

# The Origins, Ages and Flow Paths of Groundwater in Tucson Basin: Results of a Study of Multiple Isotope Systems

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Detailed maps of  $\delta^{18}\text{O}$ ,  $\delta^{34}\text{S}$  tritium and  $^{14}\text{C}$  indicate distinctive basin-scale domains of groundwater in the upper 140 m of the Tucson basin. Water in each hydro-geographic domain has isotope characteristics relating it either to recharge in the flood plain of a major stream entering the basin, or to a zone in which deep basin groundwater moves vertically upwards. Infiltration of surface water occurs rapidly into flood-plain sediment in major washes, yielding flood-plain groundwater that is distinctive in  $\delta^{18}\text{O}$  (according to catchment altitude) and  $\delta^{34}\text{S}$  (according to catchment geology), and contains tritium similar to that of contemporaneous precipitation events. In Tanque Verde Creek flood plain, recharge within 3 km of the mountain front yields groundwater with the isotope signature of small ( $< 10$  mm) precipitation events. Groundwater flow from flood plains to adjacent basin sediments is greatest south of Rillito and Tanque Verde Creeks and east of the southern part of the Santa Cruz River. Other reaches of major streams contribute little groundwater to the regional aquifer at a time scale of decades. Tucson rain since 1991 has contained 5–7 TU of tritium, representing natural cosmogenic production. Bomb tritium in Tucson rain was augmented by industrial tritium releases in the 1970s. Recharge at sub-basin scale, i.e. between major streams, is evident in the data, but is of minor importance as a source of groundwater.

## INTRODUCTION

Tucson is one of several major urban areas reliant on basin groundwater in the Basin-and Range province of the semi-arid southwest USA. In all cases, population is increasing and water levels are declining rapidly. The City of Tucson has until recently relied exclusively on groundwater from the Tucson basin and Avra Valley, west of the city, as its source of municipal water. Recycled effluent is increasingly used for irrigation, and supplementary water

from the Colorado River became available in the 1990s, reducing the need for groundwater for the present. The current urban population is near 800,000 and increasing rapidly, suggesting that groundwater will remain necessary as a major water source in the long term. A clear understanding of the hydrology and hydrogeochemistry of the basin is important for future management of the resource, and for designing any new artificial recharge facilities. Issues related to population growth and planning future water supplies in Tucson are discussed in *Gelt et al.* [1999] and *Kalin and Long* [1994].

The usefulness of groundwater isotope studies in identifying water types in Tucson was shown by *Kalin and Long* [1994] and is emerging in other urbanized basins, e.g.

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Albuquerque, New Mexico [Lambert and Balsley, 1997], and El Paso, Texas [Anderholm and Heywood, 2003].

Stable isotopes and radioisotopes of H and O in water and solutes in water provide valuable information about groundwater age and origin. Stable H and O isotopes are particularly useful where water sources are of different altitude or latitude, or are subject to evaporation. Sulfur isotopes are useful in distinguishing waters interacting with distinctive sulfate sources (or in detecting the results of bacterial sulfate reduction), but are less commonly applied. Tritium ( $^3\text{H}$ ) has a half-life of 12.3 years [Lucas and Unterwieser, 2000], and is useful in distinguishing pre-bomb from post-bomb infiltration. Carbon-14, with a half-life of 5715 years [Holden, 2001], can be applied to the dating of pre-bomb groundwater.

Over the last sixteen years, our laboratory has undertaken an isotopic study of the Tucson basin, with the goals of improving the understanding of groundwater origin, age and movement, and of demonstrating the potential of concurrent application of multiple isotope systems in a semiarid basin in which urban development allows detailed sampling. In this paper, we present isotope data for groundwater in the central part of the basin (Figure 1A), and interpret them in relation to recharge and groundwater flow. We will address: 1. The isotope composition of Tucson precipitation; 2. The relationship of recharge to seasonal precipitation; 3. The isotope character of water recharging the aquifers in active

flood plains; 4. Use of isotopes to map domains influenced by recharge from each major stream in the basin, and areas influenced by upwelling of deep basin groundwater; 5. Relationship of groundwater domains to geomorphology; 6. Location of zones of high replenishment from floodplains to adjacent sediment; and 7. The relative importance of recharge from major streams and from the areas between them.

## STUDY AREA

### Location

The Tucson basin occupies an area about 30 x 40 km within the watershed of the Santa Cruz River in southern Arizona. The basin floor lies at elevations near 800 m above sea level. The basin is bounded by mountain ranges of crystalline rock, with altitudes up to 2900 m in the Santa Catalina, Santa Rita and Rincon Mountains, and up to 1400 m in the Tucson Mountains. The Tucson metropolitan area occupies the northern half of the basin. The climate at basin elevation is semiarid, with hot summers and cool winters. Rainfall at basin levels averages 305 mm annually and is equally distributed between a summer monsoon with brief, localized convective precipitation, and a fall-winter season of longer-lasting, widespread, cyclonic precipitation events associated with Pacific cold

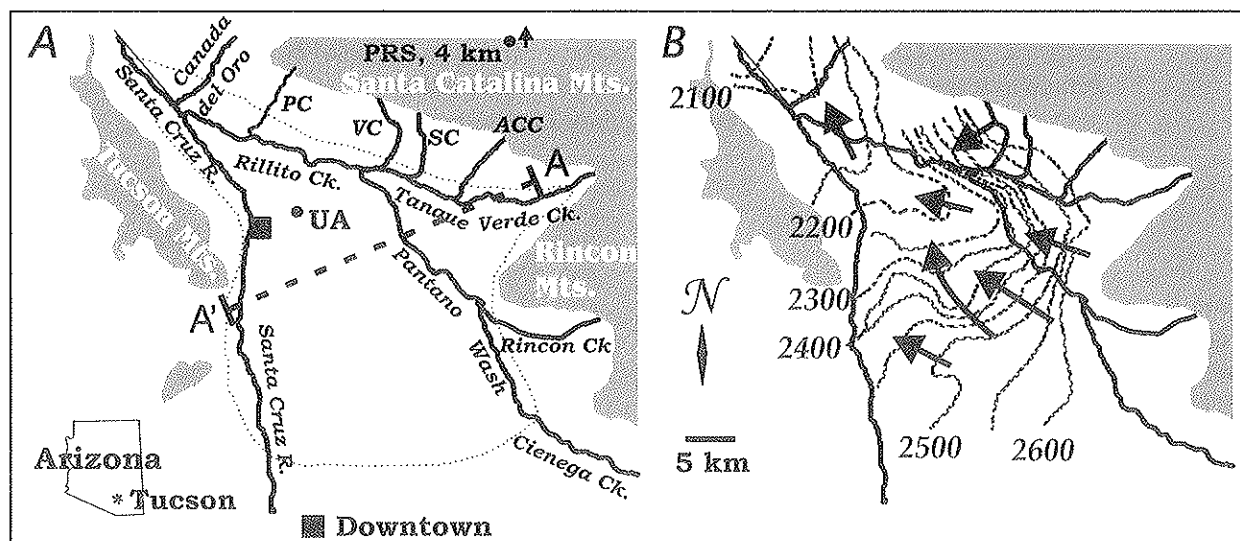


**Figure 1.** A. Location map of study area (patterned), showing major streams of Tucson basin. VC = Ventana Creek, SC = Sabino Creek, ACC = Agua Caliente Creek, PC = Pima Creek. Precipitation collection sites are shown as black circles: UA = University of Arizona; PRS = Palisades Ranger Station. B. Contours of static water level, in feet above sea level [Gelt et al., 1999].

fronts or tropical depressions [Gelt *et al.*, 1999]. The natural vegetation of the basin and lower mountain slopes is Sonoran desert. Precipitation increases with elevation, and the higher mountains are forested. Mean gradients are 114 mm/1000 m for summer, and 151 mm/1000 m for winter precipitation [Wright, 2001].

### Geology

The basin lies within the Basin-and-Range physiographic province, and formed as a result of Neogene regional extension, expressed as detachment faulting followed by high-angle normal faulting and rapid deepening of the central part of the basin [Davidson, 1973; Eberly and Stanley, 1978; Anderson, 1987; and Dickinson, 1999]. It is filled with alluvial and lacustrine sediments of Oligocene to Holocene age, with a maximum thickness of 3000 m in the central graben. Gypsum or anhydrite evaporites occur at depth. Holocene alluvial deposits are largely restricted to active flood plains. The crystalline basement consists of granitic gneiss derived from Proterozoic and Eocene protoliths in the Santa Catalina and Rincon mountains, and of Paleozoic and Mesozoic igneous and sedimentary rocks in the Tucson and Santa Rita Mountains.

### Geomorphology

The principal features of the basin surface are a number of alluvial fans and active flood plains along the major washes. A series of Pleistocene terraces rises to the south of Rillito Creek; these record the progressive erosion of alluvium that once filled the basin more deeply than at present [Klawon *et al.*, 1999]. For this study, the relevant geomorphic features (Figure 2) are the flood plains, the Jaynes and Cemetery terraces, and a large alluvial fan that radiates across the southern part of the basin from the point of entry of Cienega Creek. The course of Cienega Creek passes east of the fan at present; it appears to have been captured by a Rincon Creek tributary to form the drainage known as Pantano Wash.

