa Grande Natl Mon.	1419	4.59
025922	Nogales Old Nogales	3904	4.54
028815	Tucson UA	2478	4.29
026132	Organ Pipe Cactus N M	1678	4.19
022159	Cortaro 3 SW	2270	4.19
027058	Red Rock 6 SW	1880	4.15
027330	Helmet Peak Ruby Star R	3642	4.14
022797	Elgin 5 N	4905	4.07
021306	Casa Grande	1462	4.00
028820	Tucson WSO	2549	4.00
027880	Sierra Vista	4600	3.93
027726	Sells	2345	3.86
028619	Tombstone	4610	3.84
029562	Y Lightning Ranch	4590	3.76
020287	Anvil Ranch	2750	3.72
020080	Ajo	1800	3.52
020204	Amado	3051	3.50
020309	Apache Powder Company	3689	3.33
027403	Sahuarita 2 NW	2690	3.31
025274	Maricopa 9 SSW	1401	3.27
020680	Benson	3671	3.21
023393	Gila Bend	735	3.04
027600	Santa Rosa School	1841	3.03
020088	Ajo Well	1430	2.82
022902	Fairbank 1 S	3852	2.77
022434	Dateland Whitewing Ranch	545	2.62
023398	Gila Bend Aviation	722	2.41
027751	Sentinel	689	2.11
025627	Mohawk	541	2.06
022430	Dateland	449	1.57

Figure 10. Comparison of Winter Rainfall to Elevation



3.2 Variability of rainfall

Annual rainfall totals vary greatly from year to year and place to place. The occurrence of abnormal weather patterns created by such events as an El Niño or La Niña can either significantly increase or decrease rainfall totals in a given year or number of years. The strengths of such events, which can vary greatly, will also dictate the amount of rainfall that will occur. The summer monsoon season creates convective thunderstorms that are highly variable in nature. Rainfall can be widely scattered over a large areal extent or highly isolated over one small area. Some areas in Pima County may receive little precipitation in one year, while others are receiving a significant amount. Other years may see the opposite scenario occur.

An example of this variability is displayed in Figure 11, where average annual precipitation records for the weather station at Tucson National Weather Service Office are compared to the overall average for the period of record. As seen, most of the yearly measurements fall well above or below the average for the period of record, with only a few at or very near the average.

Standard error is a statistical device used to indicate the variability of measurements within a sample of records to the average measurement for the sample. A high standard error indicates there is more variability in the record, while a low standard error indicates less variability in the record. A list of standard errors for the precipitation records of each of the weather stations is in Table 3. Kitt Peak has the highest calculated standard error at 8.35 inches, while Santa Rosa School has the lowest at 1.51 inches.

Using a statistical theorem developed by the Russian mathematician P. L. Chebyshev (Walpole and Myers, 1989), we can roughly determine the probability that the average annual rainfall will fall within a certain range about the mean for the period of record.[1] As an example, we can expect that the annual average rainfall for the Tucson National Weather Station Office (Tucson WSO) will fall somewhere between 5.17 inches and 18.05 inches ($11.61 \pm 2(3.22)$) for at least 75 percent of the time. Actual rainfall does vary outside these boundaries, as indicated by Figure 11.

3.3 Drought

Drought is a normal, recurrent feature of climate (NDMC, 1995). The definition of "drought" can vary greatly from one region to another and from one discipline to another. Areas where people expect significant amounts of rainfall on a yearly or seasonal basis may identify the beginning, end and degree of severity of a drought differently than those that live in more arid climates. Various definitions can be derived from disciplinary perspectives such as meteorological, hydrological, agricultural and socioeconomic (Table 7). Possibly the best overall definition for drought is Palmer's 1965 definition which describes it as "an interval of time, generally of the order of months or years, during which the actual moisture supply at a given place cumulatively falls short of climatically appropriate moisture supply" (in Maidment, 1992).

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[1] Chebyshev's Theorem states that "the probability that any random variable X will assume a value within k standard deviations of the mean is at least $1-1/k^2$" (Walpole and Myers, 1989). So, the probability that a value will fall within 2 standard deviations of the mean is 3/4 or 75 percent.

Figure 11. Variability of Annual Rainfall at the Tucson Weather Service Office (Tucson WSO), 1948-1997

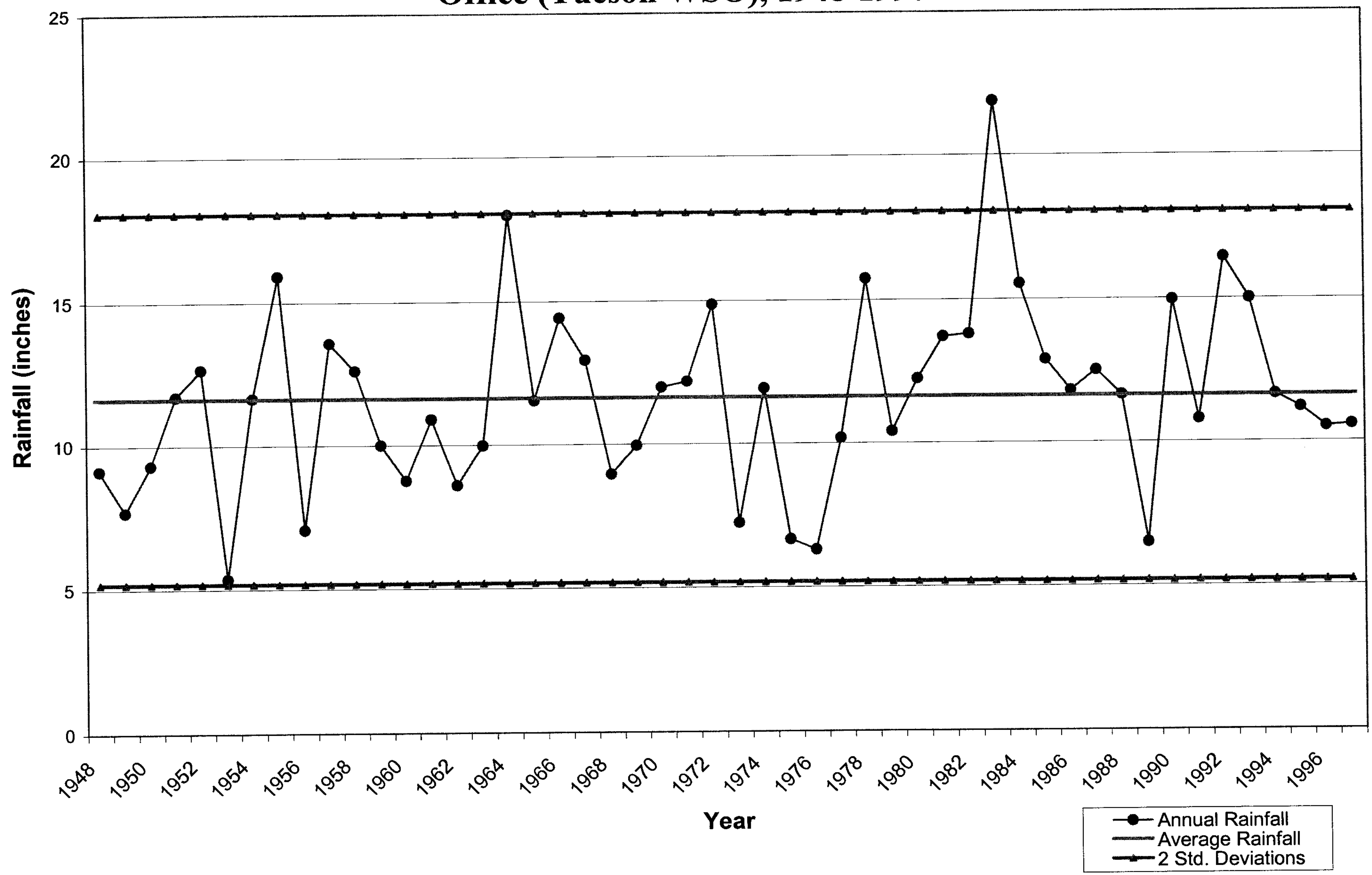


Table 7. Disciplinary Perspectives on Drought

Discipline	Perspective
Meteorological	Usually defined on the basis of the degree of dryness (in comparison to an average amount) and the duration of the dry period. This definition is considered region specific, because of the highly variable nature of atmospheric conditions from one region to another. Some definitions may characterize periods of drought on the basis of the number of days with precipitation less than some specific threshold (i.e., tropical and subtropical climates), while others are characterized by a seasonal rainfall pattern (i.e., Central United States). Other definitions may relate actual precipitation departures to average amounts on monthly, seasonal, or annual time scales.
Hydrological	Associated with the effects of periods of precipitation shortfalls on surface and subsurface water supplies (i.e., stream flows, reservoir levels, groundwater tables). The frequency and severity of hydrological drought are typically defined on a watershed or river basin scale. These definitions usually lag the occurrence of meteorological and agricultural droughts, since it takes longer for precipitation deficiencies to show up in components of the hydrologic system. Impacts are also out of phase with other economic impacts because different water users depend on these sources for their water supply (i.e., agriculturalists are almost immediately impacted by rapid losses in soil moisture, while hydroelectric power and recreational uses may not be affected for many months).
Agricultural	Agricultural drought focuses on the effects of precipitation shortages on crop production. It focuses on such characteristics as the differences between actual and potential evaporation, soil water deficits, reduced groundwater or reservoir levels, and so forth. A good definition takes into account the variable susceptibility of crops during their development, from emergence to maturity.
Socioeconomic	Socioeconomic definitions associate supply and demand of some economic good with elements of meteorological, hydrological and agricultural drought. It often occurs when the demand for an economic good exceeds the supply as a result of a weather-related shortfall in water supply.

Source: National Drought Mitigation Center (NDMC), 1995

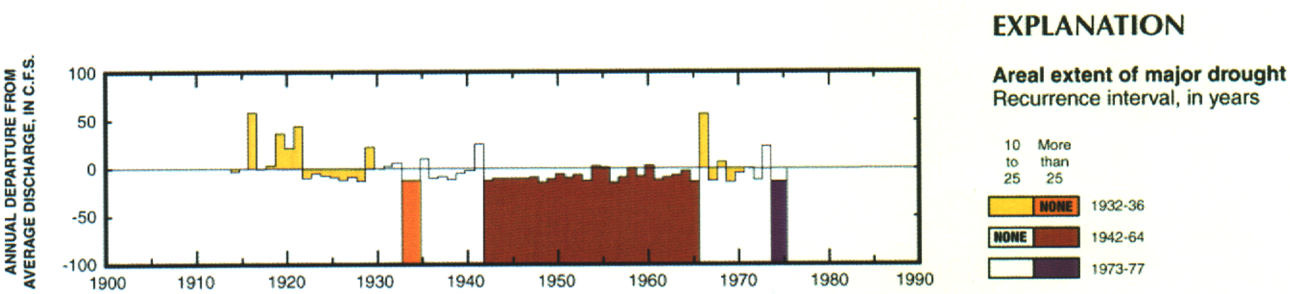
Differences in the various types of drought described in Table 7 are further emphasized by the sequence of drought impacts. In Pima County, the ranching sector is usually affected first because of its heavy dependence on surface water stored in stock tanks and the production of grasses. The farming and municipal sectors are usually affected last, because of their dependence on groundwater. As precipitation deficiencies continue, people dependent on surface water and shallow groundwater begin to feel the effects. The latter sectors may not even feel the impact (or feel very little impact) if the drought is short-term, say 3 to 6 months, depending on the characteristics of the hydrologic system and water use requirements (NDMC, 1995). When precipitation returns to normal, the sequence is repeated for recovery of the system, with soil moisture replenished first, followed by increases in stream flow, reservoir and lake levels, and groundwater tables. The length of the recovery period is a function of drought intensity, duration, and quantity of precipitation as the event terminates (NDMC, 1995).

In Arizona, including Pima County, streams are technically under drought conditions 60 to 80 percent of the time, with individual droughts commonly lasting as long as 5 years (Eychaner et al., 1990). Major droughts are less common, but much more severe. Table 8 shows a chronology of major droughts that have occurred throughout Arizona from 1932 to 1977. Severity of these droughts in Pima County are shown through records of annual departures from the average stream flow along Rillito Creek in Tucson (Figure 12).

Table 8. Chronology of Major Droughts in Arizona, 1932-1977

Date	Area Affected	Recurrence interval (years)	Remarks
1932-1936	Statewide	10 to 20	Effects differed among the basins.
1942-1964	Statewide	>100	The most severe in the last 400 years; probably the most severe in the last 1000 years.
1973-1977	Statewide	15 to 35	Most severe in eastern Arizona.

Source: Eychaner et al., 1990; Sweetnam and Betancourt, 1998



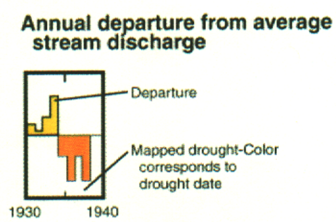


Figure 16. Departures from the average stream flow along Rillito Creek, 1862-1988

The 1950's drought (defined variously, but here from 1942 to 1964) may have been the worst drought in Arizona and New Mexico during the last 1000 years, and certainly for the last 400 years (Swetnam and Betancourt, 1998). This drought killed many woody, perennial plants in woodlands and increased the rate of shrub invasion in the grasslands in Arizona and New Mexico. The drought affected palo verde trees, range grasses, mesquite, cacti, manzanita, oaks and a variety of conifers. Although the effect of plant communities was great, the economic impact of this drought on the agricultural sector was not great since so much agricultural production in the region relied on irrigation (Swetnam and Betancourt, 1998).

By contrast, the period after 1976 shows up in thousand-year long tree-ring chronologies as a time of unprecedented growth. This unusually wet episode may have produced a big surge in tree recruitment in woodlands and may have improved rangeland conditions (Swetnam and Betancourt, 1998). This wet period is attributed to increased frequency of El Niño events. Wetter winters since 1976 may be responsible for the increase in red brome, a winter annual grass that can carry fire into the palo verde-cacti community.

Another important biologic effect correlated with drought includes fire in coniferous forests (Swetnam and Betancourt, 1998). Regionally synchronized fires have recurred over the centuries in the Southwest, according to tree-ring studies. Extreme droughts seem to cause much of the observed synchroneity in forest fires across southern Arizona and New Mexico, but antecedent wet conditions are also important factors controlling the timing of fires in some forests. Wet winters, in particular, increase the availability of grasses and understory vegetation, thus magnifying fire potential when subsequent dry periods occur (Meredith, 2001).

Drought conditions affect the amount of vegetation produced, but this effect varies according to the soil properties. The Natural Resource Conservation Service has produced estimates of how vegetation production on an annual basis varies according to rainfall and soils. This is important information for land managers, and especially the ranching community. Too much grazing can affect temperatures in a given area. For instance, analysis of temperature records for Sonora, Mexico shows that Sonoran stations are consistently warmer than stations in southwestern Arizona, when statistical controls for latitude and/or elevation are applied. The Sonoran weather stations also show a significant increase in the daily temperature range during the summer season (Balling et al., 1998). Afternoon temperatures in Sonora were up to 4°C (7°F) warmer than values measured in nearby areas in Arizona.

