TRITIUM AS A TRACER OF GROUNDWATER SOURCES AND MOVEMENT IN THE SAFFORD BASIN, GRAHAM COUNTY, ARIZONA

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INTRODUCTION

The Arizona Geological Survey (AZGS) performed a study to measure the tritium content of waters form various sources in the Safford Basin, part the upper Gila River watershed. The concentration of the naturally occurring radioactive isotope of hydrogen, known as tritium, was measured to determine the "age" of groundwater from different sources. The project area is shown on Figure 1.

Water balance calculations and aquifer tests suggest upwelling of groundwater from the deep basin-fill aquifer into the shallow alluvial aquifer of the Gila floodplain (Hanson and Brown, 1972; Brown, 1989). Based on the widespread occurrence of evaporites in the Safford basin fill (Harris, 1997) and the isotopic compositions of evaporites, deep well water, and river water (Harris, 1999a), natural water sources such as artesian leakage and springs may be an important source of TDS in the Gila River. If this is the case, attempts to mitigate water quality problems in the Gila River by focusing on specific human activities, such as agriculture, may be misdirected.

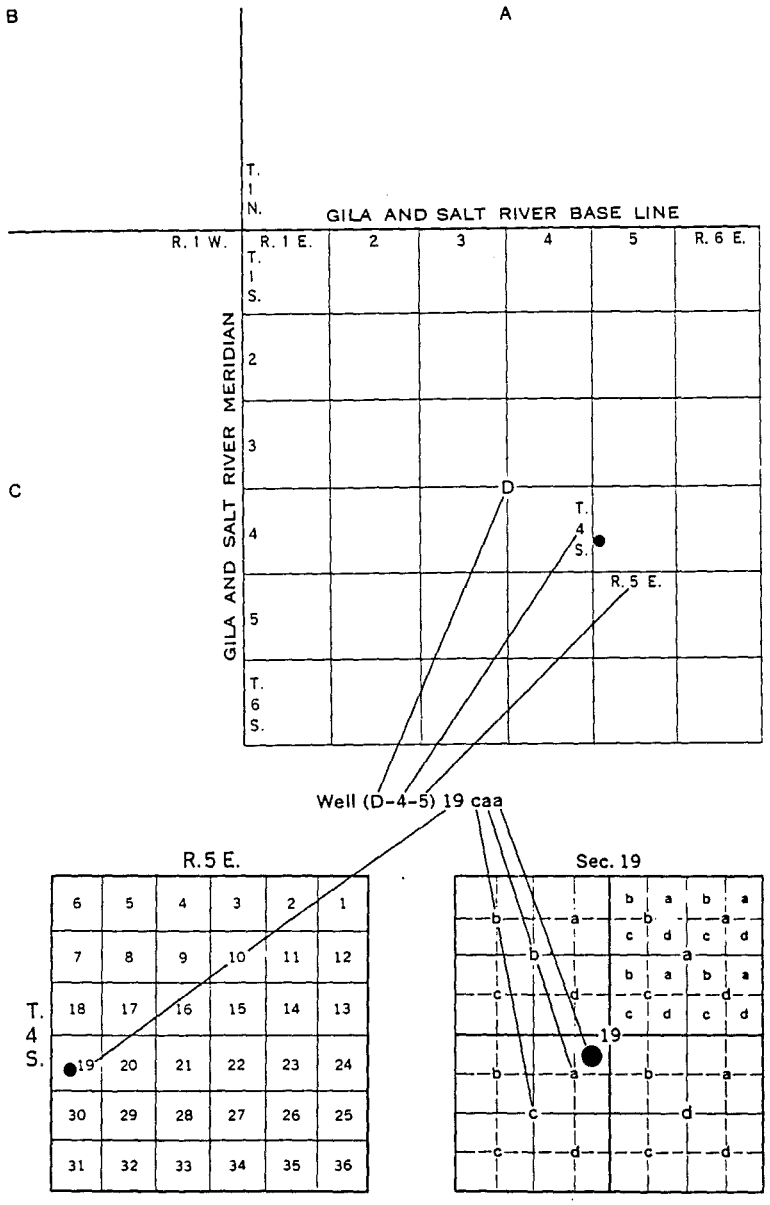
The purpose of the pilot study is to assess the utility of the tritium technique as applied to determining the degree of mixing between "old", deep groundwater in contact with highly soluble salts in the basin-fill sediments, and "young", shallow groundwater that constitutes a mixture of subflow from tributaries, infiltration of Gila River water, and possible infiltration of irrigation water. This study will help water management agencies make informed decisions regarding issues of water quality in the Gila River and how to apply appropriate mitigation measures regarding salinity.

GEOLOGY AND HYDROLOGY OF THE STUDY AREA

Geology

The study area focuses on that part of the Safford basin from where the Gila River enters the basin, near San Jose, to the San Carlos Indian Reservation (Figure 1). The Safford basin is a deep, sediment-filled structural trough containing abundant lacustrine (lake) and playa sediments, reflecting long periods of interior drainage. Gravity models indicate that the Safford basin is up to 12,000 feet deep (Oppenheimer and Sumner, 1980; 1981). Soluble minerals such as halite (salt), carbonates, gypsum, and anhydrite are common in the basin-fill sediments (Marlowe, 1961; Harbour, 1966; Harris, 1997). These minerals commonly form by evaporation of water and deposits formed in this way are called evaporites. Evaporites in the Safford area have been studied and described in *Pay Dirt* (1984), and by Peirce (1969; 1981; 1984), Koester (1971), and Eaton and others (1972).

Figure 1. Location of study area



The well numbers used by the U.S. Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants and are designated by capital letters A, B, C, and D in a counterclockwise direction beginning in the northeast quarter. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

Figure 2. Well numbering system used in Arizona.

Typical Basin-and-Range basins were formed in the late Tertiary, 12-6 million years ago (Ma), when high-angle normal faulting dropped central blocks between uplifted bounding blocks, forming a more or less symmetrical, deep structural basin. The Safford basin, however, was formed earlier than Basin and Range time by low-angle faulting resulting from crustal extension. Detachment faulting during the mid-Tertiary (30-20 Ma) extension formed the metamorphic core complex of the Pinaleño Mountains and the tilted structural basin of the Safford Valley (Spencer and Reynolds, 1989; Kruger and others, 1995). Later Basin and Range faulting did not affect the Safford region to the extent that it did other areas of the southwest.

Seismic reflection profiling (Kruger, 1991; Kruger and Johnson, 1994; Kruger and others, 1995) has revealed the Safford basin to be a tilted half-graben, with the southwest side of the basin down-faulted along a high-angle fault that is younger than the main basin-forming detachment. As detachment faulting progressed, the basin grew deeper and wider and filled with sediment as the rocks above the fault were displaced away from what is now Mt. Graham. Sediments were tilted as extension continued, with older sediments tilted more than younger deposits. This style of faulting has produced an asymmetrical structural trough filled with sedimentary deposits that are wedge shaped in cross section.

Early models of the Safford basin, such as those by Schwennesen (1919), Knechtel (1936), and Harbour (1960; 1966) treated it as a standard, symmetrical Basin and Range type basin, with essentially flat stratigraphy. Attempts at correlation of units generally assumed that equivalent layers should be at approximately the same elevation throughout the valley. Sediments in the Safford Valley were divided into an 'upper basin fill' and 'lower basin fill' by Harbour (1966). The boundary between the lower and upper basin fill was considered by Harbour to reflect a major climate change at the Pliocene-Pleistocene boundary.

More recent work has revealed a more complex stratigraphy in the Safford-San Simon basin. With a half-graben structure, equivalent layers are deeper and thicker to the southwest, and the difference in elevation between the southwest and northeast parts of equivalent layers is greater with increasing age because the southwestern part of the basin has subsided more since the sediments were deposited. The lateral and vertical changes in the basin-fill sediments reflect a combination of factors, including long- and short-term climate changes, different subsidence rates in different parts of the basins, changing sediment sources as erosion exposed older rocks, and sporadic inflow of water and sediment from outside the immediate basins.

Houser (1990) divided the main Safford-San Simon basin into four depositional sub-basins. From north to south, these are the San Carlos, Bylas, 111 Ranch, and San Simon sub-basins. Four basin-fill units have been recognized in the 111 Ranch sub-basin of the Safford-San Simon basin (Richter and others, 1983; Houser and others, 1985; Houser, 1990). The oldest unit, the Miocene-Pliocene Midnight Canyon conglomerate, is a proximal fan deposit containing only clasts of volcanic rock. The Midnight Canyon unit is inferred to extend across the Safford basin (Houser, 1990) and is equivalent to the basal conglomerate facies of the lower basin fill unit of Harbour (1966). Conformably overlying the Midnight Canyon conglomerate is the Pliocene Sanchez unit, consisting of silt and conglomerate. The Sanchez beds cover the same area and have the

same clast composition as the Midnight Canyon unit, but are finer grained and less cemented. In the center of the Safford basin, the Sanchez beds are 250 m thick and consist of clay, gypsum (or anhydrite), and salt (Houser, 1990). The beds thin and pinch out toward the northeast side of the basin. Above the Sanchez beds are the Pliocene 111 Ranch beds, which include lacustrine (lake) and fluvial (river) facies. The fine-grained lacustrine facies of the unit consists of silt, clay, limestone, marl, and diatomite. The type section of lacustrine sediments at 111 Ranch, 15 miles southeast of Safford, has been studied extensively (Van Horn, 1957; Clay, 1960; Seff, 1962; Galusha and others, 1984). The fine- to coarse-grained fluvial facies, representing a fan delta from Bonita Creek, interfingers with the lacustrine facies. The 111 Ranch beds attain a thickness of about 520 m near the center of the basin and thin toward the Gila Mountains (Houser and others, 1985; Houser, 1990). The Bear Springs Wash beds interfinger with the 111 Ranch and Sanchez beds in the southwest part of the Safford basin (Houser and others, 1985). This unit consists of fine-grained lacustrine sediments similar to the 111 Ranch beds interbedded with coarse-grained alluvial fan deposits.

Above the Sanchez, 111 Ranch, and Bear Springs Wash beds is Pliocene-Pleistocene alluvium of the ancestral Gila River. Thickness ranges from 85 feet at Safford to 30 feet at Geronimo (Black, 1991). The alluvium is similar to modern Gila River sediments, with clasts of volcanic rocks, quartzite, granite, and chalcedony (Houser and others, 1985). Capping the section is a layer of Quaternary alluvium. Along the Gila River are modern alluvial sediments of the flood plain.

Hydrology

At the time of deposition of the basin-fill sediments and evaporites in the Safford basin, an integrated drainage did not yet exist in southeastern Arizona. Drainage in most of the deep basins of Arizona, and in most of the Basin and Range Province, was internal during much of their history, except for periods when the regional climate was much wetter and some of the usually internally drained basins may have overflowed into adjacent basins.

Integration of the drainages of southeastern Arizona into a large regional system of the Gila River is geologically recent. Drainage in the lower San Pedro basin was apparently still largely, if not completely, internal at the time of deposition of the Quiburis Formation, dated at 5.35 to 6.43 million years (Ma) (Scarborough, 1975). The beginning of through-flowing drainage in the Safford basin may be constrained by the 3.6 Ma age of Flatiron Mesa basalt flows deposited on the highest terraces and pediments in the area around the San Carlos River (Houser, 1990). However, swampy to playa conditions were still present at the time of deposition of the 111 Ranch beds near Safford, which contain ash layers dated by Dickson and Izett (1981) at 2.17 to 2.67 Ma. Integration of the regional drainage had probably reached the 111 Ranch area and the Duncan Basin by 0.6 Ma, based on ash layers in Gila River gravel deposits (Houser, 1990). The Willcox and Animas Valley playas demonstrate that drainage in the upper Gila region is still not completely integrated.

Originating in New Mexico, the Gila River enters Arizona near the town of Duncan and flows northwest to the north end of the Duncan basin, where the San

Francisco River joins. The Gila then cuts across the Gila Mountains, entering the Safford basin near San Jose. San Simon Creek (or Wash), which drains the southern half of the Safford basin, enters the Gila several miles above Safford. The Gila flows northeast through the Safford basin, referred to by locals as the Gila Valley, leaving the basin near its northern extent, cutting southwest across the Mescal Mountains about 20 miles southeast of Globe.

Harbour (1966) described the groundwater hydrology of the Safford basin in terms of a single upper aquifer and a single lower aquifer, defined and separated by a "blue clay" layer separating his 'upper' and 'lower' basin fill units. This simplistic model is not borne out by an examination of logs and cuttings for wells in the valley. Logs and cuttings commonly reveal several "blue" (gray) clay layers interbedded with brown, red, yellow or green clay, and sand and gravel in many wells.

Detailed mapping of the basin fill (Richter and others, 1983; Houser and others, 1985; Houser, 1990) and examination of well cuttings (Harris, 1997) has revealed that the basin fill is interfingered on large and small scales. This produces a situation in which innumerable water-bearing layers (aquifers) consisting of relatively coarse material, such as sand and gravel, are separated by equally numerous fine-grained layers (aquitards or aquicludes) of silt, clay, and evaporites.

Drillers commonly report water from multiple intervals and deep wells of various depths produce waters of differing chemistry, temperature, and artesian head, not indicative of a simple, single aquifer. Differences in artesian head in adjacent wells have been noted in several Arizona basins (Anderson, 1995; Anderson and others, 1992). In the Safford basin, during drilling of the 1837-foot deep Whitlock Oil Co. #1 State oil exploration hole (D-10-28-36aa), salty water was encountered in six intervals between 640 and 1352 feet, while at 1363 feet, fresh artesian water was noted (Arizona Oil and Gas Conservation Commission files). Similarly, the Gila Oil Syndicate well produced strong artesian flow at six different intervals from 430 to 2405 feet (Knechtel, 1938). Logs for the Underwriters Syndicate "Mary Mack" oil well indicate numerous beds of sand and gravel, but most produced no water; only four water-bearing beds are indicated (Arizona Oil and Gas Conservation Commission files; Knechtel, 1938).

USE OF TRITIUM AS A TRACER OF WATER SOURCES

Tritium (abbreviated ^{3}H or simply T), consisting of one proton and two neutrons, is the radioactive isotope of hydrogen, with a half-life of 12.43 years. Tritium is found naturally in air and water.

The upper atmosphere interacts with many of the different types of cosmic radiation, and radioactive isotopes are produced. These cosmogenic radionuclides include ^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, ^{14}C, ^{32}Si, ^{39}Ar, ^{22}Na, ^{35}S, ^{37}Ar, ^{33}P, ^{32}P, ^{38}Mg, ^{24}Na, ^{38}S, ^{31}Si, ^{18}F, ^{39}Cl, ^{36}Cl, and ^{34m}Cl. Tritium is produced naturally in the upper atmosphere by interaction of cosmic ray-generated neutrons with nitrogen atoms, yielding tritium and carbon by the reaction: (^{14}N + neutron = ^{3}H + ^{12}C). Deuterium (^{2}H, another isotope of hydrogen) interacts with cosmic radiation in the upper atmosphere to produce tritium by the reaction: $^{2}H + {}^{2}H \rightarrow {}^{3}H + {}^{1}H$.

The tritium formed in this way is incorporated into water vapor and falls to earth as rain. The worldwide production of tritium from natural sources is 4,000,000 curies per year with a steady-state inventory of about 70,000,000 curies (Taylor and Roether, 1982). The unit curie is a measure of an amount of radioactivity; a curie (Ci) is the amount of a radioactive substance that has 3.7×10^{10} decays per second.

Tritium is also produced in nuclear power plants by irradiation of coolant water. Another source of tritium in the environment is from wristwatches and alarm clocks, where tritium is used to make watch dials luminescent (Östlund and others, 1969; 1974). When discarded, they end up in landfills, and the tritium can leach into groundwater downstream.

Large amounts of tritium were released into the atmosphere from nuclear weapons tests conducted between 1952 and 1963. Atmospheric tritium concentrations peaked between 1962 and 1965 and most of this excess (i.e. bomb produced) tritium was precipitated during the same time period and a few years afterward. Since then the deposition rate has tapered off sharply. Water with little or no tritium is generally regarded as pre-bomb in age and water that has tritium near the modern levels in precipitation are considered post-bomb.

Because of its very low levels in nature, tritium assays are often given in tritium units (TU), where one TU represents a tritium/hydrogen ratio of 10^{-18}, that is, one tritium atom per 10^{18} (1, 000,000,000,000,000,000) hydrogen atoms. In water of 1 TU, the specific activity is equal to 3.2 picocuries per liter (pCi/l) or 7.1 disintegrations per minute per liter (dpm/l). The unit picocurie corresponds to 2.2 disintegrations per second per liter. There are 10^{12} (1,000,000,000,000) picocuries in one curie.

Typical natural background levels of tritium in rainfall vary regionally and are 2-10 TU (Haskell and others, 1966). Seawater is tritium-dead because of the long residence time of an average water molecule, about 4000 years (Cherry and Freeze, 1979). Water evaporated from the oceans is also tritium dead. Water molecules exchange tritium for hydrogen during residence in the atmosphere. Generally, the longer water is in the atmosphere the more opportunity it has to pick up tritium. In theory, rain in coastal regions, nearer to the source, should be lower in tritium than rain falling in continental interior where the moisture has spent more time in the atmosphere.

For the Safford basin there exist no previous measurements of tritium levels in precipitation by which to determine a background. Repeated sampling of precipitation in the Tucson basin since 1992 by the University of Arizona has established an average of close to 5 TU (Eastoe, 1998). This tritium content is reasonably assumed to be applicable to the Safford region. Tritium levels as low as 2-3 TU were measured during the winter of 1994-95. In 1990, some surface water contained 8-10 TU, almost certainly reflecting the last remaining effects of the atomic bomb tritium spike.

In a groundwater sample the 'age' measures how long ago the water was recharged to the aquifer, that is, the time since the water was in contact with the atmosphere and able to exchange T for H in the water molecules.

Once water is isolated from the atmosphere, the tritium content decreases according to its radioactive half-life of 12.43 years (Figure 3). For example, after four half lives, about 50 years, 1/16 of the original tritium content remains. Thus, tritium content is

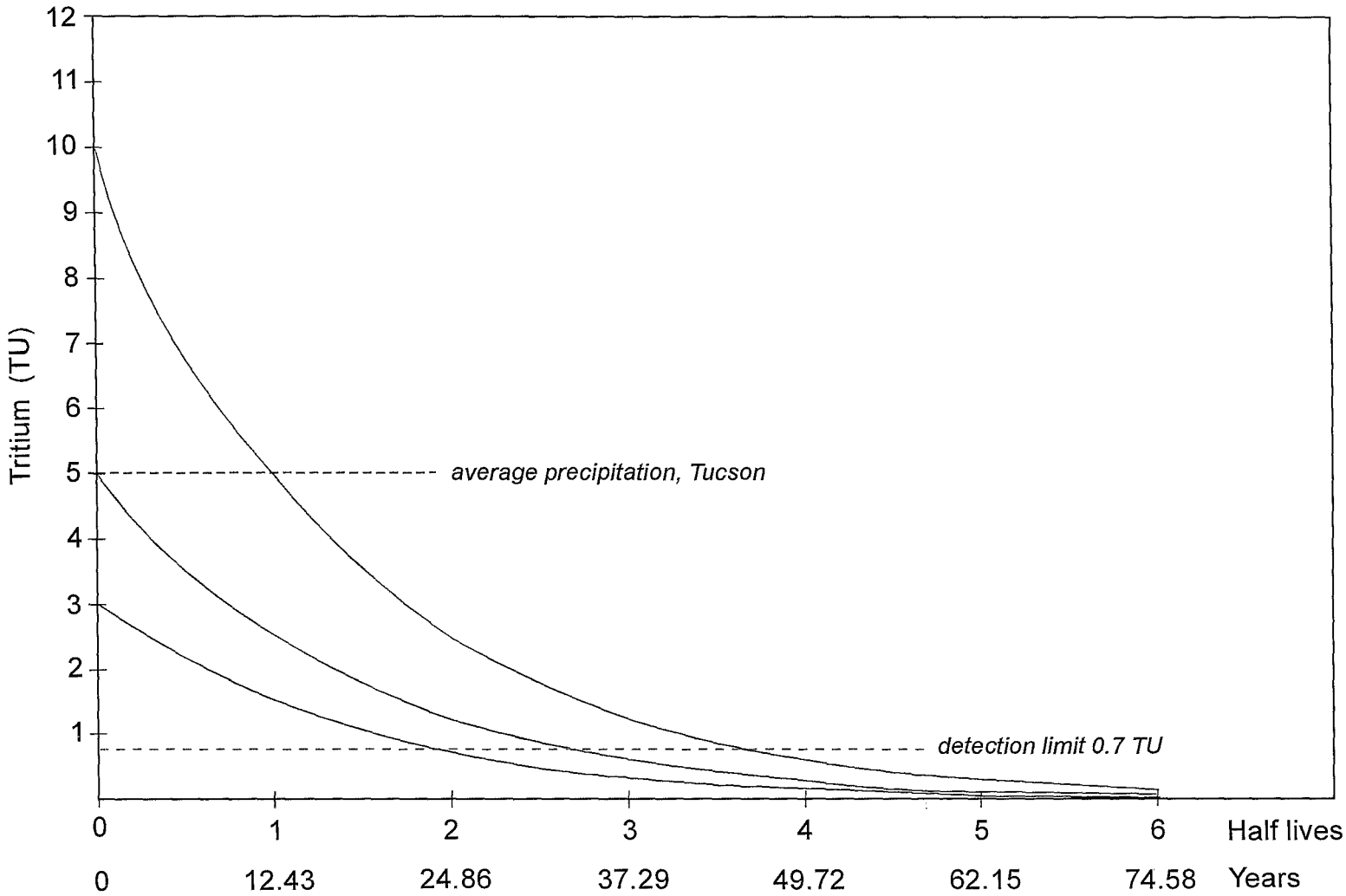
a proxy for the 'age' of a water sample, if the original content is known or can reasonably be assumed.