### Hydrogeology

Except for perched aquifers of limited extent near the major flood plains, the groundwater in Tucson basin makes up a single, regional aquifer, unconfined except at depth, hosted in alluvial sediments and spanning most of the basin. Static water levels generally decrease to the northwest, in the direction of the present surface outlet (Figure 1B). They have been strongly modified by decades of pumping

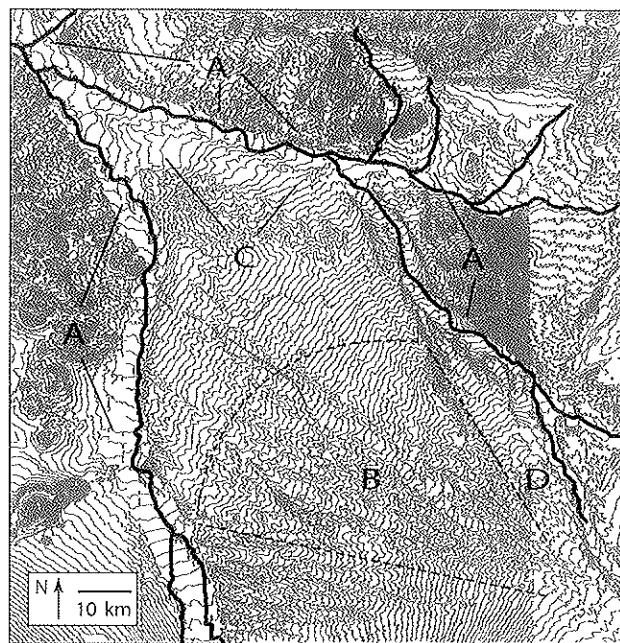


**Figure 2.** Topographic contour map of Tucson basin, with geomorphic features relevant to this study indicated thus: A. Holocene flood plains; B. A large alluvial fan originating where Cienega Creek enters the basin; C. Middle and late Pleistocene river terraces, the Jaynes and Cemetery terraces [Klawon *et al.*, 1999] south of Rillito Creek; D. Present course of Cienega Ck (upper Pantano Wash).

beneath central Tucson, where levels declined 30 to 60 m between 1940 and 1995 [Gelt *et al.*, 1999]. The decline in groundwater levels has resulted in the disappearance of perennial surface water from the basin, except where the Santa Cruz River is supplied with treated municipal effluent, and where Cienega Creek crosses an andesite sill in the southeastern corner of the basin. Most wells producing water for human consumption draw from the upper 250 m of basin sediment.

### PREVIOUS ISOTOPE STUDIES OF TUCSON BASIN

Detailed isotope maps ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ,  $\delta^{34}\text{S}$ ,  $\delta^{13}\text{C}$ ,  $^{14}\text{C}$ ) of the northern third of Tucson basin, along with limited information on tritium,  $\delta^{37}\text{Cl}$  and  $\delta^{18}\text{O}$  of sulfate [Kalin and Long, 1994] revealed basin-scale distribution patterns, and showed that, except on the western side of the basin, mountain precipitation was the ultimate source of groundwater in the study area. Other contributions include  $\delta^{18}\text{O}$ ,  $\delta\text{D}$  and tritium data for springs and wells in the Santa Catalina Mountains and foothills [Cunningham *et al.*, 1998], tritium data for Tucson groundwater [Coes *et al.*, 2000], and data

showing a tritium front in the aquifer south of Rillito Creek [Lindquist, 1992]. Additional data cited here are from theses and dissertations of the University of Arizona [Kalin, 1994; Esposito, 1993; and Pasilis, 1999]. For this report, we have increased the density of sampling points in the Tucson urban area, and have extended the area of coverage outward in all directions.

## THE DATA SET AND ITS LIMITATIONS

### Sample Sites

We have accumulated data from over 400 sites, which are numbered (Figure 3) and listed with well names, locations, depth information and the isotope data at the URL:

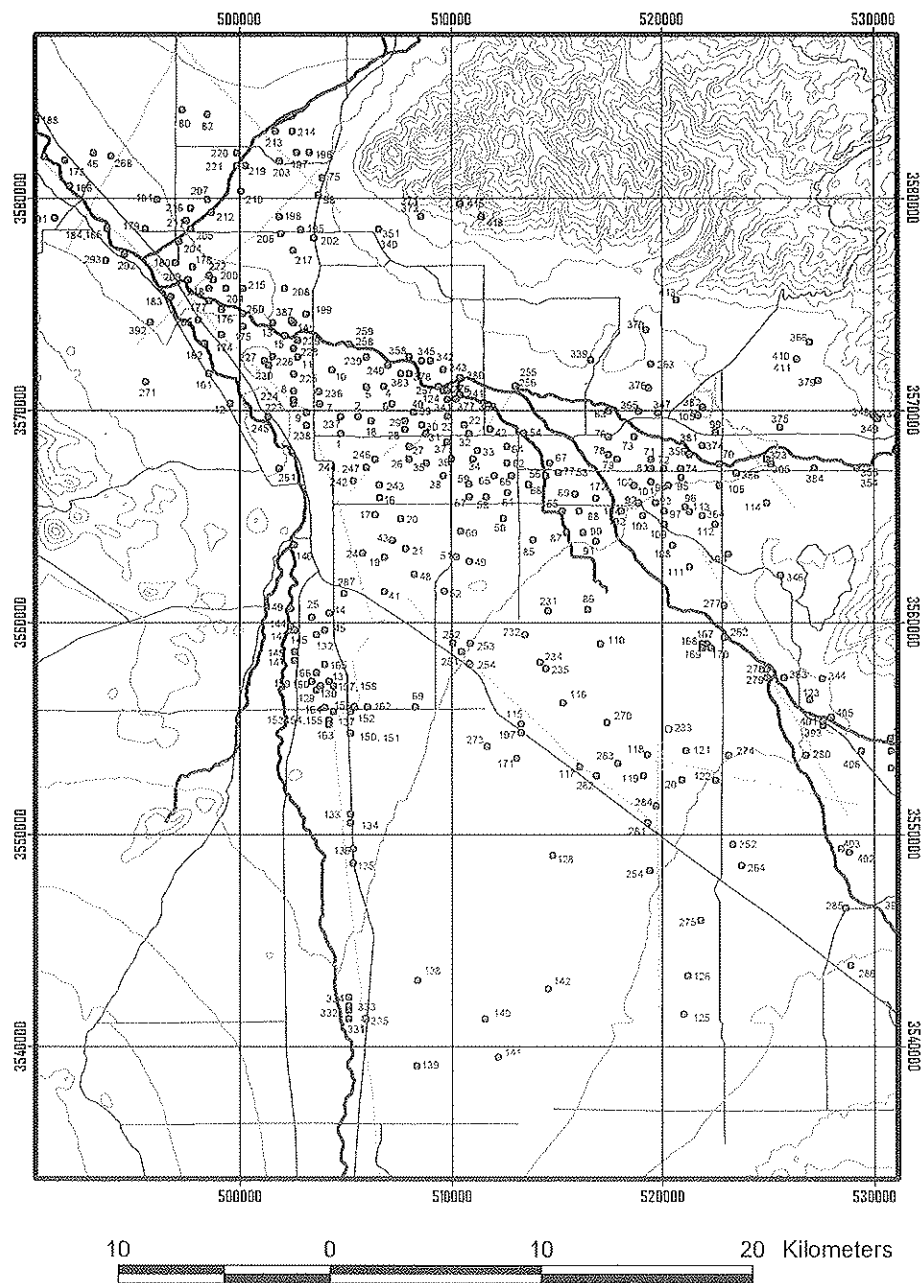


Figure 3. Sample site map. Numbers refer to the data table (<http://www.geo.arizona.edu/research/iso-gcoch-lab.html>).

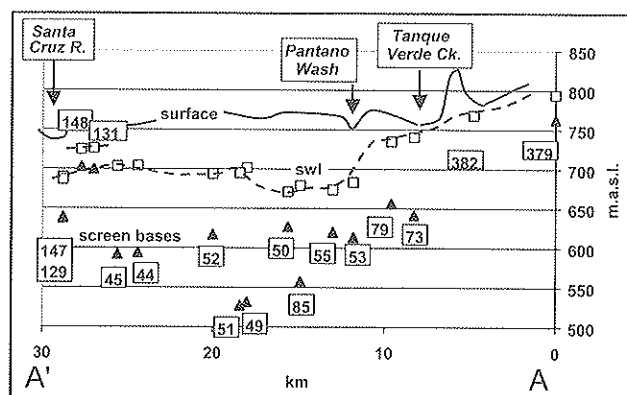


**Figure 4.** Vertical cross section A-A' of Tucson basin (see Figure 1 for location), showing static water level (swl) and well-screen bases. Site numbers (Figure 4) are in boxes.

<http://www.geo.arizona.edu/research/iso-geochem-lab.html>. Details of analytical methods are also given. In all cases, we sampled existing production and monitoring wells. A sample therefore gives a flow-weighted mean value of each isotope parameter for the screened interval of the well. Well depths and screened intervals vary depending on local needs and conditions; municipal wells in the basin center are deeper and have longer screens than private wells in flood plains (see Figure 4 and URL cited above for details). Nonetheless, static water levels (Figure 1B) indicate a basin-wide aquifer, with the exception of wells near the southwest end of the section in Figure 4, where a perched aquifer exists, e.g. at sites 131 and 148. Screened intervals lie within 240 m of the surface in most cases; a few screens extend to 300 m. Our data in general represent bulk groundwater in the upper 240 m of sediment, or generally the upper 140 m of the regional aquifer, across a 30 km width of basin. We have little information about vertical isotopic variation within that interval. We did not obtain samples from several areas of the basin, notably near downtown Tucson, where no production wells are in use.