Paired field measurements along the border at and near Organ Pipe Cactus National Monument and six miles east of Sasabe suggest an explanation for how this occurs (Klopatek, unpublished data). Decreased vegetation cover and compaction of soils in Sonora are thought to have resulted in less infiltration, more rapid runoff, and substantial decreases in soil moisture and transpiration. When evapotranspiration decreases, the sun heats up the soil. Evaporation of water from the soil and transpiration from vegetation are important cooling mechanisms for the land surface. The growth and decay of vegetation helps put carbon into the soil. Organic carbon in the soil, in turn, helps to retain moisture and make it available for growth of plants. Perhaps this is why measures of resistance and resilience to drought are reduced by more intensive grazing in desert grasslands (Whitford et al., 1999 in Noss, 2001).

3.4 Floods

Like droughts, floods too are a normal, recurring feature of climate. They represent the opposite extreme of water supply, where precipitation falls in a specific location over a given time in excess of the ability of the soil to accept and store the water, thus producing large quantities of runoff. Floods have been defined in many ways, based on characteristics such as the quantity and expected frequency of stream flow, relation of flow to stream channel geometry, and possible damage to property. Therefore, floods can be any flow event that is large, that overtops the natural or artificial banks of a stream channel, or that results in the loss of life or damage to property (Thomas et al., 1997).

The recurrence interval of a flood is the average amount of time, in years, that an event of a particular magnitude will be equaled or exceeded (Dunne and Leopold, 1978). As an example, a 100-year flood event would be expected to occur, on the average, once within a 100-year period. This is not to say that the 100-year event will only occur once every 100-years, it just states that on average over the recorded history of a watercourse the frequency for the particular flood event is once every 100 years. The 100-year flood could occur in two successive years and then not be observed over a 200-year span or more. A better way of defining the 100-year flood is to say that it is an event that has a one percent chance of occurring in any given year. Table 9 displays the odds of occurrence for a number of flood events over a 50-year time period.

Over the 30-year period of the Sonoran Desert Conservation Plan, as indicated in Table 9, a given site has a 96 percent chance of experiencing a flood at least as big as the 10-year event. A "100-year" flood or greater has a 26 percent chance of occurring at the same site. And as multiple sites or watercourses are considered, the chances of floods occurring on at least one site will increase.

Table 9. Chance of Flooding Over a Period of 50 Years (%)

Time Period (years)	Flood Size			
	10-year	25-year	50-year	100-year
1	10	4	2	1
10	65	34	18	10
20	88	56	33	18
30	96	71	45	26
50	99	87	64	39

Data provided by the California Floodplain Management Division

Floods in the southwestern deserts are generally caused by one or both of the following two events: (1) high rates of rainfall that exceed the infiltration capacity of soils, thus producing rapid runoff; and (2) the rapid melting of a snowpack as the result of high temperatures or rainfall on the snowpack (Thomas et al., 1997). In Pima County, floods during the summer have typically occurred as the result of high intensity thunderstorms producing large amounts of rainfall over a short period of time. Summer rains normally produce local flooding, which occurs primarily in basins less than 100 square miles in area because the area affected by local thunderstorms is relatively small (Eychaner et al., 1990). Most of the floods in the winter have resulted from several days of intense regional rainfall, sometimes combined with snowmelt caused by rainfall onto an existing snowpack. These floods are normally more regional in scale, occurring in drainage basins that are larger than 200 square miles (Eychaner et al., 1990).

Flooding in Pima County is affected by conditions produced from such events as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). During ENSO conditions, winter frontal storms are usually more numerous and intense, often creating flooding scenarios as observed in 1993 (described below). The number of tropical cyclones dissipating over Arizona is also increased, as was the case during the ENSO years of 1976-1977 and 1982-1983 (Webb and Betancourt, 1992). Phases of the PDO will often increase or reduce the effects of an El Niño or La Niña. Since it lasts for longer periods of time, the PDO can also serve to prolong the conditions created by ENSO events.

A chronology of major and memorable flooding events in Pima County is displayed in Table 10. Within the last twenty years, two regional events have had a severe impact in Pima County. In the fall of 1983, moisture from Tropical Storm Octave moved northeastward across Arizona for several days, with the most intense rainfall occurring along a narrow band from south Tucson to Clifton, Arizona (Eychaner et al., 1990). This resulted in heavy flooding along many of the major watercourses in Pima County including the Santa Cruz River, where the peak discharge was more than twice that observed in the previous 65 years of records. The flood caused severe damage to bridges and buildings in Tucson, as well as inundating hundreds of acres of agricultural fields in Marana, Arizona. In January 1993, a series of low pressure systems stationed over the northeast Pacific Ocean produced a warmer- and wetter-than normal system that affected both California and Arizona (PCFCD, 1993). Heavy rain fell over most of central and southeast Arizona during a fifteen day period, melting snowpack and producing significant flooding along many of the major watercourses. No lives were lost or private homes swept away, but there was significant damage to public infrastructure and private property.

Over the last few decades, Pima County has seen a shift in the seasonal occurrence of floods. From 1915 to 1986, floods along the Santa Cruz River in July and August accounted for 75 percent of the annual peaks (Webb and Betancourt, 1992). However, 39 percent of the annual flood peaks for the period 1960-1986 occurred in the fall (September to October) or the winter (November to February). Seven of the eight largest flood peaks on this watercourse were produced by winter storms, with 5 of these occurring from 1960-1986 (Webb and Betancourt, 1992). This seasonal change in annual flood peaks is not unique to the Santa Cruz River, but has also been observed along other large streams (>1240 square mile drainage) in Arizona including Rillito Creek (Slezak-Pearthree and Baker, 1987) and the Gila and San Pedro Rivers (Roeske et al., 1989).

Table 10. Chronology of Major and Memorable Floods in Pima County, 1926-1993

Date	Area Affected	Recurrence Interval (yrs)	Remarks
Sept. 27-29, 1926	San Pedro River	>100	Tropical storm. Peak flow 2-3 times larger than any other in 70 years. Damage estimated at $450,000.
Sept. 26-28, 1962	Brawley and Santa Rosa Washes	>100	1 death; $3 million damage, mostly to agriculture near Casa Grande
Dec. 22, 1965 to Jan. 2, 1966	Rillito Creek and Santa Cruz River	<100	Wettest December in Tucson on record to date, 7.27 inches; several bridges damaged and closed to traffic; sewage lines ruptured along Rillito Creek
Oct. 1977 to Feb. 1980	Southeastern Arizona	<100	Peak discharge on the Santa Cruz River reached 30,000-40,000 cfs.
Oct. 1-3, 1983	Santa Cruz River and other majors watercourses	>100	Peak Flow on Santa Cruz River 2 times larger than previous 65 years; Total damage estimated at $105.7 million
Jan. 5-19, 1993	Santa Cruz River and other major watercourses	<100	Damage to public and private structures estimated at $13.9 million
October 2000	San Pedro River	>50	Peak discharge on the San Pedro River reached 16,000-20,000 cfs.

Sources: Eychaner et al., 1990; PCFCD, 1993; B. Gungle, personal communication.

A similar scenario is observed along Cienega Creek, where summer mean daily flows in the 1960's were typically higher than in the 1990's, and winter mean daily flows in the 1990's were typically higher than in the 1960's (PAG, 2001). Winter and spring flows in the 1990's were also observed to occur later in the season than they did in the 1960's. Also, fewer large-scale floods occurred in the 1990's than in the 1960's, most likely due to the decrease in summer storm activity; like most southwestern streams, floods along Cienega Creek occur primarily during the summer (PAG, 2001).

3.5 Groundwater

Although most rainfall in the desert evaporates, a small fraction of that water goes into storage underground. Once underground, the water is less susceptible to evaporation and is available to plants for their growth during periods when there is no rainfall. Water within the first ten feet or so of soil and rock will be used by plants and any excess will be available to pass deeper through the strata and into an aquifer, where it is held for long-term storage. In a healthy water cycle, rainfall is absorbed by soil, and evaporation and runoff losses are minimized (Pima County, 1999).

Water which reaches an aquifer is said to be "recharged" (Pima County, 1999). Most recharge occurs at higher elevations from rainfall and snowmelt runoff in the mountains (USGS, 2000).

Water then begins to seep into lower elevation aquifers through sand and gravel under normally dry washes that flow during periods of runoff or by subsurface flow through fractures in bedrock beneath the mountains (Figure 13). Eventually, the water discharges from the aquifers into springs, streams, rivers and other water bodies. Movement of water through the subsurface is often very slow, taking up to tens of thousands of years before discharging (USGS, 2000). In a natural state, long-term recharge to an aquifer is balanced by discharge to streams and springs, as well as evaporation and transpiration occurring in marshes and riparian areas (Pima County, 1999).

In the lower valleys, streambed recharge is believed to be primarily derived from infiltration of winter precipitation (Gallaher, 1979; Keith, 1981). This is because the storms in the winter are generally longer in duration and the rates of evapotranspiration are much lower than in the summer. Summer storms often have greater intensities than winter storms, but they typically produce little runoff and stream flow infiltration in the lower elevation watercourses because of their short duration and localized nature, and because evapotranspiration rates are much higher. Rainfall from summer storms are a more important source for recharge along mountain fronts, because they generally provide more stream flows in these areas than do winter storms (Cunningham et al., 1998).

Past studies have generally indicated a correlation between recharge to an aquifer and the observed regional rainfall and associated runoff along a watercourse. Review of water level hydrographs in the Tucson basin indicates that groundwater levels along wells close to the Santa Cruz River and Rillito Creek often rise following large, sustained flows such as those during October 1983 and January 1993. This effect diminishes with distance from the river, as might be expected. Recharged stormflow from the October 1983 flood also increased groundwater levels along Cienega Creek, sufficiently enough to cause the normally dry streambed at Interstate 10 to flow for nearly two years. In 1998, Pima Association of Governments observed a number of instances where groundwater levels (measured in vicinity wells) rose in response to precipitation events along the lower Cienega Creek watershed (PAG, 1998). Along Tanque Verde Creek, comparison of annual discharges in the creek channel to water level changes in various wells revealed "a decline in water levels following 'dry' water years such as 1994, 1996 and 1997, and a rise in water levels following 'wet' water years such as 1993 and 1995", suggesting that groundwater levels along the creek may be affected by recharge from runoff in the streambed (Hill et al., 2000).

One of the severest, sustained droughts in southern Arizona occurred during the period 1942-1964. Along the upper reach of the Santa Cruz River, declining water levels were observed from the mid 1940's to the mid 1960's. Causes for the declines were presumed to be due to the combined effects of groundwater withdrawals and drought (Halpenny and Halpenny, 1988; ADWR, 1994). Water levels in the area began to recover in the mid 1960's due to increases in rainfall and the release of effluent from the Nogales International Wastewater Treatment Plant, which began operating in 1951 (Halpenny and Halpenny, 1998; ADWR, 1994).

Depths to water can have a profound impact on the types of vegetation that can be sustained along a watercourse. Cottonwood, willow and bulrush will only grow along watercourses with plenty of water at or close to the surface (Pima County, 2000). Mesquite trees can reach further down for

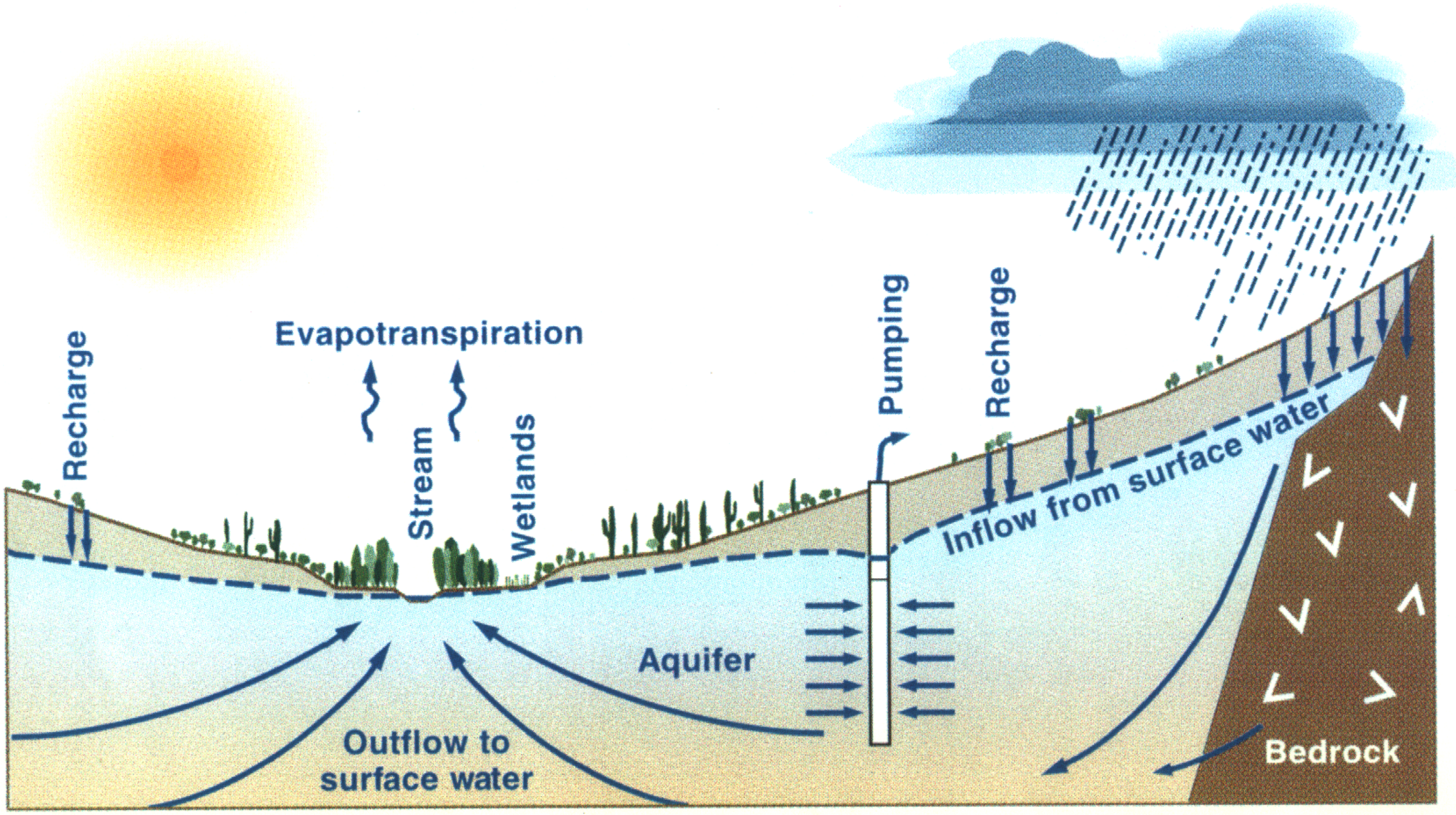


Figure 13. Hydrology of a desert basin drained by a stream. Most recharge to the aquifer occurs at higher elevations, which receive more rainfall than lower elevations. Ground water flows to the central part of the basin where it may discharge to springs, wetlands, streams, or evapotranspiration. Ground-water pumping has the local effect of removing water from storage in the aquifer and the eventual effect of reducing outflow to surface-water features and riparian plants.