Tritium is most useful as a means of sorting out water that does not have a significant fraction of recent recharge. If, for example, a ground water sample has no tritium, the water could not have had contact with the atmosphere recently. A level higher than zero, but lower than the current local concentration in precipitation can be from two possible scenarios: 1) the water is from a single source whose apparent tritium 'age' is the result of the decay of tritium to lower levels, or 2) a mix of younger water containing tritium with older water containing little or no tritium, the final level of tritium reflecting the magnitude of contribution of each source. By itself, tritium cannot distinguish between these scenarios but does indicate at least some fraction of old water.

To interpret the 'age' of a groundwater sample, the tritium value must be compared to that of the original water that infiltrated to become groundwater. The source water can be infiltration of local precipitation, surface water derived from various distances and transported by rivers, or a combination. Sampling of tritium in local precipitation and river water over time provides a means of establishing the average background level, or starting point in the decay of tritium in groundwater.

Figure 3 shows how tritium levels decrease with time by radioactive decay. This diagram should not be used to determine the 'age' of a water sample because the systematics of recharge and groundwater movement are complex. In order to properly calculate a meaningful age requires developing a tritium input function that accounts for the different tritium contents of different rains, how much of each rain infiltrates, how much time the precipitation spends in the near-surface environment before it becomes truly isolated from the atmosphere, and mixing in the recharge area (Clark and Fritz, 1997). These components were not evaluated in this study and the development of a tritium input function is beyond the scope of this study.

Figure 3. Tritium levels versus time



RATIONALE OF THIS STUDY

Most studies of groundwater quality have focused on sewage effluent, mining, or agricultural runoff as primary contributors to water quality problems. In the upper Gila River watershed, there is the important added factor that an important source of dissolved solids in the Gila River may be from natural artesian leakage of deep groundwater that is in contact with soluble minerals in lake sediments in the Safford basin.

Natural artesian flow of deep groundwater into the Gila River is suspected to be of a large magnitude (Hanson and Brown, 1972; Brown, 1989) and much of the TDS in Gila River water may be introduced from the underlying basin-fill sediment in this manner. Aquifer tests have indicated that water under artesian pressure is flowing upward from the basin-fill sediments into the valley-floor alluvial aquifer (Weist, 1971; Culler and others, 1982).

Brown (1989) concluded that water is flowing from the basin fill into the stream aquifer based on higher water levels in wells in basin fill versus levels in nearby wells producing from stream alluvium lead. The magnitude of the vertical flow in the San Carlos Reservation part of the Gila River has been computed at 106,000 cubic feet per day (1.23 cfs) per mile of river length (Hanson and Brown, 1972). Although Hanson and Brown did not study the Gila River upstream of the Reservation, artesian leakage occurring upstream of the boundary would add to the amount calculated for the Reservation.

Some shallow wells in the Fort Thomas-Geronimo area were reported to have temperatures as high as 97°F, 30° higher than the normal background for shallow wells (Hem, 1950, p.52). Artesian leakage of warm water from deep in the basin is most likely the source of this thermal anomaly.

Tritium may be useful for determining the presence of artesian leakage of deep, saline groundwater into the Gila River. By measuring the tritium levels in seeps, springs, and wells, the distribution and relative amounts of old versus young groundwater may be determined. If, for example, a seep, well or spring has little or no tritium, the water is too old (pre-bomb) to have come from recent recharge of rainfall or surface runoff. On the other hand, if a seep or well contains tritium close to the level of the local precipitation, that water is probably of recent origin.

METHODS

This study located and characterized water from seeps, springs, and wells in the upper Gila drainage. Field work consisted of taking background samples of river water to establish the prevailing local tritium levels, and comparing those levels to wells, seeps, and springs in the basin. Sample locations are shown on detailed maps in Appendix A.

Gila River survey

The first step was to survey parts of the Gila River channel to locate areas where water is entering the river from seeps and springs. These seeps are suspected of being a major source of salinity in the Gila, especially during low-flow periods. Hem (1950) sampled and analyzed dozens of seeps and springs contributing water to the Gila and interpreted many as being evidence of artesian leakage of deep groundwater that became saline from contact with lacustrine sediments. The chemistry of the seeps was highly variable, ranging from nearly fresh to extremely salty. Interestingly, many of the saltiest seeps and springs Hem found were on the north side of the Gila River, in places where there is no agriculture. Numerous observation wells installed in the river channel showed the same result. Hem (1950) interpreted this to mean that at least some of the seeps and groundwater in the floodplain represented artesian leakage, and not irrigation return. Since the time of Hem's study, the Gila River has experienced numerous major floods that have completely rearranged the river channel so it is unlikely that the seeps Hem located are still in the same locations.

Several stretches of the Gila River channel were surveyed to locate seeps. The focus of this study was on the river downstream of Pima, where the river undergoes the most important changes in salinity and isotopic composition (Hem, 1950; Harris, 1999). The stretches surveyed are:

- From the San Jose canal diversion west one mile, north and south sides;
- From the Pima bridge west 1 ½ miles, south side;
- From the Fort Thomas canal diversion downstream to east of Ashurst, south side;
- From the SW ¼ of section 7, T5S, R24E, due west of Cold Springs downstream to ½ mile downstream from Clay Mine Wash, north side;
- From the SW ¼ of the SE ¼ of section 27 to the SW ¼ of section 7, T4S, R23E (south of Tom Niece Spring) to due north of Geronimo, north side.

These stretches were chosen based on accessibility, published accounts of seeps and likely artesian leakage, and continuity of parcels where permission of landowners was granted. About one-third of the requests for permission were not returned, so large stretches of the river could not be surveyed.

Sampling

Selected seeps, springs, and wells were sampled to establish some sense of background conditions and to determine to what extent water in the river is coming from leakage of deep groundwater into the shallow aquifer, as suggested by Weist (1971), Culler and others (1982), Brown (1989), Hanson and Brown (1972), and Smalley (1983).

Selected wells were sampled twice to discern possible seasonal differences. Available well completion information and well logs are presented in Appendix B

Water temperature, pH, and electroconductivity (EC) recorded for each site. Water samples were collected in clean plastic bottles. Filtering is not required for tritium analyses because only the H_2O is analyzed. The samples have an indefinite shelf life (until the tritium decays below detection), and do not need to be preserved for storage or analysis.

Measurements of temperature and pH were taken with a Hanna Instruments HI-8424 temperature-pH meter. The instrument has a two-point internal calibration system so once the meter is calibrated, it reads any pH within the range 0-14 directly.

Conductivity was measured with a Hanna Instruments HI-9033 conductivity meter, with automatic temperature compensation. The meter does not have a two point internal calibration so must be calibrated to a conductivity standard solution with conductivity close to that of the samples for maximum accuracy. The closest choices of standards appropriate for the Safford basin are 1413 and 5000 μS/cm. Most of the sample sites had conductivities between the 1413 and 5000 μS/cm and during fieldwork the meter was calibrated to the 5000 μS/cm standard. The specifications for the instrument report an accuracy of ± 1% full scale. However, with the meter calibrated to the 5000 μS/cm standard, the 1413 μS/cm standard read about 1500 to 1600 μS/cm. When calibrated to the 1413 μS/cm standard, the 5000 μS/cm standard read about 4200-4400 μS/cm. The effect of this variability is that for samples with reported EC less than about 3500 μS/cm, the reading is 10-20% higher than if the 1413μS/cm standard is used. By leaving the meter set to one standard, the measurements are precise (i.e., constant and repeatable) relative to each other.

Sample sites located in the spring-summer fieldwork were tagged with plastic ribbon and an aluminum tag carrying the site number as a means of relocating the sites for in the future if needed. However, upon return to the sites, none of the tags remained. At every site tagged, people or perhaps animals had removed all the ribbons and aluminum tags. During fieldwork in the fall and winter of 1999-2000, the practice of tagging sites was discontinued.

GIS locations

Latitude and longitude were measured with a Garmin 12CX handheld GPS receiver. Locations were recorded in the field and reported in Table 1 using the WGS84 map datum and are in degrees and decimal minutes. Based on field tests, the WGS84 datum is identical to the North American 1983 datum (NAD83), within the accuracy of the instrument. To locate a sample point on older USGS topographic maps, which use the North American 1927 datum (NAD27), the point must be moved 5 meters south and 60 meters east of where it plots on the NAD27 map.

The latitude adjustment is not necessary because it is within the error of the map and most line widths are on the order of a few meters on the map. The shift in longitude quite is noticeable, amounting to 2.5 mm or 3/16 inch on a 7.5-minute quadrangle. In some cases, such as 5-18-99-2 and 5-25-99-2, the points plot on a different quadrangle after the shift. Comparative field measurements indicate that NAD27 latitudes and

longitudes can be approximated by adding 0.005 minutes to the latitude and 0.04 minutes to the longitude of the WGS84 values listed in Table 1.

During spring and summer sampling, GPS locations were not precise. Government-imposed restrictions on the GPS satellite system limited the accuracy to as much as ± 50 meters. Each measurement was characterized by substantial drift in the values for latitude, longitude, and elevation. Repeat measurements at several stations yielded different values. Ironically, just a few weeks after completion of all field work, government restrictions were lifted and now GPS measurements are faster to acquire, do not drift, and are much more accurate.

Adding to poor GPS accuracy was the thick vegetation at springs and along the Gila River. Vegetation reduces the strength of signals and in places such as salt cedar thickets, blocks signals completely. The lowered number of satellites in line-of-sight of the GPS unit in thickly vegetated areas further reduces the accuracy of the GPS. Sites that were revisited in the winter months when foliage was at a minimum were re-measured and the newer values are shown in Table. 1

SAMPLING CONDITIONS, SPRING-SUMMER 1999

Gila River

The Gila River floodplain in the spring and summer of 1999 was in a condition that made it difficult to survey for seeps. A very dry fall and winter meant that there had been no winter floods to clean out the channel. The river channel was choked with cattails, reeds, grasses, and algae. Many sections of the river bottom were covered with a thick, black muck of organic-rich clay.

One aspect of the river that was unexpected was that, despite the drought of the previous fall and winter, the Gila River downstream from Pima had more water than it had the previous summer. During the spring of 1999, a U.S. Court issued a ruling enforcing an injunction affecting the ability of farmers in the Gila Valley to divert water from the river for irrigation. The effect of the injunction was to periodically keep much more water in the river than is normally found during the growing season.

The periodic halting of irrigation diversions caused the flow in the river to vary tremendously over short periods of time. The effect was that the water level in the river would fluctuate, causing intermittent flooding of the active channel, as well as in channels normally dry during low flows. A key to finding seeps is to look for wet spots in an otherwise dry riverbed and floodplain. But when the river fluctuates wildly, inundating much of the riverbed, any wet spots due to seeps are obscured by periodic wetting from high water levels.

The periodic high flows were compounded by another unforeseen circumstance, the widespread presence of beaver dams. These have the effect of simulating high-water conditions even during low flow conditions because the dams raise the water level in the river up to the height of the dam, commonly 3-5 feet. Given the low gradient of the river through the Gila valley, water backed up behind a beaver dam can flood the river channel ¼ mile or more upstream, making that part of the river channel impossible to survey.

Immediately downstream from a dam, seeps in the river channel may be due to the increased infiltration and increased head of water behind the dam.

The river bottom outside the flowing channel was commonly overgrown with grasses and salt cedar. Such thick vegetation hampers the identification of seeps because evapotranspiration (ET) may take most of the water coming up in the form of low-flow seeps.

The loss of water through ET is probably one factor that prevents some artesian leakage from being seen at the surface. It is common for the river to be ½ mile or more from the high banks. Most of the area between the banks of the flood plain and the river itself is occupied by dense stands of salt cedar. Any seeps coming up into the floodplain alluvium would not only be flowing to the river under several feet of sand and gravel (making the seeps not visible at the surface), but would also have a good chance of being captured by phreatophytes before reaching the active channel.

Phreatophytes are thickest along the high banks where they are not affected by flooding. These dense stands of salt cedar form a gauntlet through which some artesian leakage and water from springs to the north of the river would have to pass. If much or all of such water is captured by plants and lost through ET, finding that water seeping into the river a hundred yards away would be unlikely.

Salt crusts were common in the Gila River channel. Most can be explained as the result of simple evaporation of river water wicking through the fine-grained sediments in the riverbed. Salt flats were most common where the riverbed was wide but shallow. These salt crusts are washed away periodically when the river rises, or when it rains.

Seeps

In many places where the high bank on the north side of the river is a distance from the river, seep water seems to be present. These sites manifest themselves as damp sediments in the lower part of the banks and as thick salt crusts. Where the river is at the base of the high bank, dampness and salt crusts may partly be due to wicking of river water, but where the river is at a distance, this explanation is difficult to invoke.

A notable site where salt crusts are due to seep water is between Ft. Thomas and Geronimo, in T4S, R23E, section 21 (near site 5-25-99-1). At this location, thick salt crusts have formed along the north bank of the floodplain at least 50 yards away from the river, which is separated from the bank by a several-foot high sand bar and an abandoned flood channel. The sediment in the lower part of the bank is moist and salt crusts are aligned perpendicular to the bank as though they were formed by seeps that flowed visibly at some time, perhaps earlier in the year when ET rates were low. Below the seepage site, a trickle of water flows from the abandoned channel into the river. This old, tritium-dead water has an EC of 5780, compared to the river EC of 4780. About 300 yards downstream, another abandoned channel has a small amount of standing water with an EC of 10,400.

Another likely site where artesian leakage or spring flow is entering the river is in T4S, R23E, section 21, where a large wash enters the river floodplain. The wash empties into an abandoned flood channel north of the river, separated from the main flow at that point by 50-100 yards. Sediment delivered by the wash has formed a large delta in the abandoned channel, creating a situation such that when the wash is flowing, the water

splits and some goes SW, in the "upstream" direction to join the Gila. Between the wash delta and the downstream confluence of the wash, the abandoned channel is choked with thick vegetation consisting of salt cedar, willow, and cottonwood saplings. Although no standing water is present, the ground is very moist. A hole was dug about a foot deep and water slowly collected in it. This tritium-dead sample, 5-25-99-2, had an EC of 6380 μS/cm, with a pH of 7.5. Gila River water at the confluence yielded an EC of 4820 μS/cm.

In a number of places, measurements of the EC of Gila River water are higher along the margins where the river flows partly through marshy areas. One such place is in T4S, R23E, at the section line between 26/35, on the north side of the Gila River between Clay mine Wash and Box Canyon. Here, cattails and marsh grasses were growing several feet out into the river channel. When measured in the cattails, where the water was flowing sluggishly, EC was 5320 μS/cm, while two feet away in the main flow of the river EC was about 4550 μS/cm. It is likely that this spot represents an area where highly saline water is entering the river, possibly from artesian leakage, or from subflow of nearby springs (e.g. Charlie Thompson and Clay Mine Wash). That the water at the edge of the river has visible flow and is obviously connected to the main river flow eliminates simple evaporation as the cause of the increased salinity.

Springs

Springs are common in the lower part of the Safford valley, from Pima north to the reservation. North of the Gila River are a series of areas with multiple springs along a fault zone. Several areas of springs were visited during the late spring fieldwork.

Northeast of Pima are four springs aligned along a fault zone. From southeast to northwest these are East Spring, Mud Spring, Big Spring, and Little Spring, in sections 4 and 5 of T6S, R25E. Little and East Springs are shown only on old, 15-minute USGS maps. Of these springs, only Big Spring has year-round flow. The other 'springs' are areas where salt crusts have formed due to periodic seepage of water, but at the time of fieldwork, no water was present.

Northeast of Fort Thomas is another alignment of springs in three adjacent washes. On the east is Charlie Thompson Spring, with an EC of 4090 μS/cm. This spring issues from a zone of deformed sediment that contains abundant layers of salty clay.

One example of the effect of evapotranspiration is found in the small wash between Charlie Thompson Spring and Clay Mine Wash, in T4S, R24E, section 35. Here, a spring with flow similar to those of the above springs issues from the bottom of a steep-sided wash about ½ mile NE of the road along the north side of the Gila River. The drainage is very narrow, generally about 2-3 feet wide at the bottom, and does not have a deep gravel bottom for water to disappear into, in contrast to the larger washes in the vicinity. Water from this spring has an EC of 5820, measured about 100 yards downstream from the source. The spring itself is inaccessible due to its position in a narrow slot with nearly vertical sides and thick vegetation.

During the winter and early spring, when vegetation is largely dormant, water from the spring crosses the road. In the spring, after the vegetation comes back to life, but before the weather turns hot, the water reaches the road during the night and into the mid-morning. But in the afternoon, when evapotranspiration is at its peak, the water from the

spring reaches only half way down the wash. During the hot part of the year, the water never reaches the road. The difference in the amount of flow reaching the road over the course of a day probably is due to changes in ET rates rather than changes in the output of the spring.

In Clay Mine Wash is a spring issuing not from the bottom of the wash but from half way up the east bank of the main wash. This water, with an EC of 4100, can only be coming up vertically in a fault zone because a large side drainage enters the main wash immediately north of the springs and would intercept any water flowing down from the Gila Mountains to the north. Clay beds in the lacustrine sediments in the wash contain visible salt, and salt crusts have formed on the sides of the wash.

Between Fort Thomas and Geronimo is a zone of springs over a mile long. Near the eastern end of the zone is Tom Niece Spring. Springs in the two adjacent washes were also visited. Conductivity of water in these springs ranges from 3690 to 4360 µS/cm. Lacustrine sediments in the area are among the best known for producing thick crusts of salt between rains. These salt crusts can easily be seen from Highway 70, 1.5 miles away.

North of Geronimo, 1½ miles east of the San Carlos Indian Reservation boundary is Salt Spring. This spring flows all year and has an EC of 6050 µS/cm. In the adjacent wash to the west is an area of abundant salt crust and very dense vegetation, marking a site where some seepage is occurring. Salt Spring is in line with the fault zone to the east through Tom Niece Spring.

Wells

Several deep artesian wells around the basin were sampled for this study. The artesian wells range from about 500 to 2645 feet deep and all are moderately to highly saline (EC 1608 to 5310 µS/cm). Measurements of the age of water in these wells may help determine the rates of water movement through the various artesian systems in the basin.

Shallow wells, including stock, irrigation, and municipal wells, were chosen as part of the study. These wells will provide information about the sources of water in the wells (recharge from surface water, or contribution from leakage of old, deep water).

Available well logs are included in Appendix B. Most wells do not have well logs. The well log for the exploratory water well (sample 3-1-00-2) had not been submitted to Gila Resources by the drilling consultant so was unavailable to AZGS at the time of this report.

SAMPLING CONDITIONS, FALL-WINTER 1999-2000

The second round of fieldwork was undertaken in late October 1999 and from January to early March 2000. During this phase, wells, seeps and springs were found and sampled, and the Gila River was resampled.

Gila River

A reconnaissance round was done in October 1999, to assess the flow of the Gila River. The flow should have decreased relative to late summer levels, but was still too

high (~200 cfs at San Jose) for efficient riverbed surveying. It was decided to wait for lower flows during the winter. During the fieldwork several new seeps at the river water line were found between Fort Thomas and Geronimo; these had not been seen the previous summer. In January to March 2000, these seeps were not found, as the water level was slightly higher, obscuring the seeps.

The river channel in October was in many places quite different from the channel in the spring and summer because of a very large monsoon flow event in August. Flows of over 8000 cfs completely rearranged the active channel in numerous reaches. Some previously abandoned channels became the new active channel. Downstream from Pima (the focus of this study), the river generally was narrower and the bottom deeper than before the summer, although with the increased flow in October vs. May-July the water level was similar. Most of the previous summer's beaver dams were washed away, as were the thick algae mats.

During January to early March 2000, the main second-round sampling was performed. It was expected that because of the very dry fall and winter the river flow would be lower than in October but the flow was about the same or even slightly higher than in the fall. With no irrigation during the winter, there were no diversions and the flow was rather uniform from Pima to Geronimo. In the summer, by contrast, irrigation diversions take much of the water out of the river downstream from Pima. (An exception was the spring and summer of 1999, when a court injunction prohibited much of the diversion.)