#### *Time as a Factor*

The Tucson basin aquifer is a dynamic system in which change will be observed, given enough time between measurements at a given site. For this study, we have accumulated data over a period of 16 years; this raises questions about the validity of isotope maps containing data from different sampling campaigns. We have repeat measurements of  $\delta^{18}\text{O}$  at 13 sites and tritium at 32 sites with separations of several years (see <http://www.geo.arizona.edu/research/iso-geochem-lab.html>). Most of the  $\delta^{18}\text{O}$  data show only small

shifts. For sites 1, 16, 27, 101, 103, a set of manual equilibration data from 1989 may be about 0.5‰ too high because of analytical error, on the basis of comparison with  $\delta\text{D}$  data. In the case of tritium, injection of Central Arizona Project water (14–15 TU) in 1993 affected sites 56, 65 and 68; for these sites, only pre-1993 data will be shown on the tritium map. Three wells south of Rillito Creek (sites 29, 30, 175) also shifted to higher tritium between 1992 and 1998, an observation discussed below.

### TUCSON PRECIPITATION

#### *$\delta\text{D}$ and $\delta^{18}\text{O}$*

Our laboratory has functioned as an observatory for  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in individual precipitation events in Tucson since 1981. We possess a smaller data set for 1 to 2 week aggregate samples representing all precipitation between 1995 and 2000 at the Palisades Ranger Station in the Santa Catalina Mountains [Wright, 2001]. At both sites,  $\delta\text{D}$  and  $\delta^{18}\text{O}$  vary widely among individual events, seasonal means and annual means. Summer monthly local meteoric water lines (MWLs) have slopes between 5.7 and 7.7, and winter monthly local MWLs have slopes between 5.2 and 8.5. Slopes less than 8 are consistent with evaporation of falling raindrops, which is characteristic of arid regions [Gat, 1981]. The mean isotopic altitude effects are 1.6‰ per 1000 m for  $\delta^{18}\text{O}$ , and 11‰ per 1000 m for  $\delta\text{D}$  [Wright, 2001].

#### *Tritium*

Bomb-derived tritium had been removed from the atmosphere by 1992 (Figure 5). Individual rain events from 1992 to 2000 varied between 2 and 12 TU. The annual mean tritium content of precipitation, weighted for precipitation amount, has increased slowly between limits of 4.3 and 6.7 TU from 1992 to 2001; a similar range is likely for pre-bomb rainwater which would now have decayed to less than the 0.6 TU detection limit of our laboratory.

Tritium in seasonal-aggregate precipitation samples from 1968 to 1991, corrected for decay, has been compared with a predicted bomb tritium curve for southern Arizona rain [Doney *et al.*, 1992]. Samples from the 1980s lie beneath the predicted curve. Precipitation samples from 1968 to 1977 depart radically from the curve (Figure 5), with values as high as 1100 TU. These correspond in time to the operation of the American Atomics factory, a manufacturer of self-illuminating signs, that was closed in 1981 for

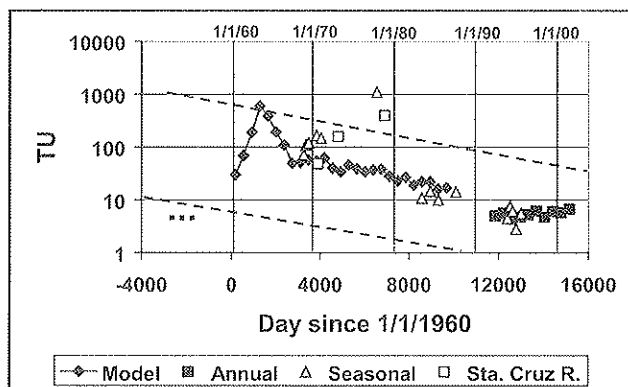


**Figure 5.** Tritium in Tucson rain, 1950 to present, showing a model curve [Doney et al., 1992]. Annual, seasonal and Santa Cruz river water tritium values are actual measurements, weighted for amount of precipitation in the case of annual and seasonal means. Thin dashed lines show the slope of radioactive decay curves. The thick dashed line (1950–1955) shows estimated pre-bomb rain tritium.

unauthorized releases of tritium into the atmosphere and the city sewers [Wasserman and Solomon, 1982]. The rain samples were collected from locations 1.5 to 4 km from the two sites used by the factory.

#### Carbon-14

The  $^{14}\text{C}$  content of  $\text{CO}_2$  in Tucson urban air, measured as percent modern carbon in deciduous or annual plant material, has decreased from about 112 pMC in 1994 to about 107 pMC in 2002. A single measurement of 179 pMC was made near the peak of bomb  $^{14}\text{C}$  in April 1965. Rural air, which is not as strongly affected by combustion of fossil fuels, is 0 to 2 pMC richer in  $^{14}\text{C}$  than urban air (Figure 6). Rainwater (not measured because of the large sample volume required) would contain the same or lower pMC values, depending on the relative proportions of carbon from dust and air.

#### $\delta^{34}\text{S}$

Sulfate precipitation occurs in rain and as dry fallout. Values of  $\delta^{34}\text{S}$  in rain samples over one year (1996–1997) show an apparent seasonal variation between 2.1 and 8.5‰, with higher values limited to summer [Kayaci, 1997]. Three dust samples gave  $\delta^{34}\text{S}$  values of 6.9, 6.4 and 3.6‰. Variation of  $\delta^{34}\text{S}$  in rain may reflect variability in the ratio of sulfate contributions from aerosols and from anthropogenic sources such as sulfide ore smelters and power stations.

### RECHARGE AND SEASONAL VARIATIONS OF O AND H ISOTOPES

Figure 7 is a plot of  $\delta\text{D}$  vs  $\delta^{18}\text{O}$  for all groundwater samples at basin elevation, with weighted mean values for mountain and basin precipitation shown for comparison. The groundwater data fall within the range of precipitation data and close to long-term means [Wright, 2001], indicating minimal evaporation during recharge despite the semi-arid climate [cf. Mathieu and Bariac, 1996]. Assuming that  $\delta^{18}\text{O}$  of groundwater represents an average isotope composition of precipitation from a single season or longer period, we can deduce that both mountain- and basin-level precipitation contribute to basin groundwater. Groundwater corresponding to mountain precipitation clusters between the winter and overall means for mountain precipitation. Likewise, groundwater corresponding to basin precipitation clusters between the winter and overall means for basin precipitation. These observations confirm the observations of previous authors that winter precipitation is a more important source of recharge than summer precipitation [Simpson et al. 1970; Kalin and Long, 1994]. The extreme negative points in Figure 7 correspond to flood-plain groundwater samples (sites 258, 361) that contain finite tritium and appear to be strongly influenced by individual precipitation events.

### SURFACE WATER AND FLOOD PLAIN GROUNDWATER

In this study, we use relatively shallow groundwater samples from active flood plains as the preferred indicators of time- and space-averaged isotope compositions of water recharging the basin beyond the flood plains. Ephemeral

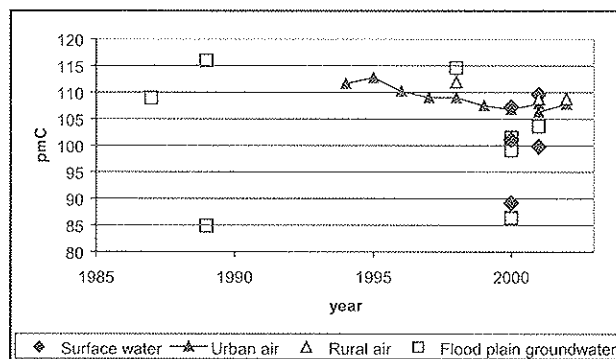


**Figure 6.** Carbon-14 content of Tucson's atmosphere (measured on annual or deciduous plant material), rural air from southern Arizona, surface water and flood-plain groundwater samples.

surface water varies widely in isotopes, particularly  $\delta D$  and  $\delta^{18}O$ , presumably reflecting the temporal variability of these parameters in rain and the potential combination in a given sample of water from a variety of events, altitudes and locations. A process of isotopic averaging begins in surface water, continues in flood-plain groundwater which is generally very young (see evidence below), and culminates in water that infiltrates from flood plains into adjacent sediment (see example of O isotopes in groundwater near Rillito and Tanque Verde Creeks, Figure 7).

### $\delta^{18}O$ and $\delta D$

Groundwater from the flood plain of the Santa Cruz River and that emerging in the perennial reaches of Cienega Creek has  $\delta^{18}O$  values  $> -8\text{‰}$  (Figure 8). Both drain extensive basins at low elevations upstream of Tucson, with a relatively small fraction of the catchment area at elevations above 2000 m. Rillito Creek and its northern tributaries, by contrast, have small catchments with large portions at elevations greater than 2000 m in the Rincon and Santa Catalina Mts. The common occurrence of  $\delta^{18}O$  values  $< -9\text{‰}$  in groundwater from the flood-plains of these streams is consistent with a predominant water input from high altitudes. Flood-plain groundwater is isotopically homogeneous ( $\delta^{18}O$   $-7$  to  $-8\text{‰}$ ) in the case of the Santa Cruz River, but changes to  $-8$  to  $-9\text{‰}$  downstream of the effluent discharge points of county wastewater treatment plants.

