Variations in climate and ephemeral channel recharge in southeastern Arizona, United States

D. R. Pool

U.S. Geological Survey, Tucson, Arizona, USA

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[1] Significant variations in interannual and decadal recharge rates are likely in alluvial basins of the semiarid southwestern United States on the basis of decadal variations in climate and precipitation and correlation of El Niño with high rates of winter precipitation and streamflow. A better understanding of the magnitude of recharge variations in semiarid and arid regions would reduce water budget uncertainty. Variability of ephemeral channel recharge with climate in southeastern Arizona was investigated through analysis of hydrologic monitoring near three ephemeral streams in southeastern Arizona during the middle to late 1990s and by relating the results to long-term hydrologic and climatic trends. The analysis used precipitation, streamflow, water levels in wells, estimates of groundwater storage change from repeat gravity surveys, and two climatic indicators of El Niño–Southern Oscillation (ENSO), Southern Oscillation index, and Pacific Decadal Oscillation (PDO). Results indicate that variations in winter recharge are related to ENSO. El Niño conditions correspond with a greater probability of high rates of winter precipitation, streamflow, and recharge. La Niña conditions are almost exclusively associated with below-average recharge. Rates of recharge along Rillito Creek near Tucson during 1977–1998, a period of frequent El Niño conditions and positive PDO values, were 3 times recharge rates during 1941–1957, a period dominated by La Niña conditions and low PDO values. Quantification of recharge variability with decadal climate cycles should improve estimates of rates of aquifer drainage and replenishment in the region. Similar methods are applicable to other regions where thick unsaturated zones can accept significant periodic recharge.

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1. Introduction

[2] Estimated rates of recharge in alluvial basins of the southwestern United States have not generally included estimates of variations in recharge that may have occurred with climate variations. Estimates of average annual recharge rates may not be representative of extended periods of below- or above-average precipitation. The likely occurrence of significant variations in recharge rates has become apparent with the recognition of multiyear and decadal variations in climate, precipitation, and streamflow driven by Pacific Ocean climate [*Redmond and Koch*, 1991; *Cayan and Webb*, 1992; *Webb and Betancourt*, 1992; *Cayan et al.*, 1999; *McCabe and Dettinger*, 1999]. Climate driven variations in recharge in the alluvial basins of the southwestern United States are likely because infiltration of runoff producing precipitation in ephemeral streams, including at the mountain front, is the most important recharge process in the region [*Phillips et al.*, 2004].

[3] Estimates of variations in recharge are now possible on the basis of several decades of climate and hydrologic data. Better estimates of variations in recharge rates will result in improved understanding of transient conditions in groundwater flow systems and will enable planning for the effects of future climate variations on groundwater availability. This analysis integrates and summarizes climate and hydrologic data in southeastern Arizona and estimates recharge variations along ephemeral channels in three study areas. Results should be applicable to the region in general.

[4] This analysis is a result of multiple investigations to quantify variations in groundwater storage and recharge in southeastern Arizona using gravity methods. Each of the investigations showed significant variations in recharge during and following the El Niño conditions of 1997–1998 and prompted the question of the influence of El Niño conditions on recharge rates. Further analysis was then done to evaluate correlations of long-term hydrologic data including precipitation, streamflow, and water levels in wells with the climate indicators.

2. Regional Hydrology and Climate

[5] Recharge to groundwater systems in alluvial basins of southeastern Arizona (Figure 1) primarily occurs through periodic infiltration of streamflow in ephemeral channels. Mountains that border the basins are composed mostly of crystalline rocks that accept little mountain block recharge [*Anderson et al.*, 1992]. Runoff from the crystalline rocks can infiltrate adjacent alluvial deposits through a process commonly known as "mountain front recharge." Infiltration also occurs farther from the mountains along ephemeral

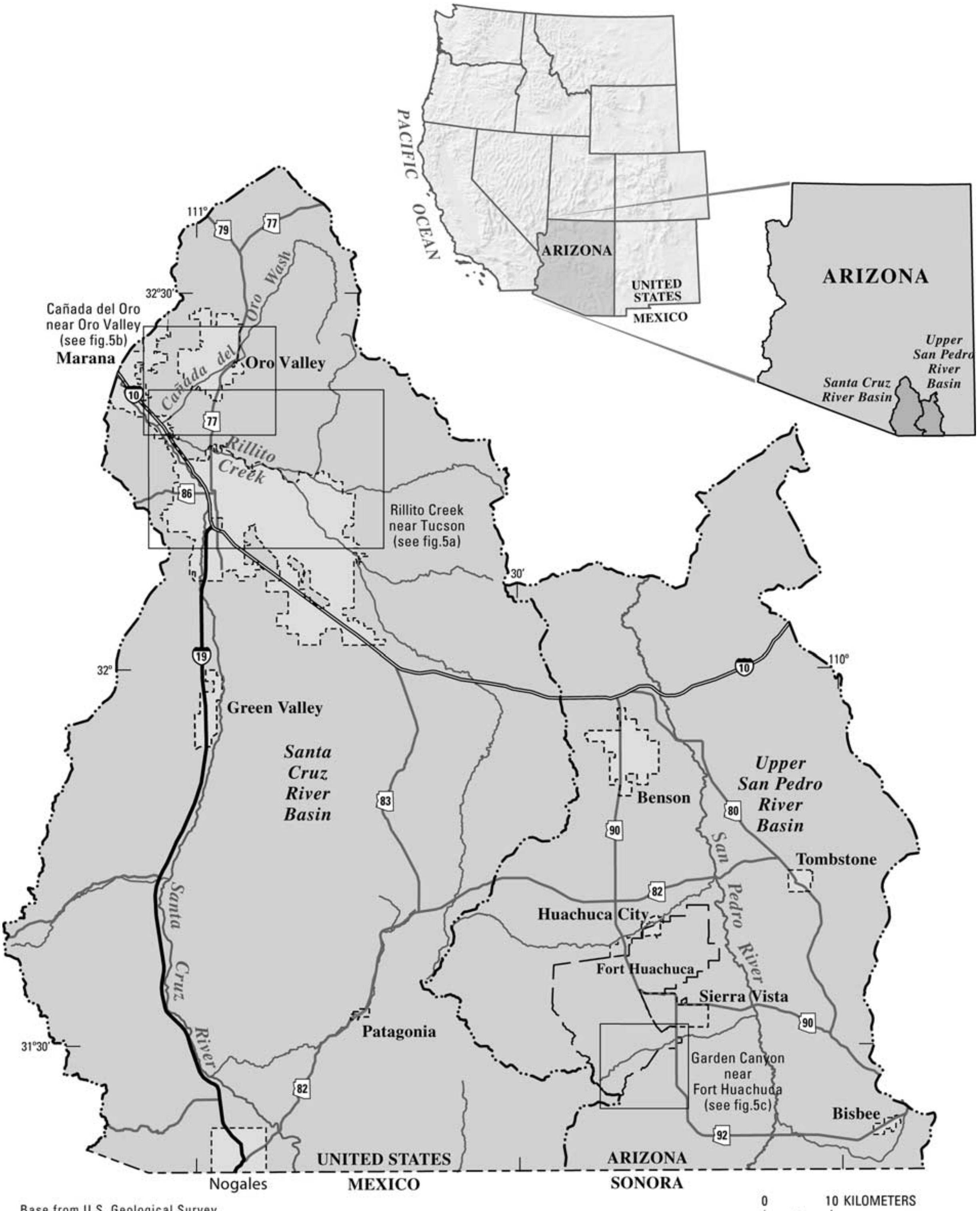


Figure 1. Study areas of Rillito Creek near Tucson, Cañada del Oro near Oro Valley, and Garden Canyon near Fort Huachuca.

streams that drain large parts of basins. Precipitation of sufficient duration and intensity to produce significant streamflow and recharge along major ephemeral streams may not occur for periods of several months or years. Recharge through direct infiltration of precipitation between drainage channels occurs rarely [*Anderson et al.*, 1992; *Scott et al.*, 2000] and is likely a minor recharge mechanism [*Walvoord et al.*, 2002; *Scanlon et al.*, 2003].

[6] The seasonality of precipitation has a strong influence on recharge rates. Streamflow and recharge-producing pre-

cipitation in southeastern Arizona result from three seasonally distinct storm types: frontal and cutoff low-pressure systems, dissipating tropical cyclones, and monsoonal thunderstorms [*Webb and Betancourt*, 1992]. Frontal and cutoff low-pressure systems predominantly occur during the winter months of November through February. Dissipating tropical cyclones occasionally enter the area during the late summer and early fall (September and October). Monsoonal thunderstorms of up to a few hours duration occur during the summer months (June to September). Winter recharge sources are believed to dominate over summer sources [*Keith*, 1981; *Kalin and Long*, 1994; *Pool and Coes*, 1999; *Eastoe et al.*, 2004] because the duration of precipitation produced by frontal storms is typically longer and evaporation and transpiration rates are lower during winter months. Summer precipitation is produced primarily by monsoonal thunderstorms that can be of greater intensity than winter frontal storms, but generally are of short duration and typically produce little runoff and streamflow infiltration because the storms are localized and evaporation and transpiration rates are high. Infiltration of summer streamflow may be a relatively more important source of recharge at the mountain front than along major ephemeral streams [*Cunningham et al.*, 1998] because total annual streamflow near the mountains is normally dominated by summer streamflow.

[7] Several climate and streamflow studies have established relations between large-scale atmospheric patterns and variations in the frequency and magnitude of streamflow-producing winter precipitation in the Southwest [*Douglas and Englehart*, 1981; *Ropelewski and Halpert*, 1986; *Andrade and Sellers*, 1988; *Cayan and Peterson*, 1989; *Redmond and Koch*, 1991; *Webb and Betancourt*, 1992; *Cayan and Webb*, 1992; *Cayan et al.*, 1999; *McCabe and Dettinger*, 1999]. The Southern Oscillation (SO) [*Walker*, 1923; *Walker and Bliss*, 1932] is a large-scale atmospheric pattern found to have significant teleconnections with precipitation and streamflow in the Southwest. SO is characterized by an east-west sea surface pressure gradient spanning the tropical Pacific Ocean [*Redmond and Koch*, 1991], the strength of which oscillates over periods of a few years. Weak pressure gradients generally are associated with El Niño conditions, which are above-average sea surface temperatures (SST) in equatorial waters off the coast of South America [*Trenberth*, 1976; *van Loon and Madden*, 1981; *Trenberth and Shea*, 1987]. The two corresponding events are known collectively as El Niño–Southern Oscillation (ENSO) [*Rasmusson and Carpenter*, 1982; *Cane*, 1983; *Ramage*, 1996]. Atmospheric teleconnections between El Niño conditions in the tropical Pacific and winter precipitation in the western United States have been found to include the occurrence of extreme high rates of winter precipitation and streamflow in the Southwest [*Kiladis and Diaz*, 1989; *Webb and Betancourt*, 1992; *Cayan and Webb*, 1992; *Swetnam and Betancourt*, 1998; *Cayan et al.*, 1999]. Conversely, winter drought tends to be associated with periods of cool SST in the subtropical Pacific Ocean, also known as La Niña conditions. No similarly strong correlation of El Niño with summer precipitation exists. *Higgins et al.* [1998], however, found that wet summer monsoons tend to follow dry winters in the Southwest. Rates of groundwater recharge in southeastern Arizona likely depend on ENSO because winter precipitation is the primary source of recharge.

[8] A common measure of ENSO is the SOI, which is the difference between standardized sea level atmospheric pressures at Tahiti and Darwin, Australia [*Trenberth and Shea*, 1987; *Elliot and Angell*, 1988; *Redmond and Koch*, 1991; *Trenberth and Hoar*, 1996]. The SOI used in this study is the standard series from the National Oceanic and Atmospheric Administration Climate Prediction Center [*Ropelewski and Jones*, 1987] (Figure 2). Values of SOI vary between −4 and 4. Negative values indicate weak east-west pressure gradients and are usually associated with El Niño conditions. Positive values indicate strong pressure gradients and are associated with La Niña conditions. Values are available for the period 1882–1999 with the exception of 12 years between 1892 and 1933. The record includes 59 years with negative SOI values and 47 years with positive values. A lag between SOI and precipitation has been recognized in the western United States. *Woolhiser et al.* [1993] identified a 90-day lag. This report uses the average SOI for the period June to November of each year as an indicator of ENSO because it has been shown to be a significant predictor of precipitation and streamflow in the western United States by several investigations [*Redmond and Koch*, 1991; *Cayan and Webb*, 1992; *Webb and Betancourt*, 1992].

[9] Some important trends in the SOI likely are related to trends in winter precipitation, streamflow, and possibly recharge in the American Southwest. The magnitude of the SOI varied between 2 and −2 during 1882–1954, but the range of values was much greater after 1954 (between −3.6 and 2.9). The SOI tends to vary between negative and positive values over periods of 3 to 5 years during most of the record [*Webb and Betancourt*, 1992]. The period 1976–1995, however, included an unusually frequent occurrence of negative values and El Niño conditions. *Trenberth and Hoar* [1996] suggest that this high frequency of El Niño conditions should occur only once in a thousand years. The greater frequency of El Niño conditions during 1976–1995 is evident in a plot of the 15-year moving average of SOI values (Figure 2); values average between −0.5 and 0 before the late 1970s, but average less than −0.5 during and after the late 1970s. These SOI trends are associated with above average rates of winter precipitation and streamflow since the mid-1970s.

[10] The strength of ENSO teleconnections with precipitation in the western United States has been shown to vary on 30-year timescales. *McCabe and Dettinger* [1999] demonstrate that the SOI was a weaker predictor of precipitation in the western United States during 1920–1950 than during recent decades. Prediction was improved by inclusion of 30-year variations in North Pacific SSTs indexed by the Pacific Decadal Oscillation (PDO) (Figure 2). PDO is calculated as the leading principal component of monthly SSTs in the Pacific basin north of 20 degrees north latitude [*Mantua et al.*, 1997]. Positive PDO values are indicative of cool temperatures in the northern Pacific and warm temperatures in the tropical Pacific and along the northern coast of North America. Although the SOI and PDO indices are anticorrelated (Figure 2), a positive correlation exists between the long and short-term tropical Pacific SSTs related to the PDO and the SOI, respectively, and may be mani-

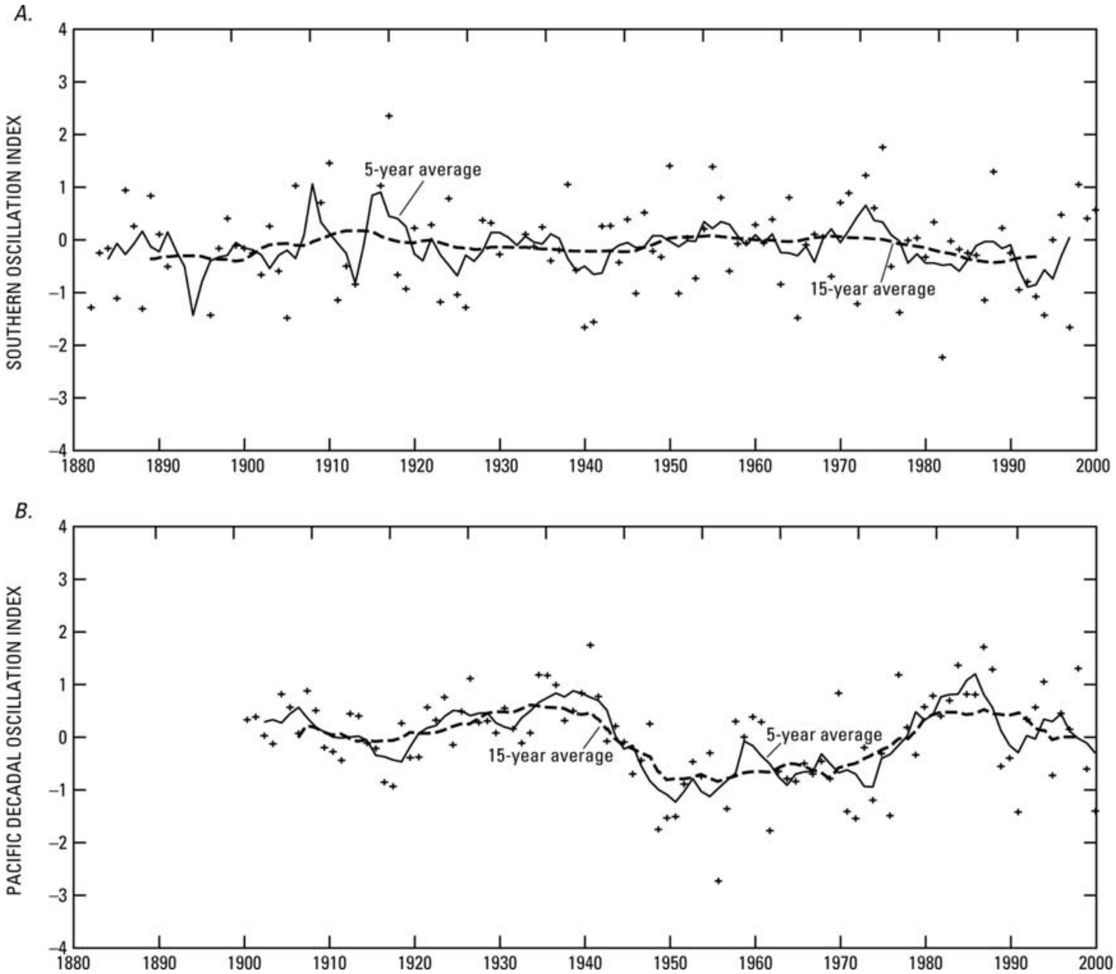


Figure 2. Oscillation indices. (a) Southern Oscillation index (SOI); average of June–November monthly values, 1882–2000 (http://www.cpc.ncep.noaa.gov/data/indices/soi). (b) Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997]; average of October–March monthly values, 1900–2000.

festations of the same phenomenon. *McCabe and Dettinger* [1999] show that 30-year average PDOs are highly anticorrelated ($r = -0.88$) with 30-year average counts of correlations of SOI and winter precipitation in the western United States. *McCabe and Dettinger* [1999] also note that the PDO has a stronger influence on precipitation in the Pacific Northwest than in the Southwest. Inclusion of the PDO with the SOI in prediction of winter precipitation in the Southwest may not therefore greatly improve results.