Seeps

Because fewer seeps than anticipated had been found during the summer 1999 sampling (due to the court injunction, beaver dams, choking algae, and other factors discussed above), surveying in early 2000 also included more searching along the edges of the floodplain away from the flowing channel. Areas of suspected seepage were numerous, but presented a challenge in that they consisted of damp to wet areas without actual flowing water present. At these sites, holes were dug 1-3 feet deep and most of them filled with water. Most of these sites were in abandoned meanders or overflow channels that had probably not received any surface flow since the high flow event of August 1999.

Water in the dug holes was generally very saline, with conductivities as high as 17,290 μS/cm, corresponding to TDS of about 10,500 to 12,000 mg/l. The water was usually found in layers of coarse sand under a layer of black mud, both derived from flood deposition. Field observations suggested that this water could not be river underflow and have such high salinity, given the relatively short distances (50 to 300 yards) from the river and the much low salinity of river water. Evaporation is very low and transpiration would be nil in mid-winter. With no lakebeds in the immediate vicinity to contribute salts, the source of salinity was surmised to be from artesian leakage or from subflow of salty water from nearby springs, such as in the Tom Niece Springs area. Dug-hole samples were submitted for tritium analysis to evaluate this origin.

Springs

Cold Springs and Teague Springs, east of Fort Thomas, were added to the list of sampled springs. Cold Springs is in the series of springs along a fault zone trending parallel to the north side of the Gila River from Pima (Big Spring) to Geronimo (Salt Spring). Teague Spring is in volcanic bedrock of the Gila Mountains near the bedrock/alluvial contact 'upstream' of Cold Springs.

Wells

Four wells were added to those sampled during the summer: one more Pima Town well, two municipal supply wells in Fort Thomas, and an exploratory water well south of Safford. Another Pima town well (290' deep) was added to confirm the lower-than-expected tritium found in the other shallow (225') Pima municipal well. Although not far apart, the two Fort Thomas wells, 80 and 90 feet deep, may be in different aquifers, judging from the different temperatures. These well may be important in determining the 'age' of low-TDS water contributions to the river. The exploratory well was sampled to obtain a background sample away from the Gila River.

RESULTS

Tritium

Samples were analyzed for tritium at the University of Arizona Laboratory of Isotope Geochemistry. Results are reported in Table 1. Detailed maps of sample location are presented in Appendix A. In addition to the samples collected for the Arizona Water Protection Fund, the University of Arizona collected samples for tritium, sulfur isotope, and oxygen-deuterium isotope analyses. Some of the WPF tritium samples were run for sulfur and O-D by the UA at no charge. These additional analyses are presented at the end of Table 1 and in Table 2. Sample sites are shown in detail on maps in Appendix A.

The detection limit for tritium analyses is calculated as the apparent TU + 2 sigma (σ) for samples yielding low counts, and applies for 8-fold enrichment and 1500 minutes of counting. A sample with a mean calculated TU value between 0 and 1σ, say 0.20 ± 0.35 TU, is reported thus: <0.9 TU [= 0.2 + (2 x 0.35)]. A sample with a mean calculated TU value between 1σ and 2σ, say 0.51 ± 0.38, is reported thus: <1.3 (apparent 0.5), where 1.3 = 0.51 + (2 x 0.38), rounded. Samples with calculated mean TU values greater than 2σ are reported thus: 1.1 ± 0.4 TU. The detection limit for the samples analyzed in 1999 was 0.7 TU. In 2000, the detection limit was adjusted to 0.9 TU because of recalibration of the scintillometers and use of a different batch of scintillation cocktail that gave inferior counting characteristics.

Measurements of pH in early 2000 are not reliable because of calibration problems with the pH meter. The pH value began drifting and would not stabilize during measurements. Although the battery may have still been good, it was replaced. After replacement of the battery, the meter would not calibrate for several days. Even after what seemed to be successful calibration, the pH would not stabilize in the field. The source of the problem may have been the probe tip partially drying out or build up of salts, dirt, and organic matter on the probe. Measurements taken during the weeks that the pH meter was not working properly are not included in the table of samples sites. Fortunately, pH is not as important a parameter in this study as other measurements and the absence of these numbers does not affect the conclusions of this study.

Oxygen-Deuterium

Isotopes of oxygen and hydrogen are fractionated by evaporation and precipitation in the hydrologic cycle, by chemical reactions with rocks, and through biological processes. The large variations in isotopic ratios resulting from these processes provide a powerful and well-understood tracer for determining the sources and movement of water.

Stable isotope ratios of oxygen and hydrogen in water are expressed with reference to SMOW (Vienna standard mean ocean water). The relative differences are expressed in the delta notation:

$$\delta^{18}O \text{ or } \delta D, ‰) = \frac{(R)_{sample} - (R)_{standard}}{(R)_{standard}} \times 1000,$$

where R is the ratio of O^{18}/O^{16} or $^{2}H/^{1}H$. The stable isotope ^{2}H is called deuterium, or D. Differences in isotope ratios are small and are reported in part per thousand (per mil, or ‰).

Oxygen and hydrogen isotopes are useful for determining the source area of groundwater because the isotopic composition of precipitation varies with temperature of condensation (related to elevation and latitude). Rain falling at higher elevations (lower temperature) has lower $\delta^{18}O$ and δD (more negative in both oxygen and deuterium) than rain falling at lower elevations. Precipitation from different latitudes and elevations plot near a straight line called the Meteoric Water Line.

Simple evaporation of water increases the δD and $\delta^{18}O$, as the lighter isotope preferentially evaporates, leaving the residual water slightly heavier, i.e., less negative. Progressive evaporation of a batch of water yields a straight line with a slope of 3 to 5 on the δD vs. δO plot. Many of the water samples show some evaporation, as indicated by their positions to the right of the meteoric water line in Figure 6.

Sulfur isotopes

Sulfur isotopic compositions are reported in the standard delta (δ) notation, which measures the relative deviation of the ratio of two isotopes in a sample from the ratio of the two isotopes in a standard:

$$\delta^{34}S, ‰) = \frac{(^{34}S/^{32}S)_{sample} - (^{34}S/^{32}S)_{standard}}{(^{34}S/^{32}S)_{standard}} \times 1000,$$

Sulfur isotopic compositions are useful for identifying sources of sulfate. Evaporite sulfate in the Safford basin can be distinguished by positive $\delta^{34}S$ values, typically in the range of +8 ‰ or higher and deep basin water that has been in contact with evaporites tends to have similar values (Harris, 1999a).

Table 1. Tritium locations and results

Number	Location	Lat deg	Lat min	Lon deg	Lon min	Type	T (°C)	pH	EC	TU	±	(~)	Description
5-5-99-1	D(8-26)20db	32	43.26	109	42.4	well	34.7	8.85	2250	<1.1		0.4	Dankworth Lake artesian well
5-5-99-2	D(8-26)8b	32	45.15	109	42.48	well	38.0	8.69	4850	<0.8			Roper Lake artesian well (at hot tub)
5-12-99-1	D(5-23)1b	33	1.86	109	56.68	seep	33.2	7.95	2990	3.3	0.5		Seep in Gila River channel
5-12-99-3	D(4-23)25dd	33	3.08	109	56.86	spring	23.4	7.80	4100	1.0	0.4		spring in Clay Mine Wash
5-12-99-8	D(4-23)22caa	33	4.21	109	58.72	spring	26.0	7.14	3990	<1.1		0.4	spring E of Tom Niece spring
5-13-99-1	D(7-24)8a	32	50.63	109	54.45	well	19.1	7.52	2810	1.0	0.3		Pima Town well- artesian; depth>500'
5-13-99-2	D(7-24)8bd	32	50.6	109	54.9	well	22.0	9.72	291	1.5	0.4		Pima Town well; depth ~180'
5-13-99-4	D(5-24)18cdd	32	59.47	109	55.59	seep	22.1	7.22	5130	5.1	0.5		Seep in Gila River channel
5-14-99-2	D(7-26)22b	32	48.77	109	40.92	well	19.6	7.40	2370	3.3	0.3		Safford Ag Center well
5-18-99-2	D(8-28)29d	32	42.33	109	30.03	well	~	8.76	1530	<1.4		0.7	W of 111 Ranch (from end of hose)
5-19-99-2	D(6-25)23b	32	54.15	109	45.78	well	39.5	7.97	5310	<1.5		0.6	Well in Watson Wash
5-20-99-1	D(6-24)12dd	32	55.14	109	50.22	seep	17.8	7.14	2630	3.3	0.5		Seep in Gila River channel
5-22-99-1	D(5-24)7bba	33	1.32	109	55.64	seep	23.0	8.06	6480	4.9	0.4		water in abandoned meander channel
5-23-99-1	D(6-24)16ab	32	55.1	109	53.6	spring	21.6	7.85	2710	3.4	0.5		Simon Spring
5-24-99-1	D(6-27)36cc	32	51.7	109	32.55	river	27.4	8.62	1250	3.6	0.5		Gila River at San Jose diversion
5-24-99-2	D(6-25)18bb	32	55.06	109	50	river	30.3	8.48	1747	4.8	0.5		Gila River at Curtis Canal diversion
5-24-99-3	D(5-24)31aa	32	57.68	109	54.9	river	29.9	8.44	2120	4.2	0.4		Gila River at Eden bridge
5-24-99-4	D(4-23)18	33	5.54	110	1.86	river	27.0	8.14	4060	5.7	0.5		Gila River at Geronimo
5-24-99-5	D(4-23)35a	33	2.85	109	57.23	river	27.2	8.27	4780	5.1	0.5		Gila River at Clay Mine Wash (Ft. Thomas)
5-25-99-1	D(4-23)21bdc	33	4.27	109	59.71	seep	27.2	7.95	5780	<1.2		0.5	water in abandoned meander channel
5-25-99-2	D(4-23)21bcb	33	4.305	110	0.09	seep	24.7	7.30	6380	<0.7			Seep in Gila River bank
5-25-99-3	D(4-23)7b	33	6.18	110	1.83	spring	21.3	7.02	6050	<0.7			Salt Spring (N of Geronimo)
6-8-99-1	D(4-23)7ddc	33	5.49	110	1.19	seep	18.5	7.87	2760	3.8	0.3		Seep in Gila River flood channel
6-8-99-2	D(4-23)7dcc	33	5.64	110	1.41	seep	18.9	7.37	1490	4.0	0.5		Seep, confluence of aban'd channel
6-8-99-3	D(4-23)17bac	33	5.3	110	0.77	seep	22.1	6.87	10370	<0.6			Seep in aban'd channel
6-10-99-1	D(6-25)5dab	32	56.33	109	48.31	spring	22.3	7.25	3280	<1.3		0.6	Big Spring (N of Pima)
6-10-99-2	D(7-23)11ab	32	50.7	109	57.67	spring	28.3	8.12	540	1.2	0.4		Spring, base of Bear Springs Knoll
7-9-99-1	D(6-25)18cac	32	54.56	109	49.89	well	19.6	7.37	2120	4.1	0.4		well, Dodge-Nevada
7-9-99-3	D(6-24)12dd	32	54.96	109	51.13	well	18.9	7.25	2250	3.1	0.3		well, Dodge-Nevada, new pipe
7-21-99-1	D(5-24)30ac	32	58.22	109	55.25	well	20.7	8.40	4270	4.1	0.4		well 60 yd N of Gila Oil
7-21-99-3	D(5-25)30aba	32	58.56	109	55.15	well	20.7	7.49	2680	3.7	0.4		well, last Ft Thomas canal N of Gila Oil
7-21-99-5	D(5-25)31aa	32	57.38	109	54.87	well	21.9	7.56	1820	3.7	0.4		well, E of Ft T canal, first S of Eden Rd
7-21-99-6	D(7-26)2					rain				5.4	0.4		Rain, monsoon storm, near Safford airport
7-22-99-1	D(6-27)36cc	32	51.7	109	32.55	river	24.1	8.10	495	5.6	0.5		Gila River at San Jose diversion
7-22-99-2	D(6-25)18bb	32	55.06	109	50.0	river	24.5	9.58	535	5.6	0.5		Gila River at Curtis Canal diversion

Table 1. Tritium locations and results, continued

Number	Location	Lat deg	Lat min	Lon deg	Lon min	Type	T (°C)	pH	EC	TU	±	(~)	Description
7-22-99-5	D(4-23)18	33	5.54	110	1.86	river	27.1	8.06	886	5.0	0.5		Gila River at Geronimo
10-20-99-1	D(523)1bdd	33	1.83	109	56.67	seep	16.4	7.32	4340	5.2	0.5		Seep - bank of GR
10-20-99-2	D(4-23)21bdc	33	4.19	109	59.7	seep	21.5	7.84	6720	1.1	0.4		Seep in GR
10-20-99-3	D(4-23)21bdc	33	4.29	109	59.74	seep	24.1	7.07	7570	<1.3			Seep - GR bank
10-20-99-4	D(4-23)7ddc	33	5.49	109	1.19	seep	20.9	7.37	2390	3.7	0.5		Seep - GR bank
1-12-00-1	D(6-37)36cc	32	51.7	109	32.55	river	8.3	8.57	795	2.9	0.5		GR-San Jose
1-12-00-2	D(7-26)22b	32	48.77	109	40.92	well	19.2	7.37	2100	5.7	0.5		Safford Ag Center well
1-12-00-3	D(6-25)18bb	32	55.06	109	50.0	river	10.8	8.34	965	3.8	0.4		GR-Pima
1-12-00-4	D(4-23)7cdc	33	5.54	110	1.86	river	11.2	8.25	1570	4.5	0.5		GR-Geronimo
1-12-00-5	D(4-23)35a	33	2.85	109	57.23	river	10.9	8.37	1400	2.5	0.5		GR-Fort Thomas
1-12-00-8	D(5-24)31aa	32	57.69	109	54.9	river	11.7		1158	3.1	0.4		GR-Eden
1-13-00-3	D(6-24)16ab	32	55.04	109	53.58	spring	22.3	7.7	2700	3	0.4		Simon Springs
1-14-00-4	D(9-25)17	32	39.08	109	48.79	snow	~	~	~	5.7	0.4		Mt Graham snow
1-18-00-1	D(5-24)18cbd	32	59.73	109	55.73	seep	15.3	7.6	6980	6.0	0.5		seep - W edge of floodplain
1-19-00-1	D(4-23)36cbc	33	2.34	109	56.88	seep	15	7.86	5950	3.1	0.4		seep (dug) in GR channel
1-19-00-2	D(7-24)8bd	32	50.53	109	54.92	well	23.2	9.33	350	<1.4		0.7	upper Pima town well
1-19-00-3	D(7-24)4ccd	32	50.82	109	54.1	well	22.3	*9.99	426	1.7	0.4		lower Pima town well
1-20-00-1	D(4-23)28aaa	33	3.73	109	59.14	seep	13.1		10070	3.6	0.4		seep (dug) in GR channel
1-20-00-2	D(4-23)28bbd	33	3.64	109	58.78	seep	9.5		7300	5.7	0.6		seep (dug) in GR channel
1-20-00-3	D(4-23)7dcd	33	5.507	110	1.2	seep	11.8		2250	3.8	0.6		seep (dug) in GR channel
1-21-00-1	D(4-23)17bbd	33	5.313	110	0.751	seep	11.5		6130	<1.4			seep (dug) in GR channel
1-21-00-2	D(4-23)17bdb	33	5.27	110	0.72	seep	9.7		7290	2.7	0.4		seep (dug) in GR channel
1-21-00-3	D(4-23)17bdd	33	5.13	110	0.7	seep	13.1		17290	1.3	0.5		seep (dug) in GR channel
1-21-00-4	D(4-23)17cdb	33	4.829	110	0.659	seep	11.6		4700	5.1	0.4		seep (dug) in GR channel
1-21-00-5	D(4-23)20adb	33	4.4	110	0.25	seep	15.4		11880	1.7	0.3		seep (dug) in GR channel
1-21-00-6	D(4-23)20ada	33	4.3	110	0.033	seep	16.4		10850	<1.4		0.6	seep (dug) in GR channel
2-29-00-1	D(5-23)1dab	33	1.55	109	56.09	seep	12	*7.27	6100	5.0	0.4		seep (dug) in GR channel
3-1-00-2	D(9-26)28abc	32	37.6	109	41.44	well	21.8	8.53	698	2.2	0.5		Exploratory water well
3-1-00-3	D(5-24)30aba	32	58.5	109	55.5	well	19.1	7.47	3430	4.7	0.5		Ft T canal N-most well
3-1-00-4	D(5-24)30ac	32	58.22	109	55.25	well	19.3	7.41	6290	4.3	0.4		Ft T canal N of Gila well
3-1-00-7	D(5-24)31aa	32	57.38	109	54.88	well	18.7	7.73	1900	3.5	0.5		Ft T canal S of Eden Rd
3-2-00-1	D(5-24)8dcd	33	0.4	109	54.18	spring	24.6	7.5	5700	1.3	0.4		Cold Springs
3-2-00-2	D(4-24)27bbd	33	3.6	109	52.83	spring	15.6	7.73	665	1.3	0.5		Teague Springs
3-2-00-3	D(6-25)18cad	32	54.54	109	49.7	well	18	7.38	2350	4.4	0.5		Dodge-Nevada well 13
3-2-00-4	D(5-23)2cbd	33	1.52	109	57.78	well	20.4	7.0	312	4.2	0.4		Ft Thomas town well
3-2-00-5	D(5-23)2cbc	33	1.55	109	57.98	well	18.6	7.27	292	4.7	0.5		Ft Thomas town well

Table 1. Tritium locations and results, continued

University of Arizona unpublished data

Date	Location	Lat deg	Lat min	Lon deg	Lon min	Type	T (°C)	pH	EC	TU	±	(~)	Description
7-15-98	19S-19W-18					river				4.1	0.4		Gila River in New Mexico
7-15-98	D(4-23)35					river				4.9	0.3		Gila River near Fort Thomas
7-15-98	D(4-23)35					seep				6.3	0.4		Seep near GR
7-15-98	D(5-24)30ac	32	58.17	109	55.22	well	35.4	7.56	30000	<0.5			Gila Oil Syndicate well
9-5-98	D(10-28)36	32	31.39	109	25.6	well	41.7	8.46	1600	<1.0			Whitlock Oil No.1 (BLM Hot Well Dunes)
5-20-00	D(6-37)36cc	32	51.7	109	32.55	river				1.9	0.3		GR-San Jose
5-20-00	D(6-25)18bb	32	55.06	109	50.0	river				4.2	0.4		GR-Pima
5-20-00	D(4-23)35a	33	2.85	109	57.23	river				5.5	0.5		GR-Fort Thomas
5-20-00	D(4-23)7cdc	33	5.54	110	1.86	river				4.8	0.5		GR-Geronimo

Lat-Lon relative to WGS-84 datum, essentially equal to NAD-83 datum - must correct to use on NAD-27 maps
EC = conductivity in µS/cm@25°C
TU = tritium level in Tritium Units
± = analytical error
(~) = apparent TU
*pH = suspect; blank if unreliable
GR = Gila River

Table 2. University of Arizona data

Fig 6	WPF Sample	University of Arizona sample Date	Lab #	δO	δD	δS	Site
1	5-5-99-1		W7614	-12.6	-92	9.9	Dankworth Lake artesian well
2	5-5-99-2		W7615	-12.4	-90	13	Roper Lake artesian well
3		5-20-00	W7677	-12.2	-80		Wet Canyon stream, Mt. Graham
4	5-13-99-1		W7616	-11.8	-85	12.9	Pima Town well, artesian
5a	5-12-99-8		W8097	-11.4	-85		East of Tom Niece Spring
5b		8-11-99	W6511	-11.4	-85	8.9	East of Tom Niece Spring
6a		8-11-99	W6510	-11.4	-84	8.9	Charlie Thompson Spring
6b		8-11-99	W6512	-11.4	-84	10.3	Salt Spring
7		8-11-99	W7572	-11.3	-83		Spring, Clay Mine Wash
8		6-18-00	W6283	-11.3	-79.5		Gila Hot Springs, New Mexico
9	3-2-00-4		W8104	-11.0	-80		Ft. Thomas town well
10	3-2-00-1		W8105	-10.9	-84		Cold Spring
11	6-8-99-3		W8106	-10.9	-83		Seep, Gila River channel
12	3-2-00-5		W8103	-10.8	-79		Ft. Thomas town well
13	5-19-99-2		W7619	-10.4	-82		Watson Wash artesian well
14	1-21-00-1		W8101	-10.4	-80		Seep, dug hole
15	10-20-99-2		W8098	-10.3	-81		Seep, Gila River channel
16	1-21-00-3		W8099	-10.2	-78		Seep, dug hole
17	5-12-99-3		W8108	-9.9	-76		Spring, Clay Mine Wash
18	5-22-99-1		W7617	-9.8	-75		Seep, GR abandoned channel
19	1-21-00-6		W8102	-9.7	-76		Seep, dug hole
20	3-2-00-2		W8111	-9.4	-73		Teague Spring
21		8-11-99	W6513	-9.4	-67		Spring Creek
22	1-14-00-4		W8096	-9.4	-62		Mt. Graham snow
23	5-13-99-2		W7620	-9.3	-61		Pima Town well, upper
24	5-25-99-1		W8107	-8.9	-76		Seep, GR abandoned channel
25		6-18-00	W6284	-8.9	-64		N. Fork GR, New Mexico
26		5-20-00	W7681	-8.5	-66		GR Geronimo
27	1-12-00-1		W7625	-8.4	-65		GR San Jose
28	7-22-99-5		W7623	-8.3	-67		GR Geronimo
29	1-12-00-5		W7677	-8.3	-64		GR Fort Thomas
30		8-11-99	W6509	-8.3	-60		GR Fort Thomas
31	1-20-00-2		W7626	-8.2	-65		Seep, dug hole
32	5-14-99-2		W7621	-8.1	-67		Safford Agricultural Center well
33		8-11-99	W6514	-8.1	-59		GR Safford
34		5-20-00	W7678	-8.0	-64		GR San Jose
35	1-13-00-3		W8100	-7.9	-65		Simon Spring
36		8-11-99	W6515	-7.9	-59	3.6	San Simon Wash at Solomon
37	1-21-00-4		W8109	-7.8	-63		Seep, dug hole
38		5-20-00	W7679	-7.6	-62		GR Pima
39		5-20-00	W7680	-7.5	-62		GR Fort Thomas
40	6-10-99-2		W8110	-7.4	-63		Bear Springs Knoll
~		6-29-00	W8095	-14.6	-103		Safford rain
~		5-20-00	W7682	-3.7	-43		Riggs Reservoir

DISCUSSION

Precipitation

Two samples of precipitation were taken during this study. These represent the first tritium analyses of precipitation for the upper Gila River watershed in Arizona. With so few samples, additional data from other parts of Arizona must be used to provide an estimate of the typical levels of tritium in precipitation in the Gila watershed.