In Rillito and Tanque Verde Creeks the  $\delta^{18}O$  range of flood-plain groundwater is broader. A longitudinal set of

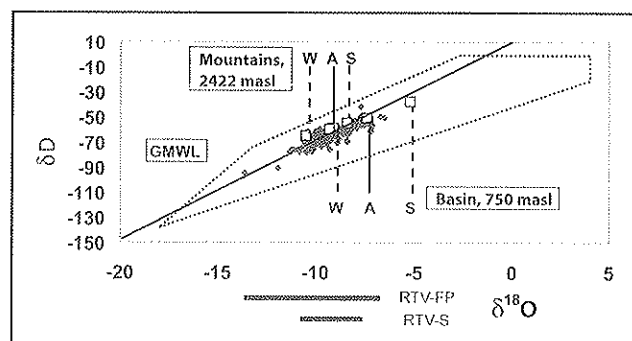


**Figure 7.** Plot of  $\delta D$  vs.  $\delta^{18}O$  for all available groundwater samples (black diamonds,  $n = 360$ ), and mean precipitation at basin elevation and in the Santa Catalina Mountains (white squares with vertical lines). The dotted polygon encloses  $>99\%$  of measurements on individual rain events at basin elevation. GMWL = global meteoric water line,  $\delta D = 8\delta^{18}O + 10$ . S = summer, W = winter, A = all data. Bold lines below graph give  $\delta^{18}O$  ranges of groundwater from Rillito-Tanque Verde flood plain (RTV-FP) and from basin sediments immediately south of the flood plain (RTV-S).

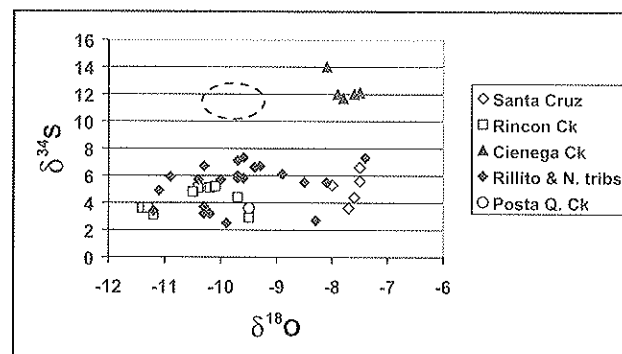


**Figure 8.** Plot of  $\delta^{34}S$  vs.  $\delta^{18}O$  in flood plain groundwater. The empty ellipse corresponds to groundwater compositions not represented in flood-plain groundwater.

samples taken on June 21, 1997 in the Tanque Verde Creek flood plain has  $\delta^{18}O$  values decreasing from about  $-7\text{‰}$  near the range front to  $-12\text{‰}$  just east of the confluence with Sabino Creek, then increasing at the confluence (Figure 9). This pattern could be explained by: 1. evaporation of shallow groundwater, 2. preferential recharge of summer precipitation near the range front following heavy pumping during spring, or 3. preferential recharge after small precipitation events yielding low runoff volumes near the range front. If evaporation from shallow groundwater were the cause, samples from the highest water tables should have the highest  $\delta^{18}O$  values; at sites 354, 355, 376, 384 the water table is at its shallowest, near 7 m below the surface; the  $\delta^{18}O$  range is  $-9.6$  to  $-7.4\text{‰}$ , indicating no such relationship. For the year prior to sampling, the weighted mean  $\delta^{18}O$  values of winter and summer rain in Tucson were  $-8.1$  and  $-8.8\text{‰}$  respectively. The weighted means for large ( $>10$  mm) and small ( $<10$  mm) precipitation events were  $-8.4$  and  $-4.8\text{‰}$  respectively. The  $\delta^{18}O$  data therefore suggest that water from small rain events infiltrates preferentially near the range front. Weighted mean values of deuterium excess, which are respectively 16 and 4 for large and small events, also support this conclusion. (The deuterium excess, defined as  $d = \delta D - 8\delta^{18}O$ , is an indicator of evaporation, in this case of falling rain;  $d = 10$  corresponds to the meteoric water line, and lower values indicate evaporation). Figure 9 shows a general correspondence between high  $\delta^{18}O$  and low  $d$  in the groundwater. The increase in  $\delta^{18}O$  at the confluence with Sabino Creek may arise from small runoff events in Sabino Creek.

### Tritium

Groundwater samples from flood plains all contain finite tritium (Figure 10), indicating that they are young water. A

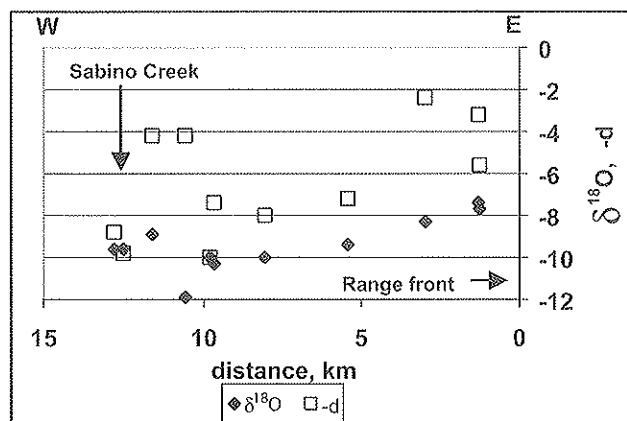


**Figure 9.** Plot of  $\delta^{18}\text{O}$  and  $-d$ -parameter in groundwater from the flood plain of Tanque Verde Creek, sampled on June 21, 1997, vs. distance from the mountain range front.

few samples containing more or less tritium than contemporaneous rainwater are mixtures of recent rainwater with pre-bomb or bomb-pulse water. Groundwater with 10 to 30 TU, the highest values found in the basin, was sampled in the Santa Cruz flood-plain north of downtown between 1993 and 1999, and may represent residual contamination from American Atomics or from disused landfills along the river.

#### $\delta^{34}\text{S}$

We possess a few measurements of  $\delta^{34}\text{S}$  in surface water: in the Santa Cruz River, 5.0‰ [Lewis, 1996]; Sabino Creek, 6.2 ‰ and Tanque Verde Creek, 7.2‰ [Barger, 1996]; and 5 measurements from the perennial reaches of Cienega Creek, 12 to 14‰. In all flood-plain groundwaters except those from Cienega Creek, the range of  $\delta^{34}\text{S}$  is 2 to 7‰. The  $\delta^{34}\text{S}$  and  $\delta^{18}\text{O}_{\text{water}}$  data for flood-plain groundwater and Cienega Creek surface water, plotted in Figure 8, fall into distinctive fields that will be used below in the interpretation of other groundwater of the basin. The empty field marked by the ellipse in Figure 8 corresponds to groundwater compositions not represented in the flood plains. The differences in  $\delta^{34}\text{S}$  between drainages indicate that rock sulfur sources, not sulfate from precipitation, govern the  $\delta^{34}\text{S}$  values of surface water in the field area.

#### Carbon-14

The  $^{14}\text{C}$  contents of surface water samples are plotted relative to atmospheric  $^{14}\text{C}$  in Figure 6. Values ranged from atmospheric (>100 pMC) to 85 pMC, and may change rapidly following rain events. Samples from a single runoff event (August 31, 2000, following rain the previous day)

gave values of 89 pMC in Sabino Creek, and 107 pMC in Tanque Verde Creek near the range front. The flood-plain groundwaters plotted in Figure 6 all have >3 TU, and, with one exception, fall at or below atmospheric  $^{14}\text{C}$  values. The exception, 115 pMC, is from site 374 in the Tanque Verde flood plain, and consists of water that effervesces  $\text{CO}_2$  as a result of mesquite root respiration. On the evidence of the data for surface water, samples with as little as 85 pMC (and possibly lower) are ambiguous: they may be recently recharged rain water, pre-bomb rainwater, or a mixture of pre- and post-bomb waters. Where no tritium is present, pre-bomb water is indicated.

### CENTRAL BASIN GROUNDWATER: LARGE-SCALE ISOTOPE DISTRIBUTION PATTERNS

We now focus on groundwater beyond the flood plains. In this section we present four detailed maps of environmental isotope distribution in the central part of the basin: for  $\delta^{18}\text{O}$ ,  $\delta^{34}\text{S}$ ,  $^3\text{H}$  and  $^{14}\text{C}$ . The  $\delta\text{D}$  map recapitulates the  $\delta^{18}\text{O}$  map, and is not presented. Each of the maps shows features at basin (5 to 10 km) scale. In this section we outline the basin-scale features and their implications for origin and age of water. Smaller-scale variations can also be observed on the maps, and some of these will be considered in the following section.