Figure 13

water resources, but are much larger and provide more productive ecosystems where depths to water are less than 20 feet (Stromberg et al., 1991).

Sustained droughts can kill riparian trees such as cottonwoods and willows outright or shift the species composition in a riparian area to a mix of plants which are more tolerant of dry conditions, such as mesquite and tamarisk. In the Tucson basin, where groundwater pumping greatly exceeds natural recharge, this shift has already occurred in many places, to the point where even the more xeric mesquite woodlands cannot be sustained.

3.6 Temperature

Average air temperatures in Pima County are generally warmest during the month of July, while the coldest average temperatures are experienced in December and January (Table 11, Figure 14). Average daily highs in the Tucson Basin usually range from 63°F in early January to 101°F near the end of July. Average low temperatures range from 38°F to 74°F during the same time periods respectively (Glueck, 1997). The hottest portion of Pima County is in the far west, where average maximum temperatures can reach up to 110°F. The coldest portions of the county are in the high mountains of Eastern Pima County, with average maximum temperatures reaching 72-78°F during the hottest part of the summer (Figure 15).

Temperatures are affected by elevation, with decreases of approximately 3 to 4°F for every 1000-foot gain in height (Lowe, 1985). Mountain peaks in Pima County are generally 20-30°F colder than the surrounding valleys. Eastern Pima County is generally 2-3°F cooler than Western Pima County, due to higher elevations in that area.

For the most part, mean monthly temperatures within Pima County are less variable than precipitation from year to year. The most variation in temperature appears to occur in February,where differences in temperature reach up to ±4.3°F (Sahuarita, Arizona).[2] Less variation occurs in the summer (July), where the highest difference is ±2.4°F at the weather station in Santa Rosa School, Arizona.[3]

3.7 Frost

Pima County experiences a great variation in weather patterns. In the warmest region, southwestern Pima County, nearly frost-free conditions permit the growth of tender plants found nowhere else in

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[2] Note: The highest variation in temperature occurs at Red Rock in January, ±4.9 °F, but the highest variations for most of the gauges occur in February. The highest variation for February is at Willow Springs Ranch, but this is outside of Pima County.

[3] Note: The weather station with the highest variation in temperature on the table is Mohawk, Arizona (±2.5°F), but this station is located outside of Pima County.

Table 11. Average Temperature and Measure of Variability by Month (Shaded Stations located outside Pima County)

Station ID	Station Name	Average Temperature ± standard error (°F)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
020080	Ajo	52.8±3.1	57.1±3.5	61.4±3.3	68.7±3.2	76.7±3.1	85.7±2.6	90.4±1.9	88.4±1.9	84.6±2.4	74.2±3.3	62.1±3.3	54.7±3.3
020088	Ajo Well	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
020204	Amado	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
020287	Anvil Ranch	49.5±2.2	52.3±2.8	56.7±2.8	63.3±2.8	71.4±2.4	81.1±2.7	85.1±1.6	82.8±2.0	78.3±1.9	68.1±2.6	56.7±2.9	49.4±2.3
020309	Apache Powder Company	45.3±2.6	48.7±3.0	53.3±2.6	60.7±2.6	67.6±2.0	76.9±2.2	80.7±1.4	78.6±1.6	73.9±1.7	63.8±2.2	52.2±2.3	45.9±2.4
020380	Arivaca 1 E	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
020680	Benson	45.9±3.0	49.2±3.3	54.4±3.5	60.7±2.8	68.4±2.7	77.6±2.1	81.0±2.2	78.8±2.4	74.1±2.1	63.9±2.4	52.8±2.9	46.4±2.6
020923	Bosley Ranch	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
021231	Canelo 1 NW	41.9±3.2	44.9±2.8	48.9±2.9	55.1±2.8	62.3±2.5	71.3±2.2	74.0±1.8	71.9±1.8	68.1±1.8	59.2±2.3	48.9±2.8	42.4±2.8
021306	Casa Grande	50.9±2.9	55.1±3.5	60.3±3.4	67.8±3.1	76.2±3.0	85.3±2.6	91.1±1.9	89.0±2.3	83.5±2.4	71.5±3.0	59.0±2.8	51.5±2.4
021314	Casa Grande Natl Mon.	50.6±2.8	54.2±3.3	59.3±3.0	66.6±3.2	74.9±3.1	84.1±2.6	90.3±1.7	88.7±1.8	83.0±2.2	71.1±2.7	58.4±2.8	51.0±2.5
021330	Cascabel	47.5±1.8	50.9±2.4	54.5±2.6	60.6±3.0	68.3±2.4	77.5±2.2	82.3±1.6	80.7±1.7	75.6±1.8	65.2±2.2	54.1±2.3	47.6±2.0
022140	Coronado Natl Mon.	45.4±2.3	48.2±2.7	52.2±3.0	58.9±2.7	66.5±2.3	75.2±2.2	76.0±1.6	73.8±1.6	70.7±1.9	62.5±2.2	52.7±2.4	45.9±2.5
022159	Cortaro 3 SW	50.6±2.6	53.8±3.7	58.5±3.3	65.9±3.0	74.1±2.6	84.1±2.3	87.9±2.0	85.5±2.1	81.5±2.1	70.7±2.6	59.0±3.0	51.6±2.8
022430	Dateland	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
022434	Dateland Whitewing Ranch	54.1±2.3	57.8±2.6	61.5±2.8	68.1±3.2	74.9±3.0	83.8±2.2	89.3±1.8	89.2±2.2	83.4±2.7	73.1±2.4	61.0±2.6	53.6±2.3
022797	Elgin 5 N	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
022807	Eloy 4 NE	51.8±2.5	55.7±3.3	60.5±3.1	67.9±3.2	76.2±2.9	85.1±2.5	89.6±1.8	87.7±2.3	82.9±2.1	72.3±2.6	59.6±3.1	52.1±2.6
022902	Fairbank 1 S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
023120	Fort Huachuca	46.3±2.6	48.8±3.2	54.0±3.4	60.0±2.6	67.5±3.0	76.8±2.8	77.3±2.4	75.2±2.3	72.1±2.4	64.1±3.2	53.5±3.6	47.1±3.8
023393	Gila Bend	53.7±2.9	57.7±3.2	62.9±3.2	69.8±3.2	77.9±3.2	86.9±2.9	93.4±1.9	91.9±2.1	86.4±2.4	74.6±3.0	61.8±2.9	53.9±3.1
023398	Gila Bend Aviation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
023981	Helvetia Santa Rita Ranch	46.9±3.5	49.7±3.6	54.4±3.3	62.1±3.0	69.4±2.6	78.3±1.8	79.5±1.8	76.9±1.7	75.0±1.6	66.4±2.4	55.6±3.5	49.4±3.0
024675	Kitt Peak	41.2±3.1	42.3±3.7	44.7±4.0	51.4±4.1	59.2±3.0	68.6±3.2	70.5±2.0	68.6±2.0	65.4±2.3	57.7±3.4	48.2±3.2	41.8±3.2
024698	Klondyke 3 SE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
025274	Maricopa 9 SSW	48.7±2.8	53.5±3.1	58.6±2.9	66.5±2.9	75.2±3.1	84.9±2.6	91.1±2.4	89.6±2.1	83.0±2.2	70.5±2.4	57.3±2.9	49.8±2.4
025627	Mohawk	54.4±3.6	59.1±3.5	65.2±4.4	72.0±3.7	79.3±3.5	88.7±3.3	94.6±2.5	92.7±2.2	88.0±3.2	76.1±3.2	63.5±3.2	56.0±3.5

Table 11. Average Temperature and Measure of Variability by Month (Shaded Stations located outside Pima County)

Station ID	Station Name	Average Temperature ± standard error (°F)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
025908	N Lazy H Ranch	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
025921	Nogales	45.5± 2.7	47.7±3.4	51.5±2.7	57.5±2.1	64.1±1.9	73.7±2.2	78.0±1.5	75.7±1.3	71.7±1.5	62.3±2.0	52.1±2.3	46.3±2.3
025922	Nogales Old Nogales	46.6±3.2	49.7±3.1	53.8±3.6	60.5±3.4	67.6±3.2	76.9±2.5	80.1±2.2	77.6±1.8	74.0±1.9	64.6±2.4	54.6±3.2	47.9±3.1
025924	Nogales 6 N	45.5±2.2	48.1±3.1	52.0±3.0	58.1±2.7	65.2±2.7	74.6±2.7	78.7±1.4	76.9±2.0	72.5±2.0	63.0±2.1	52.2±2.3	46.0±2.2
026116	Oracle	45.9±3.4	48.2±3.7	52.5±3.4	59.6±3.1	67.5±2.9	77.0±2.5	79.8±1.8	77.6±1.6	73.6±2.0	63.7±2.7	54.3±3.2	47.0±3.3
026119	Oracle 2 SE	45.6±2.6	48.2±3.4	51.9±3.5	59.0±3.4	67.7±3.3	77.4±2.8	79.6±2.0	77.4±2.2	73.7±2.0	64.6±2.9	53.2±2.9	46.3±3.0
026132	Organ Pipe Cactus N M	53.4±3.0	56.6±3.3	60.3±3.2	66.8±3.2	73.8±3.0	82.5±2.8	88.4±1.5	87.1±2.1	82.5±2.3	72.4±2.7	60.9±2.9	53.8±2.5
026202	Palisade Ranger Stn.	34.5±2.4	35.9±3.0	38.4±4.4	45.2±3.3	53.5±2.0	63.3±2.8	64.9±1.7	62.9±1.7	58.8±2.0	50.0±3.6	41.9±2.8	35.0±2.4
026282	Patagonia #2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
026506	Picacho Reservoir	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
027036	Redington	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
027058	Red Rock 6 SW	49.2±4.9	56.3±2.8	58.8±2.6	65.4±3.5	72.1±4.0	82.8±2.6	90.0±1.4	87.7±2.0	83.5±1.8	71.5±2.5	59.6±3.2	51.2±3.1
027326	Ruby 4 NW	47.7±3.8	49.4±3.5	54.3±2.9	60.2±3.2	68.6±3.4	76.5±3.4	79.4±2.0	76.9±1.9	73.9±2.3	65.1±2.2	56.4±2.3	50.3±2.9
027330	Helmet Peak Ruby Star R	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
027355	Sabino Canyon	51.9±2.7	54.6±3.4	58.6±3.0	66.0±2.5	73.8±2.3	83.6±2.2	87.0±1.5	85.0±1.7	81.3±2.0	71.1±2.8	59.6±2.9	53.1±2.7
027403	Sahuarita 2 NW	49.0±2.5	53.1±4.3	56.5±2.3	63.7±2.6	71.7±2.5	81.1±2.9	84.8±1.5	82.6±1.9	78.1±2.1	67.8±2.4	57.3±3.6	50.5±3.0
027530	San Manuel	47.3±2.6	50.7±3.5	55.6±3.8	62.2±2.7	71.2±2.3	80.9±2.2	83.3±1.4	80.7±2.4	77.0±2.4	67.2±3.2	55.3±3.0	48.3±2.5
027555	San Rafael Ranch	42.6±2.8	43.9±4.3	47.8±2.8	53.3±2.3	61.2±2.5	71.3±2.8	74.1±2.1	72.2±3.0	68.9±2.1	60.3±2.5	49.9±3.4	43.7±2.9
027583	Santa Margarita	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
027593	Santa Rita Exp Range	48.8±2.9	51.3±3.5	55.1±3.6	61.8±3.2	69.5±2.6	78.8±2.3	79.3±1.9	77.0±2.2	74.4±2.1	67.2±3.2	55.8±3.1	49.3±2.8
027600	Santa Rosa School	49.2±2.0	53.8±3.2	58.7±4.1	64.6±3.3	73.4±2.3	83.2±3.2	88.2±2.4	86.1±2.2	80.8±2.1	69.8±2.8	58.1±2.6	49.8±2.6
027619	Sasabe	49.4±2.2	51.7±2.9	54.9±3.1	61.3±3.1	68.2±2.6	77.5±2.7	80.7±1.5	78.5±1.9	74.9±1.9	66.4±2.3	56.2±2.5	49.5±2.4
027622	Sasabe 7 NW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
027726	Sells	51.1±4.0	54.3±3.8	58.3±2.5	65.9±3.6	72.8±2.6	82.6±2.2	86.4±1.6	84.2±2.4	81.3±2.2	71.8±3.0	60.3±3.6	51.8±2.8
027751	Sentinel	53.8±2.2	56.1±2.3	62.9±3.5	70.2±2.5	75.2±2.4	87.2±2.0	92.3±1.3	91.0±2.6	84.6±3.2	72.0±3.5	61.8±2.0	51.7±3.2
027880	Sierra Vista	47.0±2.7	50.6±2.9	55.1±2.7	61.7±3.0	69.4±2.4	77.5±2.3	78.5±1.6	76.7±1.7	73.1±2.0	64.9±2.2	54.3±2.5	47.0±1.6
027915	Silver Bell	52.7±4.0	56.4±4.1	60.5±4.6	66.9±3.0	75.0±3.0	84.8±2.6	85.8±2.3	84.3±2.4	81.4±2.5	72.4±2.3	61.7±3.1	52.4±3.3

Table 11. Average Temperature and Measure of Variability by Month (Shaded Stations located outside Pima County)