3. Methods

[11] Effects of climate variations on recharge rates in southeastern Arizona were quantified on the basis of estimates of winter recharge that were developed from intensive hydrologic monitoring near three ephemeral streams in southeastern Arizona and from historical hydrologic data collected during the middle to late 1990s (Figure 1). Study areas were Rillito Creek and Cañada del Oro Wash in the Tucson Basin, and Garden Canyon Wash in the Upper San Pedro River Basin. Multiple types of information were used in the analysis, including precipitation, streamflow, water levels in wells, and groundwater storage measured using microgravity methods [*Pool and Eychaner*, 1995; *Pool and Schmidt*, 1997]. Local precipitation and streamflow data were correlated with common indicators of climate, and results were compared with regional relations developed by previous investigators. Variations in long-term recharge were analyzed on the basis of estimates of streamflow infiltration during 1933–1999 along Rillito Creek and compared with common indicators of Pacific Ocean climate: Southern Oscillation index (SOI) and Pacific Decadal Oscillation (PDO). Only limited quantification of long-term variations in recharge rates was possible for Cañada del Oro Wash and Garden Canyon Wash because of sparse long-term hydrologic records.

[12] Independent estimates of recharge near Rillito Creek during the middle to late 1990s were based on estimates of streamflow infiltration and groundwater storage change using microgravity methods [*Pool and Schmidt*, 1997]. Streamflow infiltration along the mainstream channel does not account for infiltration along tributary streams and direct infiltration of precipitation, both of which are measured by gravity methods. Both methods may slightly overestimate recharge because some of the infiltrated water can be evaporated or transpired by phreatophytes before reaching the aquifer. Significant rates of evapotranspiration from the unsaturated zone near ephemeral channels have been estimated locally as about 20% of water that infiltrated during summer runoff events [*Goodrich et al.*, 2004]. Variations in

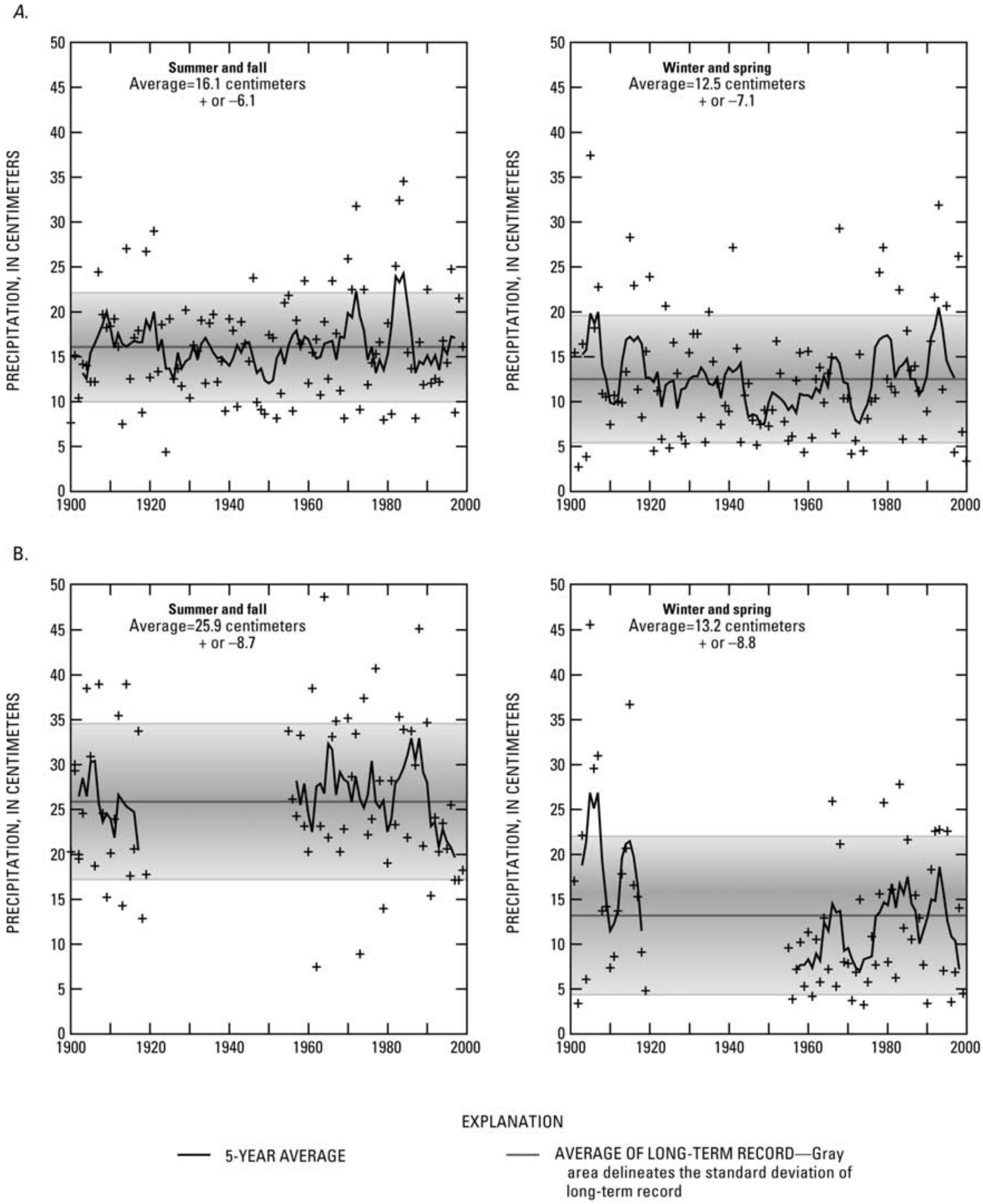


Figure 3. Seasonal precipitation at (a) the University of Arizona Campbell Road Farms and (b) Fort Huachuca, 1900–2000.

rates of winter evapotranspiration from the unsaturated zone, which are significant to this analysis of variations in recharge, are likely much less than variations in summer rates. Variations in rates of winter unsaturated zone evapotranspiration have not been estimated for this analysis and are assumed insignificant.

4. Precipitation in Southeastern Arizona and ENSO

[13] Long-term seasonal precipitation at two stations in the study areas were compared with the SOI (average value for June through November) and PDO (average value for October through March) to confirm that observed regional relations between Pacific Ocean conditions and local precipitation in the Southwest also apply to local conditions in southeastern Arizona. Long-term precipitation data were available from a station at the University of Arizona Campbell Road Farms (1900 through July 2000) near the Rillito Creek and Cañada del Oro study areas and from Fort Huachuca (1900–1919 and 1955–2000) near Garden Canyon (Figure 1). An analysis of SOI, PDO, and winter/spring precipitation was completed to develop an empirical equation that can be used as a predictor of precipitation.

[14] The Tucson Basin and Upper San Pedro River Basin have different seasonal distributions of precipitation (Figure 3). Annual precipitation near the Tucson Basin study areas is split roughly between summer/fall (June through November; 16.1 cm) and winter/spring seasons (December through May; 12.5 cm), but annual precipitation near Garden Canyon is dominated by summer/fall precipitation (25.9 cm; Figure 3) over winter/spring (13.2 cm). Spring (March through May) and fall (October and November) seasons near the three study areas are dominated by drought conditions; however, winter-like low-pressure systems can produce significant precipitation during the late fall and early spring, and tropical storms and low-pressure systems can produce significant precipitation during the fall. No long-term trends in summer/fall precipitation are evident (Figure 3), but winter/spring precipitation generally was above average during 1900–1920 and 1978–1998, and below average during the intervening period (Figure 3).

[15] Winter/spring precipitation at both stations displays moderate correlation with the average SOI value for the previous June through November (Figure 4). Data display large variability in precipitation for any SOI value, but few years had greater than average winter/spring precipitation during La Niña conditions (SOI > 0), and average precipitation tends to be greater during El Niño conditions (SOI < 0). The Tucson station recorded above-average winter/spring precipitation during 29 of the 51 El Niño years (57%) and below-average winter/spring precipitation during 33 of the 41 La Niña years (80%; Figure 4). The relation is stronger following 21 occurrences of moderate to strong La Niña conditions (SOI > 0.6) as above-average winter/spring precipitation occurred following only 3 of those years (14%). The trend in greater winter precipitation with lower SOI values is better displayed by average values calculated for ±0.5 SOI intervals (Figure 4). Least squares fit of second-order polynomials to the average values for both stations yields similar results with good correlation (correlation coefficients 0.98 and 0.88 for the Tucson and Fort Huachuca stations, respectively), suggesting that the relation may be a regional phenomenon.

[16] Variations in summer/fall precipitation do not correlate well with SOI on the basis of fitting a second-order polynomial to SOI values averaged over intervals of ±0.5, $r^2 = 0.44$ for Campbell Road Farms (Tucson) and $r^2 = 0.15$ for Fort Huachuca (Figure 4), which is consistent with previous regional evaluations.

[17] Regional analyses by *McCabe and Dettinger* [1999] indicate that variations in winter precipitation in the western United States are also related to decadal-scale variations in PDO. This hypothesis was tested on precipitation data from the station at the University of Arizona Campbell Road Farms by evaluating correlations of PDO averaged over multiple time periods with residuals from the polynomial correlation of SOI and winter/spring precipitation (Figures 4c and 4d). Fort Huachuca precipitation data are not used because of an extensive period of missing data during 1920–1955. Precipitation residuals from the polynomial correlation have a poor correlation with annual PDO values, but 15-year and 30-year moving averages of winter/spring precipitation display similar trends (Figure 4c). Fifteen-year average winter/spring precipitation residuals are moderately correlated with 15-year average PDO values on the basis of a least squares fit of a second-order polynomial to the 15-year average PDO and precipitation residuals ($r^2 = 0.60$, Figure 4d). Low 15-year average PDO values, 0 to −0.9, tend to correspond to negative residual precipitation values, that is, where the polynomial SOI and precipitation relation overestimates precipitation. High 15-year average PDO values, 0 to 0.6, correspond to negative residual precipitation values, that is, where the linear SOI and precipitation relation underestimates precipitation. The relation of *McCabe and Dettinger* [1999] appears to be true for the local data set, but only explains about 2.5 cm of the variability in winter/spring precipitation, which is small in comparison to the standard deviation of the annual residuals during any 15 year period, about 3.8 to 10.2 cm.

[18] These local data indicate that variations in winter/spring precipitation in the Tucson Basin and Upper San Pedro River Basin are consistent with widely recognized relations of Southwest precipitation to large-scale atmospheric patterns. The precipitation records also display decadal trends that are consistent with trends in the southwestern United States. Local variations in winter/spring recharge are therefore likely dominated by variations in infiltration of winter/spring precipitation that are related to large-scale climate patterns.

5. Hydrogeology of the Study Areas

[19] The three study areas lie along ephemeral streams in areas of groundwater withdrawal from alluvial aquifers (Figure 5). Responses of the aquifers to streamflow infiltration are superimposed on long-term trends of water level decline. The study area along Rillito Creek (Figure 5) is the longest monitored stream reach and includes the lower 15.1 km of stream within a 2388 km^2 drainage area. The study area along the Cañada del Oro Wash (Figure 5b) includes about 8.0 km of stream channel that drains about 647 km^2. These study areas lay at elevations of about 670 to 700 m, but the upper parts of the drainages include the highest peaks of the Santa Catalina Mountains at more than 2700 m. Monitoring along Garden Canyon Wash included about 0.6 km of stream channel at an elevation of about 1460 m (Figure 5) that drains about 26 km^2 within the Huachuca Mountains that includes elevations of greater than 2400 m.

[20] The three study areas include moderate to large ephemeral streams that cross large parts of the alluvial basin and small ephemeral streams near the mountains. Rillito Creek is a large ephemeral stream that parallels the base of the mountains at a distance of a few kilometers and receives tributary inflow from several ephemeral streams that drain crystalline and sedimentary rocks and parts of the alluvial basin. Sabino Creek is the largest of several tributary ephemeral streams that receives streamflow from the crystalline rocks of the mountains and is a major source of mountain front recharge (Figure 5). The study area along Cañada del Oro Wash (Figure 5b) includes both mountain front and basin recharge areas. The upstream part of the study area lies near the mountains where tributary streams receive streamflow from the mountains that contributes to mountain front recharge. The Garden Canyon is a small stream that contributes mountain front recharge (Figure 5) through infiltration of runoff from the crystalline and sedimentary rocks of the Huachuca Mountains.