#### $\delta^{18}\text{O}$

Plate 1A shows a basin-wide boundary between  $\delta^{18}\text{O}$  values predominantly >−8‰ to the northeast (surrounding areas of high elevation), and <−9‰ to the southwest. Groundwater northeast of the boundary derives dominantly from mountain precipitation; southeast of the boundary it

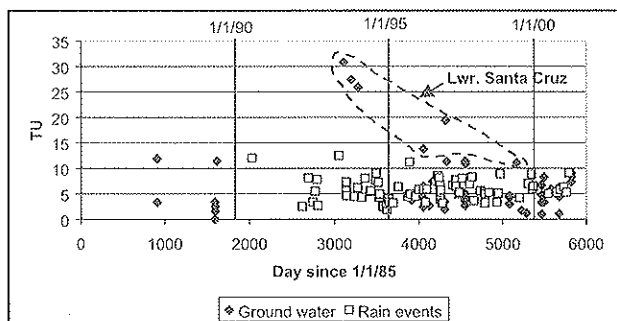


**Figure 10.** Comparison of tritium content of individual rain events and flood-plain groundwater samples. The group of wells marked "Lower Santa Cruz" is from the Santa Cruz flood plain north of downtown Tucson.

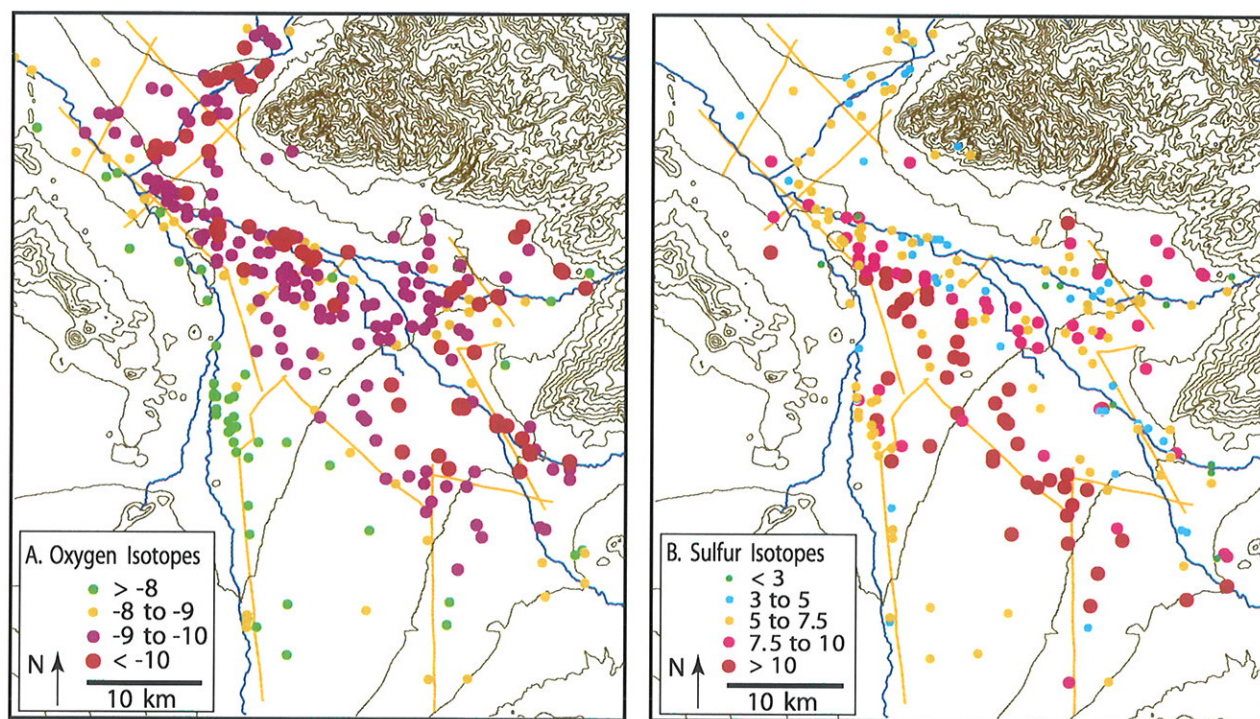


**Plate 1.** A. Map of Tucson basin showing  $\delta^{18}\text{O}$  values of groundwater. B. Map of Tucson basin showing  $\delta^{34}\text{S}$  values of groundwater. Orange linear features are major faults.

derives principally from basin precipitation. The zone with  $\delta^{18}\text{O} < -9\text{‰}$  encloses washes draining high elevations, but extends far beyond them and is not clearly related to them. A secondary feature, with  $\delta^{18}\text{O} < -10\text{‰}$ , lies within that zone, adjacent to the terminus of Rincon Creek. Two small zones with  $\delta^{18}\text{O}$  between  $-9$  and  $-8\text{‰}$  occur south of Rillito Creek near Pantano Wash (possibly representing recharge from small runoff events in Sabino Creek), and east of downtown Tucson.

### $\delta^{34}\text{S}$

The  $\delta^{34}\text{S}$  map of groundwater (Plate 1B) shows a basin-scale feature with  $\delta^{34}\text{S} > 10\text{‰}$ , its axis parallel to the predominant flow direction (cf. Figure 1B), extending from the southeast corner of the basin toward the Santa Cruz-Rillito confluence. Groundwater in the area surrounding the feature has  $\delta^{34}\text{S}$  values between 3 and 10‰. The ultimate source of dissolved sulfate with  $\delta^{34}\text{S} > 10\text{‰}$  is Permian marine gypsum, which crops out in mountain ranges south and east of Tucson basin and has been reworked into lacustrine evaporitic gypsum interbedded with alluvium in the southeastern part of the basin.

### Tritium

Outside the limits of active flood plains, a threshold of 1.5 TU serves to distinguish basin-scale features (Plate 2A); the implications of a scatter of samples with very low tritium levels within the zones of  $<1.5$  TU will be discussed below. Five zones with tritium  $>1.5$  TU are distinguished: 1. south of Rillito Creek, extending 2–3 km from the active flood plain except near the Santa Cruz-Rillito confluence; 2. south of Tanque Verde Creek, extending 2–3 km southwest from the flood plain toward Pantano Wash; 3. east of the Santa Cruz River in the southern half of the study area, extending 1–2 km from the flood plain; 4. at the confluence of Pantano Wash and Rincon Creek; and 5. a thin band of samples in the basin center. The first four zones indicate areas where natural flow of groundwater has introduced bomb-pulse or younger tritium to the upper parts of the basin from the adjacent flood plain. The fifth zone does not correspond with a major wash, although a storm-water drainage channel with a large retention basin is present at the upgradient (southeast) end. This zone coincides with the two addresses of the American Atomic factories during the 1970s, and is most likely a plume of tritium contamination, introduced either from the retention basin (which would have collected runoff from the southern factory site) or through the 50–65 m vadose zone beneath the factories.

The zone of recent recharge south of Rillito Creek (Figure 11) lies beneath the Jaynes and Cemetery river terraces (Figure 2), occupying the entire width of the terraces at the eastern end, but tapering westward to intersect Rillito Creek near site 175, at the point where static water level contours indicate the change from south to north in the direction of recharge from Rillito Creek (Figure 1B). In 1991, the leading edge of the tritiated water coincided with the base of the trough in static water-level, as shown in cross section X–X' (Figure 12). In 1996 and 1998, we re-sampled several sites straddling the tritium boundary and found that sites 29, 30 and 175 had changed from undetectable tritium to  $>1.5$  TU (Figure 11). The boundary appears to be moving slowly westward, filling the permeable river terrace sediments, but not yet penetrating south of these terraces.

### Carbon-14

Samples with  $<40$  pMC appear to be the oldest accessible water in the basin. Two linear zones with pMC  $<40$  are parallel to the Santa Cruz river, and approximate the trace of the Santa Cruz normal fault. Water as old as 6,000 years on the basis of NETPATH modeling [Kalin and Long, 1994] is present in such areas. Other instances are at sites 251, 253 and 254, also associated with a normal fault. These features are evidence for upward movement of old, deep basin groundwater into the upper part of the regional aquifer, and into the perched aquifer adjacent to the Santa Cruz river (sites 45, 151, 152). Zones of high-sulfate water parallel to the Santa Cruz river were cited as evidence for upward movement of water along the fault [Laney, 1972]. Aside from these linear zones, groundwater in the central part of the basin shows a general zonation of  $^{14}\text{C}$  content, the lowest values occurring in the parts remotest from major washes.

Only 8 of 117  $^{14}\text{C}$  data points have  $<30$  pMC, and of these, 7 are associated with normal faults. The accessible parts of the regional aquifer unaffected by upwelling therefore contain water less than 10,000 years old (most likely much less, even in the oldest instances), with evidence of older water below. No Pleistocene water appears to be present in the upper 300 m of sediment. The upper part of the aquifer has been efficiently flushed during the Holocene.