Station ID	Station Name	Average Temperature ± standard error (°F)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
028619	Tombstone	47.3±3.1	50.3±3.0	54.7±3.0	61.7±2.8	69.4±2.6	78.2±1.9	79.3±1.6	77.2±1.8	74.1±1.9	65.4±2.6	55.0±2.8	47.8±3.0
028795	Tucson 17 NW	53.6±2.5	56.5±2.9	61.1±2.8	67.9±3.8	76.5±2.3	85.2±2.4	87.7±1.8	86.3±1.6	82.1±2.2	72.2±3.0	60.9±2.5	52.8±1.6
028796	Tucson UA Exp Farm	50.1±2.6	52.9±3.4	57.4±2.8	64.2±2.6	72.1±2.7	81.4±2.7	85.8±1.6	84.2±1.9	79.8±2.1	69.0±2.4	57.3±2.4	50.4±2.3
028800	Tucson Magnetic Obsy	49.6±2.6	52.4±3.4	56.5±2.9	63.7±2.9	71.8±2.4	81.6±2.5	86.0±1.5	84.1±1.8	79.9±2.0	69.3±2.6	57.2±2.5	50.4±2.2
028815	Tucson UA	51.4±3.4	54.5±3.6	59.0±3.4	65.8±3.5	73.9±3.0	83.1±2.1	86.9±2.2	85.1±2.3	80.9±3.0	70.3±3.0	59.1±3.0	52.1±2.0
028817	Tucson U of Ariz #1	52.5±2.2	55.6±2.7	60.6±2.4	66.9±3.4	75.3±2.5	83.8±2.2	87.1±1.6	85.9±1.6	81.4±2.2	71.0±2.3	59.2±2.4	51.6±1.5
028820	Tucson WSO	51.6±2.8	54.6±3.5	58.8±3.1	66.0±3.2	74.1±2.8	83.6±2.4	86.4±1.7	84.6±1.8	80.8±2.3	70.8±2.9	59.1±2.7	52.2±2.4
028865	Tumacocori Natl Mon.	48.9±2.6	51.1±3.3	55.1±2.8	61.1±2.7	68.4±2.3	77.9±2.4	81.3±1.8	79.0±1.8	75.4±1.9	66.0±2.4	55.6±2.6	49.5±2.8
029382	Willow Springs Ranch	45.2±3.0	47.7±4.4	52.4±3.7	59.7±3.5	67.6±2.9	77.2±3.3	81.2±2.4	78.3±3.0	74.4±3.6	64.9±3.9	53.5±3.5	45.9±3.6
029420	Winkelman 6 S	47.3±2.6	50.1±3.3	55.4±3.1	61.7±2.8	70.4±2.2	80.5±2.5	86.4±2.0	83.6±1.9	78.3±1.7	66.9±2.3	54.0±2.5	46.9±2.3
029562	Y Lightning Ranch	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Figure 14. Average Monthly Temperatures For Climate Stations With Available Data

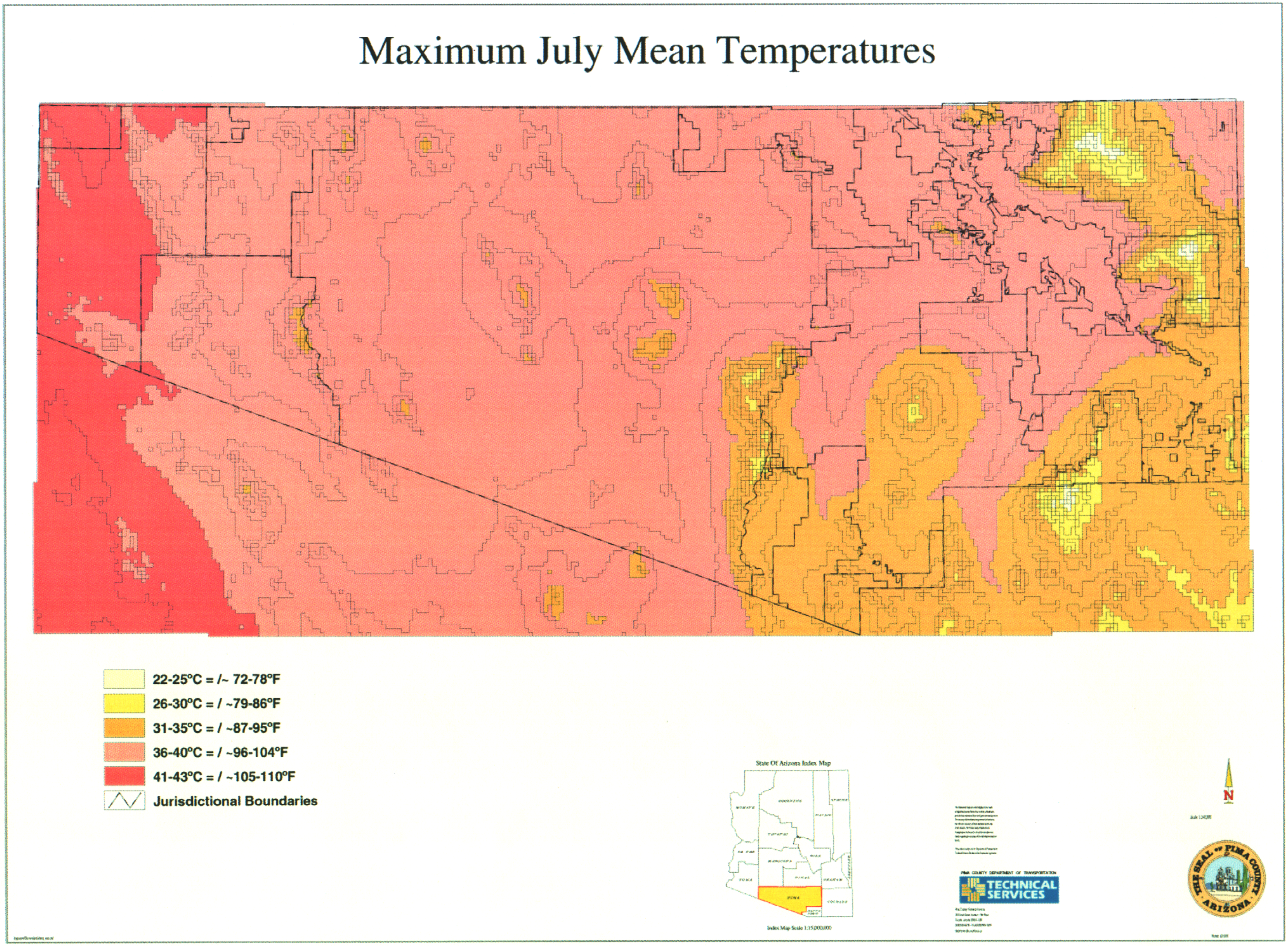


Figure 15. Maiximum July Mean Temperature

Figure 15

the United States, such as the organ pipe cactus. In the rest of the Sonoran Desert, the occurrence of hard freezes is an important influence on vegetation characteristics and the locations between the desert and grassland communities. Hard freezes in the 1970's have killed or reduced the vigor of mature mesquites in upland areas of the San Pedro River Valley (Raymond Turner, pers. communication/Glinski and Brown, 1982)). Frost is an important mortality factor for young saguaro cacti, and as such is an important limiting factor for their distribution (NPS, 1998). Ironwood is also considered to be sensitive to prolonged hard freezes.

Areas that experience temperatures at or below the freezing point, 32°F, are usually susceptible to frost-like conditions. A look at the average annual low temperatures for Pima County reveals that the primary area for frost potential is Eastern Pima County, where low temperatures in the valleys range from 28-32°F and areas in the mountains range from 23-26°F. Avra Valley and all areas west of the Baboquivari Mountain range are generally frost-free (Figure 16). However, all areas of Pima County have experienced frost-like conditions at some time in their history, as indicated in Table 12.

The duration of freezing temperatures is a highly important factor in determining mortality rates for plant species. Many desert plants can survive freezing temperatures for short durations, but begin to show stress and die-off as conditions persist over longer periods of time. A variety of desert plant species, especially cacti, have been documented to perish when temperatures plummet below 0°C (32°F) for periods of 18 hours or more (Turner 1963; Shreve and Wiggins 1964; Gibson and Nobel 1986; Bowers 1980-81).

3.8 Potential Evapotranspiration

Evaporation occurs when molecules in a liquid attain sufficient energy to escape the surface of the liquid into the atmosphere. Sources of energy most likely come from direct solar radiation, heat transfer from the atmosphere, or from in-flowing warm water into the water body. Transpiration is the loss of water from tiny openings in the leaves of plants during photosynthesis. When computing water losses over vegetative surfaces, it is usually impossible to separate transpiration and evaporation from the soil surface, ponds, lakes and rivers. Therefore, the two processes are generally considered together under the term "evapotranspiration" (Dunne and Leopold, 1978). Due to radiation being the dominant control factor, evapotranspiration is primarily a function of latitude, season, time of day and cloudiness.

As a major contributor to water loss from drainage basins, evapotranspiration controls such hydrologic phenomena as soil moisture content, groundwater recharge and stream flow. More than two-thirds of the precipitation that falls in the conterminous United States is returned to the atmosphere by evaporation from water surfaces and plants (Dunne and Leopold, 1978).

A simple way of determining potential evapotranspiration rates for a particular area is by using the Thornthwaite Method. The Thornthwaite Method uses air temperature as an index of the energy available for evapotranspiration (Dunne and Leopold, 1978). The empirical formula is as follows: $E_t = 1.6[10T_a/I]^a$; where E_t = potential evapotranspiration in cm/mo, T_a = mean monthly air temperature (°C), I = annual heat index, and $a = 0.49 + 0.01791 - 0.0000771I^2 + 0.000000675I^3$.

Average Annual Lowest Temperatures

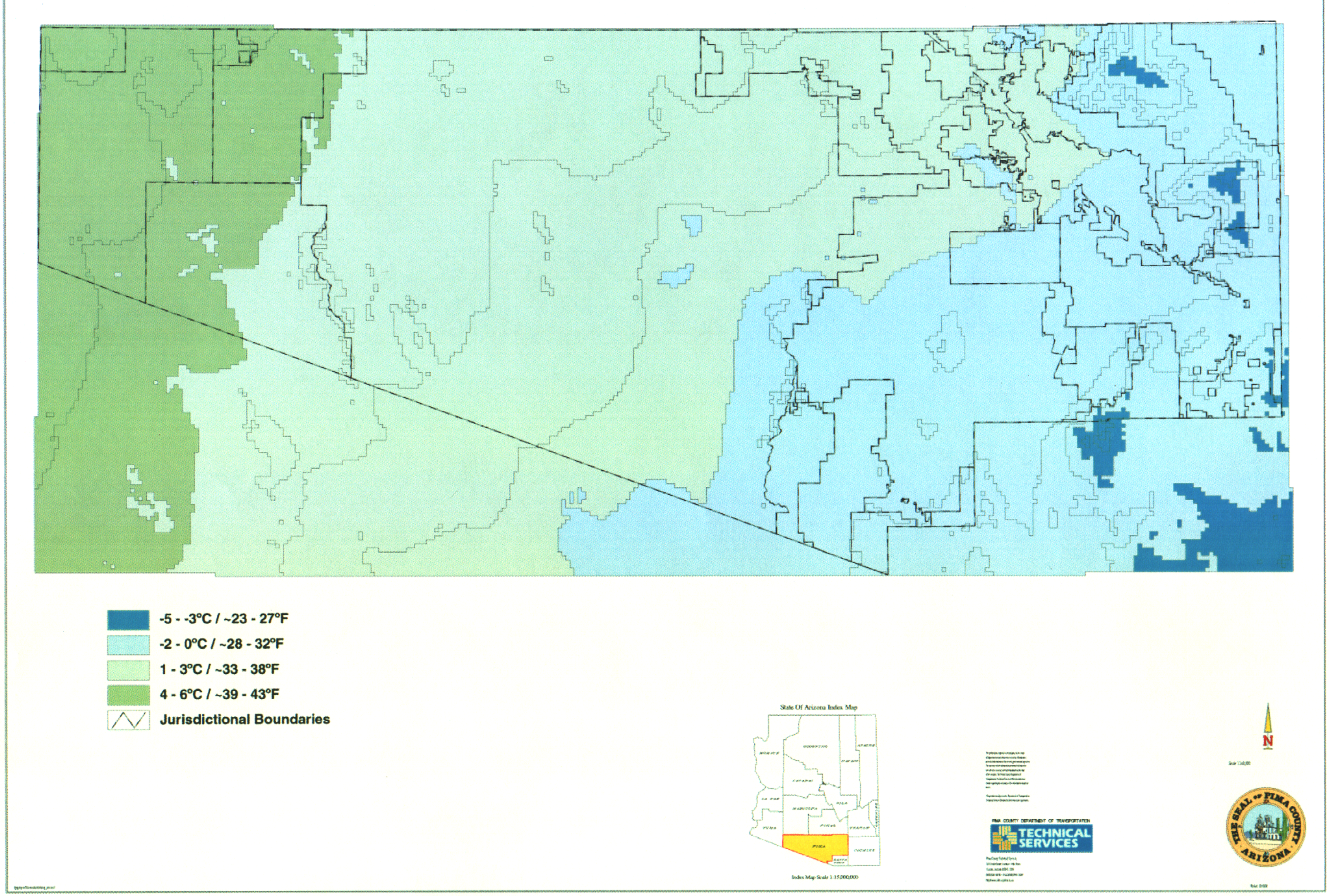


Figure 16. Average Annual Lowest Temperatures

Figure 16

Table 12. Lowest Recorded Minimum Temperature

Station ID	Station Name	Year	Lowest Min. Temp (°F)
020080	Ajo	1937	17
020088	Ajo Well	----	NA
020204	Amado	----	NA
020287	Anvil Ranch	1954	8
020309	Apache Powder	1978	-7
020380	Arivaca 1 E	----	NA
020680	Benson	1913/1921	5
020923	Bosley Ranch	----	NA
021231	Canelo 1 NW	1978	-4
021306	Casa Grande	1954	15
021314	Casa Grande Natl Mon.	1913	8
021330	Cascabel	1971/1978	6
022140	Coronado Natl Mon.	1978	1
022159	Cortaro 3 SW	1949	15
022430	Dateland	----	NA
022434	Dateland Whitewing	1990	17
022797	Elgin 5 N	----	NA
022807	Eloy 4 NE	1971	13
022902	Fairbank 1 S	----	NA
023120	Fort Huachuca	1913	1
023393	Gila Bend	1963	10
023398	Gila Bend Aviation	----	NA
023981	Helvetia Santa Rita	1937	10
024675	Kitt Peak	1979	2
024698	Klondyke 3 SE	----	NA
025274	Maricopa 9 SSW	1913	8
025627	Mohawk	1937	16
025908	N Lazy H Ranch	----	NA
025921	Nogales	1978	-3
025922	Nogales Old Nogales	1948	6
025924	Nogales 6 N	1978	-4
026116	Oracle	1937	2
026119	Oracle 2 SE	1979	5
026132	Organ Pipe Cactus N M	1962	14
026202	Palisade Ranger Stn.	1968	-3
026282	Patagonia #2	----	NA
026506	Picacho Reservoir	----	NA
027036	Redington	----	NA
027058	Red Rock 6 SW	1932	14

Station ID	Station Name	Year	Lowest Min. Temp (°F)
027326	Ruby 4 NW	1898	12
027330	Helmet Peak Ruby Star	----	NA
027355	Sabino Canyon	1971	15
027403	Sahuarita 2 NW	1962	10
027530	San Manuel	1962	12
027555	San Rafael Ranch	1964	-11
027583	Santa Margarita	----	NA
027593	Santa Rita Exp Range	1978	11
027600	Santa Rosa School	1976	12
027619	Sasabe	1971	13
027622	Sasabe 7 NW	----	NA
027726	Sells	1974	4
027751	Sentinel	1913/1916	18
027880	Sierra Vista	1985	11
027915	Silver Bell	1973	14
028619	Tombstone	1978	3
028795	Tucson 17 NW	1985	21
028796	Tucson UA Exp Farm	1950	9
028800	Tucson Magnetic Obsy	1964	13
028815	Tucson UA	1913	6
028817	Tucson U of Ariz #1	1988	21
028820	Tucson WSO	1949/1974	16
028865	Tumacocori Natl Mon.	1978	5
029382	Willow Springs Ranch	1968	8
029420	Winkelman 6 S	1953	9
029562	Y Lightning Ranch	----	NA

NA = Not available
Note: Shaded stations are located outside Pima County

Figure 17 displays a graphical solution that can be used to evaluate Thornthwaite's E_t value. The heat index, I, can be estimated using another graph exhibited in Figure 18, at least for stations located within the United States (Dunne and Leopold, 1978). The resulting potential evapotranspiration value, determined using the graph or formula, is for 360 hours of sunlight per month, and must be adjusted for the number of days per month and length of day (a function of latitude). The standard potential evapotranspiration value should be multiplied by the appropriate correction factor given in Table 13 to produce the potential evapotranspiration value for the station. Calculated potential evapotranspiration values (converted to inches per month) for selected weather stations in Pima County are displayed in Table 14.