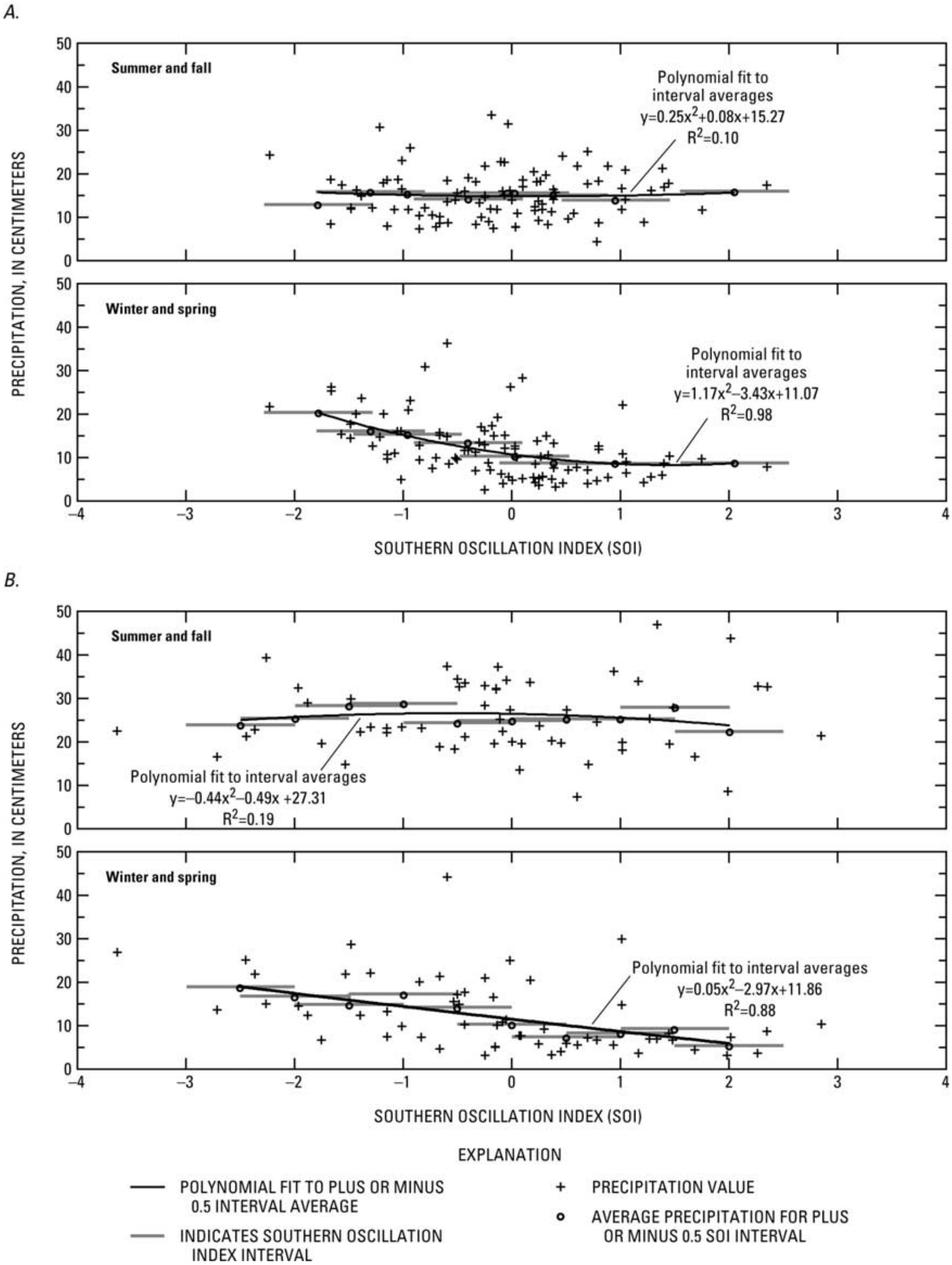
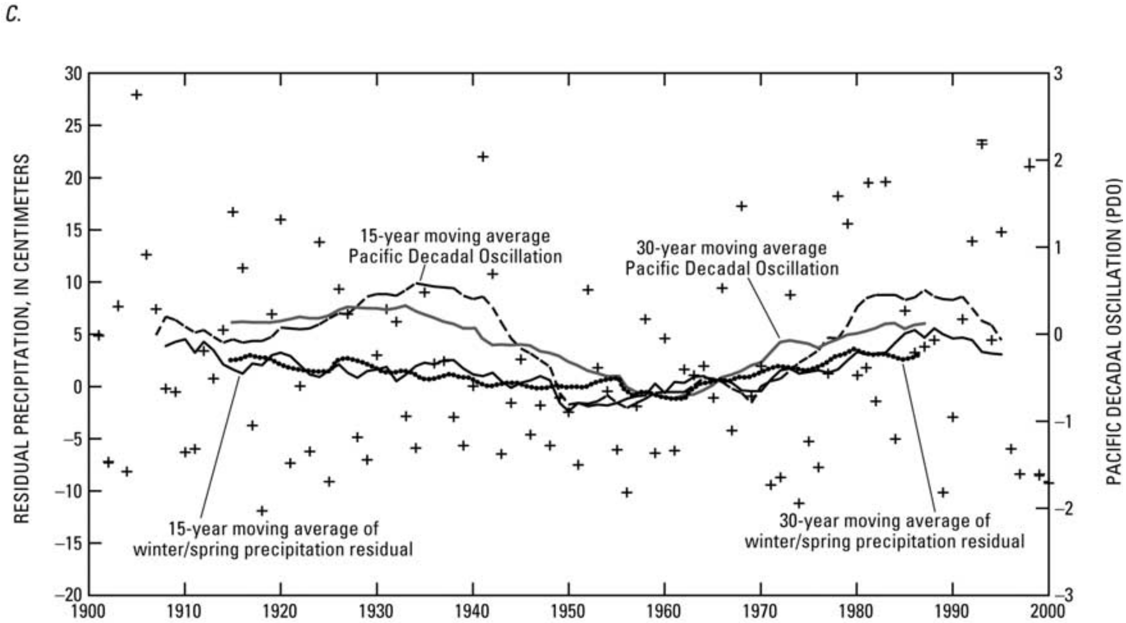


Figure 4. Relation of seasonal precipitation to the average SOI for the previous June through November at (a) the University of Arizona Campbell Road Farms and (b) Fort Huachuca, 1900–2000. Relation of (c) long-term Pacific Decadal Oscillation (PDO) index and winter/spring precipitation residual from SOI trend at the University of Arizona Campbell Road Farms and (d) 15-year average PDO and residual from polynomial fit to PDO/precipitation SOI residual at the University of Arizona Campbell Road Farms.

[21] Alluvial basin fill aquifers of regional extent underlie the Rillito Creek and Cañada del Oro Wash study areas. The alluvial channel deposits are 0–15 m thick, highly permeable, and readily accept streamflow infiltration. The Garden Canyon Wash study area is underlain by an alluvial aquifer of local extent. Localized perched aquifers occur beneath Rillito Creek [*Pool and Schmidt*, 1997; *Ripich and Hoffmann*, 2000]. Flow of groundwater in the stream channel deposits and in perched aquifers may enhance down-channel movement and lateral movement away from the stream. No



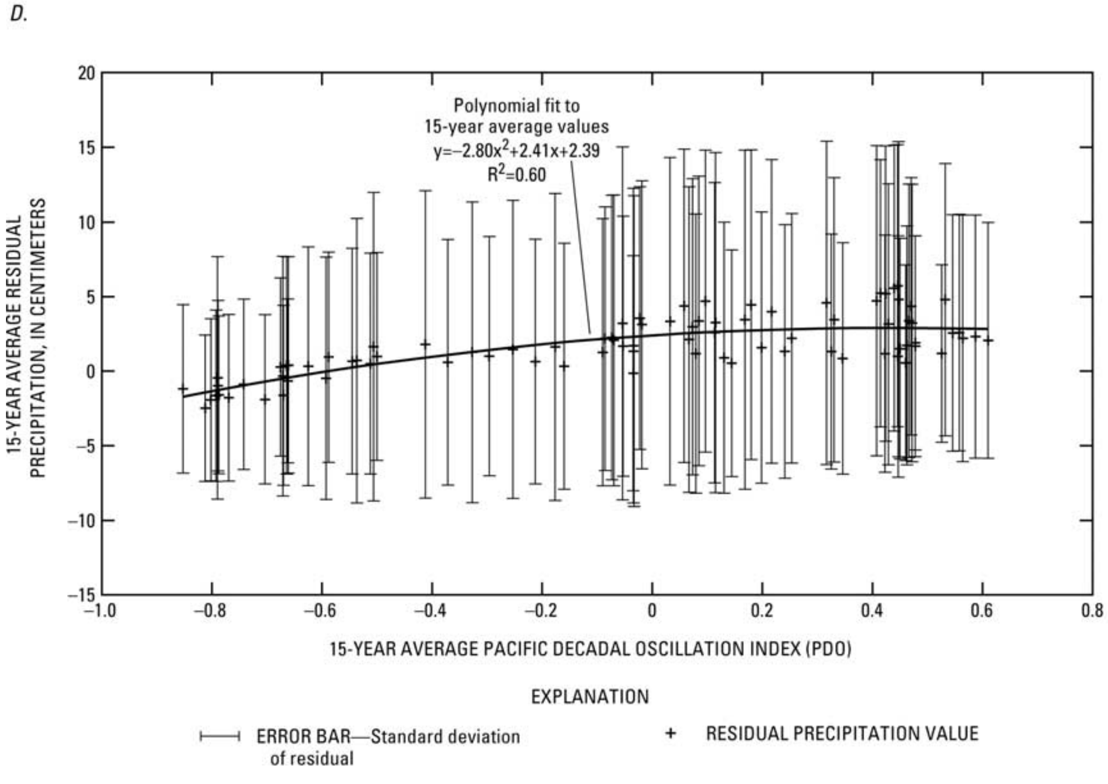


Figure 4. (continued)

groundwater mounds are evident beneath any of the three streams (Figure 5), but this could be caused by a lack of water level data or the effects of nearby production wells.

[22] Depths to water in the study areas vary spatially and temporally. Depths to water increase in the downstream direction along each of the streams from a few meters or tens of meters near the mountains to more than 30 m in the basin center. Depths to water near the upstream margins of each study area vary temporally by tens of meters in response to variations in streamflow and recharge. Water levels in the downstream parts of the study areas have declined tens of meters over the long term owing to groundwater withdrawals and vary several meters in response to variations in streamflow and recharge.

6. Previous Estimates of Recharge

[23] Recharge rates have been estimated by previous investigators for each of the study areas. Most estimates resulted in a single value for average annual recharge rates

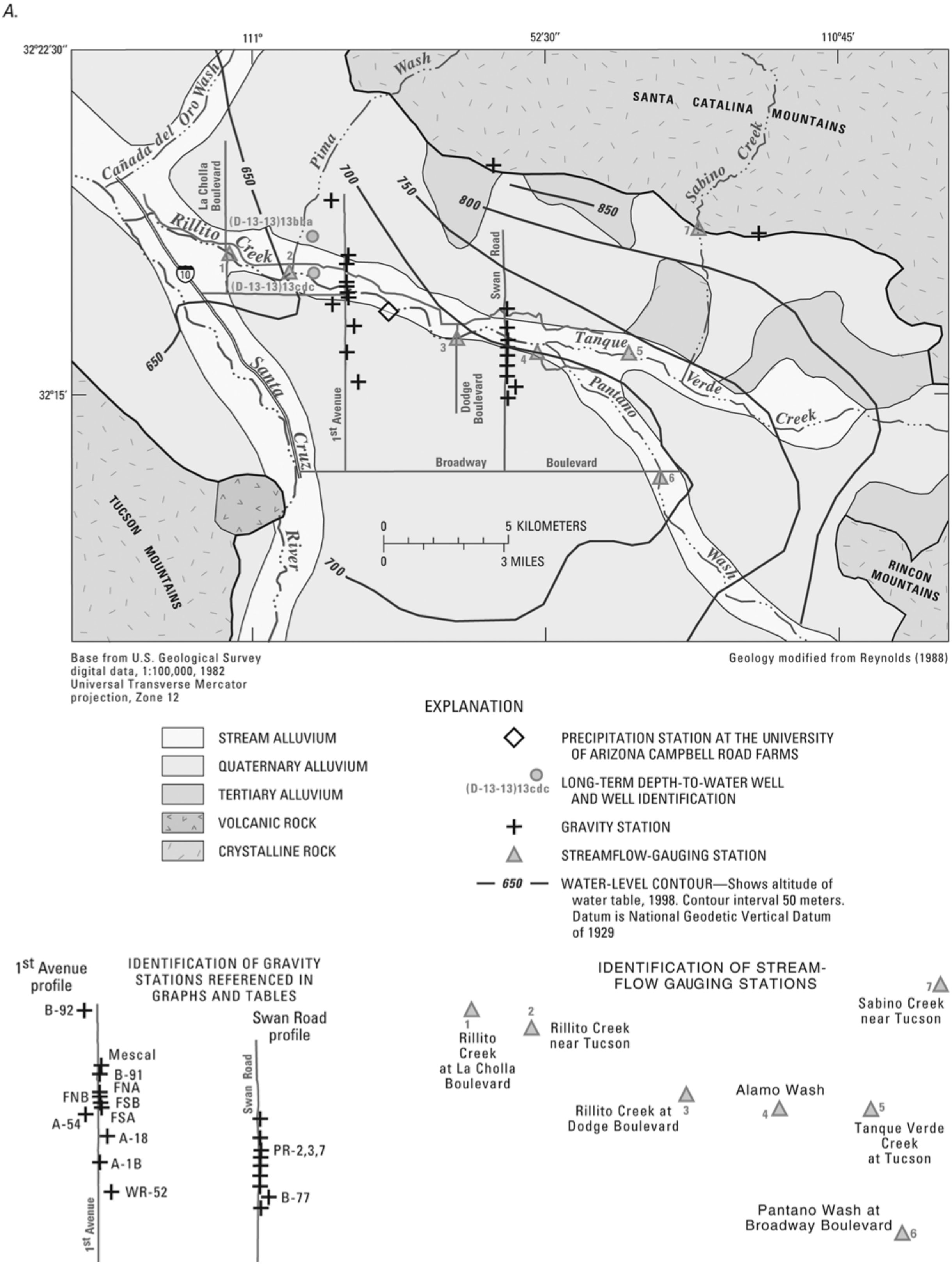


Figure 5. Groundwater flow system in the study area (a) Rillito Creek near Tucson, (b) Cañada del Oro near Oro Valley, (c) Garden Canyon near Fort Huachuca.

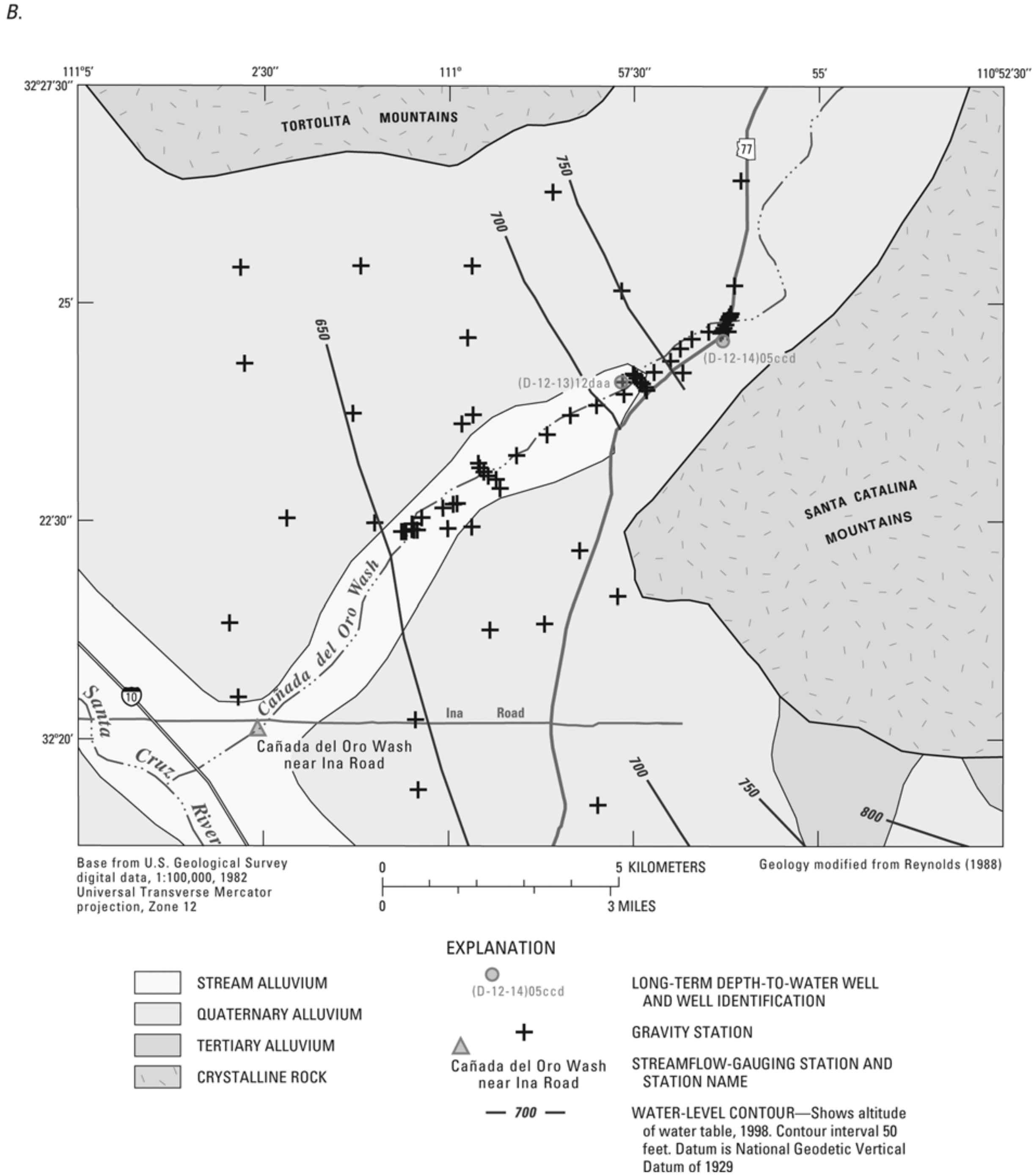


Figure 5. (continued)

and did not incorporate variations of decadal and longer scale. Some investigators, however, recognized interannual or longer-term variations in the Tucson Basin. *Davidson* [1973] estimated that annual recharge by streamflow infiltration in the Tucson Basin can vary by a factor of four. *Hanson and Benedict* [1994] included separate recharge estimates for the Tucson Basin for the periods 1940–1957 and 1958–1986 on the basis of increased frequency of winter floods on the Santa Cruz River after 1959 [*Webb and Betancourt*, 1992]. *Hanson and Benedict* [1994] modified *Burkham*'s [1970] empirical formula (loss/mile = 0.18 $Q_{in}^{0.8}$) for streamflow losses on Rillito Creek using a longer streamflow record to produce different estimates for the period prior to 1958 (0.37 hm^3/yr/km) and for 1958–1986 (0.62 hm^3/yr/km). The estimate implies an increase in ephemeral streamflow recharge relative to mountain front recharge during the second period, which is consistent with observed increases in winter streamflow along major ephemeral channels relative to streamflow near the mountains.