Kalin (1994) modeled flow times between streams and selected wells using NETPATH. Flow-paths that are plausible in light of the understanding gained from the current data set include stream (Tanque Verde creek in each case) to site 93 (285 years); stream to site 86 (231 years); stream to site 27 (1043 years); site 87 to site 16 (4617 years); site 90 to site 27 (1045 years), site 87 to site 27 (638 years). Site numbers are shown in Figure 3, and the paths cited span the

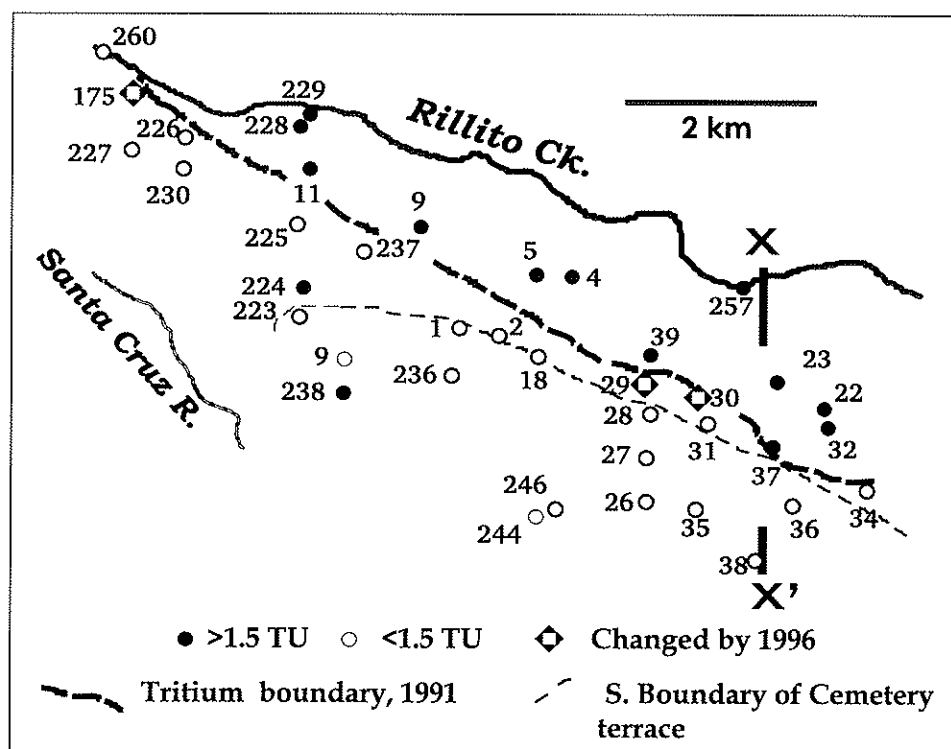


**Figure 11.** Map of tritium distribution in the Jaynes and Cemetery terraces south of Rillito Creek. Sites marked "changed" increased from  $< 1.5$  TU to  $> 1.5$  TU between 1991 and 1998. Sample sites numbers correspond to the data table. Most sites were sampled in 1991; sites numbered  $> 200$  were sampled in 1998.

basin from the northeast to the center. The flow times are consistent with efficient flushing as suggested above.

#### *Groundwater Origin and Flow Paths*

Each isotope system considered above contributes to the identification of a set of basin-scale groundwater features (Figure 13A). The existence of basin-scale features is consistent with predominant recharge from basin-scale sources, e.g. the major washes. The combined  $\delta^{18}\text{O}$  and  $\delta^{34}\text{S}$  data reveal a set of six groundwater domains (Figure 13B), each differing from adjacent domains in at least one of the two parameters. The domains can be compared with the character of adjacent flood-plain groundwater (Figure 8). Domain A ( $\delta^{18}\text{O} < -9\text{‰}$ ,  $\delta^{34}\text{S} < 10\text{‰}$ ) corresponds isotopically to Rillito and Tanque Verde Creeks. Domain B ( $\delta^{18}\text{O} > -8\text{‰}$ ,  $\delta^{34}\text{S} < 10\text{‰}$ ) corresponds to the Santa Cruz River, and the eastern domain boundary is present also in the tritium and carbon-14 maps. Domain B may also extend as far north as downtown Tucson; this would account for the high  $\delta^{18}\text{O}$  ( $> -9\text{‰}$ ) and finite tritium values at sites 238, 242 and 246. Domain C ( $\delta^{18}\text{O} > -8\text{‰}$ ,  $\delta^{34}\text{S} > 10\text{‰}$ ) corresponds to

Cienega Creek. Domain D ( $\delta^{18}\text{O} < -9\text{‰}$ ,  $\delta^{34}\text{S} > 10\text{‰}$ ) does not correspond to any known surface water; it is represented by the empty field in Figure 8. Domain E ( $\delta^{18}\text{O} < -10\text{‰}$ ,  $\delta^{34}\text{S} < 10\text{‰}$ ) corresponds to Rincon Creek. Domain F ( $\delta^{18}\text{O} > -9\text{‰}$ ,  $\delta^{34}\text{S} < 7.5\text{‰}$ ) is distinguished mainly by low pMC values, and may not be distinct from domain B. Figure 13B therefore shows which parts of the aquifer are supplied from each of the major drainages entering the basin.

The spatial associations between domains and drainages are straightforward except for domains C and D. Domain D contains mountain-derived water ( $\delta^{18}\text{O} < -9\text{‰}$ ), but has  $\delta^{34}\text{S}$  values like those of Cienega Creek water. No water with  $\delta^{18}\text{O} < -9\text{‰}$  has been observed in Cienega Creek base-flow; therefore the domain D water appears to have derived from the Rincon Mountains and to be flowing upwards at the southeastern extremity of the domain. The sulfate  $\delta^{34}\text{S}$  values are best explained as deriving from lacustrine gypsum which may exist in the subsurface in that area, an interpretation consistent with high sulfate content in water in this area [Laney, 1972]. Surface water from the Rincon Mountains is at present flowing into a small karst east of the study area; this is a potential source for Domain D water.

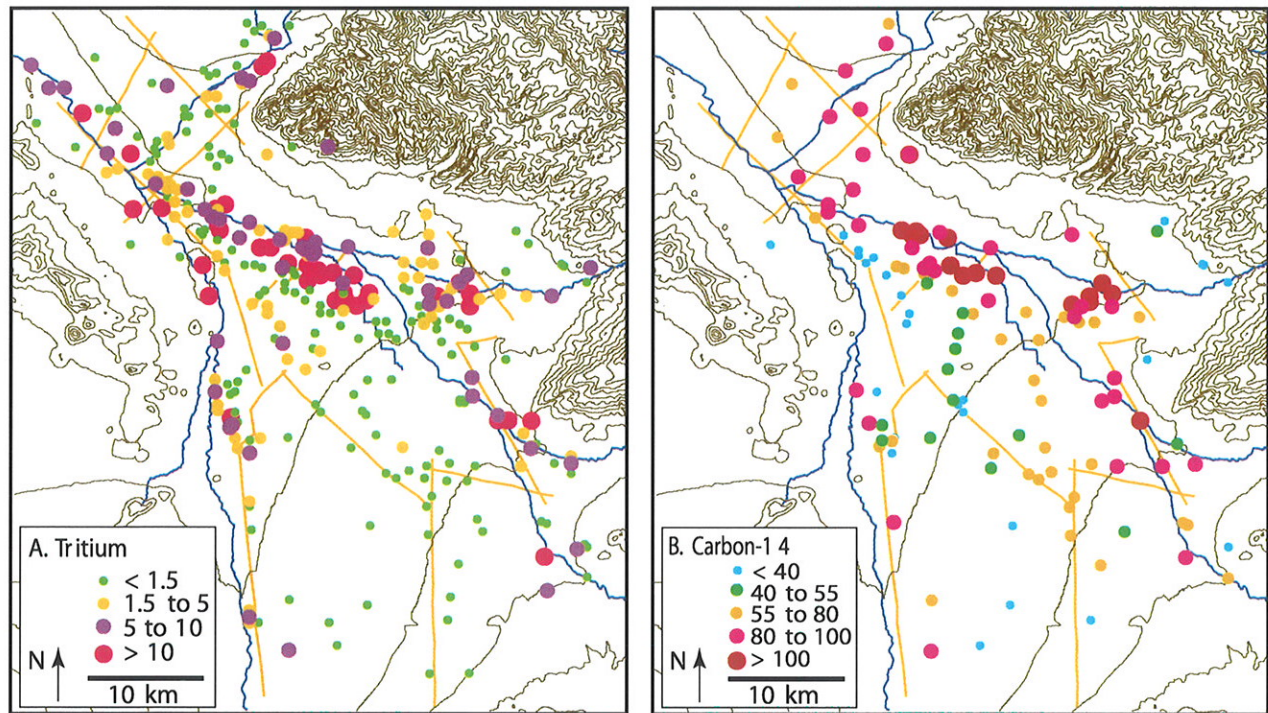


**Plate 2.** A. Map of Tucson basin showing tritium content of groundwater. B. Map of Tucson basin showing  $^{14}\text{C}$  content of groundwater in percent modern carbon (pMC). Orange linear features are major faults.

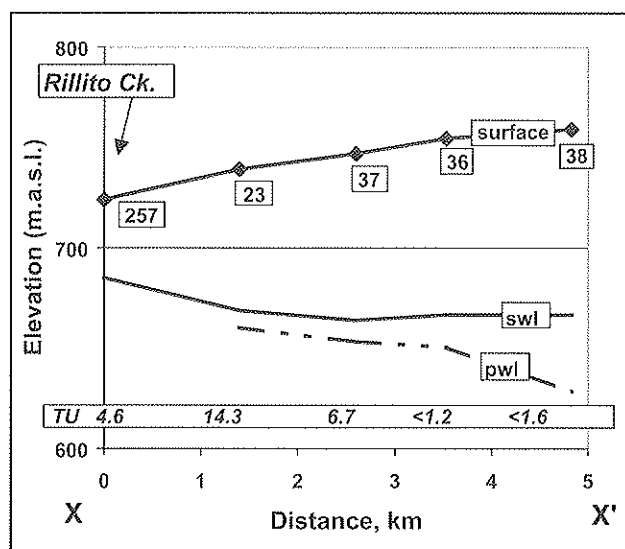


**Figure 12.** Vertical cross section X–X' (Figure 22) showing static water levels and tritium content of groundwater. Swl = static water-level, and pwl = pumping water-level. Site numbers are given in boxes.