Because these samples are from a small fraction of single events and not composites or averages of many events, the values should not be taken as representative of the true average for precipitation in the Safford region. During the course of a single rainfall event, the isotopic composition and tritium level evolves (Clark and Fritz, 1997). Groundwater is composed of rain from many events and records values close to the average for a region. For example, one rainfall sample taken at Safford on June 6, 2000 had a highly anomalous O and D composition of –14.6 ‰ and –103 ‰, respectively. This composition is beyond the range found in groundwater and surface water in the upper Gila River watershed. This point plots near the meteoric water line but is not shown on Figure 6. Another precipitation sample of snow on Mt. Graham is plotted on the graph but is not typical of high-elevation precipitation.

Pre-bomb tritium content in precipitation in the interior of the U.S. averaged about 5.2 to 8.8 TU (Reeder, 1964). Samples with greater than 9 TU were believed to contain some bomb tritium. Data from the Tucson basin (Eastoe, 1998) indicate that the average T content of rain has been close to 5 TU from 1992 to 1998.

Gila River

Sample sites and tritium levels in the Gila River are shown on Figure 4 and the trends of tritium versus distance downstream in the river are plotted in Figure 5. The most striking aspect of the trends is that regardless of the tritium content of the river near San Jose, the content is remarkably invariant at Geronimo. During low-flow periods (January and May samples), the tritium content in the river increases overall from San Jose to Geronimo, indicating that a significant amount of water is entering the river as it traverses the basin. Some evidence of the addition of old water into the river is seen in the decrease in tritium downstream from Pima in May 1999 and January 2000. The trend between Pima and Fort Thomas is apparently opposite in the University of Arizona samples in May 2000, but the tritium content at Geronimo for the UA samples ends up almost the same as the others.

Tritium measured in the Gila River at San Jose is lower during the low-flow periods than in the monsoon sampling. The river during low flow contains a greater fraction of water from deep, old, low- tritium sources, such as Clifton Hot Springs, than during the summer monsoon when the river is dominated by storm runoff.

Stable O and H isotopes in the river (Figure 7) show a trend similar to that of chemical and isotopic trends seen in an earlier isotope study of the Safford basin (Harris, 1999a). As with other isotope and chemical trends, O and D show a reversal of their trends downstream from Fort Thomas.

Trends in the Gila River between Pima and Geronimo may be somewhat exaggerated because of the fact that by the time the river reaches the Eden area, most of the water has been diverted for irrigation. During low-flow periods when farming is active, a significant fraction of the water in the river below the Fort Thomas canal diversion, located between Pima and the Eden bridge, consists of water from seeps, springs, flowing artesian wells and possibly underground return of irrigation water. Thus the chemistry of the river is dominated for many miles by these additions.

Chemistry, isotopic composition, and tritium content below Pima therefore may reflect a much smaller amount of water, which during low flow varies from no more than a trickle at Eden to an increased but still much diminished stream at Fort Thomas. By Geronimo the flow increases, but δD and $\delta^{18}O$ shifts indicate the water added between Fort Thomas and Geronimo is not all river water. The new water could be from a combination of subflow of irrigation water pumped from mountain-recharged aquifers, and subflow contributions from major tributaries such as Black Rock Wash and Goodwin Wash. The amount being contributed from these sources was not determined. Additional water comes from seeps, springs and artesian leakage. Some examples of these possible sources were sampled but the total amount being contributed from each type source was not determined.

An important aspect of the chemical, isotopic and tritium trends in the river is their reversal between Fort Thomas and Geronimo. If shifts in one direction are caused by any particular source or process, the trend reversal certainly cannot be attributed to the same source or process. For example, the shift of δD and $\delta^{18}O$ from San Jose to Fort Thomas can be explained by evaporation, but the shift between Fort Thomas and Geronimo cannot be explained by addition of river water. Only the addition of a significant amount of water with lower δO and $\delta^{18}D$ can shift the river from its original composition as shown on Figure 7. Similarly the shifts in the tritium content are not explainable in terms of additions downstream from Fort Thomas of water diverted upstream.

Wells

Several deep artesian wells were sampled for tritium to establish that deep groundwater in the basin is relatively old. As expected, all of the artesian wells had little or no tritium. This result provides a basis for the interpretation that springs and seeps with little or no tritium are also from the same deep, old source as the artesian wells.

Between Pima and Fort Thomas, shallow wells used for irrigation had tritium contents of 3.1 to 4.7 TU. This range is possibly within the range of precipitation for the valley, but how these wells compare to the average precipitation cannot be evaluated without more precipitation samples. The tritium levels are all lower than the 5 TU average for the Tucson basin and some are below the levels measured for the river reported in Table 1 and shown on Figure 5.

Tritium in the Safford Agricultural Center (SAC) well was measured at 3.3 ± 0.3 in May 1999, and 5.7 ± 0.5 in January 2000. This seasonal variation is in line with variations in chemistry and isotopic compositions reported for this well (Harris, 1999a; 1999b). Although the tritium content in the SAC well overlaps that of irrigation wells north west of Pima, and in the Gila River, other isotopes measured in this well (Harris, 1999a) preclude the well from having more than a minor fraction of Gila River water.

Shallow groundwater throughout the basin should have tritium levels reflecting the average for precipitation (minus loss due to decay), independent of proximity to the Gila River. The two Fort Thomas town wells have tritium contents close to the expected average precipitation, and their δD and $\delta^{18}O$ composition indicate a high-elevation recharge source, such as the Santa Teresa or Pinaleño mountains, rather than from the Gila River.

Municipal wells for Pima, in Cottonwood Wash, have tritium contents of <0.7 (apparent 0.7) to 1.5 TU for the upper well and 1.7 TU for the lower well. These values indicate a fairly long residence time considering the proximity to Mt. Graham and the expected permeability of the aquifer the wells are drawing from. The variation in tritium content of two samples from the upper well suggest some mixing of waters of different residence time or original T content. Interestingly, the lower well is deeper (290 vs. 220 feet) yet has more tritium than the upper well.

The well near 111 Ranch has water with a tritium content of <1.4 (apparent 0.7) TU, indicating a long residence time. According to a local rancher, water was first struck at about 500 feet and the water level then rose to about 8 feet (ADWR data), indicating significant artesian head in the well.

Water from the artesian Dankworth Lake, Roper Lake, and Pima town wells have sulfur isotopic compositions of +9.9 to +13 ‰. These values demonstrate that the water is in contact with evaporites with a typical sulfur isotope composition (Harris, 1999).

Springs

Levels of tritium in springs were generally low to nil, with the exception of Simon Springs. Residence time for groundwater in the aquifers feeding these springs is measured in decades. Significantly, all of the springs along the fault zone north of the Gila River (Big Spring, Cold Spring, Charlie Thompson, Clay Mine Wash, E. of Tom Niece, and Salt Spring) have water that is of a deep-source character, based on low to nil tritium and δD-$\delta^{18}O$ isotopic compositions. These springs plot on the lower left of Figure 6, in the same neighborhood as the deep wells, indicating that the water from these springs originated in a cool, high-elevation area, such as Mt. Graham, or perhaps at lower elevations during the late Pleistocene when the climate was cooler.

Evaporation effects easily account for an apparent exception in the deep-source stable isotopes for one of the two samples of the spring in Clay Mine Wash. Sample 5-12-99-3 was collected on a hot dry day, while sample W7572 was collected on a very humid monsoon day. Water is this spring issues from a diffuse area of several meters, thick with large mesquites and other vegetation. Possibly because of higher evaporation rates the flow of the spring seemed to be slightly lower during the earlier sampling. The effect of evaporation is also clear in sample 6-10-99-2, near Bear Springs Knoll. This sample was taken near noon on a very dry June day from a trickle flow several meters from the source, which was inaccessible due to the small slot wash and thick vegetation. By contrast, two samples of the spring east of Tom Niece Spring show no evaporation effect because of the strong flow that can be sampled at the source, contrasted to the diffuse or trickle flow at Bear Springs Knoll and Clay Mine Wash.

Sulfur isotopic compositions of the springs near Fort Thomas and Geronimo range from +8.9 to +10.3 ‰. These values overlap with the deep basin water that is in contact with typical evaporite sulfate (Harris, 1999a).

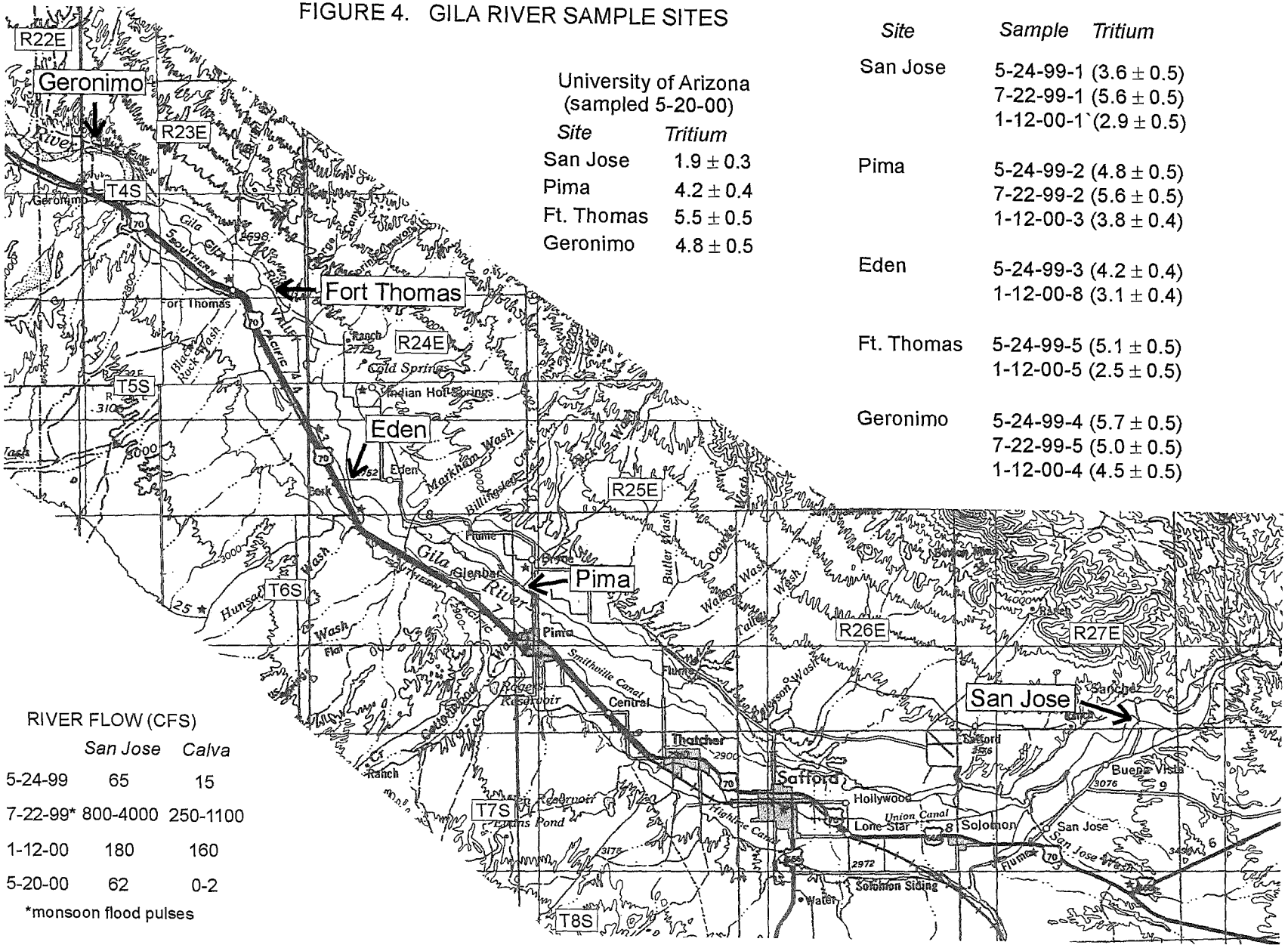
Tritium levels and δD-$\delta^{18}O$ composition of Simon Springs, SW of Pima are quite different from the springs on the north side of the valley. Simon Springs is an area where springs issue from the side of a ridge over a distance of about a half-mile. Water in the springs is relatively salty, having a conductivity of 2700 μS (TDS ≈1800 mg/l) and two tritium analyses returned values of 3.0 ± 0.4 and 3.4 ± 0.5 TU. A tritium content of 3to 3.4 TU is best explained as a mixture of some pre-bomb water with post-bomb water. The sample plots to the right of the meteoric water line on Figure 6, indicating that the water issuing from the spring has been evaporated. These results indicate fairly recent, evaporated source water for the springs. However, there is no obvious source for this water. The springs are above the Gila River and the nearby irrigation canal, so the water cannot be from either of these sources. The logical source would be infiltration of evaporated Mt. Graham water, the same source as for the Pima town wells and springs in Bear Springs Flat area.

Seeps

Seeps in the Gila River floodplain were analyzed for tritium to determine if any of them contain low-tritium water indicative of a deep-aquifer source. Many of the seeps have tritium levels and δD-$\delta^{18}O$ compositions (Table 2 and Figure 6) that overlap the range of tritium and δD-$\delta^{18}O$ measured in Gila River water. These seeps may represent river water that infiltrates into the sand and gravel of the riverbed and emerges some distance downstream, or water that is a mix of river and groundwater.

Many of the seeps, however, are low to nil in tritium and have δD-$\delta^{18}O$ compositions indicative of a deep-water source. These seeps contain little or no river water despite their location in the active floodplain of the river. Some of these seeps are literally at the water's edge in the actively flowing river channel.

FIGURE 4. GILA RIVER SAMPLE SITES



University of Arizona
(sampled 5-20-00)

Site	Tritium
San Jose	1.9 ± 0.3
Pima	4.2 ± 0.4
Ft. Thomas	5.5 ± 0.5
Geronimo	4.8 ± 0.5

Site	Sample	Tritium
San Jose	5-24-99-1	(3.6 ± 0.5)
	7-22-99-1	(5.6 ± 0.5)
	1-12-00-1	(2.9 ± 0.5)
Pima	5-24-99-2	(4.8 ± 0.5)
	7-22-99-2	(5.6 ± 0.5)
	1-12-00-3	(3.8 ± 0.4)
Eden	5-24-99-3	(4.2 ± 0.4)
	1-12-00-8	(3.1 ± 0.4)
Ft. Thomas	5-24-99-5	(5.1 ± 0.5)
	1-12-00-5	(2.5 ± 0.5)
Geronimo	5-24-99-4	(5.7 ± 0.5)
	7-22-99-5	(5.0 ± 0.5)
	1-12-00-4	(4.5 ± 0.5)

RIVER FLOW (CFS)

	San Jose	Calva
5-24-99	65	15
7-22-99*	800-4000	250-1100
1-12-00	180	160
5-20-00	62	0-2

*monsoon flood pulses

Figure 5. Tritium trend in the Gila River

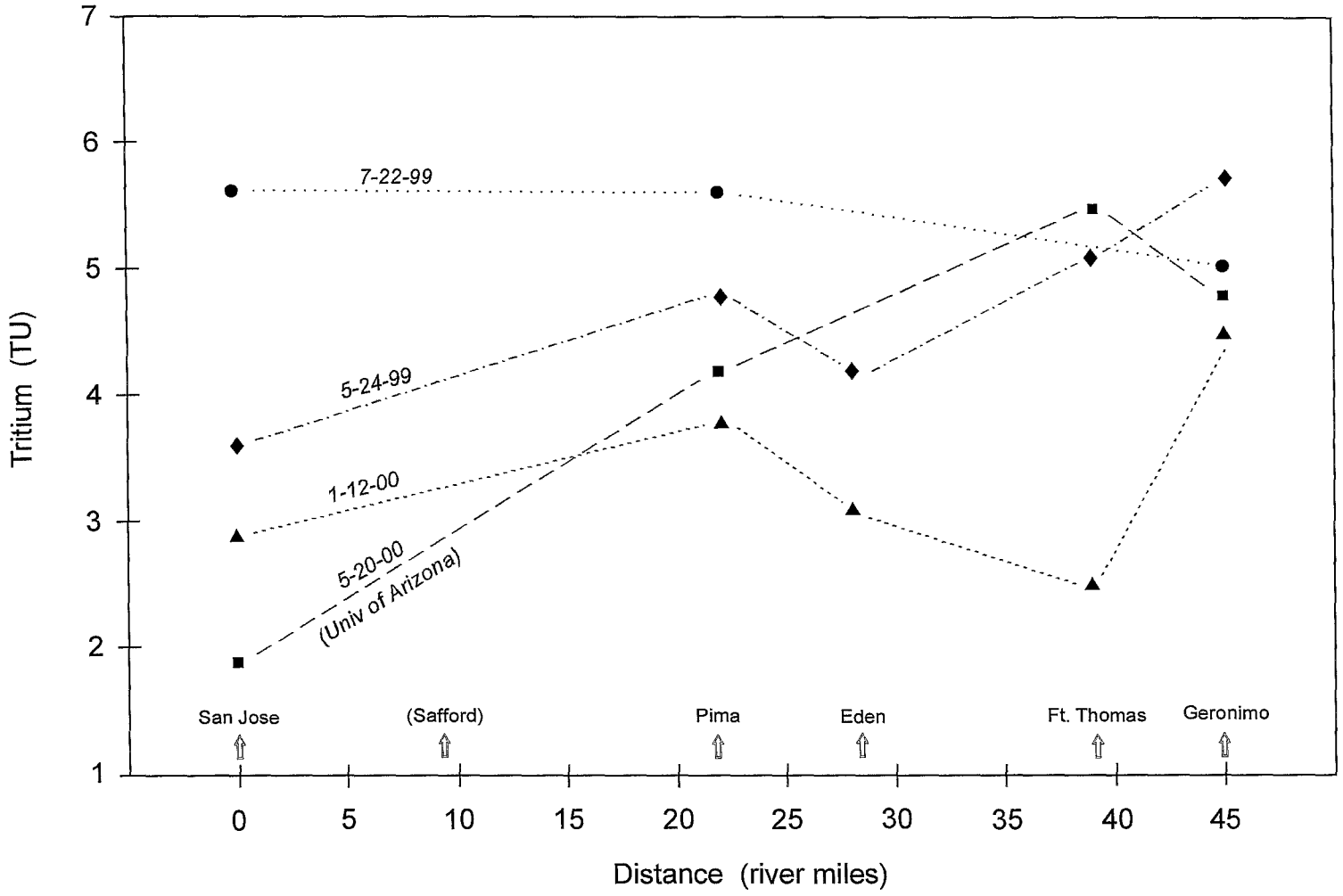


Figure 6. Stable O-H isotopes in the Safford basin.