7. Recharge and Climate Relations

[24] Variations in winter/spring recharge rates were estimated for Rillito Creek, but only qualitatively assessed for

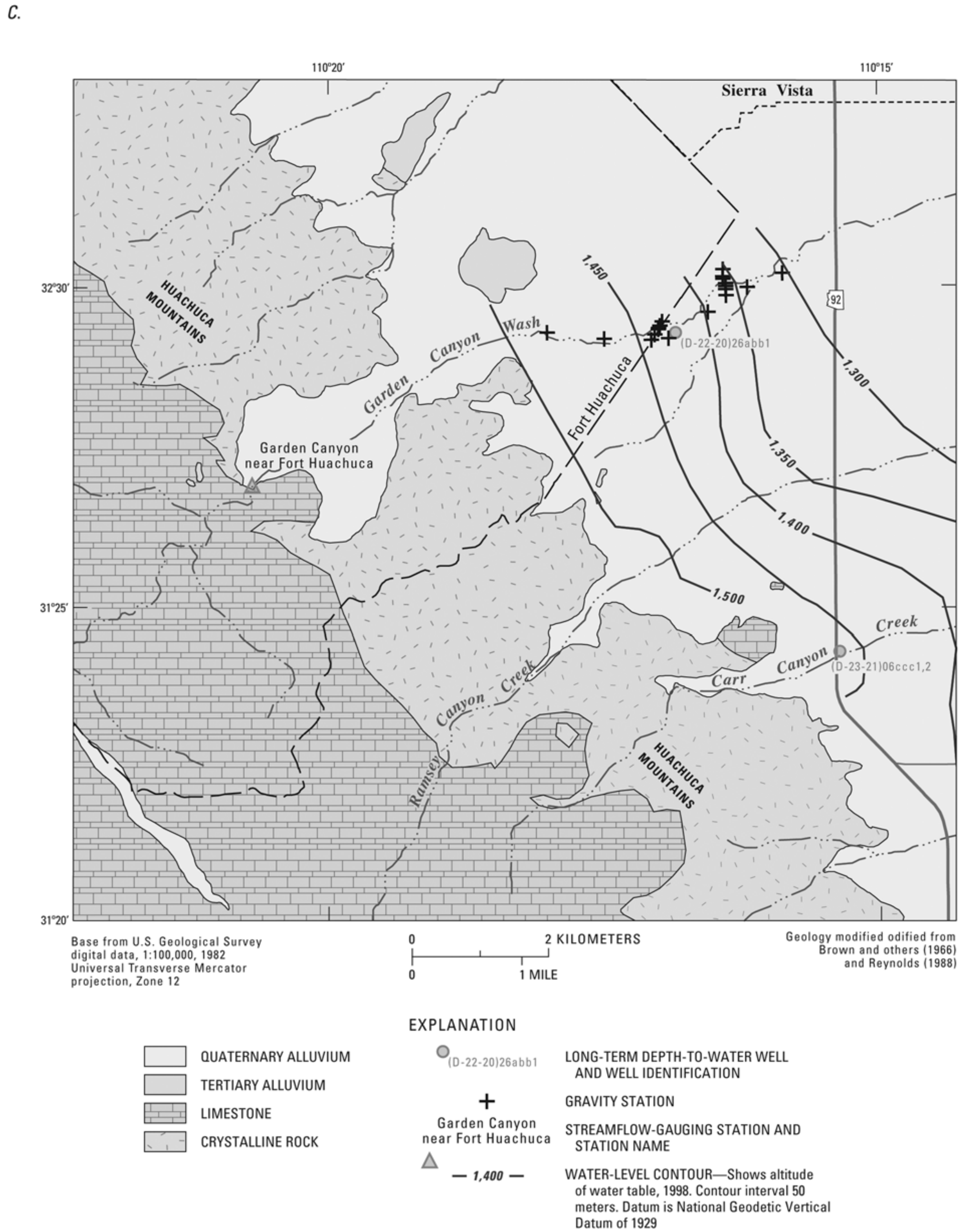


Figure 5. (continued)

the other study areas. Quantification of recharge was possible on the basis of independent hydrologic data sets collected near Rillito Creek during the 1990s. Recharge was estimated using two methods: streamflow infiltration and groundwater storage change. Streamflow infiltration was estimated by using differences in monitored streamflow at inflow and outflow gauging stations. Groundwater storage change was estimated using gravity methods. Neither method directly measures recharge, but similarity in results indicates that infiltrated streamflow went into groundwater storage. Long-term estimates of variations in recharge require hydrologic data sets for the period of interest. These

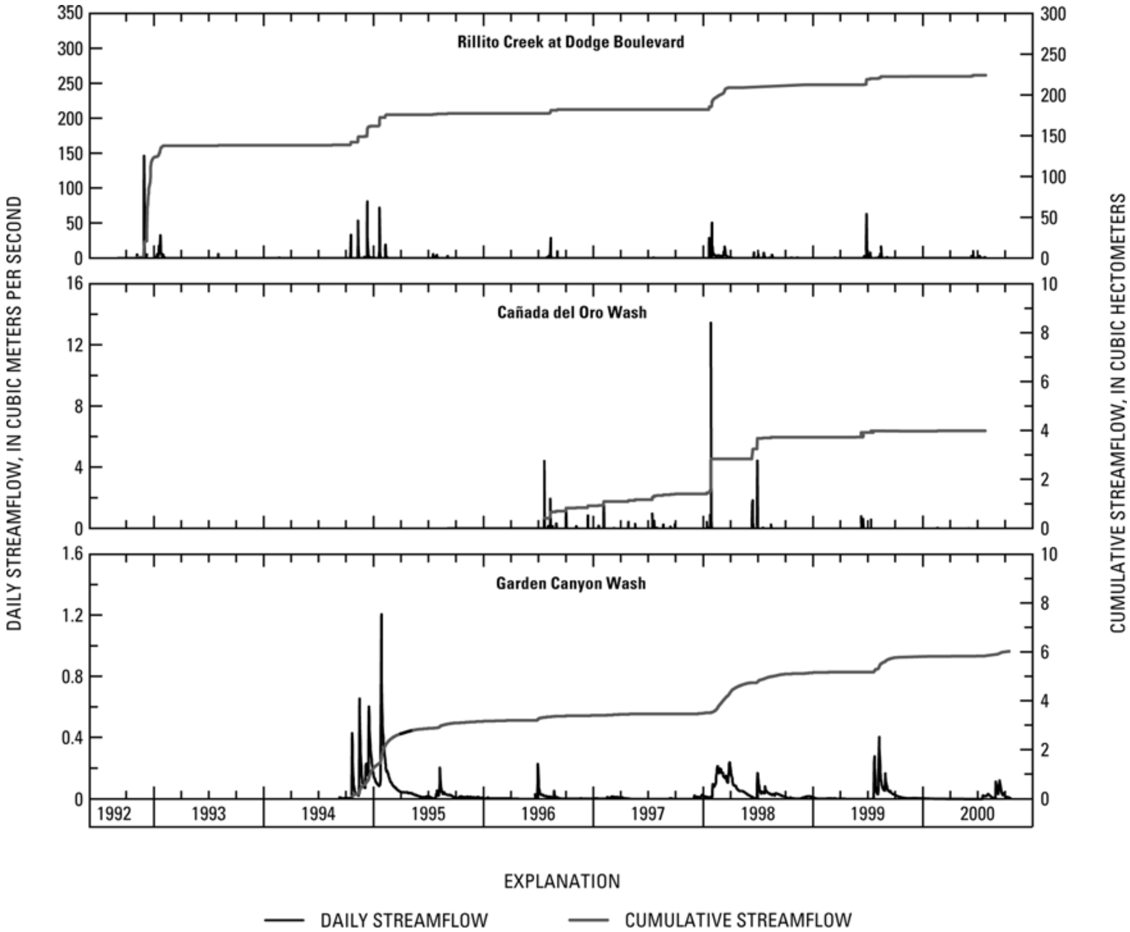


Figure 6. Daily and cumulative streamflow at Rillito Creek at Dodge Boulevard in Tucson, October 1992 through July 2000; Cañada del Oro Wash near Ina Road, near Tucson, October 1995 through July 2000; and Garden Canyon Wash near Fort Huachuca, October 1992 through September 2000.

data were available only along Rillito Creek where streamflow losses can be estimated on the basis of monitored or estimated inflow and outflow during 1933 to 2000. Variations in long-term winter/spring recharge rates along Cañada del Oro Wash and Garden Canyon Wash can only be qualitatively assessed on the basis of incomplete streamflow and water level data.

7.1. Analysis of Recent Recharge

[25] Hydrologic conditions in the three study areas were monitored continuously from the winter of 1998 through the middle of 2000 for the purpose of observing aquifer responses to streamflow infiltration, groundwater storage change, and recharge. The monitoring period included higher-than-average winter/spring precipitation and streamflow (Figure 6) following 1997–1998 El Niño conditions, which included an average June through November SOI value of −2.4. La Niña conditions prevailed during 1996, 1998, and 1999, and resulted in little winter/spring runoff.

7.1.1. Rillito Creek

[26] Rillito Creek was the most intensely monitored of the three study areas (Figure 5). Streamflow was monitored at five locations (Figure 5). Two streamflow gauging stations were at the upstream boundary of the study area along the two primary tributaries, Tanque Verde Creek and Pantano Wash. Two stations were along Rillito Creek; one at the downstream boundary of the study area and one midway along the creek at Dodge Boulevard. One tributary stream, Alamo Wash, was monitored near its confluence with Rillito Creek to provide information that was used to estimate input from several small ungauged drainages. Groundwater storage was monitored along two microgravity profiles across Rillito Creek at Swan Road and First Avenue. The profiles included closely spaced stations near Rillito Creek and several stations at wells where water levels were monitored.

[27] Outflow was measured during most of the period and inflow from about 90% of the watershed was measured during 1990–1999 at gauging stations on Tanque Verde Creek and Pantano Wash (Figure 5). Additional inflow from ungauged minor drainages was estimated as 10% of the total precipitation on the basis of the percentage of precipitation that discharged to Rillito Creek from the Alamo Wash drainage (23.3 km^2; Figure 5) during the winter/spring of 1998.

[28] The intensive monitoring included three periods of seasonal precipitation resulting in streamflow infiltration. The only significant winter/spring streamflow occurred during December 1997 through early April 1998. Significant summer streamflow occurred during July through September of 1998 and 1999 (Figure 6) A total of 72.3 hm^3 of streamflow was lost to infiltration and evapo-

ration during the monitoring period. Most of the losses occurred during the winter/spring of 1998, 45.3 hm^3, and the remainder was lost during the summers of 1998 and 1999.

[29] Gravity change during late 1997 through early June 2000 indicate that storage increases that occurred during and after winter/spring 1997–1998 were followed by general declines in storage. The greatest increases in gravity of 100–134 microgal occurred adjacent to the creek during winter/spring 1998 (Figure 7). These increases in gravity are equivalent to 2.4–3.2 m of water on the basis of a one-dimensional approximation of 41.9 microgal per meter of water. The equivalent water thickness represents the thickness of an infinitely extensive slab of water that would produce the observed gravity change and does not represent a change in aquifer thickness. Estimation of an equivalent change in aquifer thickness requires an additional estimate of specific yield. Increases in storage were likely greater near the stream because the one-dimensional approximation underestimates change in the strongly two-dimensional zone of infiltration beneath the stream. Significant increases in storage also occurred at most stations farther from the stream by late spring. The area of increased storage tended to migrate away from the stream during the spring and early summer (Figure 7). Maximum increases in gravity at most stations outside of the stream alluvium were about 40 microgal along Swan Road and 60 microgal along First Avenue and occurred during late May 1998. Only one station, SP-11, located farthest from the creek along Swan Road, displayed no increase in storage (Figure 7). Changes at well B-92 resulted mostly from infiltration of streamflow in nearby Pima Wash. Summer streamflow during 1998, 1999, and 2000 resulted in increases in gravity and groundwater storage only at stations on the stream alluvium (Figure 7).

[30] Water level responses to ephemeral stream infiltration and recharge during the winter of 1998 ranged from immediate recovery near stream channels to gradual recovery or decreased rates of decline over periods of several months to more than a year far from the channels (Figures 7a and 7b). This is in contrast to distinct gravity increases at all stations during the winter to early summer of 1998. Water level rises of 13.7 m at a well on the alluvial floodplain and adjacent to Rillito Creek at Swan Road, well PR-7, were contemporaneous with gravity change at nearby gravity station SP-4 (Figure 7). Water levels in wells that are not adjacent to Rillito Creek, however, displayed recovery or reduced decline rates for as long as a year. Well B-92 had a water level rise of about 0.8 m during spring 1998 that likely was in response to recharge from deep infiltration (105 m to water) along nearby Pima Wash. The gradual water level response with respect to gravity change at many wells indicates that much of the storage increase measured by gravity methods may have occurred above the water table before the infiltrated streamflow percolated down to the regional aquifer, or that the water levels in the wells are representative of deep confined or semiconfined aquifers.

[31] Storage change since December 1997 was estimated by integration of gravity changes along the two profiles (Figure 8). The distributions of change along the profiles were similar, and similar changes were assumed to occur throughout the study area, with the exception of changes at the northern extent of the First Avenue profile, well B-92, where most changes likely were caused by infiltration in nearby Pima Wash. Storage increased from about 13.1 hm^3 during early March 1998 to a maximum of 48.8 hm^3 during late May 1998. Storage generally declined after May 1998, but was above preexisting levels until spring of 2000. High rates of storage decline that occurred soon after recharge in winter/spring 1997–1998 could have been caused by temporarily increased hydraulic gradients across outflow boundaries and greater rates of evaporation and transpiration. Recharge from summer streamflow infiltration in 1998 and 1999 was sufficient to cause short-term reversals in the declining storage trend.

[32] Estimated streamflow losses along Rillito Creek during the winter/spring of 1997–1998 were about 45 hm^3, slightly less than gravity based estimates of storage change (Figure 8). The agreement between the two measures is good considering possible errors in the streamflow estimates of inflow and the small number of gravity stations in the study area. Estimates of summer streamflow losses during 1998 and 1999 were about 15 hm^3 and 10 hm^3, respectively. Associated gravity increases during the summer months were small limited to the area of stream alluvium (Figure 7). The summer infiltration is small, but reduces the long-term rate of storage loss in the regional aquifer.