Domain C groundwater follows an old course of Cienega creek across alluvial fan B (Figure 2), and clearly does not follow the present surface-water course, upper Pantano Wash. Domain D appears to interrupt the two areas of Domain C. Given the sampling density in this area, it is possible that the connection between the two areas was missed.

However, it is also possible that no connection exists at present, that domain D water has displaced domain C water, and that water from Cienega Creek is finding a new flow path.

Our data set gives no indication of whether groundwater from Rincon Creek currently follows present surface drainage (Pantano Wash between Rincon and Rillito Creeks). The distribution of  $^{14}\text{C}$  in Domain E (compare Plate 2B and Figure 13B) suggests that groundwater from Rincon Creek has, at least in the past, flowed west of Pantano Wash, a path inconsistent with present water surface contours modified by pumping (Figure 1B).

#### *Flow From Flood Plains to Adjacent Sediment*

Figure 14 indicates that groundwater in broad areas of the central basin derives from major drainages. Recharge of surface water into flood-plain alluvium occurs rapidly and visibly after precipitation events. Subsequent flow from flood-plain sediment into adjacent, more consolidated sediment undoubtedly occurs from every flood plain in the basin to some extent, but is concentrated in certain reaches, as indicated by the spatial age distribution of groundwater. The tritium and  $^{14}\text{C}$  maps show that the age of groundwater adjacent to flood plains varies greatly from place to place. Three cases can be distinguished where sufficient data exist (Figure 14): 1. Post-bomb water present (finite tritium, pMC >100); 2. Younger pre-bomb water

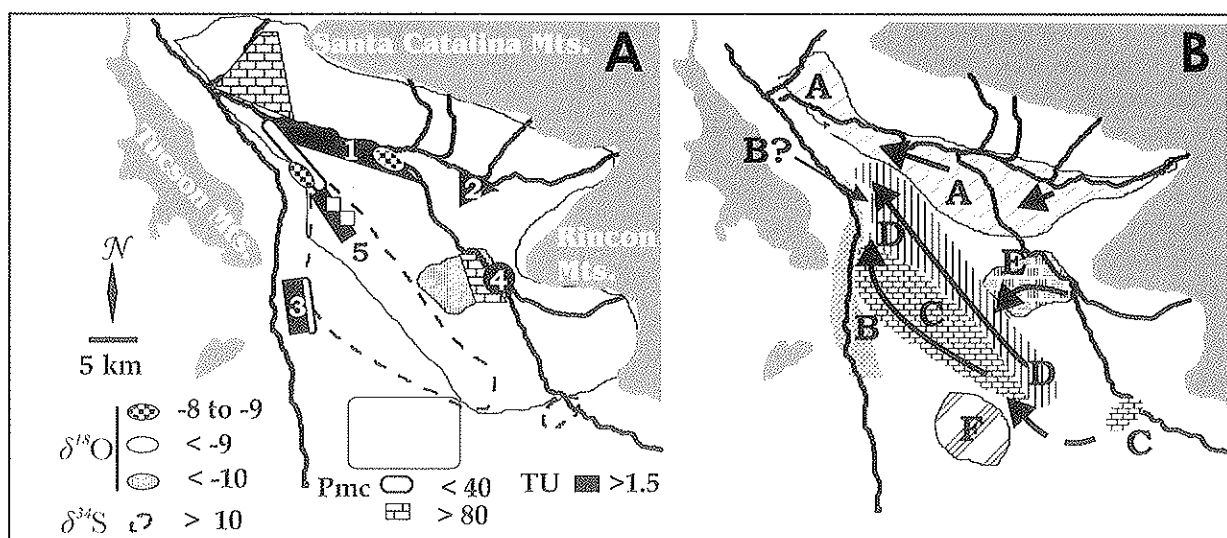


**Figure 13.** A. Map of Tucson Basin showing basin-scale isotope features from Plates 1 and 2. Areas with > 1.5 TU are numbered to match the text. B. Map of Tucson basin showing groundwater isotope domains and flow directions. Domain designations are explained in the text.

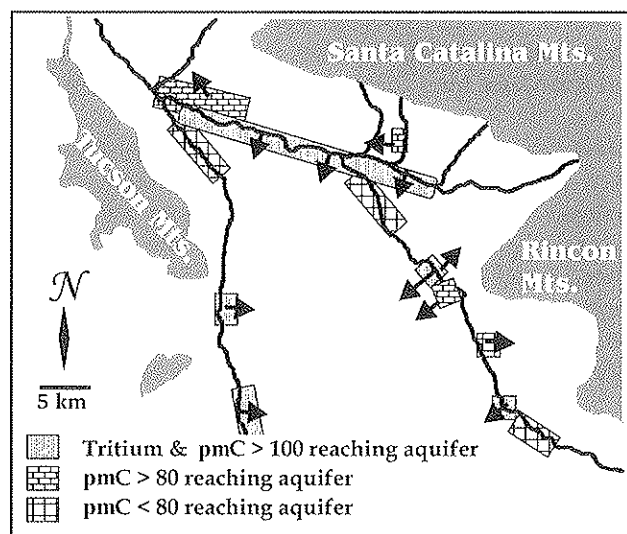


**Figure 14.** Map of Tucson basin showing age of groundwater adjacent to major Tucson basin drainages. Each rectangle encloses the interval of wash to which the age estimate applies. No estimate is available where there is no rectangle.

present ( $> 80$  pMC, no tritium); 3. Older pre-bomb water with  $< 80$  pMC present. A much greater density of tritium and  $^{14}\text{C}$  data adjacent to the major washes would be necessary to provide more detail.

#### SMALL-SCALE RECHARGE

Recharge at small spatial scale (less than the 5–10 km features described above) almost certainly occurs from small drainages or between them, but its importance relative to basin-scale recharge is unclear. Evidence for small-scale recharge may be found in the scatter of data inconsistent with certain basin-scale isotopic features. It is possible to evaluate the relative importance of basin-scale and small-scale recharge sources in the following cases: 1. In the basin-scale feature with values of  $\delta^{18}\text{O}$  less than  $-9\text{‰}$ , local, small-scale recharge could add water derived from basin-level precipitation with a time-integrated  $\delta^{18}\text{O}$  value between  $-7$  and  $-8\text{‰}$ . 2. In the basin-scale feature with tritium below detection, small-scale recharge in the last 40–50 years could add detectable tritium.

Figure 15A shows the frequency distribution of  $\delta^{18}\text{O}$  in a set of 85 sites. Excluded are flood-plain samples and samples defining the features with  $\delta^{18}\text{O} > -9\text{‰}$  (Plate 1A). As explained above, a few  $\delta^{18}\text{O}$  measurements may be  $0.5\text{‰}$  too positive; these are distinguished in Figure 15A. Nonetheless, the distribution remains bimodal, with at least 10 sites composing the minor peak. About half the sites are

in the area between Tanque Verde Creek and Pantano Wash (Plate 1A), where groundwater is less than 30 m below the surface (Figure 5). The minor mode ( $-8.5\text{‰}$ ) corresponds with mixing of sub-equal proportions of the major mode ( $-9.5\text{‰}$ ) with integrated basin-level precipitation ( $-7.4\text{‰}$ ), including both summer and winter rain.

The tritium data are more difficult to represent as a histogram because measurements are close to the detection limit, which has changed over time. For low-counting samples, it is customary to distinguish finite values ( $>95\%$  probability of being distinct from zero) and apparent values (67–95% probability). Of 37 sample sites defining the basin-scale feature; 7 have finite tritium, and 6 have apparent tritium (Figure 15B). Only two samples with 1.8 TU approach

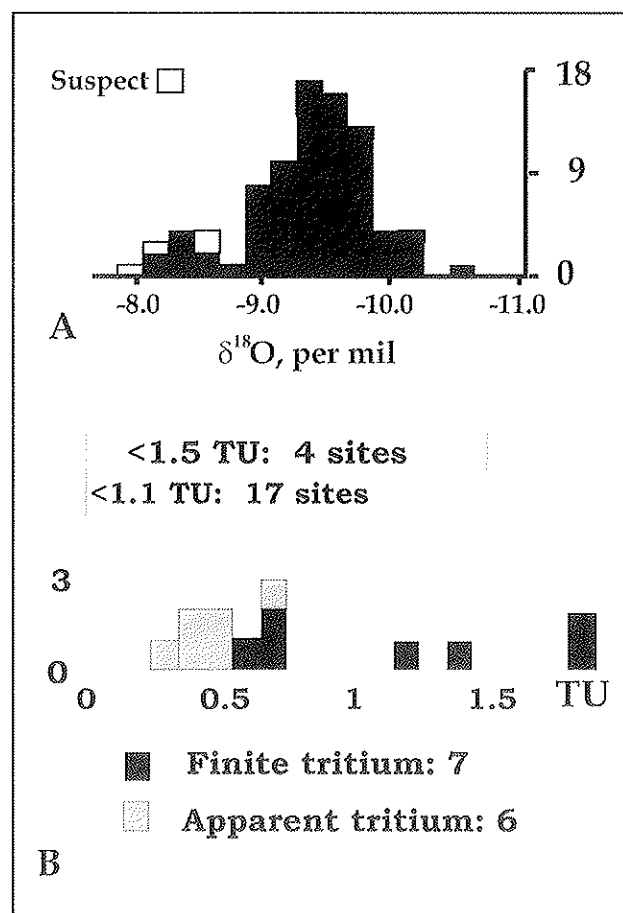


**Figure 15.** A. Frequency histogram of  $\delta^{18}\text{O}$  values of groundwater in the basin-scale feature with  $\delta^{18}\text{O} < -9\text{‰}$ . Data marked “suspect” are 1989 measurements thought to be approximately  $0.5\text{‰}$  too high. B. Frequency histogram of tritium data from the basin-scale feature with  $<1.5$  TU. “Apparent” and “finite” data are explained in the text.

the 2.5 TU that would result from rapid mixing ( $< 1$  half-life) of equal proportions of 5 TU rainwater with 0 TU groundwater. The degree of mixing indicated by the remaining samples is much lower ( $< 20\%$  5 TU rainwater; less for rainwater containing bomb tritium). If the  $\delta^{18}\text{O}$  data indicate the prevalence of 50-50 mixing, then the tritium data imply that such mixing has occurred over many half-lives.