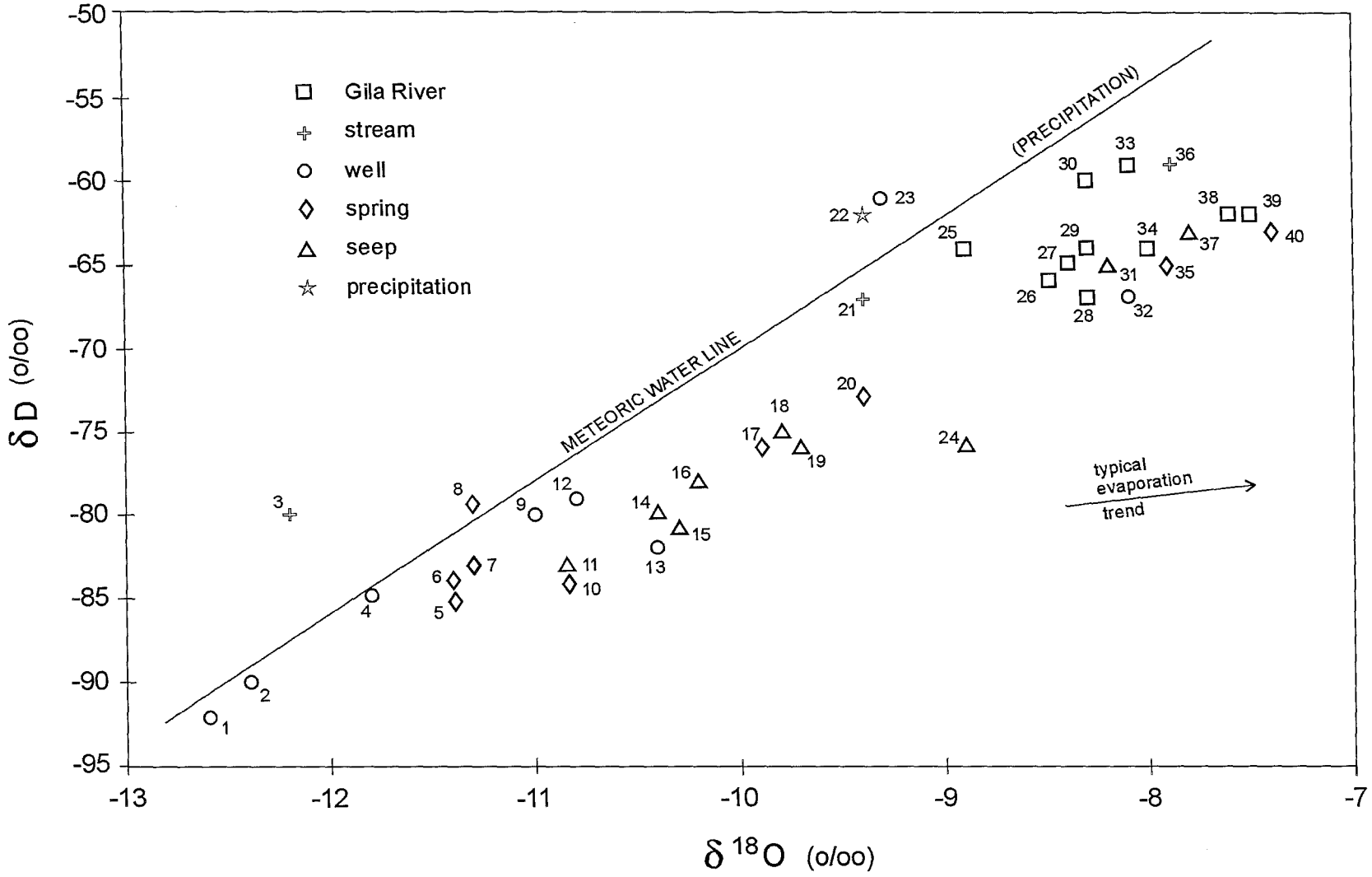
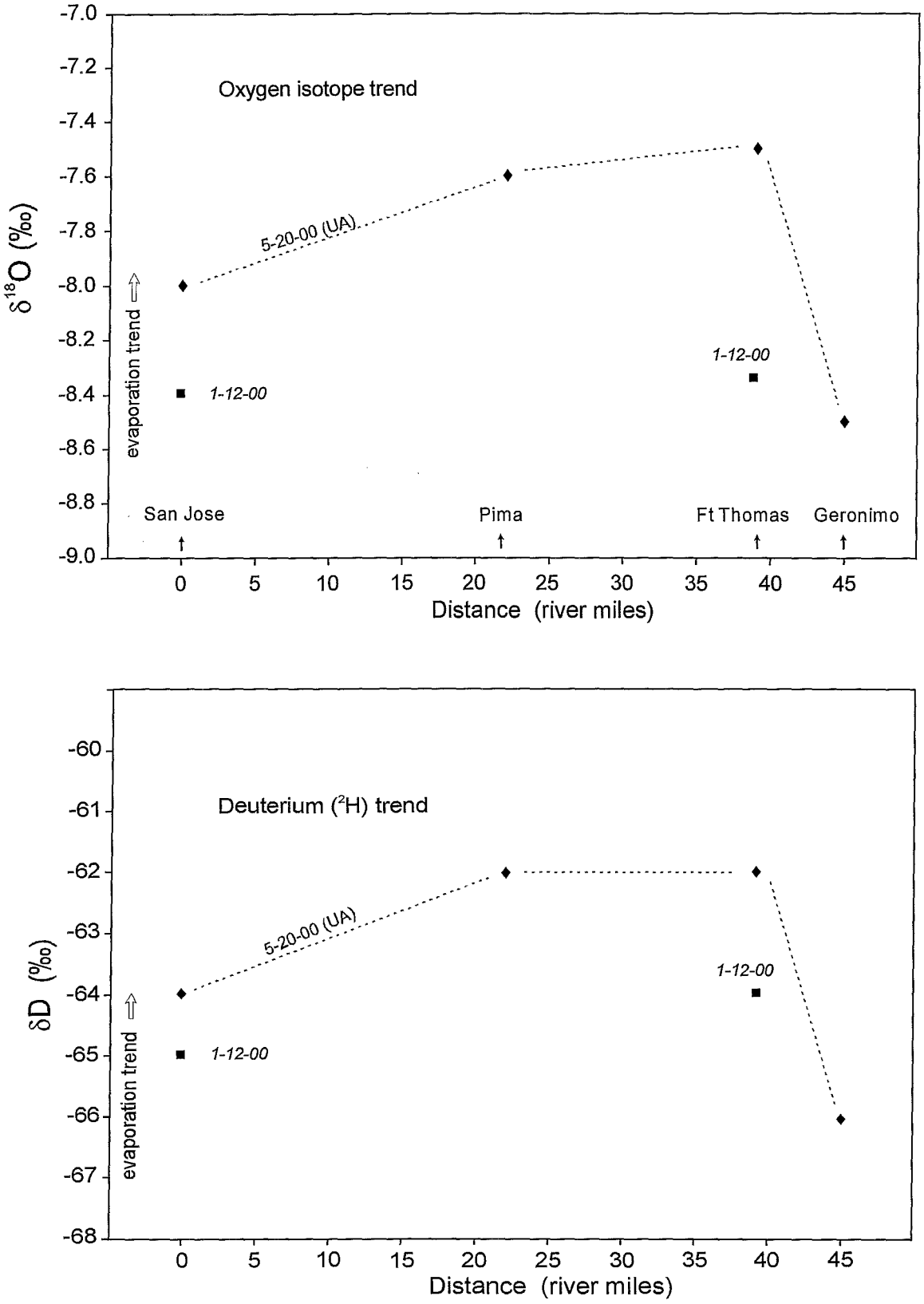


Figure 7. Stable O-H isotope trends in the Gila River



CONCLUSIONS

Tritium is useful for distinguishing pre-bomb (~1955) water from post-bomb water. In the Safford basin, tritium measurements indicate that much of the groundwater, even some of that in the active Gila River channel, is too old to be derived from short-term infiltration of river water. Stable isotopes also indicate a deep-aquifer source for springs and some seeps. It is significant, given the argument that much or all of the groundwater being pumped in the valley is river water, that *some water in the river channel itself is not river water*.

Owing to the limited number of samples in the study, the groundwater and river water have not been fully characterized, and others such as irrigation return and tributary inflows were not characterized at all. The results of this tritium pilot study should not be taken as proving an average, typical, or characteristic value for any of the types of water sampled.

As in a previous isotope study (Harris, 1999a), plots of isotope trends downstream in the Gila River show important shifts in the isotopic composition of the river water occur in the Safford basin, mostly below Pima. These trends reverse below Fort Thomas, for reasons that are still largely unexplained.

Repeated sampling at several sites shows seasonal variations. Seasonal variations are important in mass-balance calculations because they demonstrate that the results from a single sampling event do not fully characterize a typical or average chemical or isotopic composition of waters in a complex geohydrologic system such as the Safford basin. In order for isotopic studies such as these to be truly effective at defining "the" isotopic composition of a source water, that source must be sampled at many places enough times under different conditions to characterize a typical isotopic composition or tritium content.

Conditions that change seasonally and from year to year in the Safford basin include:

- different flow regimes in the Gila River due to:
  - weather (dry vs. rainy periods) and
  - diversions for irrigation
- temperature and humidity (affects evaporation, ET rates)
- stage of crops (affects amount of irrigation, ET rates, fertilizer use)
- amount of groundwater used for irrigation (depends on flow and salinity of Gila River)

All of these conditions change tremendously over the course of a year, and vary from year to year, and such variations must be taken into account in order to fully characterize water in the Safford basin. Because conditions are constantly changing, for example, from short- and long-term climatic variations, it is not always possible or meaningful to place an 'average' value on a constantly shifting system. Statistical methods of dealing with seasonal variability in water quality analyses are discussed in Montgomery and others (1987) and Harris and others (1987). In light of these factors, the results of this tritium

pilot study should not be taken as proving an average, typical, or characteristic value for any of the water samples. The tritium contents for samples reported here are valid only for the conditions that were present at the time of sampling. Sampling at different times could yield different results. A single sampling, or two, does not give an accurate picture. Sampling must be repeated many times before a true understanding can be achieved. Attaching significance to any individual number presented here may constitute over-interpretation.

In order to properly calculate a more meaningful 'age' requires developing a tritium input function that accounts for the different tritium contents of different rains, how much of each rain infiltrates, how much time the precipitation spends in the near-surface environment before it becomes truly isolated from the atmosphere, and mixing in the recharge area (Clark and Fritz, 1997). These components were not evaluated in this study and the development of a tritium input function is beyond the scope of this study.

Other methods are available for 'dating' of water, including the ^{3}H-^{3}He (tritium-helium ingrowth) method and the thermonuclear ^{36}Cl method (Clark and Fritz, 1997). The ^{3}H-^{3}He method determines the age based on the principal that as tritium decays, helium is produced at the same rate. Calculations do not require a tritium input function, but the downside is that ^{3}He measurements are expensive and are not routinely done.

The rationale behind the ^{36}Cl method is the same as tritium in that because the isotope is produced only in trace amounts naturally but was produced in massive quantities during atmospheric nuclear detonations in the 1950s and early 1960s, water with little or none of the isotope was precipitated before this date. A shortcoming with this method is the high cost and the lack of labs that perform this analysis.

Another method for dating water is the use of chlorofluorocarbon compounds. The rationale behind this method is that because the chemicals did not exist prior to a certain date, water with none of the chemical was precipitated before this date, and water containing the chemical fell after the chemical was in use. These methods tend to give an either/or age, that is, either the chemical is there or it isn't, and the age obtained is 'before date x' or 'after date x'. Another shortcoming with some dating methods such as these is their high cost and the extraordinary care that must be taken to avoid contamination during sample collection and analysis.

Carbon-14 dating is used for dating groundwater but is restricted to water that is at least hundreds of years old. In the Safford basin, tritium measurements indicate that some of the old water sampled in artesian wells may be decades old, but some of the deep well still have detectible tritium, which means the water may be too young to date with ^{14}C. For very deep wells in the basin, such as the Gila Oil Syndicate well, 2645 feet deep, or others that tap the deepest and oldest aquifers, ^{14}C may be appropriate. The calculation of an age with ^{14}C is complicated because of the possibility of mixing of old and young water. Carbon-14 data always need geochemical modeling to yield estimates of water age.

RECOMMENDATIONS

More extensive and repeated sampling
An expanded investigation of the natural sources of TDS and distribution of old groundwater in the upper Gila River watershed is warranted. This pilot study showed that tritium is useful for identifying old water not connected to the Gila River. In some places, old water was found in the Gila River channel. Only much more extensive and repeated sampling will be adequate to reach any kind of understanding of the amount and distribution of older versus younger groundwater in the Safford basin and its relation to water in the Gila River.

Establish intensive local monitoring program
This study is the first to measure tritium levels in the Safford basin. With the exception of O-D measured by Smalley (1983) the previous WPF isotope study (Harris, 1999a) was the first to measure the isotopic composition of sediments, groundwater, and river water in the basin. Establishing the average tritium content of precipitation would require years of constant monitoring. Similarly, there has been no uniform, consistent monitoring of the Gila River for chemical and isotopic composition, and therefore, it is difficult to assess whether there has been an improvement or degradation of water quality over time. Establishing the distribution of isotopic compositions of groundwater in the basin would also require a major effort.

Expand studies into San Carlos Indian Reservation
This study covered only the portion of the upper Gila River upstream of the San Carlos Indian Reservation boundary. Lacustrine sediments and evaporites such as salt are known on the reservation (e.g. Marlowe, 1961) and likely represent a further possible source of TDS to the Gila River. Given the large amounts of salt in clay outside the Reservation in the Fort Thomas-Geronimo area, it is logical that these salty deposits continue onto the Indian land. Artesian leakage of deep groundwater into the shallow aquifer and the river has been calculated to be 106,000 cubic feet per day per mile of river in the Reservation (Hanson and Brown, 1972). Mass balances require knowledge of all the major gains and losses of constituents. Without information from that part of the Gila on the Reservation, any study of water quality is incomplete. Including the Reservation would require the permission and cooperation of the San Carlos Apache Tribe.

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Figure 8

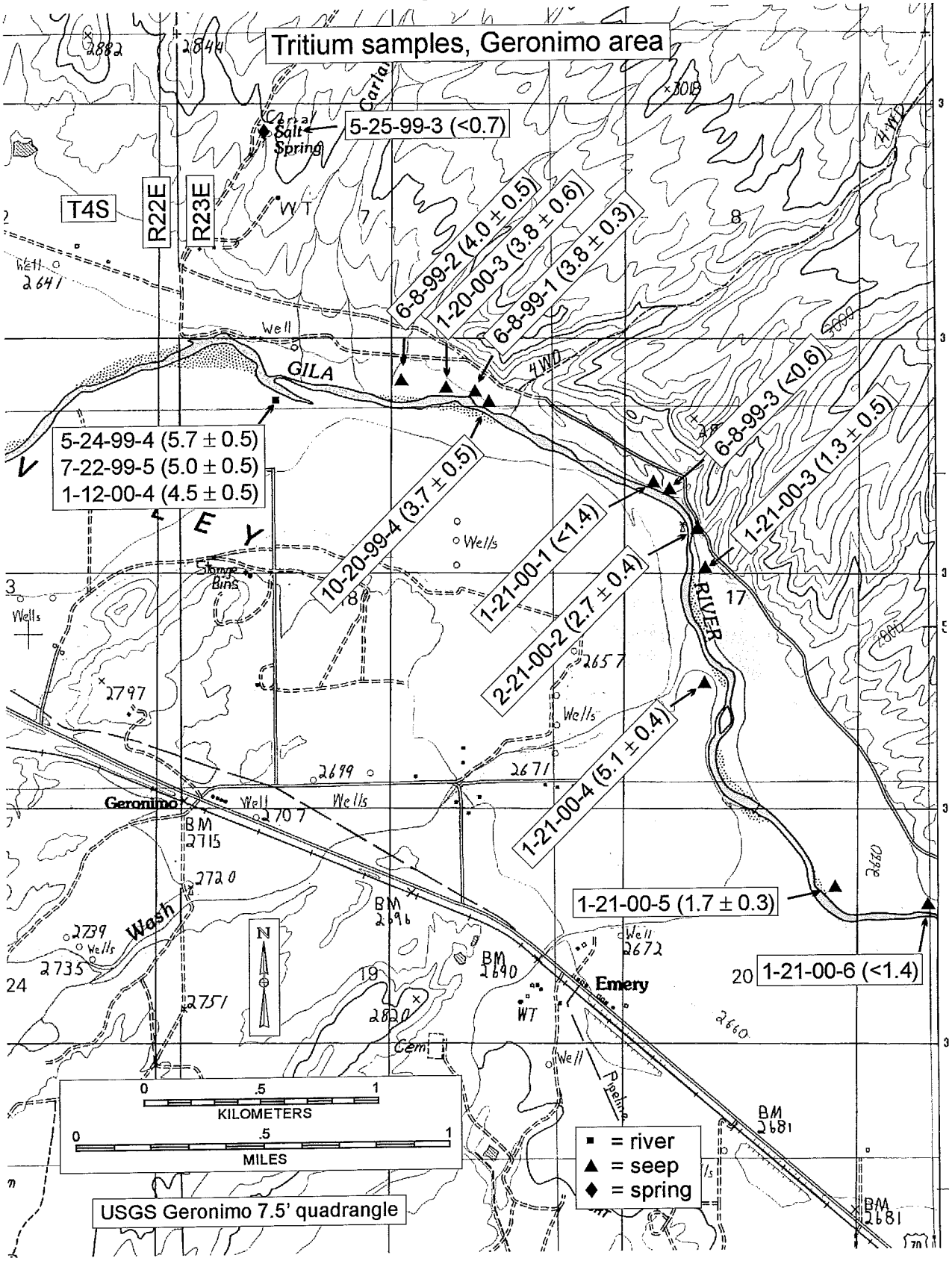

Tritium samples, Geronimo area
5-25-99-3 (<0.7)
6-8-99-2 (4.0 ± 0.5)
1-20-00-3 (3.8 ± 0.6)
6-8-99-1 (3.8 ± 0.3)
6-8-99-3 (<0.6)
1-21-00-3 (1.3 ± 0.5)
5-24-99-4 (5.7 ± 0.5)
7-22-99-5 (5.0 ± 0.5)
1-12-00-4 (4.5 ± 0.5)
10-20-99-4 (3.7 ± 0.5)
1-21-00-1 (<1.4)
2-21-00-2 (2.7 ± 0.4)
1-21-00-4 (5.1 ± 0.4)
1-21-00-5 (1.7 ± 0.3)
1-21-00-6 (<1.4)
T4S
R22E
R23E
GILA
RIVER
Geronimo
Emery
Salt Spring
Wash
KILOMETERS
MILES
= river
= seep
= spring
USGS Geronimo 7.5' quadrangle

Figure 9

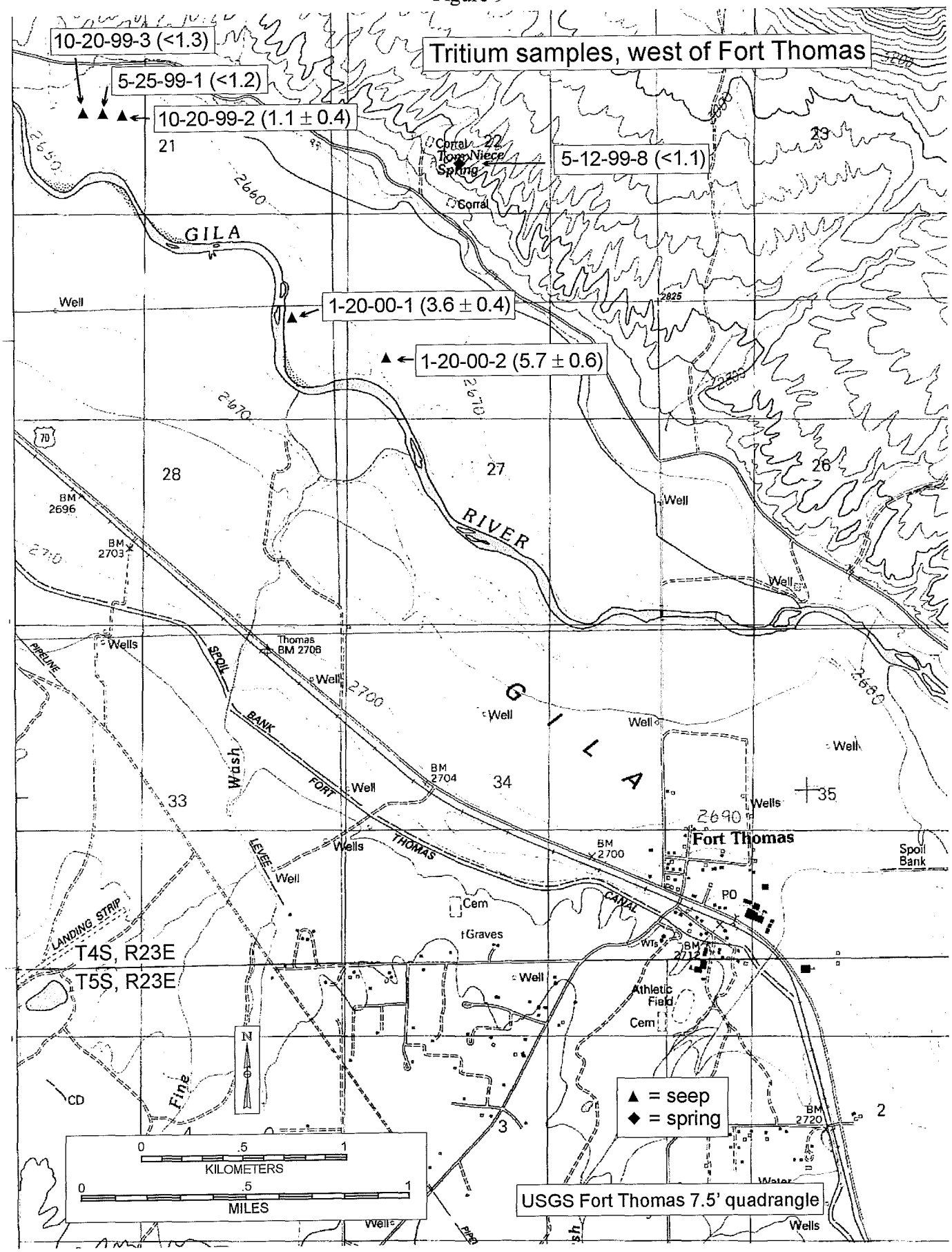

Tritium samples, west of Fort Thomas
10-20-99-3 (<1.3)
5-25-99-1 (<1.2)
10-20-99-2 (1.1 ± 0.4)
5-12-99-8 (<1.1)
1-20-00-1 (3.6 ± 0.4)
1-20-00-2 (5.7 ± 0.6)
GILA
RIVER
Fort Thomas
T4S, R23E
T5S, R23E
▲ = seep
◆ = spring
KILOMETERS
MILES
USGS Fort Thomas 7.5' quadrangle