Since temperature is a major factor in determining potential evapotranspiration (PET), it would seem that PET values should be at their highest in the summertime and at their lowest during the winter months. This is the case for Pima County, where PET ranges from 6.4 to 8.8 inches/month in July and from 0.6 to 0.7 inches/month in both January and December (Table 14).

Based on this observation and the fact that about half of our rainfall occurs in the winter, we would expect to see excess moisture available during the winter months. Figure 19 displays monthly precipitation versus potential evapotranspiration for a number of weather stations of varying elevations within Pima County. As shown, the average monthly precipitation exceeds potential evapotranspiration for all of the selected weather stations during the months of January and December. For two of the weather stations, Kitt Peak and Palisade Ranger Station, average precipitation is also higher than potential evapotranspiration during the peak summer months (June through August) as well. This is most likely due to decreasing temperatures and increasing precipitation as elevation increases (Sections 3.1 and 3.6). For the weather stations at lower elevations, PET is higher than mean monthly precipitation during the summer, suggesting that we can expect moisture deficits in the soil during this period of time.

Although it is a simple method for determining trends in evapotranspiration rates, the Thornthwaite method does not provide an accurate estimate of actual evapotranspiration in a given area. For one thing, it assumes that there is a constant source of moisture available in the soil to be evaporated into the atmosphere. Soils in arid regions are typically dry for much of the year because of low annual rainfall totals. Also, this method uses direct solar radiation, in the form of mean monthly temperatures, as a source to determine PET values, and does not take into account any biological factors such as type of vegetation and foliage density. Most likely, the PET values determined for the summer months (as displayed in Table 14) are closer to the monthly mean precipitation totals for those months.

With evapotranspiration presumably higher than precipitation, we would expect there to be very little to no plant growth during the summer months. This is not necessarily the case, however, since most native plants have adapted to the harsh conditions of the desert climate over time. Some native plants have developed a waxy coating on their leaves or drop their leaves completely during the hot summer months to minimize water loss through transpiration. Other plants (i.e., mesquite trees) develop long tap roots to take advantage of water sources deep within the ground. Plant growth may often be limited to the early morning hours when temperatures and evaporation rates are low, or shortly after periods of rainfall when moisture availability is high. These adaptations and others have allowed native plants to sustain production during the hottest months of the year.

Table 13. Correction factors for monthly sunshine duration for multiplication of the standard potential evapotranspiration from Figure 18.

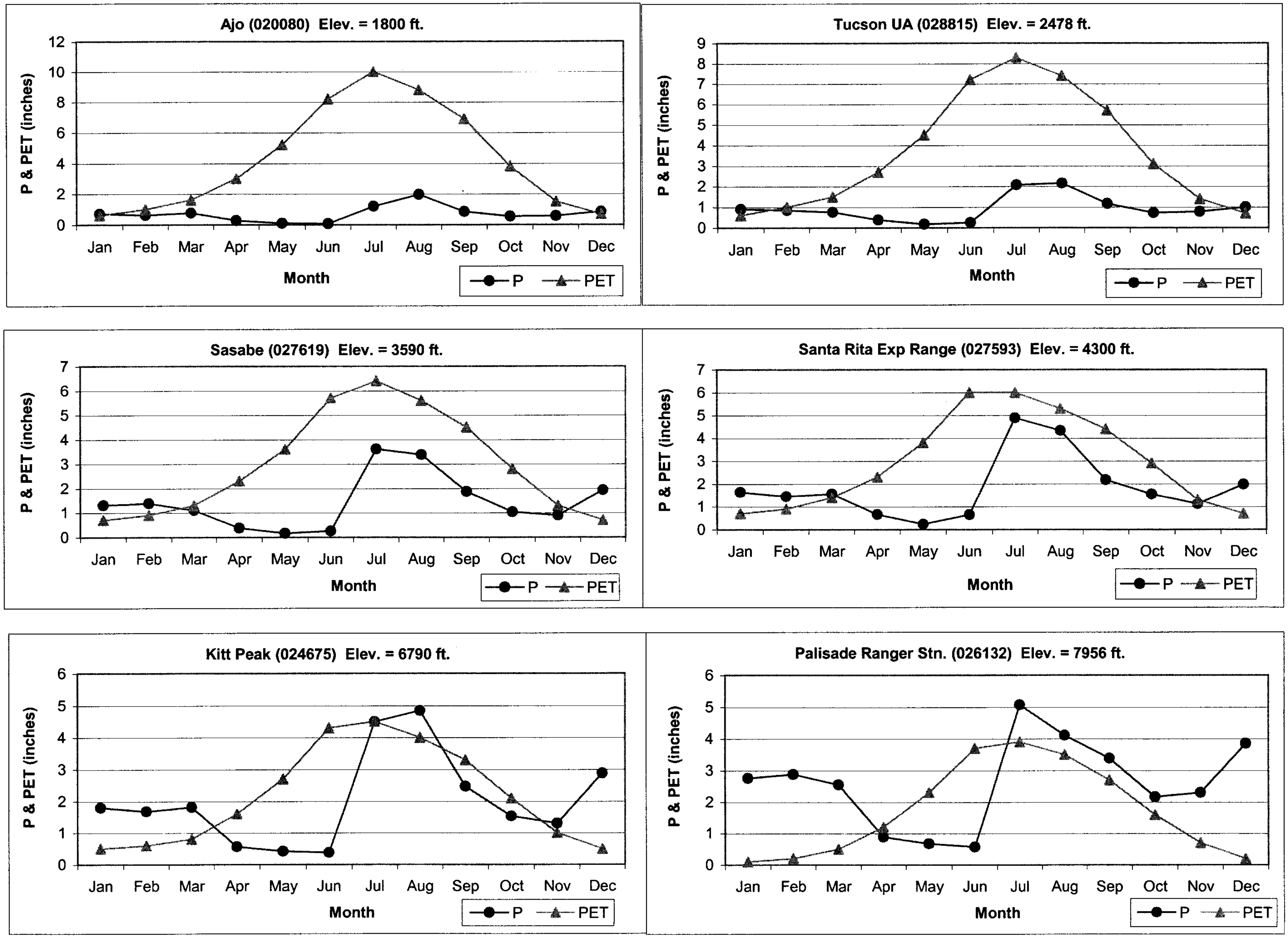
Latitude	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
60°N	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50°N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40°N	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30°N	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20°N	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91
10°N	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96

Source: Dunne and Leopold, 1978

Table 14. Potential evapotranspiration for selected weather stations in Pima County, as calculated using the Thornthwaite Method (converted to inches per month).

Station Name	Potential Evapotranspiration (in/month)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ajo	0.6	1.0	1.6	3.0	5.2	8.2	10.0	8.8	6.9	3.8	1.5	0.7
Anvil Ranch	0.6	0.9	1.4	2.5	4.1	6.5	7.6	6.6	5.1	2.9	1.3	0.6
Cortaro 3 SW	0.6	0.9	1.5	2.7	4.6	7.5	8.6	7.5	5.9	3.2	1.4	0.6
Helvetia Santa Rita Ranch	0.6	0.8	1.4	2.5	3.9	5.8	6.0	5.2	4.5	2.8	1.3	0.7
Kitt Peak	0.5	0.6	0.8	1.6	2.7	4.3	4.5	4.0	3.3	2.1	1.0	0.5
Organ Pipe Cactus N M	0.8	1.1	1.6	2.8	4.5	7.0	8.9	8.1	6.2	3.5	1.5	0.8
Palisade Ranger Stn.	0.1	0.2	0.5	1.2	2.3	3.7	3.9	3.5	2.7	1.6	0.7	0.2
Red Rock 6 SW	0.5	1.1	1.4	2.5	4.1	7.1	9.5	8.3	6.5	3.3	1.4	0.6
Sabino Canyon	0.7	0.9	1.4	2.7	4.5	7.4	8.4	7.4	5.9	3.3	1.4	0.7
Santa Rita Exp Range	0.7	0.9	1.4	2.3	3.8	6.0	6.0	5.3	4.4	2.9	1.3	0.7
Santa Rosa School	0.5	0.9	1.5	2.5	4.5	7.2	8.7	7.7	5.7	3.1	1.3	0.5
Sasabe	0.7	0.9	1.3	2.3	3.6	5.7	6.4	5.6	4.5	2.8	1.3	0.7
Sells	0.6	0.9	1.4	2.7	4.3	7.0	8.1	7.1	5.8	3.4	1.5	0.7
Silver Bell	0.7	1.1	1.7	2.8	4.8	7.8	8.0	7.2	5.9	3.5	1.6	0.7
Tucson 17 NW	0.7	1.1	1.7	2.9	5.1	8.0	8.8	7.9	6.1	3.4	1.5	0.7
Tucson UA Exp. Farm	0.6	0.9	1.4	2.5	4.2	6.6	7.8	7.0	5.4	3.0	1.3	0.6
Tucson Magnetic Obsy	0.6	0.8	1.3	2.4	4.1	6.7	7.9	7.0	5.5	3.0	1.3	0.6
Tucson UA	0.6	1.0	1.5	2.7	4.5	7.2	8.3	7.4	5.7	3.1	1.4	0.7
Tucson U of Ariz #1	0.7	1.0	1.7	2.8	4.8	7.4	8.5	7.7	5.9	3.2	1.3	0.6
Tucson WSO	0.7	1.0	1.5	2.7	4.6	7.3	8.1	7.2	5.7	3.2	1.4	0.7

Figure 19. Monthly Precipitation (P) versus Monthly Potential Evapotanspiration (PET)



4.0 How Short-Term Climate Variation Affects Species

Pima County, with its location between the subtropics and temperate climatic zones, hosts a variety of plant and wildlife species. Some are residents, staying all year long, while others migrate here for the summer or winter. To some species, Pima County represents the northernmost limits of their range, while others have their southernmost limits here, and for others Pima County is the center of their range.

The presence of "sky islands" creates a unique situation, where species with similar climatic preferences sort themselves along the elevation gradient based on the blend of temperature and precipitation that best supports them (SIWN, 2000). Species originating in the northern temperate areas tend to congregate in the high elevations, while species from the more tropical south stay near the lower elevations (Lowe, 1985). Many species that might normally be widely separated intermingle in these areas (Felger and Wilson, 1995).

Locations and population sizes of species can be directly affected by changes in climate. Changes in distribution appears to have been the primary way that species have responded to past climate change (Noss, 2001). As climate varies, species may respond by shrinking or enlarging their ranges and seeking appropriate microclimates. Varied elevations, soils and riparian environments may provide options for species' movements in response to climatic variation. However, some species typical of cooler climates might be eliminated during droughts, and recolonization across hot, dry basins might be difficult (McDonald and Brown, 1992; in SRAG, 2000). Aquatic and riparian obligate species are particularly limited, given the regional limitations of suitable aquatic and riparian habitats.

Temperature is not necessarily the defining factor in determining species distributions and population densities in an area. Other climate factors can directly or indirectly affect wildlife and plants, thus changing their behaviors or reducing the numbers observed from year to year. Below are a number of species of concern to the Sonoran Desert Conservation Plan with their potential, short-term responses to climatic change:

Listed cats: Jaguar (*Panthera onca*) and **Ocelot** (*Felis pardalis*) - These species most likely respond to changes in vegetative cover and differences in behavior and movement of their prey species, which are directly affected by seasonal changes in climate.

Mexican gray wolf (*Canis lupus baileyi*) - Most likely responds to movements of large ungulate species, which may be directed by daily and seasonal climate change.

Lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae*) - These bats cannot withstand prolonged exposure to cold. They migrate to Mexico in September or October, where they breed and spend the winter. They return to Arizona in the spring or summer (late April to late July) to bear their young (AGFD, 1998a). Warming trends would most likely extend their time of stay in the summering grounds, and may even extend their range northward. Cooling trends would create the opposite effect; bats would most likely breed in the southernmost areas of Arizona and stay for shorter durations of time.

Unlike most other bats and rodents in arid and semiarid areas, *Leptonycteris* are not adapted for water conservation and salt excretion. This is related to its feeding on nectar, most especially agaves, with their high water and low salt content. Its diet on nectar allows the lesser long-nosed bat to essentially be independent of free water (AGFD, 1998a). Any climate conditions that affect the production and sustainability of agaves or saguaros will also affect the sustainability of *Leptonycteris* populations.

Mexican long-tongued bat (*Choeronycteris mexicana*) - Like the lesser long-nosed bat, *C. mexicana* is only a summer resident of Arizona, which is the northernmost limit of their range. Females migrate north into the United States from Mexico to bear their young, which are born sometime between mid to late June and early July (AGFD, 1997a). Warming and cooling trends can have the effect of expanding or reducing the range of this species, along with the duration of their stay after breeding has occurred.

The Mexican long-tongued bat feeds primarily on the nectar and pollen of agaves and saguaros (RECON, 2001a). Any climatic changes affecting the production and distribution of these plants will also affect the sustainability of *C. mexicana* populations.

Allen's big-eared bat (*Idionycteris phyllotis*) - This species is known to be dependent on available water (RECON, 2001a). Lack of water resources during times of drought could severely limit the range of this species and make it more susceptible to competition from other species.

Western red bat (*Lasiurus blossevillii*) - The western red bat is known only to occur in broadleaf riparian deciduous forests and woodlands (RECON, 2001a). The loss of riparian vegetation due to reduced water tables from drought or by removal from damaging floods can have a more profound affect on riparian dependent species, such as the western red bat, since this habitat type has been severely reduced over the last century (mostly due to human activities).

Western yellow bat (*Lasiurus xanthinus = ega*) - The western yellow bat is a tropical species, whose range has been increasing into urban areas within the southwestern United States (RECON, 2001a). It is found primarily in planted fan palms within urban settings and in riparian areas. Warming trends may continue to allow this species to expand its range further northward, while cooling trends may force it retreat southward. Its adaptation to the urban setting may allow this species to withstand short-term losses of riparian vegetation.

California leaf-nosed bat (*Macrotus californicus*) - The California leaf-nosed bat is well adapted to the desert due to its ability to conserve water (RECON, 2001a). Lu and Bleier (1981) reported some individuals in captivity lasting for at least six weeks without drinking water. Other sources, including Bell et al. (1986) suggest that this species is well adapted to the desert because they roost in sites with a stable year-round temperature, thus limiting their energy expenditure on thermal regulation. M. californicus cannot withstand sustained temperatures less than 26 °C (79°F) for longer than a few hours (AGFD, 1997b).