## DISCUSSION

### *Relative Importance of Large- and Small-scale Sources of Recharge*

The water in the upper 140 m of the regional aquifer originates predominantly from large areas of recharge such as major washes and major fracture systems conveying water from the basin depths. In domains where mountain-derived water predominates, basin-level precipitation is also available for recharge, yet  $\delta^{18}\text{O}$  data indicate its presence in only 12% of the group of 85 wells. Many of the affected wells are in an area with groundwater within 30 m of the surface, in contrast to the rest of the basin where groundwater is usually about 100 m below the surface. This observation suggests the possibility that small-scale recharge of basin-level precipitation is more common than shown by this study in areas with deeper groundwater. There, the recharge may be too slow to keep pace with the decline of the water table (as much as 60 m in 55 years), and water resulting in part from past small-scale recharge may already have been pumped away.

### *Dynamics and Anthropogenic Effects*

The long interval of sampling in this study has permitted us to identify one case in which an isotope boundary is moving: the tritium front in the Jaynes and Cemetery terraces (Figure 11). The rate of movement of the boundary is difficult to measure given the spacing of sample points, but may be 10 to 20 m per year. The relationship of the boundary to the trough in static water levels (Figure 1B) poses the question: does the movement of post-bomb water into this area represent a local change in groundwater flow direction as a result of pumping-induced depression of the water table? We do not have enough  $^{14}\text{C}$  data on the west side of the boundary to indicate whether recharge yielding  $> 80$  pMC and undetectable tritium was occurring prior to bomb effects; the two sites available (224 with 30.5 pMC, 230 with 24.6 pMC) appear to belong to a different, linear isotope feature as explained above. We can conclude that pre-bomb recharge in the area was insufficient to mask this fea-

ture. The groundwater flow field is such that there is upward movement of water along the linear feature and limited westward movement of groundwater originating in Rillito Creek, both pre- and post-bomb. About 5 km east of the confluence of Rillito Creek and the Santa Cruz River, the trough in the water table crosses to the north of Rillito Creek (Figure 1B); pre-bomb recharge occurred on the north side and almost certainly pre-dates the effects of pumping.

Upward movement of deep basin groundwater water has been suggested in two linear isotope features (Plate 2B) and at the origin of domain D (Figure 13B). Could such movement also be caused by pumping-related disturbance of the aquifer? In the case of the linear features it is not possible to tell from the available isotope data. In the case of domain D, pMC values range from 79 pMC near the point of origin to 40–50 pMC at the northwest limit of the domain, suggesting that domain D has existed for at least several hundred years. This observation, and the lack of severe pumping-related disturbance of the aquifer near the point of origin, suggest that the upward supply of domain D water pre-dates pumping.

### *Practical Implications for Tucson Basin*

Most of Tucson's municipal wells in the central part of the basin yield water with tritium below detection, and water levels have declined 30 to 60 m since 1940. Groundwater levels are declining even where tritiated water is present near Rillito Creek. Viewed at a time scale of decades (the time scale of city growth), natural replenishment is therefore relatively slow compared with water consumption even where the tritium data indicate that surface water has moved into the regional aquifer since the 1950s.

Does all of the water recharging flood-plain alluvium reach the regional aquifer, or does some, perhaps most, leave the basin laterally through perched aquifers in the flood-plain alluvium? Few sample sites are located in stream beds. Transient perched aquifers form in response to rainfall in Rillito Creek [R. Marra, Tucson Water, pers. comm.]. In this study, we observed a permanent perched aquifer at about 10 m depth at site 278 (Pantano Wash at Rincon Creek. In both areas, tritiated water is reaching the regional aquifer, but the data do not preclude lateral water movement.

Artificial recharge by way of infiltration through the beds of the major washes has been proposed as a method of recharging the regional aquifer. Water placed in flood plains will rapidly recharge the flood plain alluvium, and part might move laterally to flood plains downstream. Our tritium and  $^{14}\text{C}$  data imply that the flow of water into adjacent

sediment will vary greatly from place to place. The best replenishment could be achieved south of Tanque Verde and Rillito Creeks, and east of the Santa Cruz River in the southern part of the basin. All of these reaches except Tanque Verde Creek are compromised by industrial pollution or landfills.

#### *Implications for Recharge Studies in Other Basins*

As noted above, the accessible parts of the regional aquifer in Tucson basin are well-flushed with minimally evaporated water up to a few thousand years old. Flow events in the major drainages appear to contribute most of the recharge, which is strongly localized. All of the drainages rise in areas with higher annual rainfall than Tucson basin, either in the adjacent high mountains or in the uplands near the Arizona-Mexico border. Another relevant factor is the predominance of sand or coarser sediment in the upper levels of the basin (Anderson, 1987). Other semi-arid basins in the southwest USA that are supplied with surface water from areas with higher rainfall might be expected to recharge in similar fashion. Basins or parts of basins with little surface water supply during the Holocene provide the contrasting case. Basin floor precipitation is the predominant source of recharge, which will be broadly distributed rather than localized, and small in quantity. Such basins will contain relatively old water. Where clay predominates at the surface, recharge will be slow and surface evaporation high.

Every basin is unique, and isotopic techniques that are effective in one may not be useful in another. Where altitude differences or evaporative effects are relevant, O and H isotopes provide a rapid and cost-effective first evaluation. S isotopes are now also an inexpensive tool. They are effective in Tucson because of the isotopic contrast between Permian marine and other local sources of sulfate. S isotopes are less likely to be effective where local rock-types provide no contrasting sulfur sources, unless bacterial reduction (not important in Tucson basin) is present. Tritium and radiocarbon are slower and more expensive measurements, best used after a first evaluation. Both are effective in well-flushed basin, while radiocarbon is more useful in other cases.

#### *Limitations of This Study*

Commonly in earth science investigations, the higher the density of sampling, the greater is the degree of complexity revealed. The number of sample sites available from this study is unusually large. Nonetheless, certain complex

water interactions remain poorly resolved. This is true particularly in the area immediately southwest of the confluence of Rillito Creek and the Santa Cruz River, where, groundwater converges laterally from domains A, D and probably B, and upwards along the Santa Cruz fault. A higher sampling density (unavailable) and consideration of water chemistry in conjunction with isotopes (to be presented in a separate article) could help resolve the details of water movement.

Another consideration of interest in the context of recharge is the identification of water replenishing the basin aquifer through fractures in the mountain block (as distinct from recharge of mountain-derived water at low elevations through major stream channels, as is indicated by our data set). The present data set gives no basis for distinguishing the two pathways, or estimating their relative importance.

### CONCLUSIONS

1. Multiple isotopic parameters in combination with a large set of sample sites enable us to map detailed features of the aquifer. In the central part of the basin, distinct groundwater domains exist, and can be associated with large-scale sources of recharge from drainages, or with water moving upward in major fracture systems. Present flow paths of groundwater are strongly influenced by Pleistocene geomorphology.
2. Smaller, local sources of infiltration have been detected, but are of secondary importance in supplying water to the regional aquifer.
3. Winter precipitation dominates basin recharge, and evaporation during recharge is minimal.
4. O and H isotopes in flood-plain groundwater reflect mountain precipitation in Rillito Creek and tributaries draining high-altitude areas, and basin-level precipitation in the Santa Cruz River and Cienega Creek which have dominantly low-elevation catchments. Mountain precipitation is the source of groundwater beneath most of the urban area.
5. Runoff from small precipitation events preferentially recharges the Tanque Verde flood plain closer to the mountain front than runoff from large events.
6. Bomb tritium had "rained out" of Tucson precipitation by 1991. Rain since 1991 contains 4.7 to 6.7 TU, the level increasing slowly with time. Contamination from

the American Atomics factory augmented bomb tritium in Tucson basin in the 1970s. Tritium in flood-plain groundwater is largely consistent with tritium levels in contemporaneous precipitation.

7. Groundwater flow from flood-plain alluvium to the regional aquifer varies greatly from reach to reach of the major drainages.
8. Urban air in Tucson still contains bomb  $^{14}\text{C}$ , which had decreased to 107 pMC by 2002. Rural air is 0–2 pMC more enriched. Surface water reaching the basin at present contains 85–107 pMC.
9. Artificial recharge would be efficient in flood-plains; from flood plains into adjacent basin sediment the process would be less effective, and feasible only in limited areas not compromised by the presence of landfills or other contaminant sources.

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