Figure 10

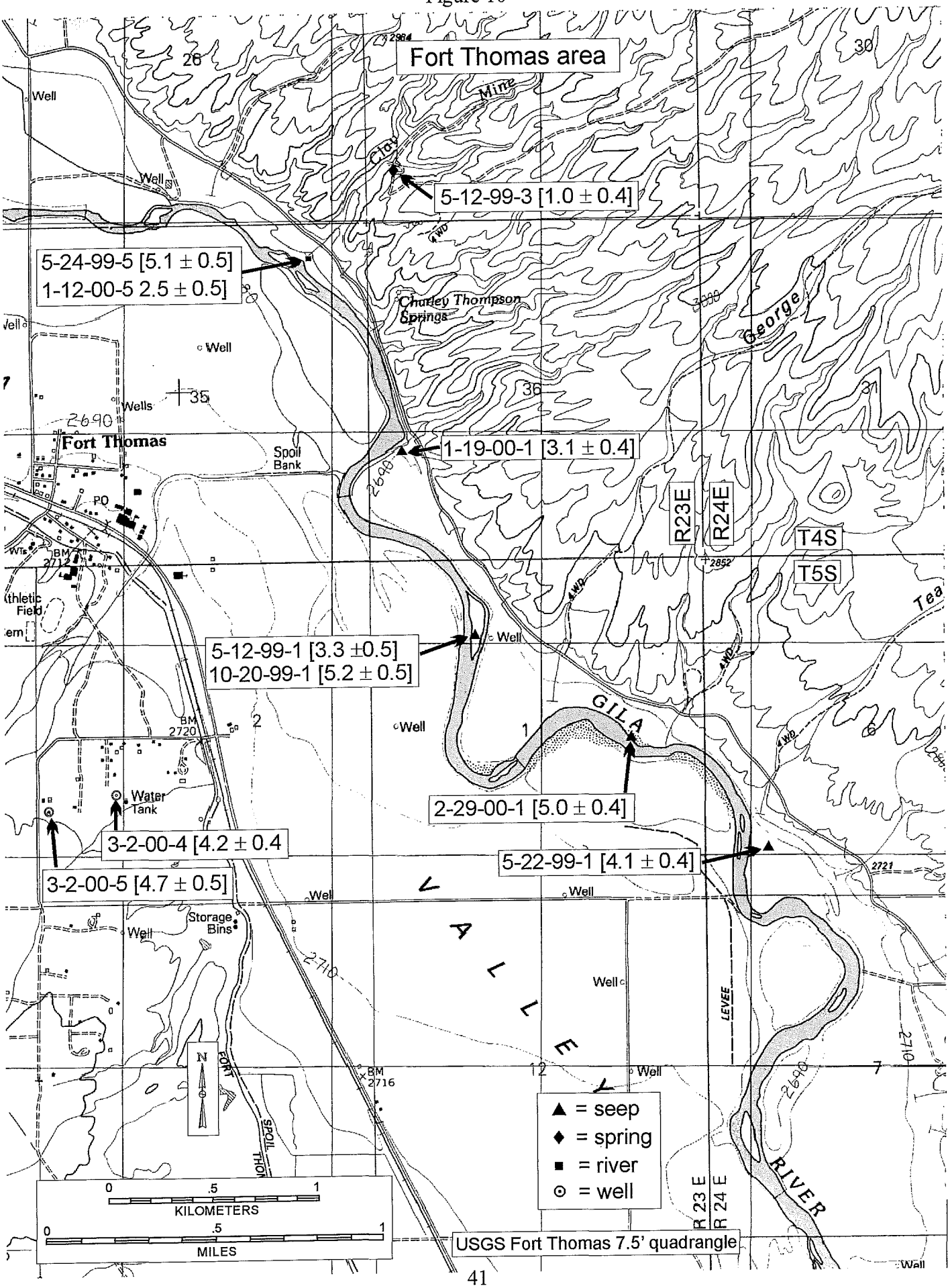

Fort Thomas area
5-12-99-3 [1.0 ± 0.4]
5-24-99-5 [5.1 ± 0.5]
1-12-00-5 2.5 ± 0.5]
1-19-00-1 [3.1 ± 0.4]
5-12-99-1 [3.3 ±0.5]
10-20-99-1 [5.2 ± 0.5]
2-29-00-1 [5.0 ± 0.4]
5-22-99-1 [4.1 ± 0.4]
3-2-00-4 [4.2 ± 0.4
3-2-00-5 [4.7 ± 0.5]
Fort Thomas
Charley Thompson Springs
Clay Mine
George
Spoil Bank
Water Tank
Storage Bins
Athletic Field
GILA
VALLEY
RIVER
LEVEE
R23E
R24E
T4S
T5S
R 23 E
R 24 E
▲ = seep
♦ = spring
■ = river
⊙ = well
KILOMETERS
MILES
USGS Fort Thomas 7.5' quadrangle

Figure 11

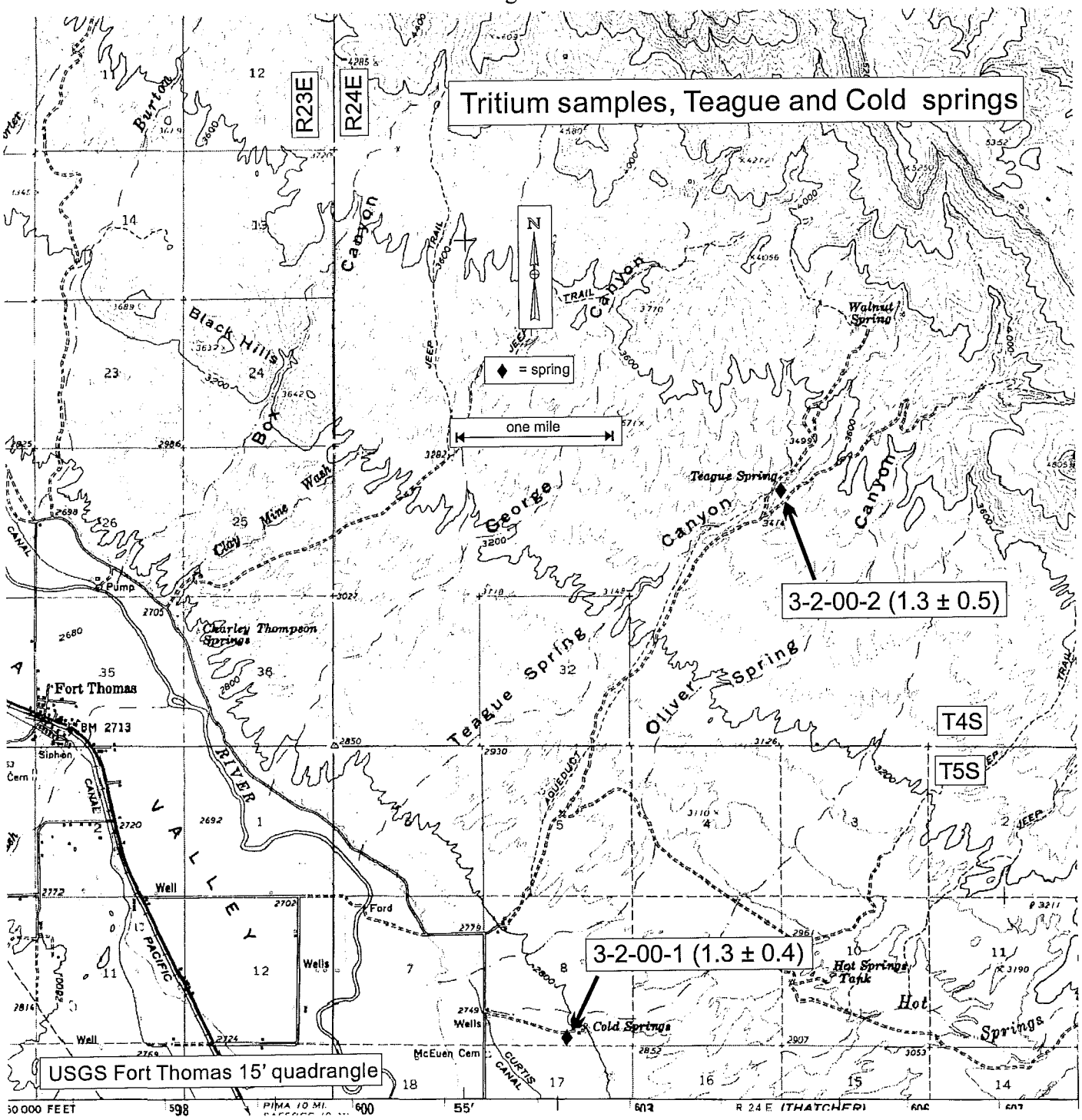

Tritium samples, Teague and Cold springs
R23E
R24E
N
= spring
one mile
Teague Spring
3-2-00-2 (1.3 ± 0.5)
3-2-00-1 (1.3 ± 0.4)
Cold Springs
Hot Springs
Walnut Spring
Charley Thompson Springs
Fort Thomas
T4S
T5S
USGS Fort Thomas 15' quadrangle

Figure 12

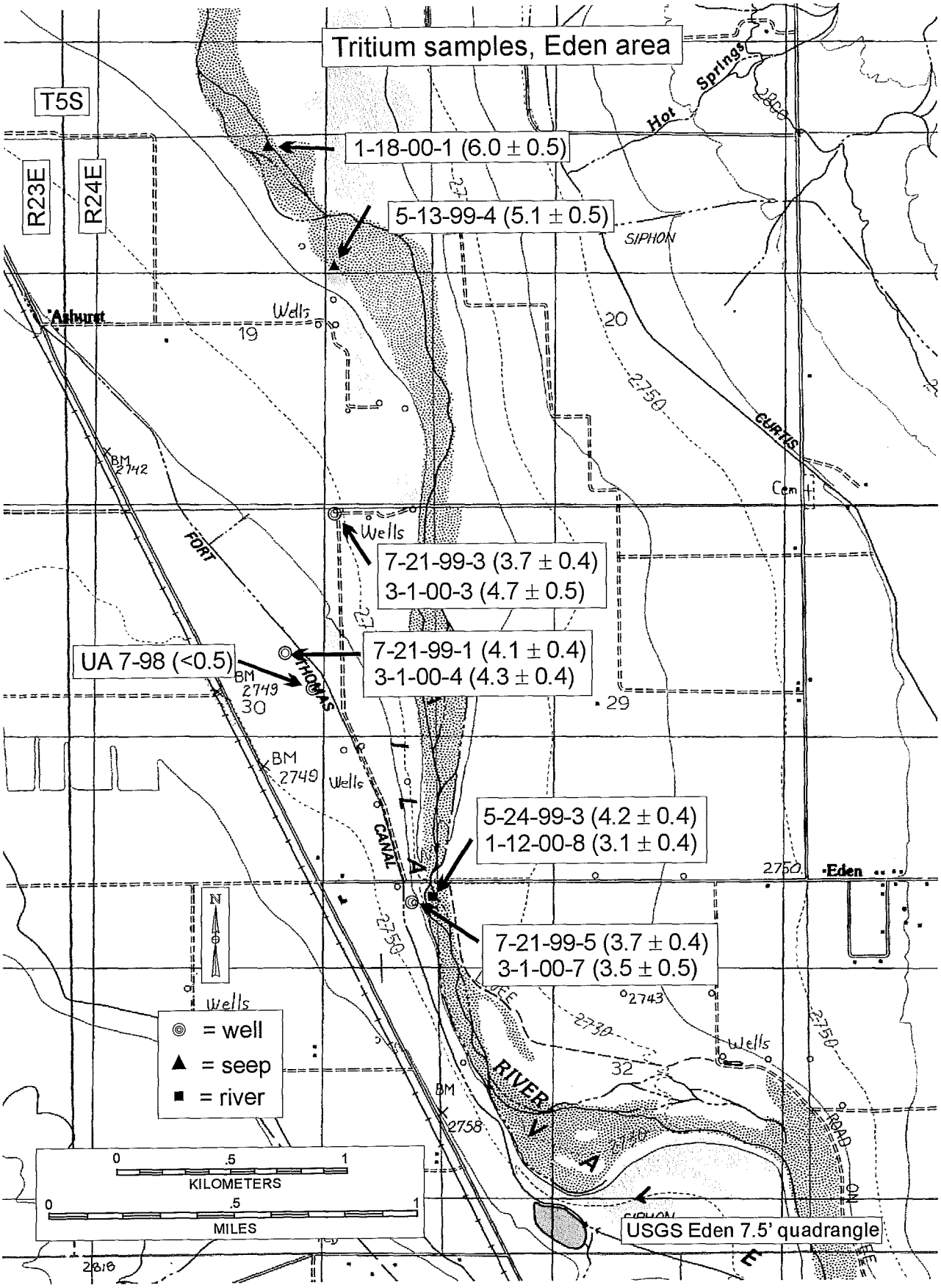

Tritium samples, Eden area
T5S
R23E
R24E
1-18-00-1 (6.0 ± 0.5)
5-13-99-4 (5.1 ± 0.5)
7-21-99-3 (3.7 ± 0.4)
3-1-00-3 (4.7 ± 0.5)
UA 7-98 (<0.5)
7-21-99-1 (4.1 ± 0.4)
3-1-00-4 (4.3 ± 0.4)
5-24-99-3 (4.2 ± 0.4)
1-12-00-8 (3.1 ± 0.4)
7-21-99-5 (3.7 ± 0.4)
3-1-00-7 (3.5 ± 0.5)
= well
= seep
= river
KILOMETERS
MILES
USGS Eden 7.5' quadrangle
Hot Springs
SIPHON
CURTIS
FORT
THOMAS
CANAL
RIVER
Ashurst
Eden
Wells
BM
Cem

Figure 13

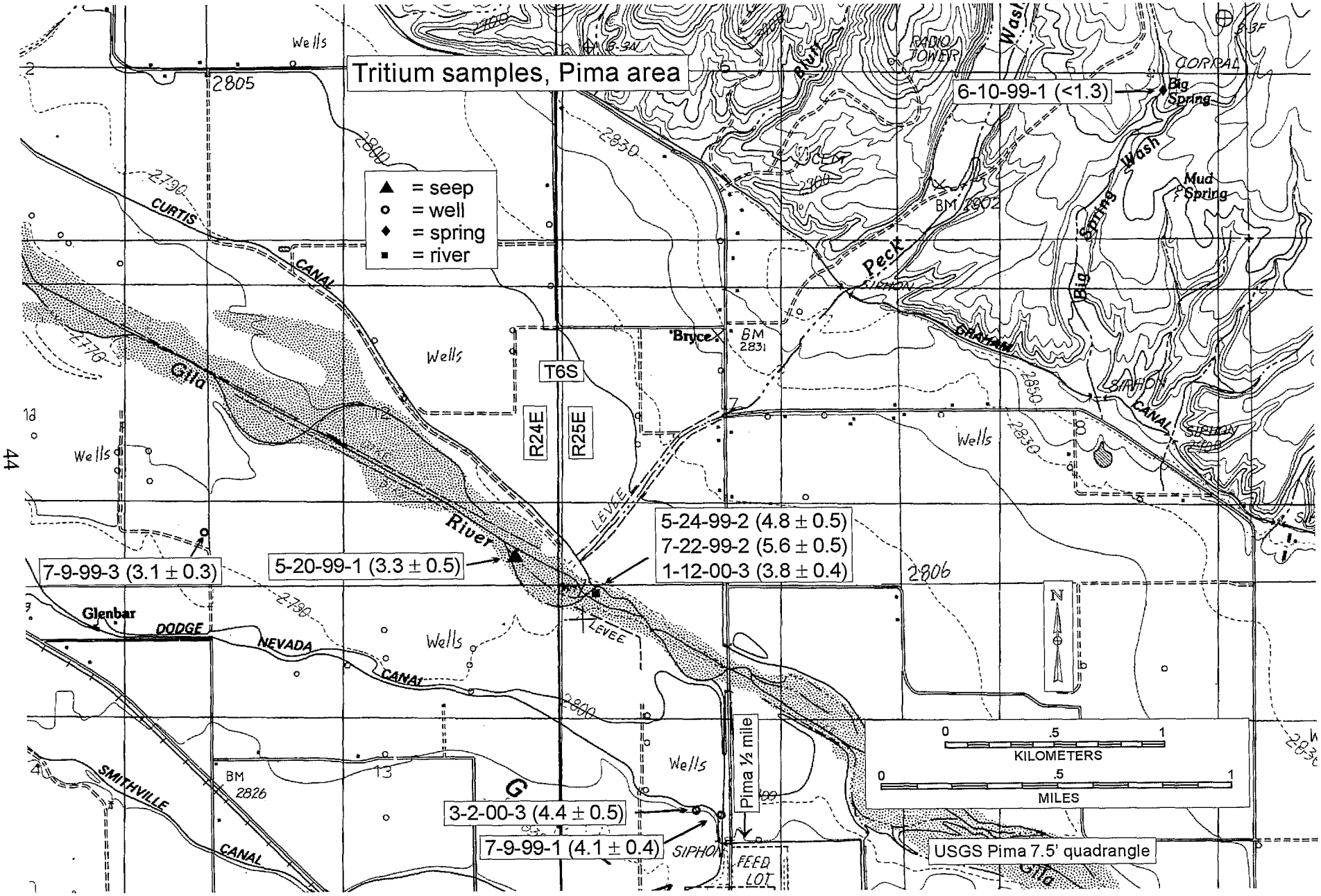

Tritium samples, Pima area
▲ = seep
o = well
♦ = spring
■ = river
6-10-99-1 (<1.3)
Big Spring
Mud Spring
Big Spring Wash
Peck
Bryce
BM 2831
T6S
R24E
R25E
Gila
River
CURTIS
CANAL
LEVEE
5-24-99-2 (4.8 ± 0.5)
7-22-99-2 (5.6 ± 0.5)
1-12-00-3 (3.8 ± 0.4)
5-20-99-1 (3.3 ± 0.5)
7-9-99-3 (3.1 ± 0.3)
Glenbar
DODGE
NEVADA
CANAL
SMITHVILLE
CANAL
BM 2826
3-2-00-3 (4.4 ± 0.5)
7-9-99-1 (4.1 ± 0.4)
Pima ½ mile
SIPHON
FEED LOT
Wells
N
0 .5 1
KILOMETERS
0 .5 1
MILES
USGS Pima 7.5' quadrangle