Arizona Shrew (*Sorex arizonae*) - It is speculated that summer rainfall triggers the breeding and dispersal of Arizona shrews (Van Pelt et al., 1994, in RECON, 2001a). The Arizona shrew is a "sky island" species (RECON, 2001a), and it may respond to climatic changes by expanding its range downslope during cooling trends, and retreating back to mountain peaks during warming trends. One threat to this species may be the loss of habitat due to fire, which can be greatly affected by climatic change as mentioned previously within this report.

Merriam's mouse (*Peromyscus merriami*) - Merriam's mouse is heavily dependent on the presence of riparian woodlands and dense mesquite forests (RECON, 2001a). Since these vegetation types have been in serious decline over the years, any further reduction could have severe impacts to riparian dependent species such as the Merriam's mouse. Both droughts and floods can affect the health and extent of riparian vegetation along a watercourse.

Sonoran pronghorn (*Antilocapra americana sonoriensis*) - During a study using collared Sonoran pronghorn in 1984, it was determined that four males had home ranges from 40 square miles to 750 square miles, while six females had home ranges ranging from 25 square miles to 710 square miles. The large variation in home range size appears to be linked to forage and possibly water availability (AGFD, 1998b). Hervert (1996) states that they are exhibiting a "nomadic behavior that is typical of other desert dwelling animals like the oryx of the Sahara Desert or the Dorcas gazelle of the Kalahari Desert. These desert ungulates at times appear to be wandering randomly, but this movement is associated with living in desert conditions, where resources may be widely scattered or ephemeral."

Changes in climate can have a profound affect on Sonoran pronghorn populations. During drought cycles, food and water resources become more scarce, causing herds to expand the size of their home ranges. This puts more physical stress on individuals (especially young), making them more susceptible to predation or disease. It also increases their likelihood of running into movement barriers or hazards (i.e., roads), which increases stress and may lead to higher mortality. In contrast, wet years may allow for populations to reduce their home range sizes, thus reducing stress and allowing for higher survival rates.

Masked bobwhite quail (*Colinus virginianus ridgwayi*) - Breeding normally begins when summer rains commence, generally in July. Nesting success is correlated with the amount of ground cover and distribution of summer precipitation (USFWS, 1995). This species is peripheral to the United States where it is influenced by widely fluctuating summer rainfall, therefore, large annual population fluctuations are likely (Denniston, 1978). Annual mortality rates are believed to be similar to other bobwhite races, approximately 70 percent (Rosene, 1969).

Much of the demise of the masked bobwhite quail is due to the loss of its grassland habitat from overgrazing in the late 1800's, coupled with several years of drought. This statement is backed up by Brown (1904), who stated: "Causes leading to the extermination of the Arizona masked Bobwhite are due to overgrazing of the country with cattle, supplemented by several rainless years." Past efforts to restore wild populations have met with little success, due in part to grazing pressure and insufficient precipitation to provide adequate brood habitat or winter foods (USFWS, 1995).

With existing populations of masked bobwhite quail severely limited (they are only known within the Buenos Aires Wildlife Refuge in Pima County), climatic changes can have a profound impact on the species. Reproduction activity of the masked bobwhite can be severely depressed during drought years, with drought modeled as resulting in a 75 percent reduction in reproduction success. Individual survival was better, however, with only a 10 percent reduction across all age and sex classes (USFWS, 1995). Several years of sufficient rains (both winter and summer) along with a reduction in grazing pressure would be needed to help restore populations of this species.

Mexican spotted owl (*Strix occidentalis lucida*) - Forests throughout the owl's habitat are at high risk from fire, insects and disease. These conditions exist within the natural range of weather variations and short or long-term climate cycles. Large-scale catastrophic fires destroy habitat components for nesting and foraging. Small-scale fires are beneficial in reducing fuel loading and improve the horizontal diversity, which is an important habitat component for owls. Natural fire regimes prior to 1890 favored frequent small fires (Moody et al., 1992). Insects may produce large scale community changes after periods of climatic stress that predispose forests to insects or pathogenic occurrences (Colhoun, 1979). Both large-scale fire and insect damage are more common in seral tree stands than in climax tree stands. Seral stands generally provide habitat where the greatest concentrations of spotted owls occur.

Southwestern willow flycatcher (*Empidonax traillii extimus*) - Climatic factors (any climate induced change in the riparian forest communities) affect suitable flycatcher habitat and include inundation, massive annual floods that scour habitat, lack of flooding and widely fluctuating water levels. Flycatchers require dense riparian habitat of intermediate sized shrubs or trees often with an over-story of scattered larger trees usually with water or moist soil beneath the canopy (Tibbitts et al., 1994).

Swainson's hawk (*Buteo swainsoni*) - The Swainson's hawk primarily nests in grassland and semidesert grassland vegetation communities (RECON, 2001a). Fire and winter rains are two components necessary for a healthy grassland community. Any climatic factors that affect these activities will affect the production of native grasslands and, subsequently, affect the breeding range of Swainson's hawks in Pima County.

Bell's vireo (*Vireo bellii*) - Bell's vireo is generally found in dense shrubland or woodland along lowland stream watercourses (RECON, 2001a). Considering that much of these riparian areas have been in serious decline over the years, what remains is crucial for the continuing existence of riparian dependent species such as Bell's vireo. Climatic factors that affect riparian habitats, most notably droughts and floods, will in turn affect the range and distribution of this species.

Abert's towhee (*Pipilo aberti*) - Abert's towhee is found within Sonoran Riparian Deciduous Woodland and Riparian Scrubland communities (RECON, 2001a). As mentioned previously, these communities have been in serious decline over the years (mostly due to human intervention). Climatic factors, such as drought and floods, can affect the health and extent of these communities, thus affecting the distribution and range of Abert's towhee.

Rufous-winged sparrow (*Aimophilia carpalis*) - Nesting of rufous-winged sparrows if timed with the summer rains, so there is extreme fluctuations in populations from year to year (RECON, 2001a). There are historical records that this species had been extirpated from Arizona for at least some period of time, indicating that it is an extremely rare species. Populations of this species may reduce their size significantly during periods when there is little to no summer rains, and regain their numbers during periods of high summer rainfall.

Chiricahua leopard frog (*Rana chiricahuensis*) – One suspected threat for adult Chiricahua leopard frogs is oxygen depletion. Drought conditions, silt-laden runoff, vegetation die-off and other factors could result in oxygen depletion in still-water habitats such as stock ponds. The result could prove fatal to adult leopard frogs as they spend their winters in the mud bottoms of a pond. This "winterkill" has been documented in other *Rana* species and appears to be a viable hypothesis for *R. chiricahuensis*, which is probably better adapted to stream habitats than to artificial ponds subject to events of extreme oxygen depletion (NMGF, 2000). Currently 70% of the population exists in dirt stock ponds (Stredl, 1993).

Lowland leopard frog (*Rana yavapaiensis*) - The lowland leopard frog is highly dependent on aquatic ecosystems. Historically, aquatic ecosystems were more prevalent along streams and rivers in the Tucson Basin, but many of these areas have since disappeared (mostly due to groundwater pumping and channel changes). Populations are now mainly limited to small, upper canyon watersheds and stock ponds. These isolated populations are subject to extinction during times of drought as reported by Rosen for Alamo Canyon (personal communication in RECON, 2001a) and Hall for the population in Cargodera Canyon (pers. communication in RECON, 2001a).

Sonoyta mud turtle (*Kinosternon sonoriense longifemorale*) – "Aquatic habitat in the Rio Sonoyta is extremely dynamic due to climatic extremes (Ives, 1936; Hendrickson and Varela-Romero, 1989)." "Because turtle populations have a low growth rate, they are incapable of expanding rapidly during periods of high precipitation but populations can decline rapidly during drought years".

Giant spotted whiptail (*Cnemidophorus burti stictogrammus*) - The giant spotted whiptail is active during the daytime from spring through early autumn, and hibernates in the winter (RECON, 2001a). This species will emerge from hibernation in April or early May, depending on yearly climatic conditions (Goldberg, 1987 in RECON, 2001a). Although not much is known specifically for this subspecies of Cnemidophorus, survival and reproduction rates for the other Arizona subspecies of this lizard have been linked to weather conditions (Rosen and Lowe, 1996).

Red-backed whiptail lizard (*Cnemidophorus burti xanthonotus*) - Red-backed whiptails are active during the daytime, from mid-spring through early autumn. They are normally inactive during the remainder of the year (RECON, 2001a). Both survival and reproduction rates for this species are believed to be related to weather conditions (Rosen and Lowe, 1996).

Mexican garter snake (*Thamnophis eques megalops*) - The Mexican garter snake is primarily found within areas of permanent water ranging from desert grasslands to oak-pine communities, including cottonwood-willow riparian communities (RECON, 2001a). Since these habitats have been in serious decline, the range and distribution of the Mexican garter snake has also been in decline. Since its numbers are low and distribution limited, climatic factors such as drought and flooding could have damaging effects to the continued existence of this species within Pima County.

Desert box turtle (*Terrapene ornata luteola*) - Box turtles breed in both the spring and autumn (RECON, 2001a). Sex of the species is determined by temperature at which the egg was incubated, with lower temperatures producing more males and warmer temperatures producing more females (Degenhardt et al., 1996). Thus, changing air temperatures can have a profound affect on populations of this species.

In general, the desert box turtle occurs in grassland and desert grassland communities of arid and semi-arid, treeless plains and rolling grass and shrub land (RECON, 2001a). As mentioned previously, fire and the amount of winter rainfall (which are affected by climate) can affect the health and distribution of these types of communities.

Gila topminnow (*Poeciliopsis occidentalis*) - These fish are found in two different habitats, springs and streams. Desert springs and streams are characterized by infrequent and unpredictable water inputs. Climatic factors differ between the two and affect the populations and life cycles differently. Topminnows can tolerate temperatures from 0° C (32° F) to 37° C (99 °F), but respond to temperature ranges differently, both in growth and reproduction.

The temperature of spring flows are generally more stable year-long, while streams are more variable. There is a difference in topminnow growth and reproduction between springs and streams. Springs and their immediate outflows are ecosystems that fluctuate less with weather changes. In springs, topminnows exhibit different external morphology, mature at an earlier age and reproduce yearlong producing large numbers. Seasonal changes appear to be affected primarily by changes in the solar cycle, an exceedingly gradual and predictable progression (Brown, 1971; Constantz, 1976; Cox, 1966; Deacon, 1968).

Desert streams are generally characterized by short reaches with pools that are relatively closed ecosystems except during periods of runoff. Most of the year there is little or no in-flow or out-flow, and pools show stratification of temperatures and oxygen. Desert springs and streams are characterized by infrequent and unpredictable water inputs (Greenfield and Deckert, 1973). Discharge is important to fishes in pools. Low flows recharge the detrital cycle in pools. Flash floods rearrange pools, scour algae and invertebrates and may displace fish downstream. Temperatures fluctuate more with seasonal changes. Water temperature is controlled by local weather and generally restricts the breeding season to a period between March and September. Topminnows are slower growing and reproduce in small numbers in streams. Torrential storms displace fishes into vast temporary reaches. They spread from tiny refugia to repopulate entire drainage systems. In dry periods, they concentrate in the few remaining pools. They exhibit greater variations in population numbers and structures in local abundance and periodic extinction than do spring populations. This results in large inter-annual variations in reproduction and population densities (Lehtinen and Echelle, 1979). Desert streams are affected by variations caused by seasonal changes due to solar input, air temperature and precipitation. Occasional high mortality that results from downstream displacement and desiccation may result in extreme competition with other fishes.

Desert pupfish (*Cyprinodon macularius*) - Pupfish can tolerate great extremes of environmental conditions under desert climatic regimes (Minckley, 1973). They have the ability to survive in water temperatures up to 45° C or 113 °F (Lowe et al. 1967). They survive and reproduce in temperatures (22-26° C or 71.6-78.8°F) that are lethal to most fishes (Kinne 1960, Lowe and Heath 1969; Moyle 1976). Along the Salton Sea in California, Barlow (1958, 1961) observed groups of these fish moving from place to place in response to changes in local temperatures and salinities. By this activity, populations of these fish appear to remain in areas that are the most hospitable throughout the day and season (Minckley, 1973). As with most other aquatic species, increasing temperatures and aridity will reduce the amount and extent of available habitat for pupfish (Doug Duncan personal communication, 2001).

Longfin dace (*Agosia chrysogaster*) - The longfin dace is a hearty native fish, adapted to the harsh desert climate. In response to the onset of floods, the fish will move directly into the current, and then move laterally as the intensity of turbulence increases. The dace will remain in the margins of the current, and then move back into the channel as discharge declines; they are rarely ever caught in flood pools or backwaters (Minckley and Barber, 1971; Rinne, 1975). In response to drought, longfin dace retreat to side pools or under algal mats, logs or stones during the day, and can move and feed at night in water with depths as little as a few millimeters of water (Minckley and Barber, 1971). Even though this species is well adapted to the harsh climate of the desert southwest, increasing temperatures and aridity in the area will reduce the amount and extent of available habits for longfin dace.

Desert sucker (*Catostomus clarkii*) - Like most other native fish species, the desert sucker can tolerate a wide range of water temperatures (RECON, 2001a). Also, like other highly aquatic species, the extent of its available habitat will be reduced by increasing temperatures and aridity in the area.

Sonora sucker (*Catostomus insignus*) - The Sonora sucker is found within a variety of habitats ranging from warm water rivers to trout streams (BISON-M, 2000). This species is intolerant of lake conditions created by dams (Minckley, 1973). Like other fishes, it requires permanent water for survival. Increasing temperatures and aridity can greatly reduce its available habitat.

Gila chub (*Gila intermedia*) - Gila chubs are restricted to streams, springs, and cienegas (RECON, 2001a). Much of their historic habitat, as with other native fishes, has disappeared over the last century. Increasing temperatures and aridity in the area could further limit the extent of available habitat for this species.

Arkenstone Cave pseudoscorpion (*Albiorix anophthalmus*) - This species of pseudoscorpion is only known from Colossal Cave in Pima County, Arizona (RECON, 2001a). Much of the water that enters the cave system is provided by winter rains which soak the soils above the cave. Cave communities are also affected by plant and animal resources outside the cave, which influence the energy input potential for the cave (Muchmore and Pape, 1999). Climate, therefore, has a profound affect on the cave environment, and any change in the available moisture or changes in temperature can influence the status of cave species such as *A. anophthalmus*.

Talussnails (*Sonorella spp.*) - *Sonorella* species apparently live in isolated, undisturbed areas of rocks, usually near hilltops or in rocky canyons (RECON, 2001a). Relatively minor perturbations of their habitat may result in changes that impact the snails. Talussnails are thought to be particularly sensitive to climate change (Terkanian, 1999; in RECON, 2001a).

Tumamoc globeberry (*Tumamoca macdougalii*) - These plants usually spend most of the year in dormancy. Growth and reproduction occur in July and August with summer monsoonal thunderstorms. During periods of drought it may not emerge and give the appearance that the population is extirpated (Reichenbacher, 1985).