[33] Groundwater storage change was also monitored during late 1992 through December 1993 near Swan Road and Rillito Creek [*Pool and Schmidt*, 1997] using repeated gravity surveys and water level measurements at a subset of sites that were monitored during the later period. The earlier montoring followed El Niño conditions during June to November 1992 (average SOI of −1.3) and included the second highest winter/spring precipitation at the University of Arizona Campbell Road Farms, 31.9 cm, and record streamflow of more than 145.6 hm^3 at the Dodge Boulevard gauging station (Figure 6). The 1993 period was preceded by two winters of above-average precipitation and moderate streamflow. In contrast, the later monitoring period was preceded by two years of drought. As a result, initial depths to water near Rillito Creek at Swan Road during November 1992 were less than during December 1997 (about 13.7 m and 19.8 m, respectively). Water level and gravity changes following the extreme streamflow of 1993 were less than following the moderate streamflow of 1998 because less void space was available to accept streamflow infiltration.

7.1.2. Cañada del Oro Wash

[34] Hydrologic monitoring near Cañada del Oro Wash during the middle to late 1990s included streamflow monitoring at the lower boundary of the study area, water level monitoring at wells, and storage monitoring at a network of gravity stations (Figure 5b). Storage monitoring included quarterly gravity surveys at a regional network of 22 stations and a detailed network near Cañada del Oro Wash that included 17 stations along the wash and 4 profiles of 7–8 stations each across the wash. Recharge rates were estimated for the period of investigation as the residual of estimated groundwater withdrawal and storage change.

[35] The period of investigation was dominated by lack of streamflow, lack of recharge, and losses in groundwater storage. Small increases in storage resulted from streamflow infiltration during the winter of 1997–1998 [*Pool*, 1999]. Streamflow trends along Cañada del Oro Wash during

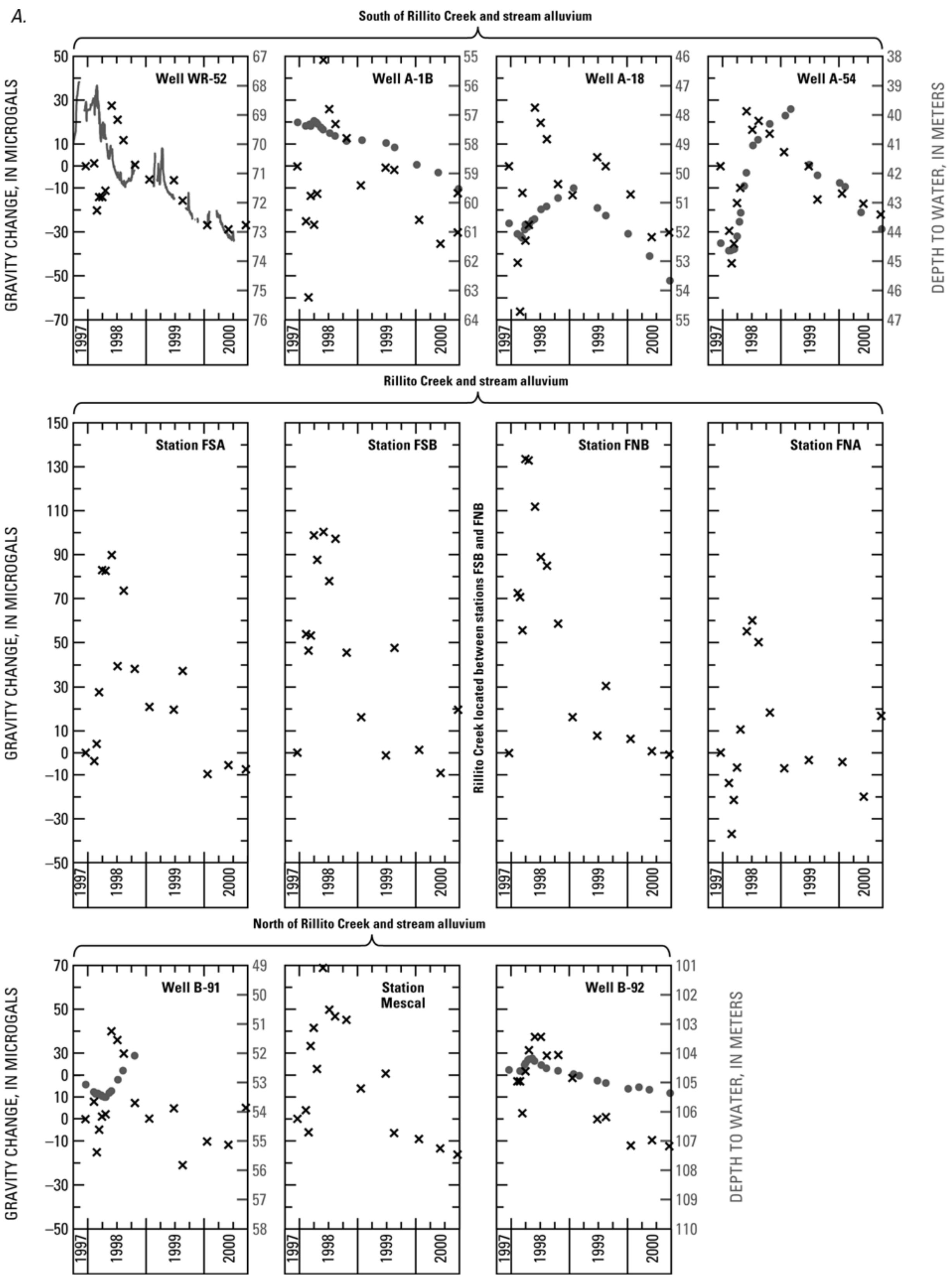


Figure 7. Gravity change and depth to water, October 1997 to September 2000, at gravity stations along (a) First Avenue and (b) Swan Road.

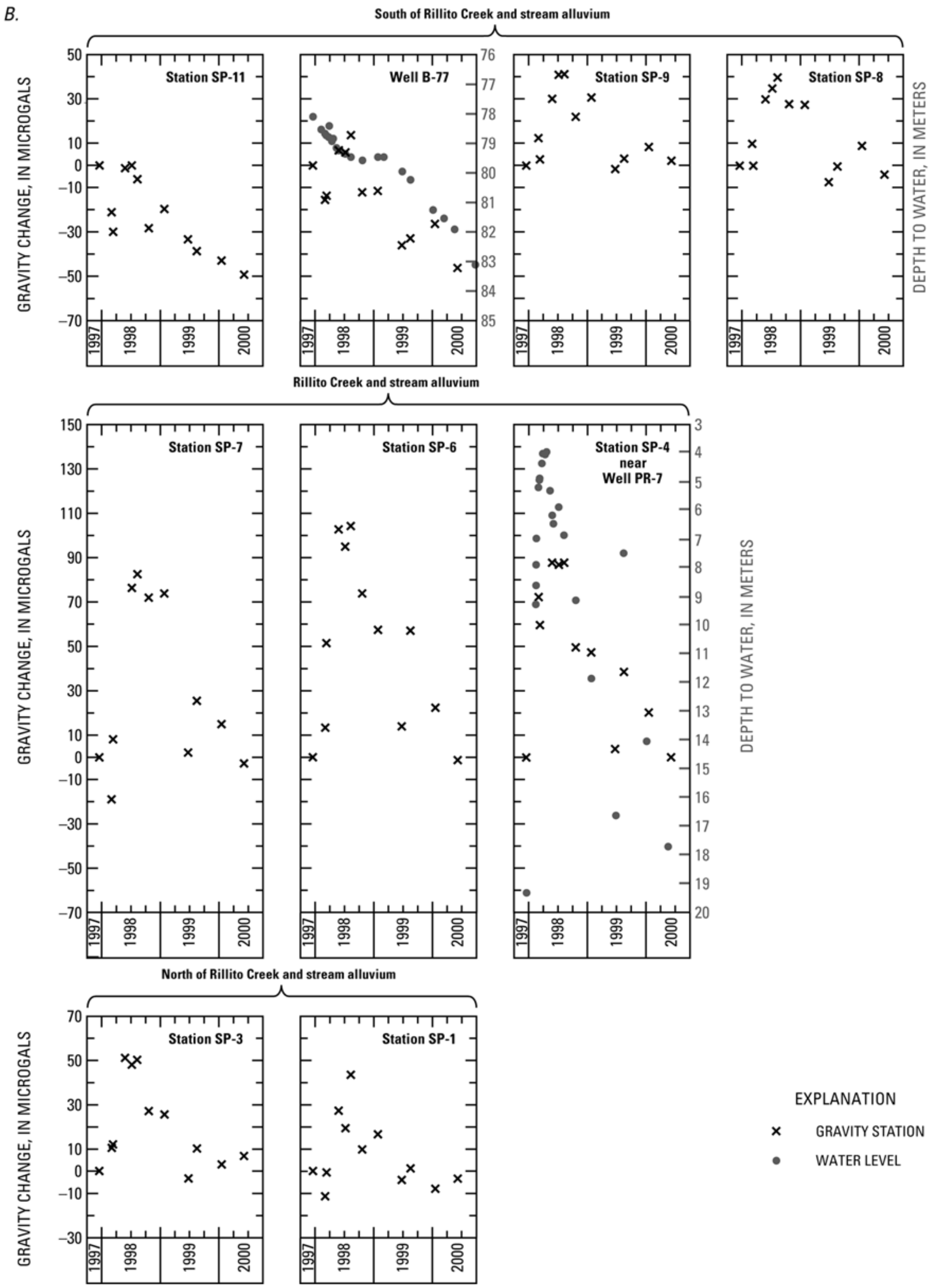


Figure 7. (continued)

October 1995 through June 2000 are similar to trends along Rillito Creek, but magnitudes of flow were much less (Figure 6).

[36] Changes in storage throughout the study area during 1997 through the summer of 2000 were dominated by losses despite increases during the winter of 1997–1998 (Figure 9). The greatest variations in gravity, 10–94 microgal, occurred along the wash near the mountains [*Pool*, 1999]. Water level changes at two wells near Cañada del Oro Wash, (D-12-13)12daa and (D-12-13)24cbd1, indicate an overall rate of decline of 0.6–1.2 m/yr during the summer of 1997 through the spring of 2000. Rates of decline stabilized for a few months following winter of 1997–1998 streamflow infiltration before resuming previous rates. Increases in gravity

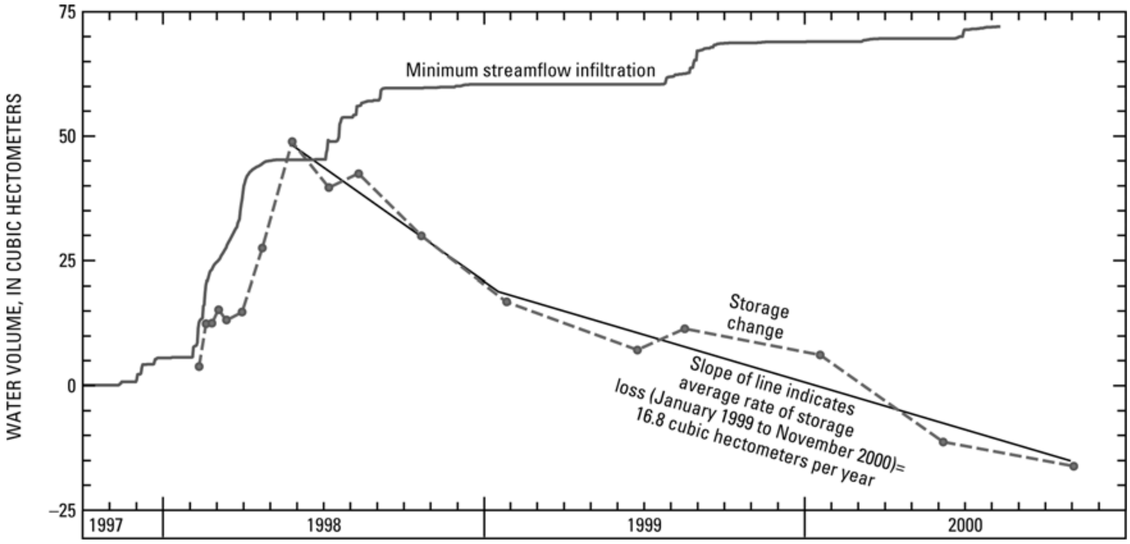


Figure 8. Estimated minimum streamflow infiltration and estimated groundwater storage change from repeat gravity surveys near Rillito Creek between Craycroft Road and La Cholla Boulevard, December 1997 to November 2000.

during 1998 at well (D-12-13)12daa, which is adjacent to the wash, are not reflected by a water level increase indicating that some of the storage change occurred in the unsaturated zone near the channel.

[37] Recharge in the Lower Cañada del Oro subbasin was estimated as the residual of storage change and withdrawals from supply wells. Evapotranspiration was not estimated, but is likely insignificant in comparison to recharge rates

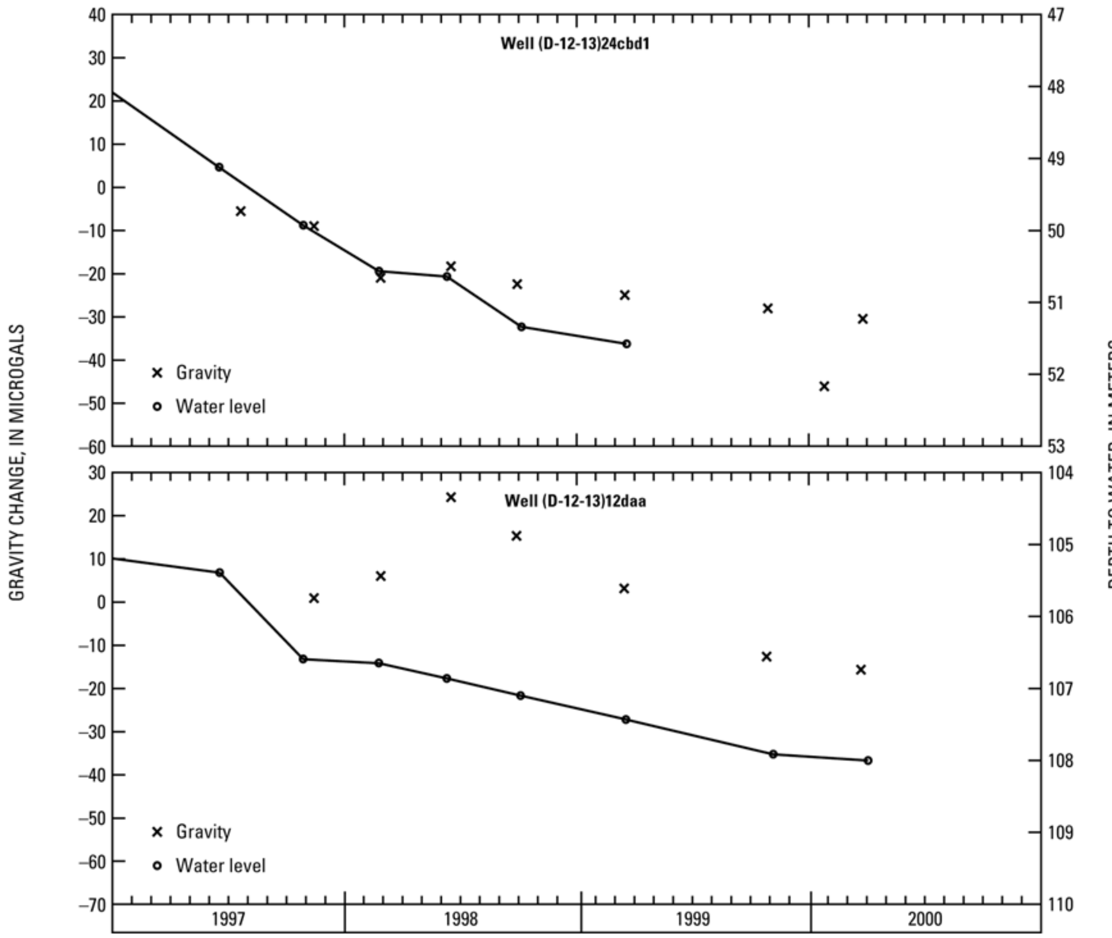


Figure 9. Gravity and water levels at selected wells in the Cañada del Oro study area.