Figure 14

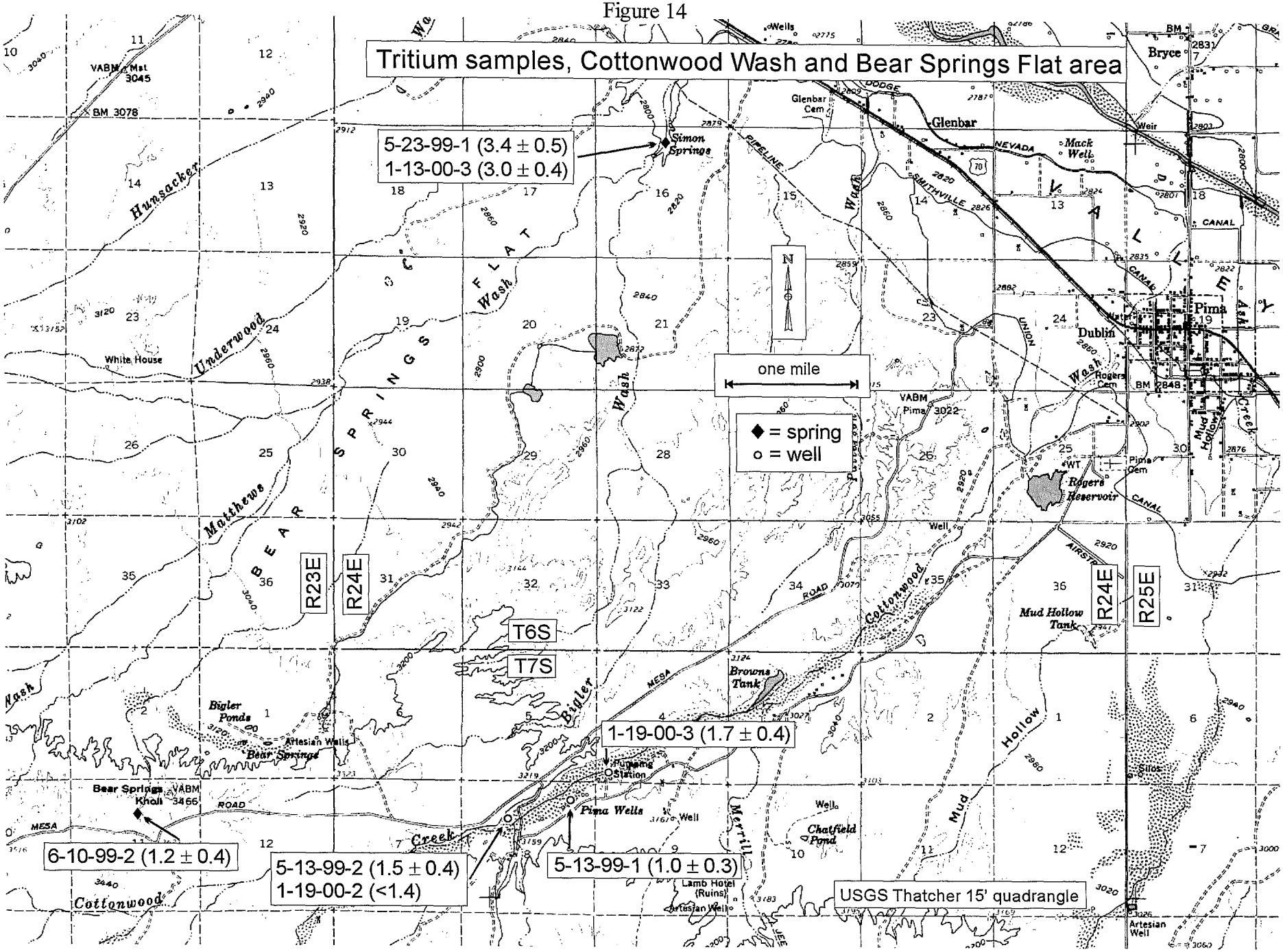

Tritium samples, Cottonwood Wash and Bear Springs Flat area
5-23-99-1 (3.4 ± 0.5)
1-13-00-3 (3.0 ± 0.4)
1-19-00-3 (1.7 ± 0.4)
6-10-99-2 (1.2 ± 0.4)
5-13-99-2 (1.5 ± 0.4)
1-19-00-2 (<1.4)
5-13-99-1 (1.0 ± 0.3)
one mile
◆ = spring
o = well
USGS Thatcher 15' quadrangle
R23E
R24E
R25E
T6S
T7S
Simon Springs
Bear Springs
Pima Wells
Bigler Ponds
Browns Tank
Mud Hollow Tank
Rogers Reservoir
Chatfield Pond
Glenbar
Dublin
Pima
Bryce
Cottonwood
Bigler
Mud Hollow
Hunsacker
Underwood
Matthews
Merrill
Bear Springs Flat
Cottonwood Wash
Mud Hollow Creek
Pumping Station
Lamb Hotel (Ruins)
Artesian Well
Silos
White House
Bear Springs Knoll
Rogers Cem
Pima Cem
Glenbar Cem
Mack Well
Weir
Wells
Well
VABM Mat 3045
BM 3078
VABM Pima 3022
BM 2848
BM 2831
NEVADA
SMITHVILLE
UNION
DODGE
PIPELINE
CANAL
AIRSTRIP
ROAD
MESA
JEEP
N

Figure 15

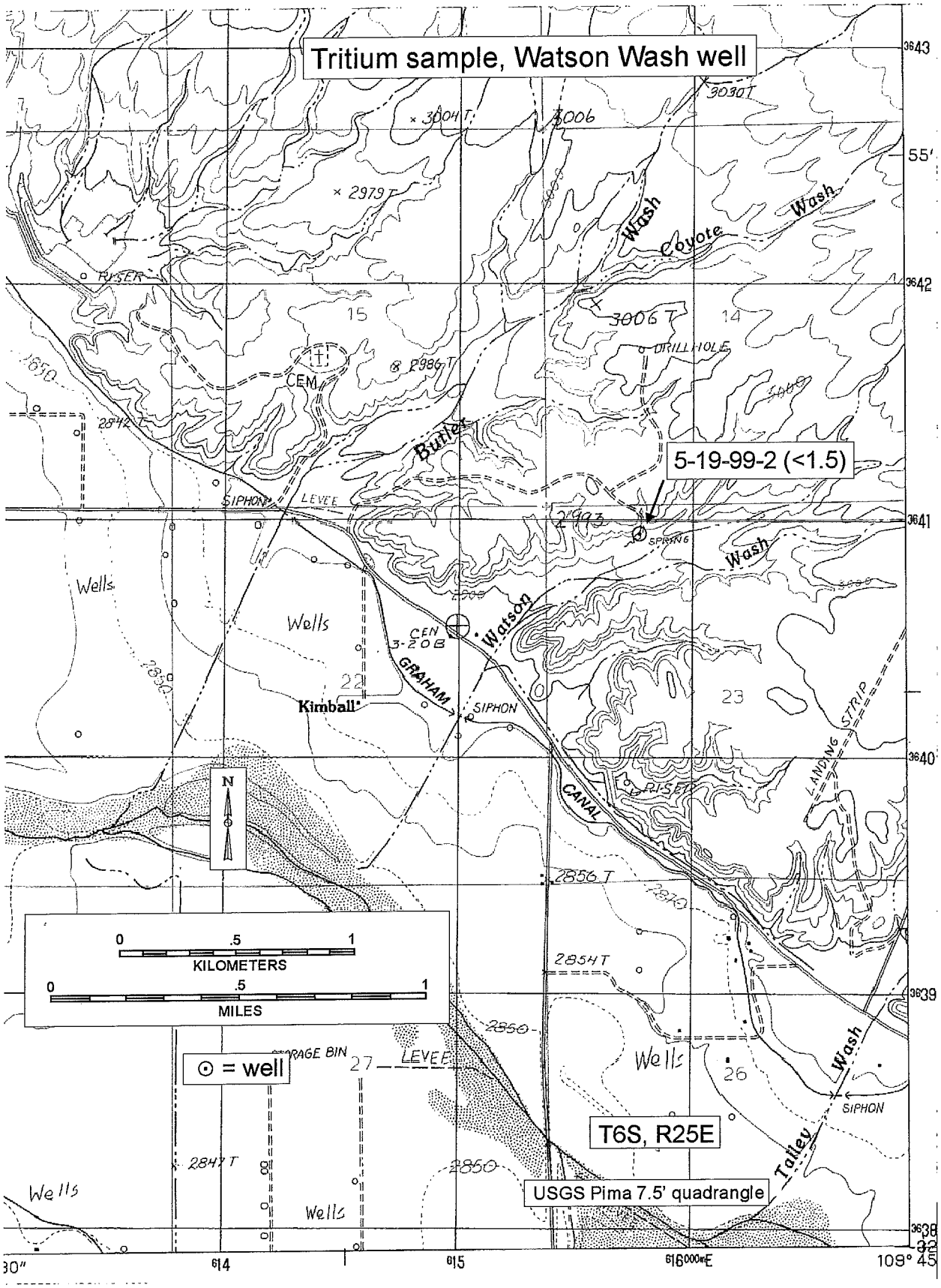

Tritium sample, Watson Wash well
5-19-99-2 (<1.5)
Coyote Wash
Butler Wash
Watson Wash
Talley Wash
GRAHAM
CANAL
Kimball
CEM
SIPHON
LEVEE
SPRING
DRILLHOLE
LANDING STRIP
RISER
Wells
N
0 .5 1
KILOMETERS
0 .5 1
MILES
⊙ = well
T6S, R25E
USGS Pima 7.5' quadrangle

Figure 16

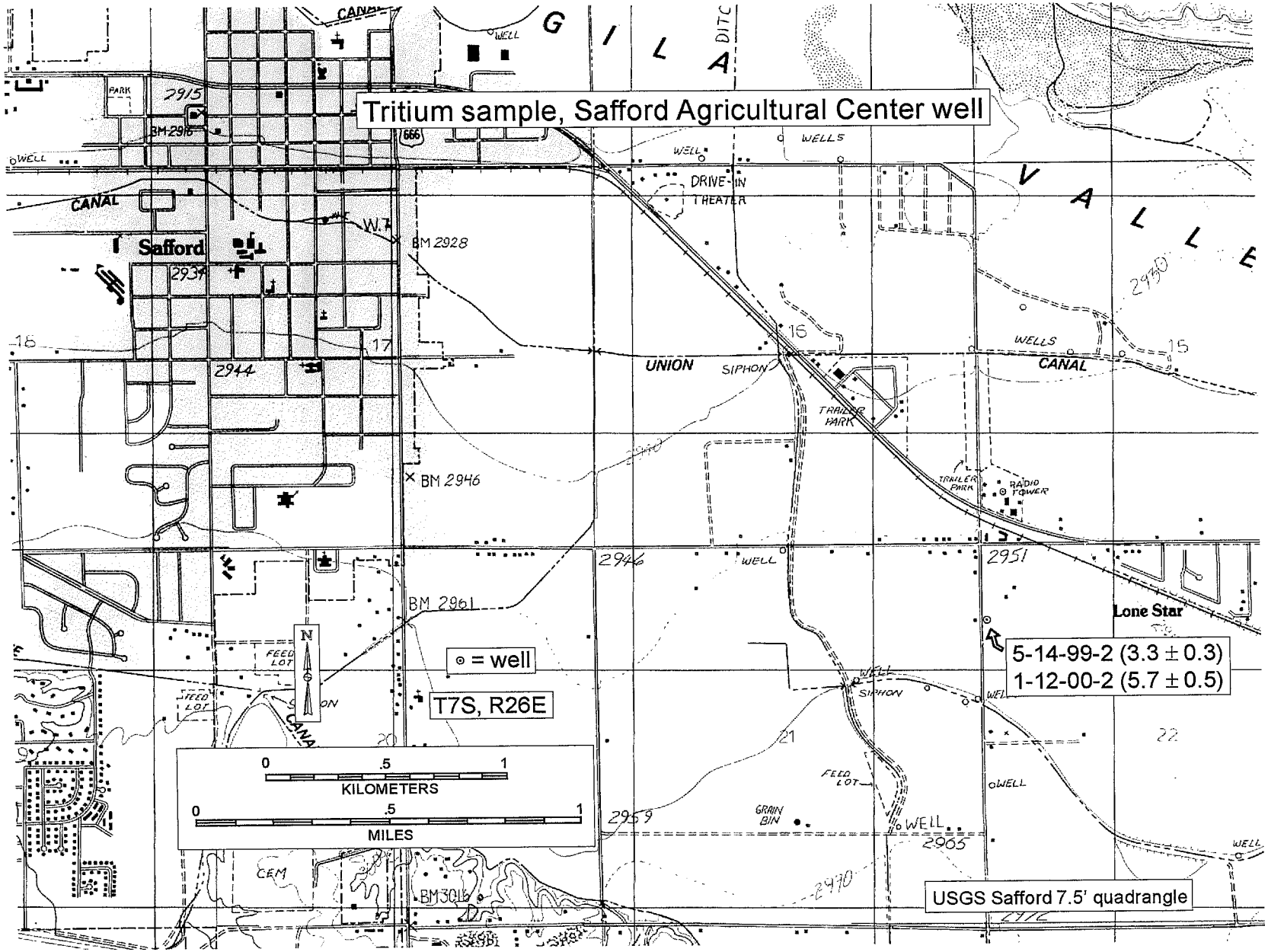

Tritium sample, Safford Agricultural Center well
G I L A
V A L L E
Safford
Lone Star
CANAL
UNION
SIPHON
DRIVE-IN THEATER
TRAILER PARK
RADIO TOWER
FEED LOT
GRAIN BIN
WELL
WELLS
BM 2928
BM 2946
BM 2961
BM 3016
2915
2934
2944
2946
2951
2959
2965
2970
2980
666
= well
T7S, R26E
5-14-99-2 (3.3 ± 0.3)
1-12-00-2 (5.7 ± 0.5)
0 .5 1
KILOMETERS
0 .5 1
MILES
USGS Safford 7.5' quadrangle

Figure 17

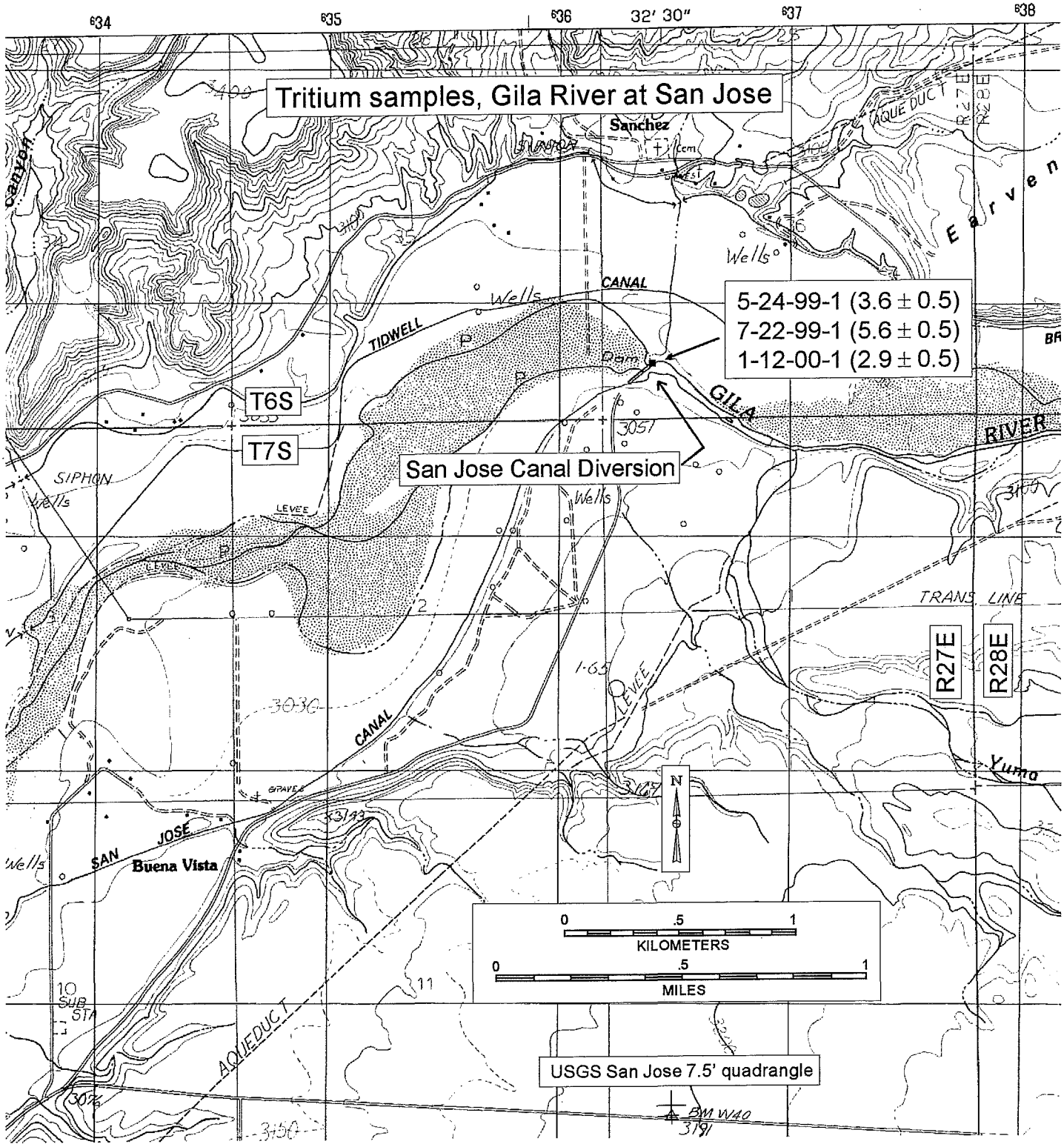

Tritium samples, Gila River at San Jose
5-24-99-1 (3.6 ± 0.5)
7-22-99-1 (5.6 ± 0.5)
1-12-00-1 (2.9 ± 0.5)
T6S
T7S
San Jose Canal Diversion
R27E
R28E
GILA
RIVER
CANAL
TIDWELL
SAN JOSE
Buena Vista
Sanchez
TRANS LINE
AQUEDUCT
SIPHON
LEVEE
Yuma
N
0 .5 1
KILOMETERS
0 .5 1
MILES
USGS San Jose 7.5' quadrangle

Figure 18

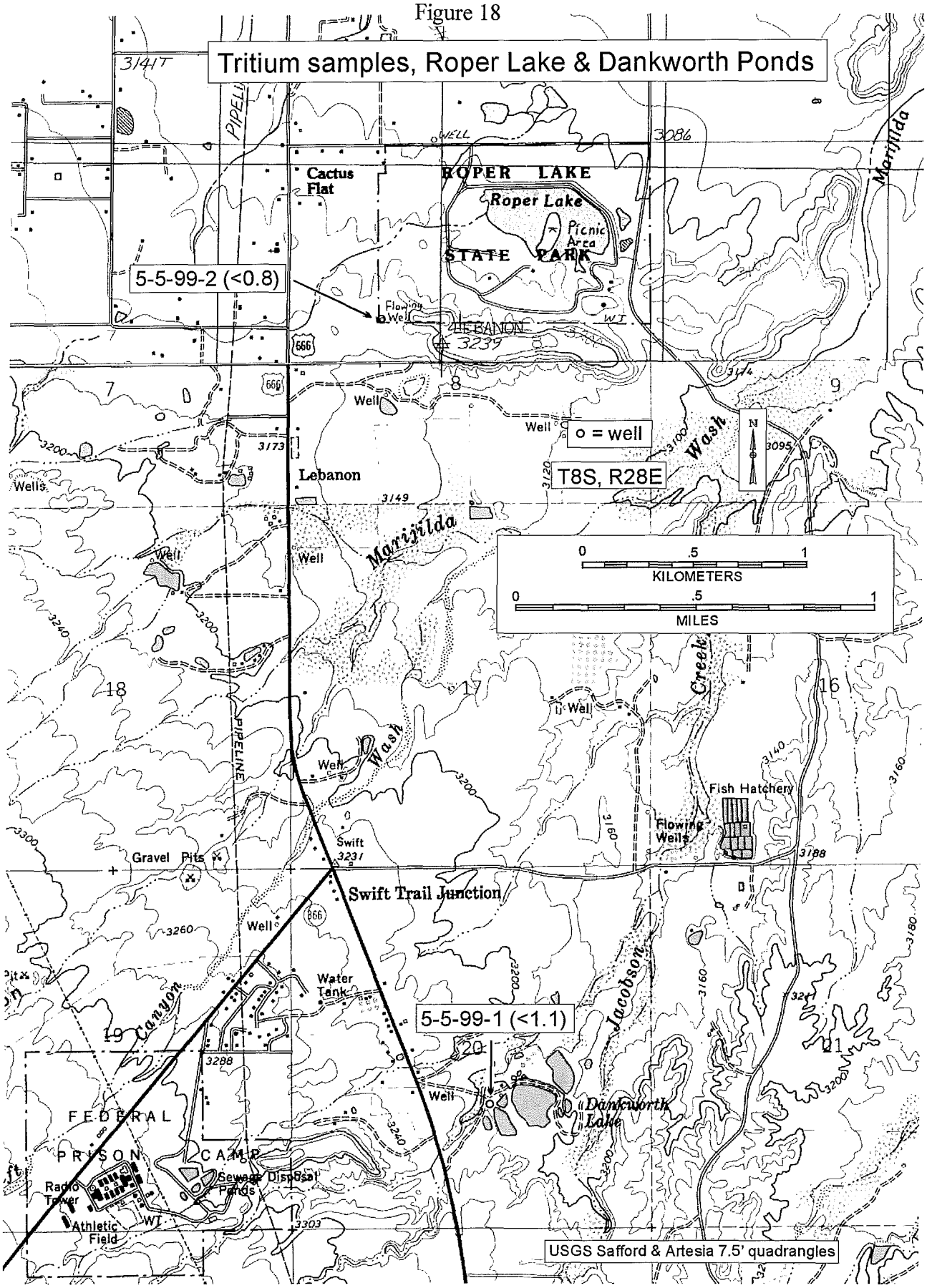

Tritium samples, Roper Lake & Dankworth Ponds
5-5-99-2 (<0.8)
5-5-99-1 (<1.1)
o = well
T8S, R28E
Cactus Flat
ROPER LAKE
Roper Lake
Picnic Area
STATE PARK
LEBANON
Lebanon
Marijilda
Wash
Swift Trail Junction
Gravel Pits
Fish Hatchery
Flowing Wells
Water Tank
Jacobson
Creek
Canyon
Dankworth Lake
FEDERAL PRISON CAMP
Radio Tower
Athletic Field
Sewage Disposal Ponds
PIPELINE
Well
Wells
0 .5 1
KILOMETERS
0 .5 1
MILES
USGS Safford & Artesia 7.5' quadrangles