Pima pineapple cactus (*Coryphantha scheeri var. robustispina*) - Flowering is likely triggered by rain or humidity. The 1988 blooming period closely followed the first significant rains (Mills, 1991). With flower production linked to water availability, increasing aridity could reduce natural populations of this species, whereas increasing rainfall could boost its production.

Acuña cactus (*Echinomastus erectocentrus var. acuñensis*) - Flowering for this species takes place from March to mid-April (AGFD, 1997c). Water availability appears to limit flower production. The primary germination period for the Acuña cactus is during the summer monsoons (Johnson, 1992 in RECON, 2001a). Increased summer aridity would decrease production of this species.

Pima Indian mallow (*Abutilon parishii*) - These plants can be found flowering throughout the year in response to rains. Flowers open only in mid-afternoon in full sunlight, closing if clouds occur. (AGFD, 1997d). Increasing aridity could reduce natural populations of this species, whereas increased rainfall could boost its production.

Pringle lip-fern (*Cheilanthes pringlei*) - Dormant through the dry seasons, the pringle lip-fern reproduces only when there is sufficient moisture (Phillips and Phillips, 1991; Sue Rutman 1991 personal communications with Arizona Game and Fish Department 1991). Fluctuations in the abundance of this species may result from the amounts of rainfall that occur from year to year.

Nichol's Turks head cactus (*Echinocactus horizonthalonius var. nicholii*) - This cactus is a poor competitor with shrubs and trees for space, moisture, light and nutrients (USFWS, 1986). During years with little to no rain, there may be a decline in the population of this species as a direct result of competition with other species for moisture.

Gentry indigobush (*Dalea tentaculoides*) - As with many other species of *Dalea*, *D. tentaculoides* appears to flower in both the spring after winter rains and again in the fall following summer rains (Gori et al., 1992). Its main flowering season is in the spring, late March to mid-May. Lack of rainfall in either the winter or summer would affect this reproductive behavior.

Based on observations by Toolin (1986), seedling establishment of this species may be dependent on summer rainfall. No seedlings were observed from 1980 to 1983, during which there were drier-than-normal summers and average winter rains. Observations by Gori and others (1992) found that mortality of this species is related to size, with large plants having a better survival rate (>50%) than smaller plants. Although some grazing by cattle was noticed, lack of soil moisture was presumed to be the most likely reason for the loss of small plants.

Presently, the gentry indigobush is only known to occur in Arizona in Sycamore Canyon, which is located in the Atacosa Mountains in Santa Cruz County. Although it occurs in areas subject to periodic flooding, the largest clumps are normally found near obstructions that reduce flow velocities and provide protection from scouring (Gori et al., 1992). A catastrophic flood within this canyon, however, could possibly wipe out the entire population by removing plants and depositing them downstream in soils and elevations that are not suitable for reestablishment.

Kearney's blue star (*Amsonia kearneyana*) - Threats to the species include catastrophic flooding and soil erosion accelerated by losses in plant cover and vigor due to livestock grazing (USFWS, 1993). Kearney's blue star is susceptible to damage from catastrophic floods (Phillips and Brian 1982). Torrential rains during the summer of 1990 destroyed 76% of the plants of the Brown Canyon population. Drought conditions in the Spring of 1998 and 1989 necessitated hand-watering of a transplanted population to ensure survival (USFWS, 1993).

Huachuca water umbel (*Lilaeopsis schaffneriana var. recurva*) - Climate and suitable habitat are closely tied. Suitable habitat requires sufficient perennial base flow to provide a permanently or nearly permanently wetted substrate for growth and reproduction and a stream channel that is relatively stable, but subject to periodic flooding that provides micro-sites for *Lilaeopsis* expansion (USFWS, 1999).

5.0 Long-Term Climate Change

Variations in climate from year to year affect the number and intensity of heat waves and storms, the amount of water flowing in rivers and streams, the extent and duration of snow cover, and the amount of soil moisture that can be utilized by plant species. Some current analyses of climate in the southwestern United States show an overall trend of increasing temperatures, increasing and higher intensity rainfall, and shorter duration of snow pack cover (SRAG, 2000). Causes for climate change are both natural and human induced. This section will look at past trends and future predictions of climate changes for southern Arizona, and discuss the implications of these changes on both human and natural environments.

We live in an interglacial period. Our modern climate is the driest, warmest period during the last 32,000 years (Van Devender et al., 1991). Pinyon pine, juniper, and oak trees grew on the slopes of the Waterman and Ajo Mountains 10,000 to 20,000 years ago; Douglas fir and ponderosa pine grew on Pontatoc Ridge at the base of the Catalina Mountains (Van Devender, 1990). Because interglacial periods are short (10,000 years long) relative to glacial periods (100,000+ years long), the glacial episodes can be considered the "normal theater of evolution" (Martin, 1999). This perspective only heightens the significance of conserving biological diversity during our time.

Saguaro cacti and palo verde trees arrived in Pima County approximately 8,900 years ago, when the climate warmed (Anderson and Van Devender, 1991). The plant communities 8,900 to 4,000 years ago also differed from today. For instance, plants now typical of riparian areas such as catclaw acacia (*Acacia greggii*), blue palo verde (*Cercidium floridum*), and velvet mesquite (*Prosopis velutina*) grew on exposed slopes. As more modern desert scrub communities formed around 4,000 years ago, the species discussed above retreated to the riparian zones and subtropical plants moved northward from Sonora, Mexico.

Over the last century, the southwest region of the United States has experienced an increase in temperatures of 2° to 3°F (SRAG, 2000). Southern Arizona has warmed at a rate of 0.05°C (0.09°F) per year for the period 1969 to 1983 (Balling et al., 1998). As can be seen in Figure 20 (from Balling et al., 1998), the warming rate observed during 1969 to 1983 has continued into the 1990's. The figure shows that temperatures during the late 1990's approached the record-breaking temperatures that occurred during the 1890's. Even more rapid warming is occuring in northern Sonora. The 1990's have been one of the warmest decades on record across the globe, potentially being the warmest decade since 1400 (SRAG, 2000).

Precipitation has also moderately increased over the last century. Karl and Knight (1998) reported an approximate 10 percent increase in precipitation across the contiguous United States from 1910 to 1996, with the percentage of precipitation derived from extreme and heavy events also increasing. This trend appears to hold true for much of the Southwest, but not as strong as in the eastern United States. Increases in rainfall have been observed in southern Nevada, Utah, New Mexico and central Arizona, while southeastern California, the central Rockies and southern Arizona are experiencing declines (SRAG, 2000).

The frequency and intensity of summer drought will greatly affect the pace of shrub invasion in the semi-arid Southwest (Betancourt, 1996, in Swetnam et al., 1999). Some have attributed on-going expansion of creosote bush (*Larrea tridentata*) in the middle Rio Grande Basin and southern Arizona/New Mexico to recent climate change (e.g. Betancourt 1996 in Swetnam, et al., 1999).

Climate models are predicting continued increases in temperature over the next century, and substantial increases in annual precipitation. Based on the United Kingdom Hadley Centre's climate model (HadCM2), predicted temperature increases for Arizona appear to be evenly distributed throughout the year (3-4°F in the spring and fall and 5°F in the winter and summer). Predictions for precipitation are more variable, with moderate increases (20% to 30% respectively) expected in the spring and fall, a slight decrease (0 to 15%) in the summer and a substantial increase (60%) in the winter (EPA, 2001). Although other climate models may show different results, especially in precipitation, the overall patterns of temperature and precipitation change are roughly the same (Table 15).

Table 15. Results from global climate model calculations averaged over the Southwest region at various years in the future.

Predicted Change in Temperature (°F) from the Year 2000							
Year	**2030**		**2060**			**2090**	
Model	HC	CC	HC	CC	RM	HC	CC
Winter	4.5	5.4	3.6	7.2	7.2	7.2	12.6
Spring	2.7	3.6	2.7	5.4	7.2	3.6	10.8
Summer	2.7	3.6	4.5	5.4	9.0	5.4	9.0
Fall	2.7	2.7	5.4	7.2	7.2	5.4	9.0
Predicted Change in Precipitation (in/day) from the Year 2000							
Year	**2030**		**2060**			**2090**	
Model	HC	CC	HC	CC	RM	HC	CC
Winter	0.04	0.06	0.06	0.06	-0.04	0.20	0.18
Spring	0.02	0.01	0.01	0.02	0.01	0.08	0.04
Summer	0.01	0	0	-0.01	-0.01	0	0
Fall	0	0.02	-0.01	0.04	0	0.12	0.04

HC = Hadley Centre model; CC = Canadian Climate Centre model; RM = NCAR regional model
Note: Numbers presented here are average values taken from the range of values produced by the future climate scenario model results for the Southwest region as a whole.
Source: Southwest Regional Assessment Group, 2000

Water availability is highly dependent on climate. Temperature increases in Pima County would most likely result in increased evaporation rates, thus reducing water supplies. Lower supplies and higher prices for water could result in severe consequences for many sectors in the area, including rural farmers, ranchers, mining operations and urban areas (SRAG, 2000). Reduced water tables will also negatively impact aquatic and riparian ecosystems, which are already in danger of disappearing due to human activities. Predicted increases in rainfall during the winter, spring and fall months may help balance higher evaporation losses by recharging water to the aquifer system.

Perhaps an even greater consequence of future climate change could be the increase in frequency of El Niño events. Current research suggests that the occurrence of such events is more frequent as temperatures rise over time (SRAG, 2000). Greater frequency of El Niño events will produce more winter rainfall in Pima County. This can be beneficial, with more rain providing increased water storage and increased plant productivity. However, many areas in the Southwest, including Pima County, cannot handle the excess water produced by such events. This results in flooding, which can increase soil erosion, destroy structures, interrupt transportation, and threaten lives (SRAG, 2000). Cycles of El Niño and La Niña events, coupled with increasing temperatures, can also build up fuel reserves for wild fires, making them more intense and frequent in occurrence. Most "Sonoran Desert" native plant communities cannot handle high fire intensities and frequencies, making them susceptible to severe damage or competition by fire-loving, nonindigenous species. Human intervention often serves to increase the impacts of floods and fires, therefore making the situation even worse.

A changing climate can affect both plant and animal species. This is especially true in Pima County, where many of these species are highly specialized and adapted to the landscape. Warmer and wetter winters, along with an overall increase in temperatures can alter the number, type and range of species in the area (SRAG, 2000). Although it is difficult to determine the extent of these changes based on future climate predictions, it is possible that they may be very significant to some species.

Future patterns of climate change can increase current health concerns in Pima County. Diseases such as valley fever and Hantavirus pulmonary syndrome, which are endemic to the Southwest, are presumed to be strongly connected to patterns of precipitation (SRAG, 2000). Projected increases in temperature may produce a greater number of heat-induced illnesses, reduced air quality and an increased number of respiratory cases due to the presence of allergens and dust. Future climate scenarios increase the possibility of expanding the range of mosquitos carrying harmful diseases such as dengue fever and encephalitis (SRAG, 2000). Although we usually think only of human diseases, wildlife diseases may impact several isolated populations, and wildlife disease incidence may change as a result of climate change.

6.0 Conclusions and Recommendations

Weather will vary, and there will be ecological responses. Habitat Conservation Plans (HCPs) will need to consider the inherent variability of climate and how the ecological responses will affect species and habitats, as well as human land use, especially grazing and water demands. HCPs need also to consider global climate change, and its local expression.

A key issue for USFWS and the applicants will be the differentiation of climatic events which are "unforeseen circumstances". USFWS will not require the commitment of additional land, water, or financial compensation, or additional restrictions on the use of land, water or money when it finds that an unforeseen circumstances has occurred, unless the landowner consents. Changes in circumstances affecting a species or geographic area covered by an HCP, that can be reasonably anticipated and that can be planned for, are "changed circumstances". For changed circumstances, the applicant will be expected to implement the measures specified in the HCP for changed circumstances, but only those measures and no others.

In defining what constitutes a changed circumstance, U. S. Fish and Wildlife Service (USFWS) will need to consider the frequency and magnitude of fires, floods and droughts. This report provides some data for the recurrence of these natural phenomena in Pima County, and where available, some information about how the natural systems have responded or are thought to respond. While no specific recommendations on the recurrence intervals of climatic events to be considered changed circumstances are provided in this report, the longer the permit period and the greater the land area covered by the permit, the greater the natural variability expected. This could be statistically examined for most basic climatic phenomena.

The habitats of priority vulnerable species, which are already limited in size by natural conditions and historic losses, will continue to be at risk to climatic variability. Strategies which might be used to reduce the risks will to some degree depend on the species. However, more recently, conservation biologists (e.g. Noss, 2001) have contemplated the rapid pace of global climatic change and its meaning for conservation of certain ecosystems.

Some ecosystem protection and management strategies we recommend for minimizing the adverse effects of climatic variability on the SDCP include:

Keep wildland ecosystems as intact and functioning as possible. Less fragmented, functioning ecosystems may better able to handle climatic change. The biological goal of the Sonoran Desert Conservation Plan is to ensure the long-term survival of the full spectrum of plants and animals that are indigenous to Pima County through maintaining or improving the ecosystem structures and functions necessary for their survival. In core reserves, the goal of maintaining the species and the structure and functions necessary for them to survive should take precedence. However, in many areas, the economic needs of other users will inevitably conflict with this goal. Some limit to the degree of change in the ecosystem due to economic pressures is needed in multiple use areas if these are to function as reserves. Ecosystems will be most resilient when we keep the rates, scales and intensities of man-made changes within the range of variability experienced by them in their recent evolutionary past (Noss, 2001).

Increase redundancy of representative habitats by preserving and rehabilitating multiple sites in the reserve system. To a limited degree, the STAT species goals address this by incorporating requirements for multiple patches in certain cases.

For some riparian and aquatic species, selecting sites on different reaches of the same watercourse can still provide some redundancy. For instance, along Cienega Creek, the confluence with Davidson Canyon is an important reach boundary. Large storm flows may affect the reach downstream of Davidson Canyon without affecting upstream reaches. Likewise, drought conditions affecting base flows in upper reaches are not necessarily reflected in decreased base flows downstream of Davidson Canyon. This type of variability can be exploited in preservation, restoration and re-establishment efforts.

Represent species and special elements across environmental gradients. Redundancy may not be sufficient. It may be more important to select sites which allow the distribution of the species to shift up or down in elevation within a watershed as climate varies. Reserves which represent only a small part of the natural elevational range of the species may not be adequate.

In addition to elevation, a measure of the heterogeneity of a reserve system could be developed using soil characterstics as an index of microclimatic heterogeneity. This index would be based on the premise that soil texture, structure and soil horizons are important in modulating the response of vegetation to rainfall. This is a premise with which many plant biologists in the Southwest seem to agree (McAuliffe, 1995; Burgess, 1995; USFWS, 2000).