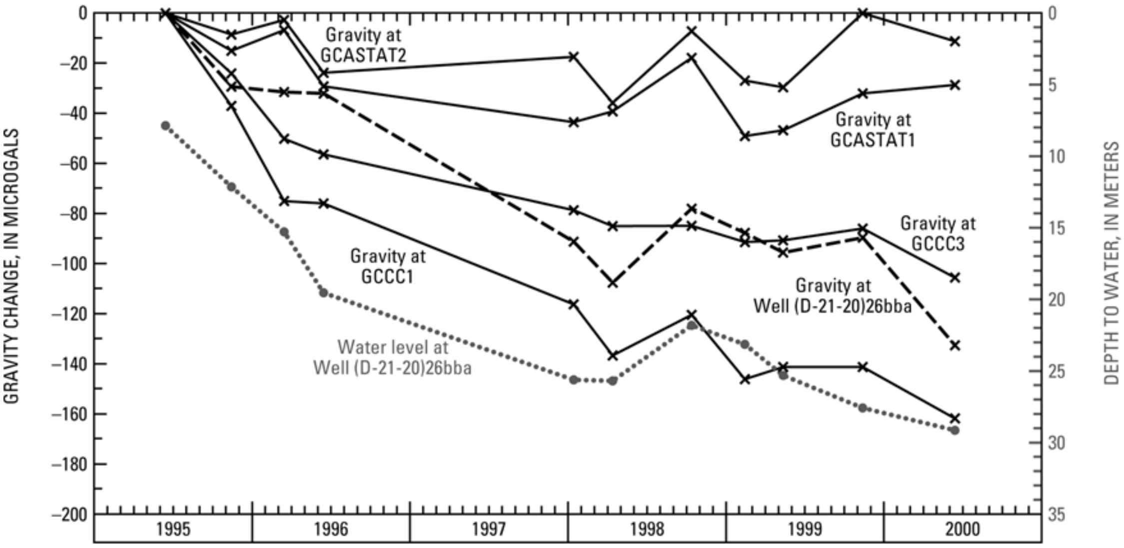


Figure 10. Gravity and water level change near Garden Canyon, 1995–2000.

and groundwater withdrawals [*Hanson and Benedict*, 1994; *Pool*, 1999]. Storage loss during the summer of 1997 to the summer of 2000 averaged about 25.9 hm^3/yr on the basis of gravity change across the study area. Withdrawals were about 30.8 hm^3/yr during the period (Ariz. Department of Water Resources, written communication, 2001). The difference in rates of storage loss and withdrawals during the 3 years of monitoring, 4.9 hm^3/yr, is equivalent to the minimum average rate of inflow to the groundwater system through infiltration of streamflow and net groundwater flow across study area boundaries. Net flow across study area boundaries is difficult to assess, but probably is positive into the study area because of induced flow into the area of general overdraft conditions. Most of the estimated recharge during the study period, more than 14.8 hm^3, probably occurred during the winter of 1997–1998 because little streamflow occurred during the remainder of the period.

7.1.3. Garden Canyon Wash

[38] The study area near Garden Canyon Wash was monitored during 1994 through July 2000 with a network of gravity stations near the Wash, a gauging station above the study area, and water levels at two wells (Figure 5). The monitoring period included greater-than-average precipitation and streamflow during the winter of 1994–1995, the winter of 1997–1998, and the summer of 1999. Precipitation at nearby Fort Huachuca varied from less than 4 cm to about 23 cm during the winter/spring and less than 18 cm to about 25 cm during the summer/fall (Figure 3). During the monitoring period, about 6.2 hm^3 of streamflow (Figure 6) was available for infiltration and recharge below the base of the mountains. The greatest seasonal flow of more than 2.5 hm^3 occurred during the winter of 1994–1995. Only about 1.2 hm^3 of streamflow occurred during the winter of 1997–1998 in contrast to the high winter flow at Rillito Creek during the same period. The remaining 2.5 hm^3 of the streamflow occurred during the summers of 1998–2000.

[39] Declining water levels and losses in groundwater storage dominated the monitoring period. Depths to water at well (D-21-20)26bba declined more than 21 m during June 1995 to June 2000 (Figure 10). The accompanying gravity decline of 120 microgal indicated a storage loss at the well of about 2.7 m of water on the basis of a one-dimensional approximation of 41.9 microgal per meter water (Figure 10). The greatest change, 150 microgal, occurred at the farthest station from the mountains. Less than 50 microgal of gravity variation occurred at stations near the mountain, which is likely in an area of thin aquifer that may have drained and filled in response to sporadic recharge during the winter of 1997–1998 and the summers of 1998, 1999, and 2000. Gravity recovery of about 12 microgal (about 0.3 m of water) occurred at most stations after streamflow during the winter and summer of 1998.

[40] Storage change and recharge cannot be quantified for the Garden Canyon area on the basis of available data because the extent of the local aquifer is not defined. Streamflow and gravity data, however, place a limit on maximum amounts of recharge. Recharge before the summer of 1995, including part of the available 2.5 hm^3 of streamflow during the winter of 1994–1995, was apparently sufficient to nearly fill the local aquifer prior to the initial gravity survey. Subsequent outflow from the aquifer during the summer 1995 to summer July 2000 through groundwater withdrawals and downgradient groundwater flow was far greater than recharge. Resulting water level decline and storage loss was about 4.0 hm^3 on the basis of gravity change within the monitored area of approximately 172 hectares. The winter of 1997–1998 was the only period when recharge of streamflow was sufficient to briefly reverse the trend of storage loss.

7.2. Analysis of Long-Term Hydrologic Records

[41] Long-term records of streamflow, groundwater levels, and groundwater use are necessary to correlate variations in climate and precipitation. Complete long-term hydrologic records are unavailable in the study areas, however, nearly complete records are available at a few sites and are sufficient to characterize long-and short-term trends.

7.2.1. Streamflow

[42] Annual variations in streamflow in the study areas follow seasonal precipitation patterns. This analysis focuses on winter streamflow because summer/fall streamflow has varied randomly with precipitation (Figure 3) and has no

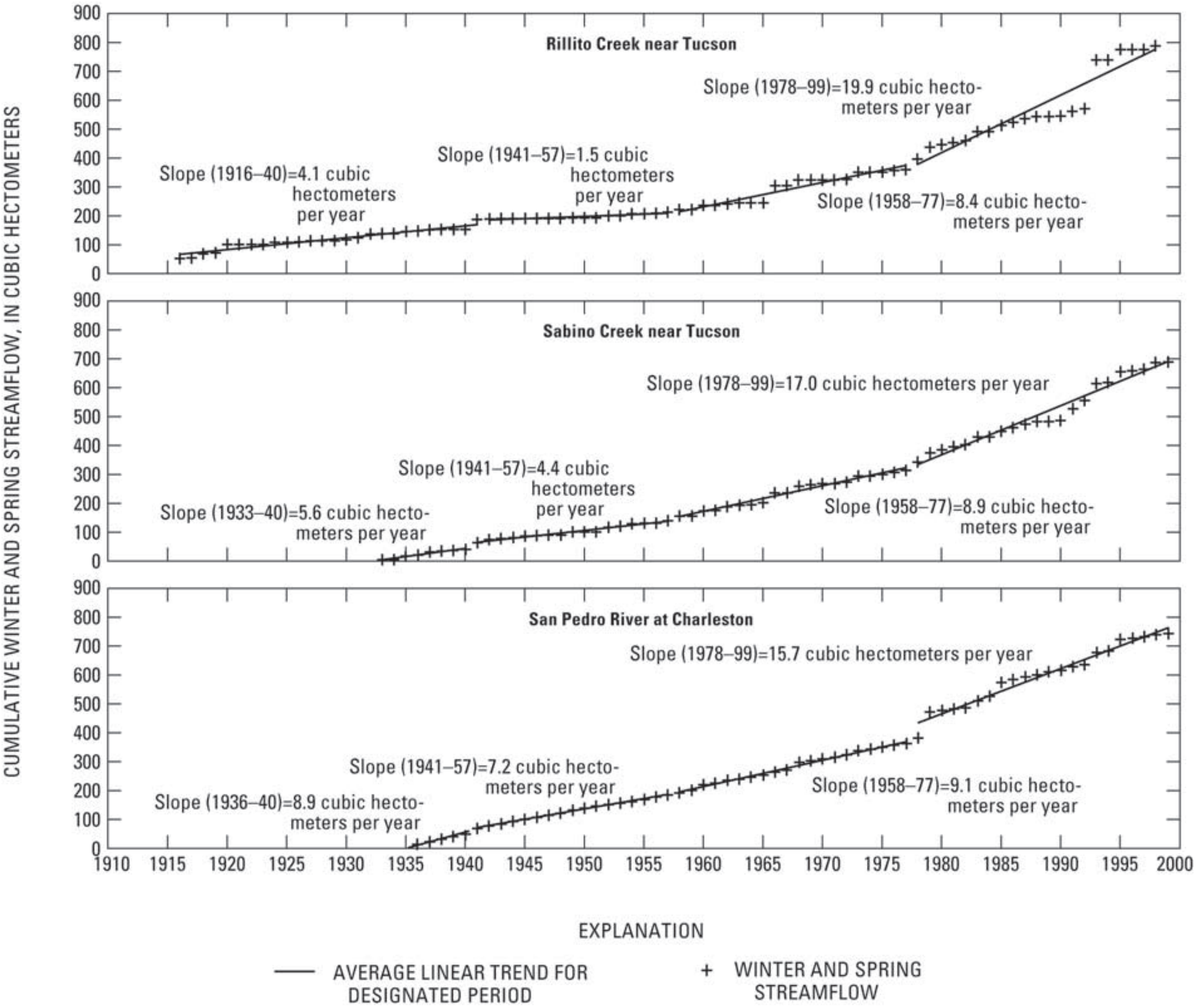


Figure 11. Cumulative winter and spring streamflow at Rillito Creek near Tucson, Sabino Creek near Tucson, and the San Pedro River at Charleston.

apparent relation to climate indices used in this investigation. Spring streamflow is normally extremely low; however, it is included with the winter season in this analysis in order to include flow resulting from snowmelt and from low-pressure storm systems that may cross the region during early spring.

[43] The streamflow record for Rillito Creek is the most complete of any station in the study areas. Streamflow near the outflow from the study area was monitored during 1915–1975 at the station designated Rillito Creek near Tucson (Figure 1). Streamflow was not monitored during 1976–1989, but was reestablished in 1990 at a station at La Cholla Boulevard, 2.9 km downstream from the station Rillito Creek near Tucson. Tributary inflow from crystalline rocks in the Santa Catalina Mountains was monitored at Sabino Creek (Figure 1) during 1930–1979 and 1990–1999. Missing winter/spring record for the Rillito Creek and Sabino Creek gauging stations was estimated by correlating rainfall at the University of Arizona Campbell Road Farms with available records.

[44] Streamflow on the Cañada del Oro and Garden Canyon Washes was not monitored routinely before 1995 and 1993, respectively. Variations in streamflow in Rillito Creek should serve as a substitute for variations on Cañada del Oro Wash on the basis of proximity. Similarly, streamflow variations in the San Pedro River at Charleston (Figure 1) should be qualitatively representative of variations along the nearby Garden Canyon drainage. Records for the San Pedro River at Charleston are continuous from 1935 to 2000.

[45] Plots of cumulative winter/spring streamflow for Rillito Creek, Sabino Creek, and the San Pedro River show an increasing trend during the climate periods pre-1940, 1941–1957, 1958–1977, and 1978–1999 (Figure 11). A general increase in winter/spring streamflow during the period of record has resulted from three types of changes: an increase in the frequency of moderate winter/spring streamflows beginning in 1958, further increase beginning in 1978, and an increase in the magnitude of the largest winter/spring streamflows resulting primarily from floods during 1966 and 1993. The latter changes result in large annual steps in the plots of cumulative annual winter/spring streamflow that greatly exceed rates for low-flow years. The period 1978–1999 had the greatest rates of streamflow in each of the study areas and included the greatest frequency and magnitude of high winter/spring streamflows.

[46] Winter/spring streamflow variation in the three study areas is related to ENSO (Figure 12), similar to precipitation. La Niña conditions are dominated almost exclusively

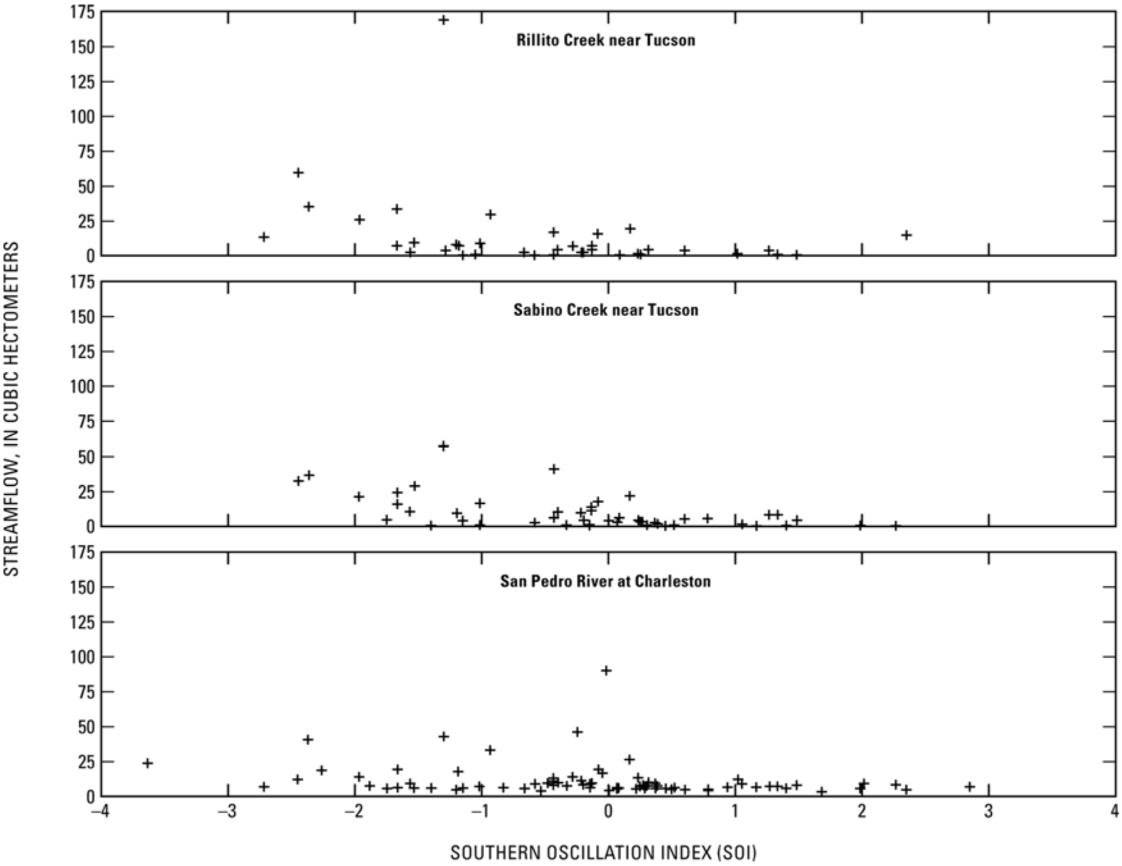


Figure 12. Average SOI for the previous June through November and winter and spring streamflow at Rillito Creek near Tucson, Sabino Creek near Tucson, and the San Pedro River at Charleston.

by below average winter/spring streamflow. An SOI value of 0.2 or greater was followed by low seasonal streamflow at Rillito Creek near Tucson where 1.2 hm^3 was exceeded only once. Conversely, about one third of El Niño or neutral ENSO conditions correspond with high winter/spring streamflow. Seasonal streamflow following an SOI of less than or equal to 0.2 averaged more than 12.3 hm^3/yr and only 5 of 39 years registered less than 4 hm^3 of flow. Winter/spring streamflow in Sabino Creek and the San Pedro River display similar SOI relations (Figure 12). High winter/spring flows did not always occur at each of the streams with El Niño conditions. A good example of this is the significant flows in Rillito Creek during the winter/spring 1993 that are not mirrored by significant flows in the San Pedro River.