Figure 19

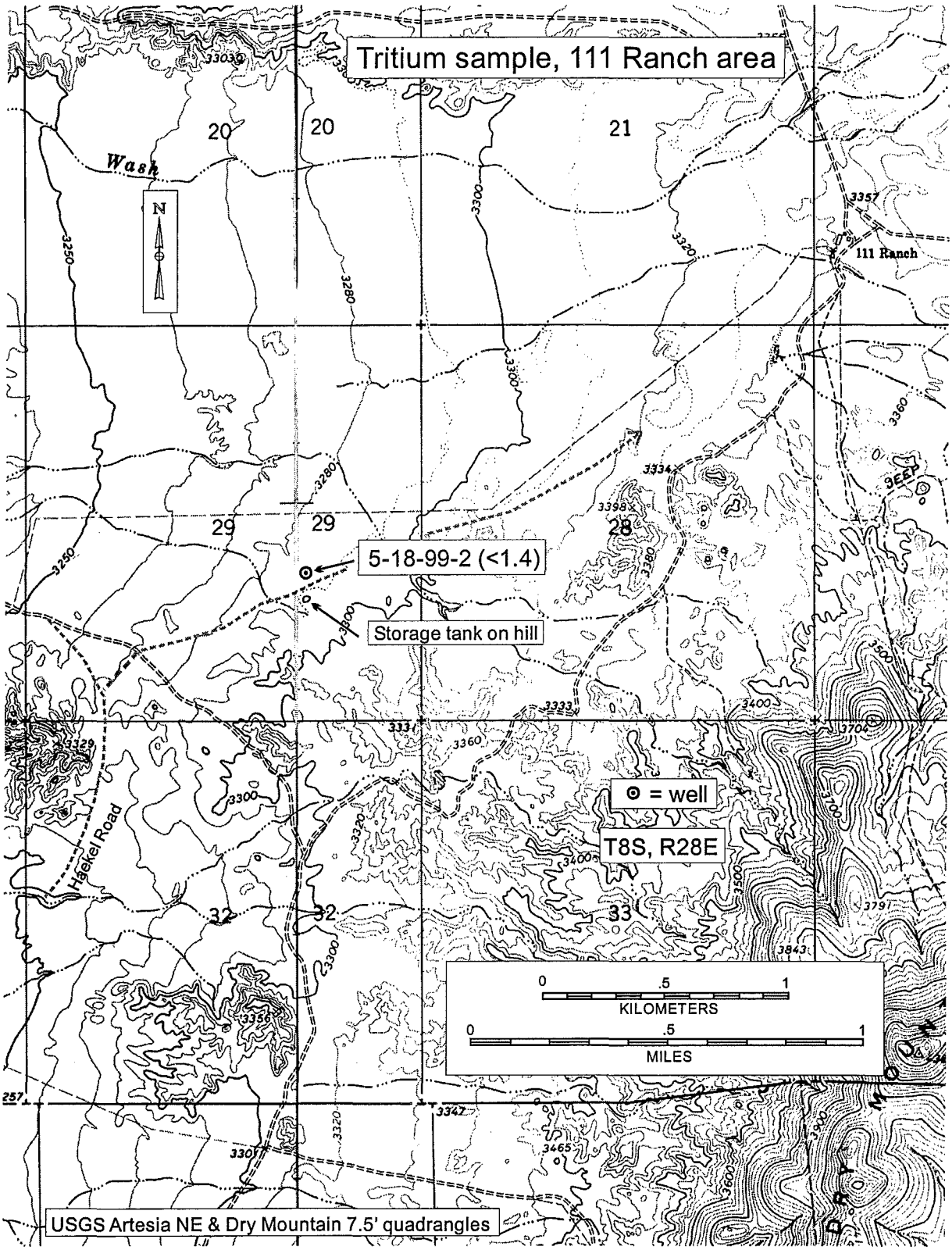

Tritium sample, 111 Ranch area
20
20
21
Wash
N
111 Ranch
29
29
28
5-18-99-2 (<1.4)
Storage tank on hill
⊙ = well
T8S, R28E
Haekel Road
32
32
33
0 .5 1
KILOMETERS
0 .5 1
MILES
USGS Artesia NE & Dry Mountain 7.5' quadrangles

Figure 20

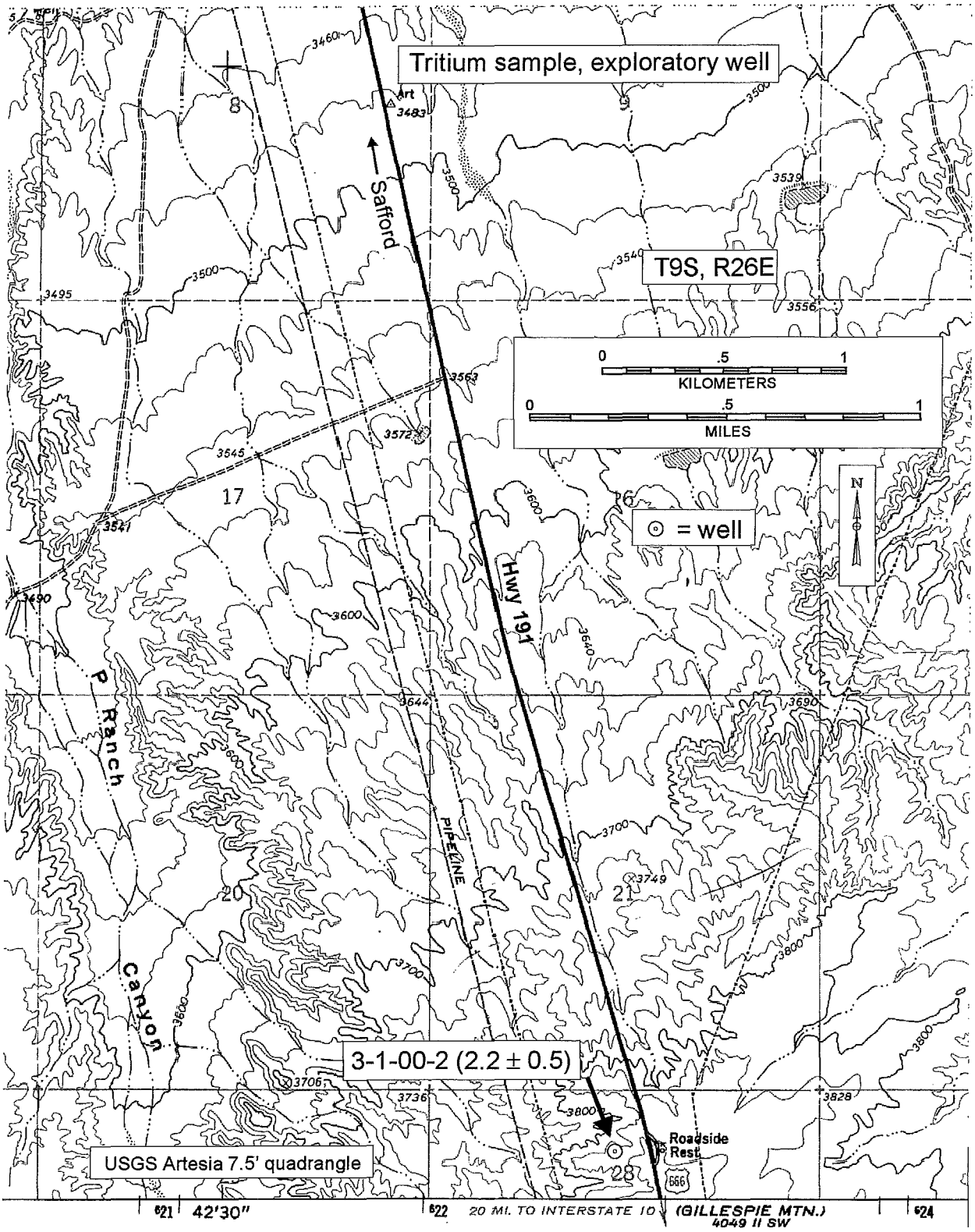
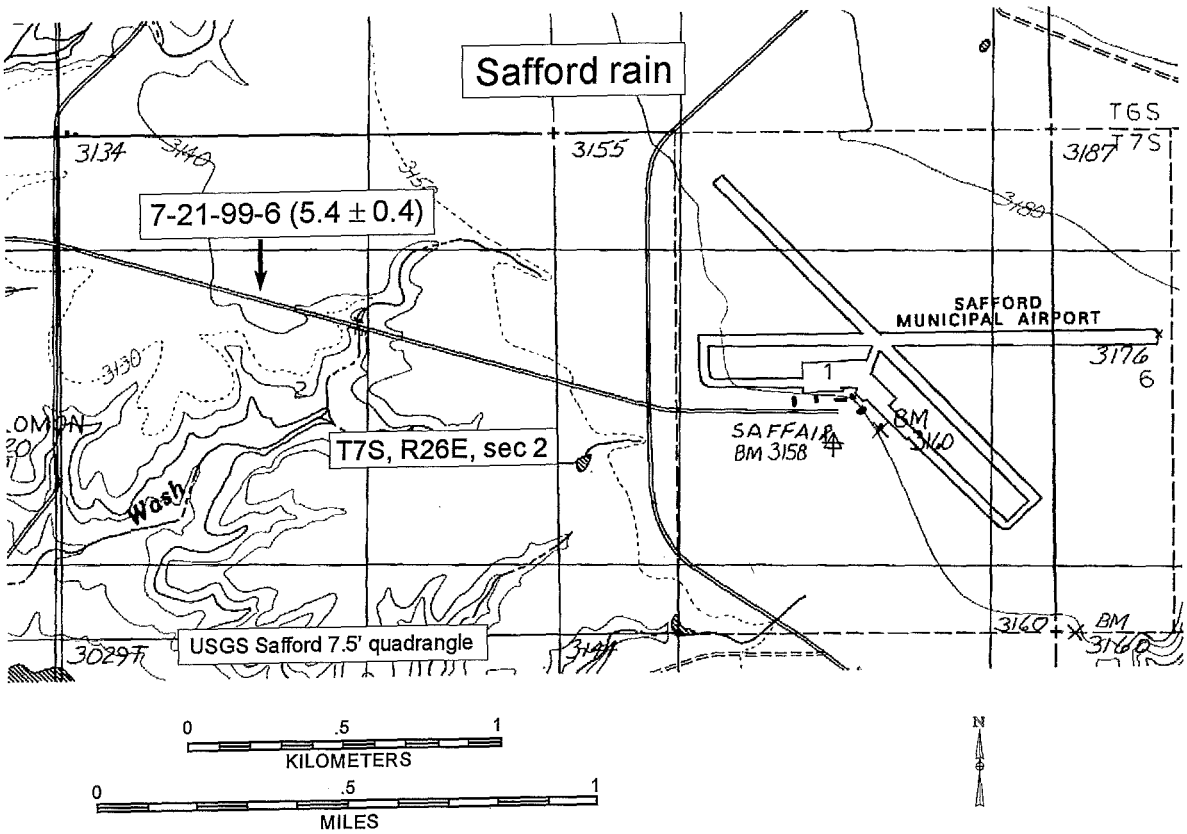
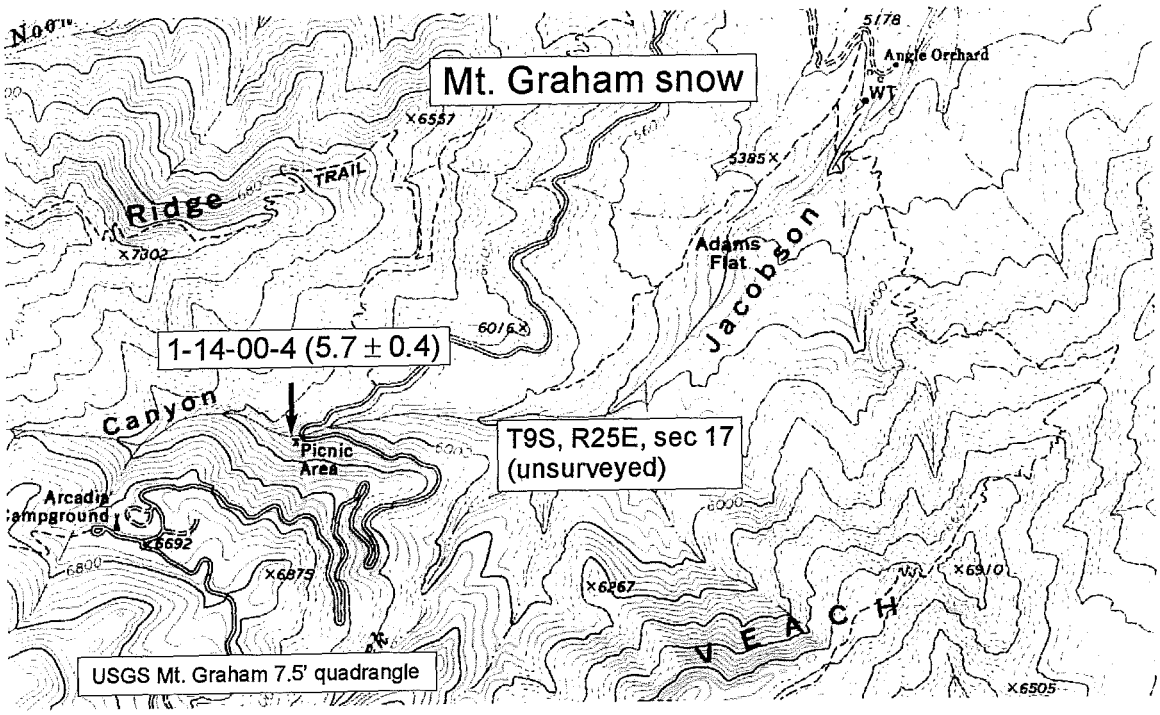

Tritium sample, exploratory well
Safford
T9S, R26E
0 .5 1
KILOMETERS
0 .5 1
MILES
N
⊙ = well
Hwy 191
PIPELINE
P Ranch
Canyon
3-1-00-2 (2.2 ± 0.5)
USGS Artesia 7.5' quadrangle
Roadside Rest
8
9
17
16
20
21
28
42'30"
20 MI. TO INTERSTATE 10
(GILLESPIE MTN.)
4049 II SW

Figure 21


Safford rain
7-21-99-6 (5.4 ± 0.4)
T7S, R26E, sec 2
SAFFORD MUNICIPAL AIRPORT
USGS Safford 7.5' quadrangle
KILOMETERS
MILES
N


Mt. Graham snow
1-14-00-4 (5.7 ± 0.4)
T9S, R25E, sec 17
(unsurveyed)
Ridge
Canyon
Jacobson
Adams Flat
Picnic Area
Arcadia Campground
USGS Mt. Graham 7.5' quadrangle

APPENDIX B

WELL COMPLETION INFORMATION

AND WELL LOGS

Data and logs from the Arizona Department of Water Resources

Table 3. Well completion information (ADWR Well-55 database).

Location	Reg #	UTM-X	UTM-Y	Date	Well depth	Water level	Cased depth	Case dia	Well log	Owner
Fort Thomas town well										
D(5-23)2cbd	606087	596869.8	3654260.8	Apr-59	80	30		16(12)	no	Graham County Utilities
Fort Thomas town well										
D(5-23)2cbc	605863	596666.9	3654458.1	Apr-59	90			16(12)	no	Graham County Utilities
Fort Thomas Canal Co. well			N-most							
D(5-24)30aba	607333	600961.4	3648872.5	Jan-57	51	18	51	16	no	Ft. Thomas Canal Co.
Fort Thomas Canal Co. well			N of gila well							
D(5-24)30aca	607332	600969.7	3648270.5	Jan-47	60	20	54	16	no	Ft. Thomas Canal Co.
Fort Thomas Canal Co. well			S of eden road							
D(5-24)31aaa	607326	601383	3647271.4	Jan-46	54	18	58	16	no	Ft. Thomas Canal Co.
	or 607327	601383	3647271.4	Jan-54	74	23	56	16	no	
Dodge-Nevada Canal Co. well			next to cottonwood							
D(6-25)18cad	607513	609702.3	3641558	Jan-44	40	11	40	16	no	Dodge-Nevada Canal Co.
Dodge-Nevada Canal Co. well			2nd from cottonwood							
D(6-25)18cac	607514	609507.6	3641555	Jan-44	50	14	50	16	no	Dodge-Nevada Canal Co.
Dodge-Nevada Canal Co. well			new well ?							
D(6-24)11d	574805?	607300.8	6342730	May-99?	0	0	0	0		Dodge-Nevada Canal Co.
Watson Wash well										
D(6-25)23)bb	643412	615693	3640791	?	?	flowing		2		BLM
Pima town well - upper										
D(7-24)8bdb	545487	601538.4	3634028.3	Jan-95	225	40	220	12	yes	Graham County Utilities

Table 3. Well completion information (ADWR Well-55 database).

Location	Reg #	UTM-X	UTM-Y	Date	Well depth	Water level	Cased depth	Case dia	Well log	Owner
Pima town well - artesian										
D(7-24)8bbc	606081	602342.6	3634229.5	Dec-58	585	flowing	585	12 (1)	no	Graham County Utilities
Pima town well - lower										
D(7-24)4ccd	605856	602945	3634629	Jan-59	290	10	290	12	no	Graham County Utilities
Safford Agricultural Center										
D(7-26)22bb	618700	623656.6	3631326.5	Jan-39	100		90	14	no	AZ Board of Regents
Roper Lake well- artesian										
D(8-26)8bdc	628222	620823.5	3624393.1	?	1450	flowing	?	6	no	AZ Game & Fish
Dankworth Ponds well - artesian										
D(8-26)20dbc	803625	621270.1	3620786.8	Jan-50	1260	flowing		?	no	AZ State Parks
	(or 803626, 627, 628)			Jan-60	900			6		
111 Ranch well - artesian										
D(8-28)29dbd	608751	640603.1	3619379	Dec-68	600	8 (art)	?	16	no	BLM
Gila Resources test well										
D(9-26)28abc				Feb-00	700 (?)					AZ State Land

Data from ADWR Well-55 database, version of September 1999
Data for Fort Thomas town wells in parentheses from Graham County Utilities

DEPARTMENT OF
JAN 30 1995
OPERATIONS DIV.

ARIZONA DEPARTMENT OF WATER RESOURCES
15 South 15th Avenue
Phoenix, Arizona 85007

WELL DRILLER REPORT

This report should be prepared by the driller in all detail and filed with the Department within 30 days following completion of the well.

1. Owner Name: Graham County Utilities Inc.
   Address: PO Box Drawer B (Street) Pima (City) Arizona (State) 85543 (Zip)
2. Driller Name: Cueto Drilling Co
   Address: 334 Shannon Hill (Street) Clifton (City) Arizona (State) 85533 (Zip)
3. Location: 7 (N/S) Township; 24 (E/W) Range; 8 Section; NW 1/4 10-acre; SE 1/4 40-acre; NW 1/4 160-acre
4. Well Registration No. 55- 545487 (Required)
5. Permit No. File # D(7-24) 8 BDB (If issued)

DESCRIPTION OF WELL

6. Total depth of hole 225' ft.
7. Type of casing Steel 24' of 20" x 1/4" Wall Starter Casing
8. Diameter and length of casing 12" in. from 0 to 220', _____ in from _____ to _____.
9. Method of sealing at reduction points _____
10. Perforated from 120' to 220', from _____ to _____, from _____ to _____.
11. Size of cuts 1/8" x 3" + 12 Ar. Number of cuts per foot 24
12. If screen was installed: Length _____ ft. Diam _____ in. Type _____
13. Method of construction Drilled
    (drilled, dug, driven, bored, jetted, etc)
14. Date started December (Month) 2 (Day) 1994 (Year)
15. Date completed January (Month) 3 (Day) 1995 (Year)
16. Depth to water 40'-7" ft. (If flowing well, so state)
17. Describe point from which depth measurements were made, and give sea-level elevation if available
    Ground level
18. If flowing well, state method of flow regulation: _____
19. Remarks:
    Pump capacity 150 gal/min
    GW 40'7"

DO NOT WRITE IN THIS SPACE
55-545487
D(7-24)8BDB
Re
Fil
Re
Er
ENTERED FEB 8 1995

DWR-55-55-7/91 (Rev.)

LOG OF WELL

Indicate depth at which water was first encountered, and the depth and thickness of water bearing beds. If water is artesian, indicate depth at which encounterd, and depth to which it rose in well.

From (feet)	To (feet)	Description of formation material
0	35'	Fill brown clay and rocks (Hit water @ 21')
35'	84'	Gray clay few rocks
84'	106'	Brown sandy clay (Hard at 88')
106'	121'	Brown solid clay
121'	126'	Sand gravel and little clay
126'	143'	Gray clay
143'	152'	Sand gravel and little clay
152'	154'	Brown clay
154'	161'	Redish clay
161'	180'	Gray sandy clay
180'	183'	Brown clay
183'	198'	Brown sandy clay
198'	214'	Gray (Hard) like sandstone
214'	221'	Gray sticky clay
221'	225'	Brown clay

I hereby certify that this well was drilled by me (or under my supervision), and that each and all statements herein contained are true to the best of my knowledge and belief.

Driller Name: Joe Cuets

334 Shannon Hill
Street

Clifton Ariz 85533
City State Zip

Date Jan. 26 1995