Protect climatic refugia at multiple scales. Refugia are places where plants and animals persist during times of unfavorable conditions. In our region, during the present interglacial time period, mountaintops, springs, flowing streams and riparian areas serve as climatic refugia for some species. On a smaller scale, talus slopes, steep, north-facing slopes, and limestone outcrops also serve as refugia for species which would not otherwise have persisted during the last several thousand years of climatic variability. Of these potential refugial sites, the STAT has chosen all but mountaintops and steep, north-facing slopes as special conservation targets in the SDCP. Mountaintops have been included in the biologically-preferred reserve design where they are surrounded by high-value piedmonts (RECON, 2001b). Perhaps north-facing slopes should also be added to the list of special elements.

The need for protection does not end with reserves designation. Land managers should inventory microsites which may function as refugia, many of which may not have been identified at the scale of the SDCP. This is particularly true of springs, limestone outcrops, talus slopes and steep north-facing slopes. They should be careful stewards of the integrity of potential refugial sites in the development of trails, utility corridors and other facilities.

Implement and evaluate mitigation techniques as far in advance of "take" as possible. This strategy has been specifically recommended for HCPs by Kareiva and others (1999) and for wetlands mitigation by a recent panel convened for the National Academies of Science (NRC, 2001). This is desirable because flaws with the mitigation or minimization techniques might only become apparent during climatic extremes. Problems in the design and construction of revegetation projects often become apparent during normal drought and flood conditions, for example. Mitigation and minimization techniques must work during the full range of climatic conditions in order to be successful.

Prepare contingency plans for mid-course corrections in mitigation and minimization techniques. Failure to achieve performance goals due to drought, fire and floods will happen. What will be the response? Contingency planning is recommended for HCPs and a proprosed response to forest fires has been made part of a recent HCP for the Karner blue butterfly (Watchman 2001). A contingency plan should contain actions other than additional monitoring and research commitments. Perhaps additional sites will be needed, or removal of additional stressors. Performance bonding or other measures to ensure sufficient funding may be needed to implement contingency plans.

Monitor climatic variables. Collecting and reviewing precipitation, stream flow, and temperature data may be necessary to support the interpretation of biological data for the adaptive management plan. Those responsible for Sonoran Desert Conservation Plan monitoring will need to consider whether existing climatic monitoring programs can provide the necessary information, or if special efforts are needed to augment existing programs.

Incorporate scientific findings on biotic and abiotic responses to climatic change. It is one thing to determine correlations with climatic parameters, and another to measure response of biodiversity to climate change. The experimental design needed to determine causality is likely to be much more expensive and time-consuming than is the compliance monitoring for the Sonoran Desert Conservation Plan. Nonetheless, the adaptive management team for the SCDP should consider whether adequate information will be generated by existing efforts, and keep abreast of findings from those regional climate change studies to inform their decisions.

Restore pre-settlement fire regimes in forests and woodland. The potential for catastrophic, stand-reducing fires in woodlands and forests can be reduced through an aggressive program of low intensity, controlled burns and natural ignitions that are allowed to burn when the weather and/or geographic conditions for a catastrophic, stand-reducing fire are low and property is not in danger. To maximize success of such a program, its goal should be to approach the pre-settlement fire regime. In our area, pre-settlement fire regimes are well known and the cause of recent change is attributed to livestock grazing and fire suppression, not climate change (see Swetnam et al., in press).

In contrast, the degree to which shrub conversions in the semi-desert grasslands are the consequence of climate change is not yet known (Swetnam et al., 1999) and the pre-settlement fire histories are also less well known. The restoration of fire as a disturbance process might also benefit these areas, but the lack of information suggests a cautious approach to the assumption that all woody shrub incursions are in need of fire.

Restore floodplain hydraulics to help store water and reduce the destructive impacts of flood waters downstream. Specifically, by restoring channelized washes to a condition where they have a functioning floodplain during high frequency flows, and avoiding the concentration of stormwater flows in distributary flow areas. Eliminating overbank flooding and distributary flow areas, where sediment and water naturally spread out, speeds the transit time of water through the system, which in turn can make it more susceptible to drought. Maintaining overbank flooding and distributary flow zones will help direct more water into storage beneath the bed of the river and reduce the destructive energy of flows. In the most highly urbanized areas where maintaining floodplain hydraulics is not possible, stormwater harvesting and detention basins can lessen some of the damage.

Consolidate grazing allotments. Small ranches are likely to have fewer options than large ranches to respond to climatic variability. A large ranch will have greater ability to take advantage of spatial variability in rainfalls, fires, floods and freezes. Large operations such as the Empire-Cienega Ranch operate several allotments as one ranch, adjusting rotation schedules and water sources in response to drought. Not only do large ranches have more ability to respond to climatic variations, but they are also generally better capitalized and more economically viable. In general, a ranch operation needs at least 200 head to be viable (Conley, et al, 1999). For these reasons, consolidating allotments makes sense. Economic viability might also reduce the likelihood of conversion to other more damaging land uses.

Relieve grazing stress by deferring or retiring livestock grazing. Ranchers in other counties have created grass banks, where herds can be directed during times of drought, or to allow for vegetation to grow following fires. Grass banks are not grazed every year. The Malpais Borderlands grassbank requires donation of conservation easements in exchange for access to the grassbank.

Another strategy is to reduce herd size during droughts. For instance, Coronado National Forest has reduced the number of permissible livestock when dry spells reduced production of biomass suitable for grazing.

Some agencies have removed livestock grazing entirely, in order to protect riparian vegetation or species which are otherwise vulnerable to grazing stress. Lands too steep or too unproductive for grazing have been permanently removed from grazing leases by Coronado National Forest. Pima County and the Bureau of Land Management have excluded livestock from riparian areas along Cienega Creek.

Another tool is the Emergency Watershed Protection Drought Assistance Program. This past year, the U. S. Department of Agriculture, working through the Pima County Flood Control District, paid eight local ranchers to reduce the size of their livestock herds during a specified contract period at a cost of $324,596. Ranchers have entered into contract to reduce herds and apply grazing management practices per Natural Resources Conservation Services requirements on the ranch for one year. Only ranches with more than 10 inches of average annual rainfall are eligible for this emergency assistance, because "significant permanent improvement of vegetative cover can not be reasonably achieved" on rangelands with less than 10 inches of average annual precipitation (USDA, 2000). Grazing allotments which are ineligible due to rainfall are located near Ajo, the Aguirre Valley, and the extreme northern floodplain of the Lower Santa Cruz River of unincorporated Pima County.

Develop and implement localized drought plans for domestic and municipal water uses. Locally developed plans, if implemented, could protect or mitigate damage to ecologically significant habitat. It would be useful to have drought plans for distinct areas, which would account for local hydrogeologic conditions, existing exploitation patterns, and a long-term perspective of likely future conditions, based both on the historic record and on new information generated by models of potential climate change. For instance, there may be ways to conserve water in the Summerhaven area during droughts that would reduce demands on spring and stream systems in the Catalina Mountains. An analysis of existing supplies and water use patterns in that area could help identify which conservation measures might provide the most relief to aquatic systems.

A drought management plan developed for the entire state, Pima County, or even the Tucson Active Management Area would be too general to address the particular concerns of residents in a given area or to consider the particular needs of vulnerable species and environments. The range of useful drought mitigation measures in Summerhaven, for example, would be quite different than the measures which might be appropriate in other areas, such as for the populace using groundwater from lower Sabino Creek. Water conservation in some areas, such as Avra Valley and Northwest Tucson Basin, would not be effective in reducing stress on riparian areas, because it comes from deep aquifers which did not yield water to the root zone of riparian trees even during pre-development conditions. For ecosystem benefits, water conservation should target the areas which will make the greatest difference first.

Plan land uses to avoid increased stress during droughts, both inside and outside the reserve system. While options to reduce existing demands are useful, land use planning should take into consideration the new water demands that might be imposed upon an area. Keeping ranches going can help prevent large increases in water demand, which might result if an area were converted to residential or commercial uses. For example, a single person in Sonoita consumes ten times as much water as a cow and her calf (Conley, et al, 1999). If an area cannot be placed into an existing reserve, then to decrease the threat of escalating water demand, zoning changes and variances which increase density should be avoided in land overlying ecologically significant aquifers.

Acquire water rights (surface water and groundwater) to reduce diversions of water from riparian habitats. In some areas, the use of accrued grandfathered irrigation rights could result in depletion of shallow groundwater tables. For instance, in the Arivaca watershed, AWET (2001) estimated that the amount of currently accrued water rights is equal to approximately the next 50 years of Arivaca Valley recharge. Water rights could be purchased or their use constrained in the negotiation of conservation easements with willing sellers, or the rights could be transferred when property is acquired for new reserves by public agencies. Where this is not possible, perhaps water rights could be leased for the purpose of deferring use during droughts.

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8.0 Glossary of Terms

Adaptive management - a type of natural resource management that implies making decisions as part of an on-going process. Monitoring the results of actions will provide a flow of information that may indicate the need to change a course of action. Scientific findings and the needs of society may also indication the need to adapt resource management to new information.

Andesite - a fine-grained igneous rock of intermediate composition; composed of equal amounts of iron/magnesium-rich minerals and a mixture of sodium and/or calcium, aluminum and silicon minerals.

Argillic soil horizon - a reddened, clay rich soil horizon with a prismatic (prism-like) structure

Arroyo - a watercourse that is dry most of the time; this term is usually used to describe a dry wash with steep sides cut by erosion.

Arid - characterized by extremely dry conditions; an arid climate is often referred to as a "true desert" climate.

Basalt - a fine-grained igneous rock composed of such minerals as iron, magnesium, calcium, sodium, silicon and aluminum.

Biological constraint - a condition or force that restricts the activities of living things.

Bioturbation - destruction of depositional layers by animals

Cienega - a marshy area

Convective thunderstorm - a storm with dense and vertically developed clouds that are produced predominantly by rising air currents due to surface heating. Heavy rainfall and lightning normally accompany such storms.

Correlated - two things that are so related that one directly implies or is complementary to the other.

Cryptogamic crust formation - an encrusted deposit of materials from plants (ferns, moss, alga, or fungus) that reproduce from spores as opposed to producing flowers or seed.

Dengue fever - an acute infectious disease that is caused by a virus transmitted by insects, most notably mosquitos, and is characterized by headache, severe joint pain and a rash.

Distributary flow - flow of water that spreads out into more than one channel, the positions of which sometimes change over time.

Diurnal - of, relating to, or occurring in the daytime.

Drainage basin - the total area contributing runoff to a particular point along a watercourse.

Ecosystem - the complex of a community of organisms and its environment.

Ecotone - a transition area between two adjacent ecological communities, usually exhibiting competition between organisms common to both.

Elevation gradient - the ascent or descent along a mountainside.

Encephalitus - inflamation of the brain.

Ephemeral stream - a stream that flows only in direct response to precipitation, and whose channel is at all times above the water table.

Fauna - the animals characteristic of a region, period or particular environment.

Floodplain - the area in and near a watercourse that may be inundated during floods.

Flora - the plants characteristic of a region, period or particular environment.

Frontal storm - a storm that forms in response to forced convection, or forced lifting, along a transition zone between two distinct air masses.

Genotype - all or part of the genetic constitution of an individual or group of species.

Habitat - the area where a plant or animal lives and grows under natural conditions.

Hantavirus pulmonary syndrome - a disease contracted by exposure to rodents (especially deer mice) or their droppings with symptoms beginning with fever and muscle aches, followed by shortness of breath and coughing. Once symptoms begin, the disease spreads rapidly, necessitating hospitalization within 24 hours.

Heating day - heating day or heating degree day is computed as the difference between the base temperature and the daily average temperature

Heterogeneity - being dissimilar; consisting of diverse ingredients or constituents.

Horizontal diversity - the distribution and abundance of different plant and animal communities or different stages of plant succession across an area of land; the greater the numbers of communities in a given area, the higher the degree of horizontal diversity.

Hydrology - the science dealing with the study of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere.

Infiltration - the movement of water into the soil.

Intrusive rock - rock that appears to have crystallized from magma placed on surrounding rock.

Latitude - the angular distance north or south from the earth's equator measured though 90 degrees.

Limestone - a sedimentary rock composed mostly of calcite ($CaCO_3$)

Metamorphic schist - a metamorphic rock characterized by coarse-grained minerals oriented approximately parallel.

Meteorology - a science that deals with the atmosphere and its related phenomena, especially weather and weather forecasting.

Microclimate - The climate structure of the air space near the surface of the earth.

Net primary productivity - the net flux of carbon from the atmosphere into green plants per unit time. It is often used to indicate the conditions of the land surface and the status of a wide range of ecological processes.

Nonindigenous species - any species that enters an ecosystem beyond its historic range, including any such organism transferred from one country into another.

Nonnative species - a species that has been moved by humans (actively or passively, intentionally aor unintentionally) to an area outside of its native range, but is still on the continent of its origin.

Orographic effect - the production of dry air on the leeward side of a mountain due to the loss of moisture (as precipitation) as the air moves up and over the mountain.

Pathogenic - causing or capable of causing disease.

Perennial stream - a watercourse that has at least a little water all year round.

Petrocalcic horizon - a soil horizon with thick layers of caliche, a crust of calcium carbonate that forms in soils of arid regions.

Photosynthesis - the formation of carbohydrates in the leaf tissues of plants when exposed to light.

Piedmont - the area between the mountain front and the valley; the foothills area.

Recolonization - the natural establishment of species populations in areas where they formerly occurred.

Reestablishment - the stocking of populations of species within their historic range where documentation of earlier, natural presence at the specific sites may or may not exist.

Refugia - populations established for the primary purpose of preventing extinction of a species from the United States.

Regression - a functional relationship between two or more correlated variables that is often empirically determined from data and used to predict the values of one variable when given the values of the other.

Riparian - originates from the Latin word meaning "along the river." In the semi-arid western United States, it means along a watercourse, arroyo, seep, pond, or other location where the availability of water is increased.

Riparian obligate species - species found only in riparian habitats

Semiarid - characterized by light rainfall; having from about 10 to 20 inches of annual precipitation.

Sinuosity - the quality or state of having a wave-like form or pattern

Spatial scale - extent of areal spreading

Synchroneity - the state of recurring or operating at the same period of time.

Type A soil horizon - the mineral horizon at the surface or just below the O horizon, the layer of organic material on the surface of a soil. The A horizon is one in which living organisms are most active and therefore marked by accumulation of partially decomposed plant or animal matter.

Type B soil horizon - the mineral horizon below and A horizon. It has distinctive characteristics caused (1) by accumulations of clay, decaying plant or animal matter or iron and aluminum oxides; (2) by a prismatic or blocky structure; (3) by redder or stronger colors than the A horizon; or (4) by some combination of the first three.

Ungulate - any of the hoofed mammals (i.e., deer, bighorn sheep, pronghorn antelope), of which most are herbivorous and many are horned.

Valley fever - a disease caused by a fungus and characterized by fever and localized pulmonary (relating to the lungs) symptoms.

Watercourse - any lake, river, stream, creek , wash, arroyo or other body of water or channel having banks and bed through which water flows at least periodically.

Xeric - characterized by or requiring only a small amount of water