7.2.2. Groundwater Levels and Well Withdrawals

[47] Water level records beginning in the early 1940s are available for some wells in each of the study areas. There is not sufficient continuous data, however, from any single well to define variations through 1999. Long-term trends are therefore defined by data from pairs of wells in proximity to each other in each study area. The records typically display water level declines caused by groundwater withdrawals and lack of recharge, and periodic recovery or reduced decline rates during periods of high streamflow.

[48] Information on groundwater withdrawal trends are needed to assess variations in decline rates. Groundwater withdrawals are available for the Tucson Basin from the Arizona Department of Water Resources (written communication, 2003). No long-term withdrawal data are available near the Garden Canyon area. There were no public supply wells open to the local aquifer for most of the period of water level record, however, and withdrawal rates were likely minimal.

[49] Water level variations near Rillito Creek are defined by data from wells north of the stream and near the streamflow gauging station, Rillito Creek near Tucson (Figure 13). The longest continuous record is for well (D-13-13)13bba, which is about 1.6 km north of the creek (Figure 5). Water level variations at this well are dominated by long-term declines related to regional groundwater withdrawals and short-term recovery or reductions in rate of decline caused by recharge through streamflow infiltration along Rillito Creek and Pima Wash, a major tributary. Water levels in this well declined about 25 m during 1948–1998. Average rates of water level decline are calculated for the periods 1948–1957, 1958–1977, and 1978–1998, corresponding with the climate periods. The greatest rate of decline, about 1.2 m per year, occurred during 1948–1957, coincident with low streamflow. Subsequent rates of decline decreased from about 0.5 m/yr during 1958–1977, to about 0.3 m/yr during 1978–1999. Brief periods of high decline rates also occurred during the early to middle 1970s and during the late 1980s to early 1990s; both periods included little streamflow. Significantly reduced rates of water level decline occurred during periods of higher streamflow during 1958 through the late 1960s and 1978 through the middle 1980s. Water levels at well (D-13-13)13cdc were variable during the 1990s but displayed no overall decline during the period that included

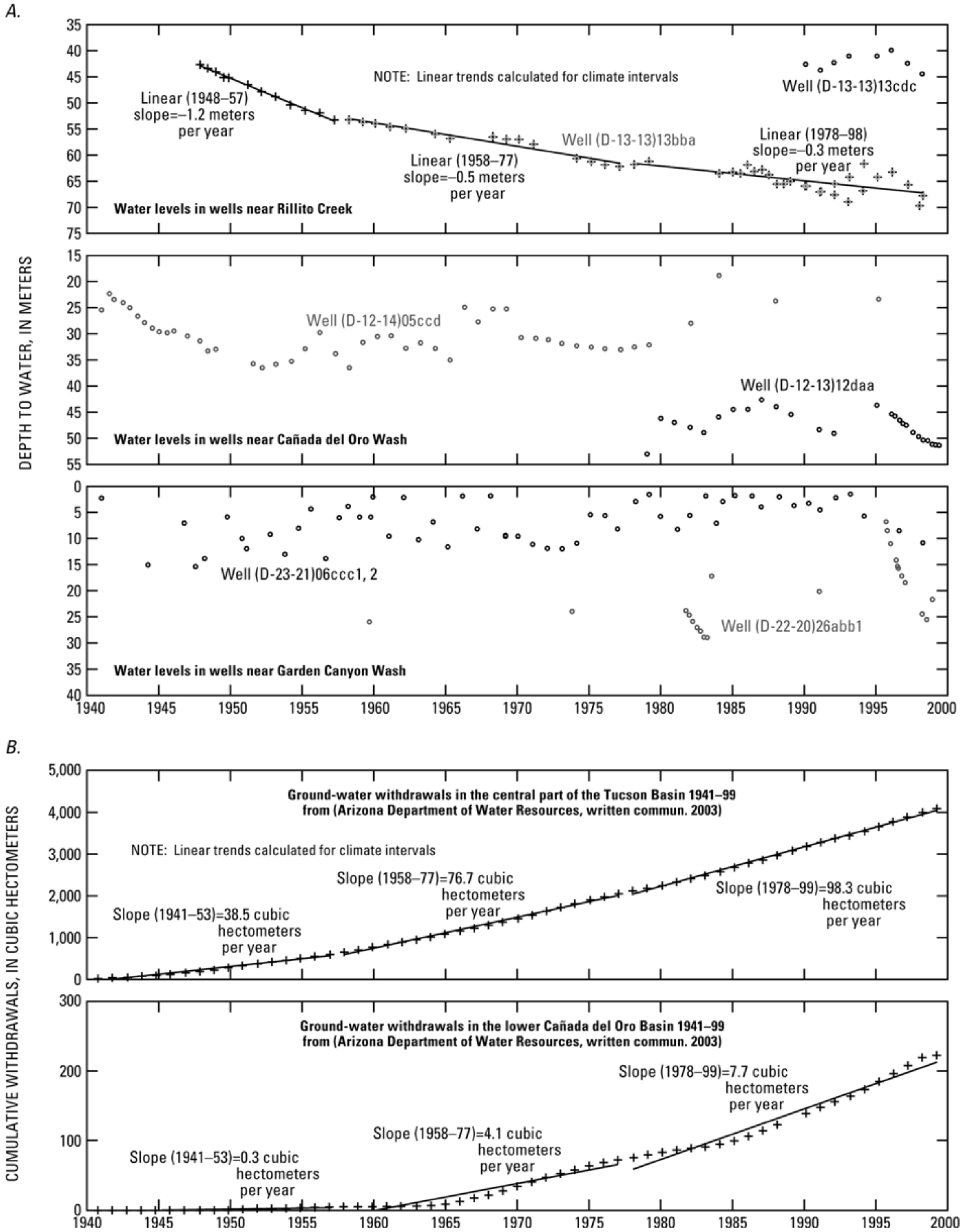


Figure 13. Groundwater withdrawals and water level trends in the study areas. (a) Water levels at selected wells in the Rillito Creek, Cañada del Oro, and Garden Canyon Wash study areas. (b) Groundwater withdrawals in the central part of the Tucson Basin and in the lower Cañada del Oro Basin. Wells near Garden Canyon Wash near Fort Huachuca are far from supply wells and water levels are unaffected by regional groundwater withdrawals.

the highest recorded streamflow during the winter of 1992–1993 and moderate flow during 1998.

[50] No major groundwater withdrawals occur near these wells, but the Tucson Central Well field includes a broad region south of Rillito Creek (Figure 5) and influences water levels at wells near the stream. A trend of increasing regional withdrawals is in opposition, however, to the observed trends in decreasing rates of water level decline. Annual withdrawals in the area of the Central Well field have gradually increased since 1940 from about 38.5 hm^3/yr during 1940–1957, to 76.7 hm^3/yr during 1958–1977, and to about 98.3 hm^3/yr during 1978–1999 (Figure 13) (Arizona Department of Water Resources, written communication, 2003).

[51] Water level variations near Cañada del Oro Wash are defined by data from two wells in the upper reaches of the study area (Figure 13). The longest continuous record begins about 1940 at well (D-12-14)05ccd, which is near the aquifer boundary and base of the mountains, but data after about 1980 are sparse. Water level variations at this well are caused by nearby agricultural withdrawals before about 1980 and periodic recharge through streamflow infiltration. A more complete recent record of water levels is available from well (D-12-13)12daa, about 1.6 km downstream from well (D-12-14)05ccd, beginning in 1978. Water level variations at this well are related to variations in recharge and municipal groundwater withdrawals. The record is dominated by recovery followed by declines after major streamflow and recharge during the middle 1980s and 1993. Both wells display little net water level change during the period of record, but declines occurred during the 1940s and 1950s drought and were followed by recovery. The main period of decline occurred during 1940–1952 when water levels declined about 1.4 m/yr and dropped to the lowest recorded level of 36 m below land surface at well (D-12-14)05ccd. Water levels after 1952 generally recovered, but brief periods of decline occurred with periods of low streamflow during 1969–1977, 1987–1992, and 1995–1997.

[52] Effects of groundwater withdrawals on water levels near Cañada del Oro Wash appear to be overwhelmed by variations in recharge (Figure 13b). Groundwater withdrawals in the vicinity have increased since 1940. The greatest rate of withdrawal occurred after about 1985 (Arizona Department of Water Resources, written communication, 2003); therefore the dominant cause of recovered water levels during the 1980s and 1990s most likely is increased rates of recharge.

[53] Long-term water level variations in the local aquifer near Garden Canyon Wash are defined by data at two wells (Figure 13). Sporadic water level data at the well closest to the wash (D-22-20)26abb documents variations in depth to water from about 6 m to more than 27 m over periods of a few months to years during 1983 and 1993. Water level decline subsequent to periodic water level recovery is attributable to drainage of the aquifer and withdrawals by a nearby small public supply well. Water level variations at the well more distant from the wash (D-23-21)06ccc1,2 are not influenced by nearby withdrawal wells and are indicative of periodic recharge from infiltration along Carr Canyon Wash followed by drainage of the aquifer. Water levels before 1958 typically varied 6–9 m from year to year depending on recent streamflow infiltration. Annual variations were less during 1958–1968 and depths to water rarely were greater than 6 m during 1978–1993.

[54] Long-term water levels in wells near the streams in each of the study areas (Figure 13) display variations related to winter/spring streamflow and ENSO. Water levels decline in response to groundwater withdrawals and lack of recharge. Periodic recovery or reductions in decline rates occur during periods of frequent El Niño conditions and high streamflow.

[55] Average rates of water level decline are calculated for the same climatic periods defined for streamflow in the previous section. The greatest rates of decline near Rillito Creek and lowest water levels near Cañada del Oro Wash and Garden Canyon Wash occurred during 1941–1957, coincident with common La Niña conditions and low streamflow. Rates of decline decreased or recovered during frequent El Niño conditions and occasional high streamflow during 1958–1999. Other brief periods of high decline rates also occurred during the early to middle 1970s and during the late 1980s to early 1990s; both periods included little streamflow and no El Niño conditions.

[56] Water level records in the three study areas display significant variations that are related to ENSO. Nearby groundwater withdrawals enhance rates of water level decline during La Niña periods. The effects of recharge during El Niño periods range from significantly reduced rates of water level decline near Rillito Creek to periodic water level recovery near Cañada del Oro Wash and Garden Canyon Wash. The magnitude of water level recovery is likely related to the amount of recharge in proportion to the storage capacity of the local aquifer and rates of groundwater withdrawal. The local aquifers in the vicinity of Cañada del Oro Wash and Garden Canyon Wash tend to completely fill during major El Niño related recharge, indicating that local withdrawal rates are far less than the recharge rate during these periods.

[57] Withdrawals near Rillito Creek are sufficiently large that increased El Niño related recharge rates briefly reverse water level declines before previous rates of decline resume. Although water level declines are expected to decrease as the well field captures groundwater flow from more recharge areas, similarity in the timing of decreases in rates of water level decline to periods of climate change and increased streamflow suggests that some of the decreased rate of decline is related to increased recharge.

8. Estimates of Variations in Long-Term Ephemeral Channel Recharge

[58] Estimates of variations in long-term winter/spring recharge could be quantified only for Rillito Creek because of available streamflow data that enable estimation of streamflow losses for the period 1993–1999. The difference between winter/spring inflow and outflow along Rillito Creek indicate that rates of streamflow infiltration increased fourfold during 1933–1999 (Figure 14). Infiltration averaged 4.3 hm^3/yr before 1958, about 7.4 hm^3/yr during 1958–1977, and 16.6 hm^3/yr during 1978–1999. The three periods of increasing winter/spring streamflow infiltration correspond to increasing frequency of El Niño conditions (Figure 11) and reduced rates of water level decline near Rillito Creek (Figure 13). Rates of decline calculated by

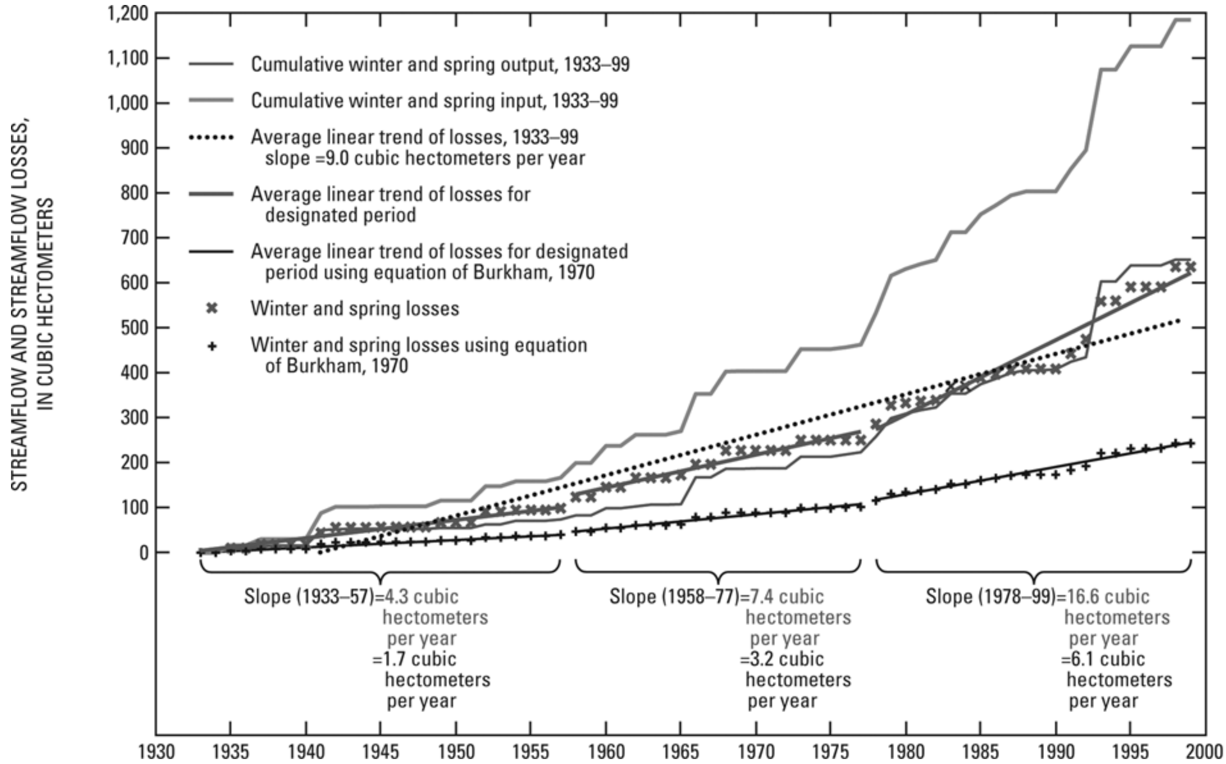


Figure 14. Winter and spring streamflow losses along Rillito Creek, 1939–1999. See color version of this figure at back of this issue.

using data from wells (D-13-13)13bba and (D-13-13)13cdc (Figure 13) indicate the greatest decline rate occurred during 1948–1957, 1.2 m/yr, and the least during 1978–1999, about 0.3 m/yr. The intervening period, 1958–1977, had a moderate rate of water level decline, about 0.5 m/yr.

[59] Estimates of winter/spring streamflow infiltration using the empirical formula of *Burkham* [1970] result in similar trends, but rates are 35–43% of those estimated in this study (Figure 14). Differences between the two estimates likely have two causes. *Burkham* [1970] did not include a seasonal analysis of infiltration. As a result, the empirical equation probably overestimates summer infiltration and underestimates winter infiltration. Also, the Burkham analysis relied on streamflow data prior to 1970 and therefore was deficient in data from high streamflows.

[60] Trends in winter/spring streamflow at Sabino Creek during 1933–1999 (Figure 11) indicate trends in mountain front recharge were similar to those along Rillito Creek. Winter/spring streamflow contributions from the crystalline rocks above the gauging station increased more than threefold from about 4.4 hm^3/yr during 1941–1957 to about 8.9 hm^3/yr during 1958–1977, and to about 17.0 hm^3/yr during 1978–1999. Increases in mountain front recharge are less than the increased streamflow because much of the flow discharges to Rillito Creek, especially during high-flow events, and increased vegetation may have developed with greater frequency of winter precipitation [*Swetnam and Betancourt*, 1998], resulting in greater evapotranspiration.

9. Conclusions

[61] Variations in recharge rates in ephemeral channels of southeastern Arizona for the period 1933–1999 were estimated using climate and hydrologic information from three study areas of different size and hydrogeology: Rillito Creek and Cañada del Oro Wash in the Tucson Basin and Garden Canyon in the Upper San Pedro River Basin. Intensive monitoring of precipitation, streamflow, water levels in wells, and groundwater storage change using gravity methods during the middle to late 1990s through the summer of 2000 established recharge rates for that period. Long-term variations in streamflow infiltration (1933–1999) along Rillito Creek were estimated using streamflow data. Variations in recharge that correspond with climate indicators SOI and PDO were quantified for Rillito Creek near Tucson.

[62] Advances in understanding of teleconnections between Pacific Ocean climate and precipitation in the western United States provide improved insight into the causes of variations in streamflow and recharge in southeastern Arizona. In particular, teleconnections between sea surface temperature and atmospheric pressure in the subtropical Pacific Ocean result in atmospheric circulation patterns that influence the probability of any year having extreme winter precipitation. Annual winter streamflow in southeastern Arizona is dependent on the occurrence of El Niño and La Niña conditions. El Niño conditions correspond with the increased probability of above normal winter/spring precipitation and recharge. About one third of winters that followed average June–November SOI values of less than 0.2, representing neutral to ENSO conditions, resulted in extreme precipitation and streamflow. La Niña conditions correspond almost exclusively to below-average winter/spring precipitation and streamflow. High precipitation winters in the Rillito Creek and Cañada del Oro Wash areas, however, did not always correspond to

large amounts of precipitation in the Garden Canyon area. A greater frequency of ENSO and decreasing frequency of La Niña conditions during 1978–1998 resulted in an increased frequency of winters having extreme precipitation and streamflow in comparison to previous periods.

[63] Basin-scale annual recharge rates have varied greatly since the 1930s on the basis of observed variations in winter precipitation, streamflow, and a factor of four variation in estimated infiltration along Rillito Creek. Previous estimates of recharge in the Tucson Basin, about 98.7 hm^3 annually, were based on streamflow infiltration and water budgets developed during an extended period of below-average recharge during 1940–1963 [*Burkham*, 1970]. Recharge rates may have averaged closer to 197.4 hm^3 annually since about 1977 in which much of the increase resulted from the extreme wet winters of 1982–1983 and 1992–1993.

[64] Variations in recharge rates that resulted from this regional analysis emphasize the need for consideration of recharge variations in the assessment of groundwater availability. Basins in arid and semiarid regions are particularly suitable for similar analyses of recharge variations including application of gravity methods. Thick unsaturated zones that can accept and store periodic recharge are common in these areas. In addition, years of drought are commonly interrupted by short duration wet periods that can result in significant variations in groundwater storage and stream base flow. Gravity and water level based detection of subdecadal-scale recharge variations require measurements on a monthly or seasonal basis. Monitoring stations should be concentrated near potential recharge areas where draining or filling of pore spaces occurs nearly continuously in response to periodic recharge. Continuous streamflow monitoring at paired gauging stations can provide additional control on variations in infiltration along ephemeral channels. A single gauging station can provide an estimate of potential variations in recharge or can be used with water level records to estimate recharge for individual recharge events. Separation of base flow from gauge records along perennial stream reaches can provide an independent measure of variations in groundwater storage. Estimates of recharge variations can be made on the basis of climate and streamflow data provided records are continuous over several decades. Further improvements in the projection of long-term climatic conditions combined with knowledge of past climate and recharge relations will enable better forecasts of recharge and general water availability.

References

Anderson, T. W., G. W. Freethey, and P. Tucci (1992), Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent states, *U.S. Geol. Surv. Prof. Pap., 1406-B*, 67 pp., 3 plates.

Andrade, E. R., and W. D. Sellers (1988), El Niño and its effect on precipitation in Arizona and western New Mexico, *J. Clim.*, *8*, 403–410.

Burkham, D. E. (1970), Depletion of streamflow by infiltration in the main channels of the Tucson Basin, southeastern Arizona, *U.S. Geol. Surv. Water Supply Pap., 1939-B*, 36 pp.

Cane, M. A. (1983), Oceanographic events during El Niño, *Science*, *222*, 1189–1198.

Cayan, D. R., and D. H. Peterson (1989), The influence of North Pacific atmospheric circulation on streamflow in the west, in *Aspects of Climate Variability in the Pacific and the Western Americas*, *Geophys. Monogr. Ser.*, vol. 55, edited by D. H. Peterson, pp. 375–397, AGU, Washington, D. C.

Cayan, D. R., and R. H. Webb (1992), El Niño/Southern Oscillation and streamflow in the western United States, in *El Niño Historical and Paleoclimatic Aspects of the Southern Oscillation*, edited by H. F. Diaz and V. Markgraf, pp. 29–68, Cambridge Univ. Press, New York.

Cayan, D. R., K. T. Redmond, and L. G. Riddle (1999), ENSO and hydrologic extremes in the western United States, *J. Clim.*, *12*, 2881–2893.

Cunningham, E. E. B., A. Long, C. J. Eastoe, and R. L. Bassett (1998), Migration of recharge waters downgradient from the Santa Catalina mountains into the Tucson Basin aquifer, *Hydrogeol. J.*, *6*, 94–103.

Davidson, E. S. (1973), Geohydrology and water resources of the Tucson Basin, Arizona, *U.S. Geol. Surv. Water Supply Pap., 1939-E*, 81 pp.

Douglas, A. V., and P. J. Englehart (1981), On a statistical relationship between autumn rainfall in the central equatorial Pacific and subsequent winter precipitation in Florida, *Mon. Weather Rev.*, *109*, 2377–2382.

Eastoe, C. J., A. Gu, and A. Long (2004), The origins, ages and flow paths of groundwater in Tucson Basin: Results of a study of multiple isotope systems, in *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Sci. Appl. Ser.*, vol. 9, edited by J. F. Hogan, F. M. Phillips, and B. R. Scanlon, pp. 217–234, AGU, Washington, D. C.

Elliot, W. P., and J. K. Angell (1988), Evidence for changes in Southern Oscillation relationships during the last 100 years, *J. Clim.*, *1*, 729–737.

Goodrich, D. C., D. G. Williams, K. L. Unkrich, J. F. Hogan, R. L. Scott, K. R. Hultine, D. Pool, A. L. Coes, and S. Miller (2004), Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona, in *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Sci. Appl. Ser.*, vol. 9, edited by J. F. Hogan, F. M. Phillips, and B. R. Scanlon, pp. 77–99, AGU, Washington, D. C.

Hanson, R. T., and J. F. Benedict (1994), Simulation of ground-water flow and potential land subsidence: Upper Santa Cruz Basin, Arizona, *U.S. Geol. Surv. Water Resour. Invest. Rep., 93-4196*, 47 pp.

Higgins, R. W., K. C. Mo, and Y. Yao (1998), Interannual variability of the U.S. summer precipitation regime with emphasis on the Southwestern monsoon, *J. Clim.*, *11*, 2582–2606.

Kalin, R. M., and A. Long (1994), Application of hydrogeochemical modeling for validation of hydrologic flow modeling in the Tucson Basin aquifer, Arizona, United States of America, *Tech. Doc. 777*, pp. 209–254, Int. At. Energy Agency, Vienna.

Keith, S. J. (1981), Stream channel recharge in the Tucson Basin and its implications for ground water management, M.S. thesis, 84 pp., Univ. of Ariz., Tucson.

Kiladis, G. N., and H. F. Diaz (1989), Global climatic anomalies associated with extremes in the Southern Oscillation, *J. Clim.*, *2*, 1069–1090.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

McCabe, G. J., and M. D. Dettinger (1999), Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, *Int. J. Climatol.*, *19*, 1399–1410.

Phillips, F. M., J. F. Hogan, and B. R. Scanlon (2004), Introduction and overview, in *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Sci. Appl. Ser.*, vol. 9, edited by J. F. Hogan, F. M. Phillips, and B. R. Scanlon, pp. 1–14, AGU, Washington, D. C.

Pool, D. R. (1999), Aquifer-storage change in the Lower Cañada del Oro subbasin, Pima County, Arizona, 1996–98, *U.S. Geol. Surv. Water Resour. Invest. Rep., 99-4067*, 3 sheets.

Pool, D. R., and A. L. Coes (1999), Hydrologic investigations of the Sierra Vista subwatershed of the Upper San Pedro River Basin, Cochise County, southeastern Arizona, *U.S. Geol. Surv. Water Resour. Invest. Rep., 99-4197*, 41 pp., 3 plates.

Pool, D. R., and J. Eychaner (1995), Measurements of aquifer-storage change and specific yield using gravity surveys, *Ground Water*, *33*, 425–432.

Pool, D. R., and W. Schmidt (1997), Measurements of ground-water storage change and specific yield using the temporal gravity method near Rillito Creek, Tucson, Arizona, *U.S. Geol. Surv. Water Resour. Invest. Rep., 97-4125*, 30 pp.

Ramage, C. S. (1996), El Niño, *Sci. Am.*, *254*, 76–83.

Rasmusson, E. M., and T. H. Carpenter (1982), Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño, *Mon. Weather Rev.*, *110*, 354–384.

Redmond, K. T., and R. W. Koch (1991), Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices, *Water Resour. Res.*, *27*, 2381–2399.

Ripich, M., and J. P. Hoffmann (2000), Integrating geophysical and geological data to delineate the geometry of deposits underlying Rillito Creek, Pima County, Arizona, paper presented at 13th Annual Arizona Hydrological Society Symposium, Phoenix, Ariz., 20–22 Sept.

Ropelewski, C. F., and M. S. Halpert (1986), North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO), *Mon. Weather Rev.*, *114*, 2352–2362.

Ropelewski, C. F., and P. D. Jones (1987), An extension of the Tahiti-Darwin Southern Oscillation index, *Mon. Weather Rev.*, *115*, 2161–2165.

Scanlon, B. R., K. Keese, R. C. Reedy, J. Simunek, and B. J. Andraski (2003), Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0–90 kyr): Field measurements, modeling, and uncertainties, *Water Resour. Res.*, *39*(7), 1179, doi:10.1029/2002WR001604.

Scott, R. L., W. J. Shuttleworth, T. O. Keefer, and A. W. Warrick (2000), Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest, *Water Resour. Res.*, *36*, 2233–2247.

Swetnam, T. W., and J. L. Betancourt (1998), Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest, *J. Clim.*, *11*, 3128–3147.

Trenberth, K. E. (1976), Spatial and temporal variations of the Southern Oscillations, *Q. Rev. R. Meteorol. Soc.*, *102*, 639–653.

Trenberth, K. E., and T. J. Hoar (1996), The 1990–1995 El Niño–Southern Oscillation event: Longest on record, *Geophys. Res. Lett.*, *23*, 57–60.

Trenberth, K. E., and D. J. Shea (1987), On the evolution of the Southern Oscillation, *Mon. Weather Rev.*, *115*, 3078–3096.

van Loon, H., and R. A. Madden (1981), The Southern Oscillation, part I: Global associations with temperature and pressure in northern winter, *Mon. Weather Rev.*, *109*, 1150–1162.

Walker, G. T. (1923), Correlation in seasonal variations of weather, part VIII: A preliminary study of world weather, *Mem. Indian Meteorol. Dep.*, *24*, 75–131.

Walker, G. T., and E. W. Bliss (1932), World Weather, part V, *Mem. R. Meteorol. Soc.*, *4*(36), 53–84.

Walvoord, M. A., M. A. Plummer, F. M. Phillips, and A. V. Wolfsberg (2002), Deep arid system hydrodynamics: 1. Equilibrium states and response times in thick desert vadose zones, *Water Resour. Res.*, *38*(12), 1308, doi:10.1029/2001WR000824.

Webb, R. H., and J. L. Betancourt (1992), Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona, *U.S. Geol. Surv. Water Supply Pap., 2379*, 40 pp.

Woolhiser, D. A., T. O. Keefer, and K. T. Redmond (1993), Southern Oscillationeffects on daily precipitation in the southwestern United States, *Water Resour. Res.*, *29*, 1287–1295.

D. R. Pool, U.S. Geological Survey, 520 North Park, Tucson, AZ 85719, USA. (drpool@usgs.gov)

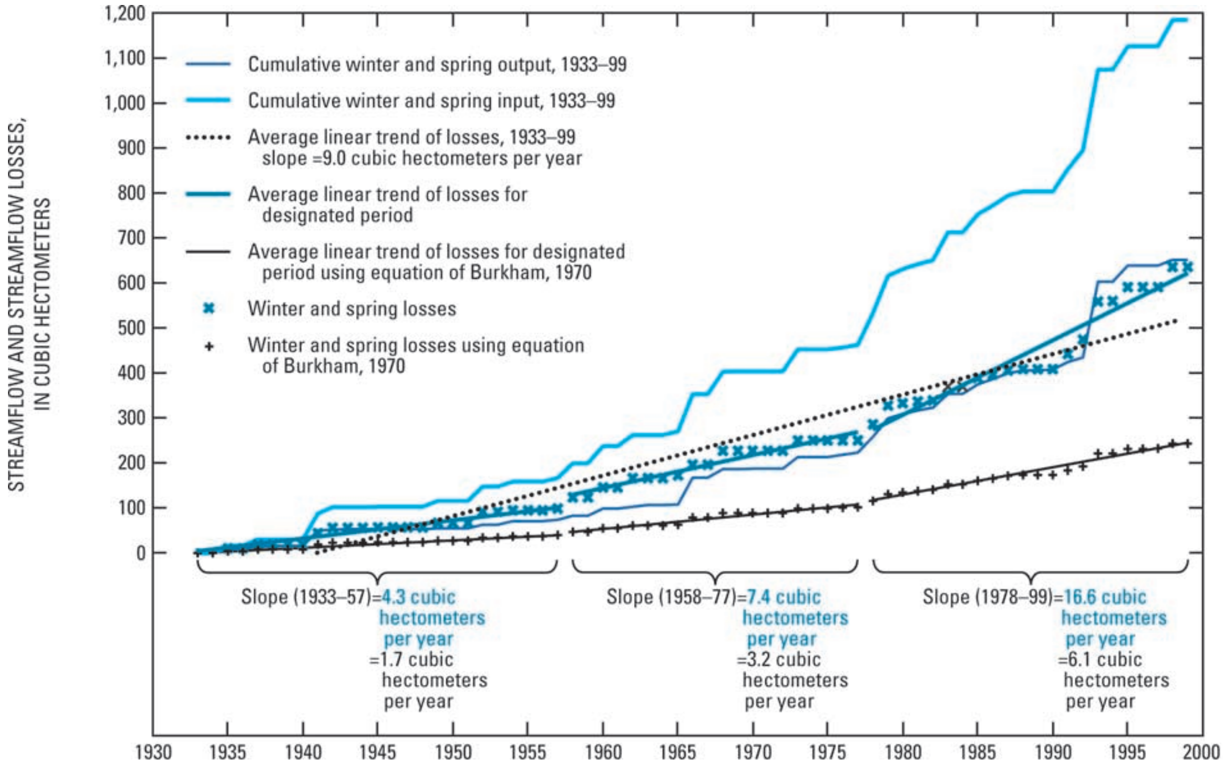


Figure 14. Winter and spring streamflow losses along Rillito Creek, 1939–1999.