CHAPTER TWO: HYDROLOGY

2.1 GEOGRAPHY

The geology of the Tucson Active Management Area (TAMA) is characterized by broad, gently sloping alluvial basins separated by north to northwest trending fault-block mountains. The TAMA covers approximately 3,900 square miles (mi^2) and includes two parallel north-south trending alluvial basins that are separated by block-faulted mountains. The two alluvial basins divide the TAMA into two sub-basins, the Upper Santa Cruz (USC) Sub-basin and the Avra Valley Sub-basin *(See Figure 2-1*). The Avra Valley Sub-basin contains Altar Valley, south of the line between Township 15 and 16 South, and Avra Valley to the north of the line. Elevations within the TAMA range from 1,860 feet above mean sea level near Red Rock to 9,453 feet above mean sea level at Mount Wrightson located in the southeastern part of the TAMA.

The Santa Cruz River and its tributaries constitute the major surface water drainage within the TAMA. The Santa Cruz River enters the TAMA across its southern boundary from the Santa Cruz AMA (SCAMA) and exiting into the Pinal AMA (PAMA). The Santa Cruz River flows north through the USC Sub-basin before turning to the northwest and flowing across the northern part of the Avra Valley Sub-basin. Major tributaries to the Santa Cruz River include Rillito Creek, Tanque Verde Creek, Pantano Wash, Sabino Creek, Cañada del Oro Wash and Brawley Wash. The Avra Valley Sub-basin is drained by Brawley Wash, which flows south to north through the Sub-basin before emptying into the Santa Cruz River in the northwestern part of the TAMA *(See Figure 2-1*).

2.2 CLIMATE

The TAMA is located within the Sonoran Desert Sub-province of the Basin and Range physiographic province. The climate at the lower elevations is semiarid with sparse vegetation consisting of creosote, mesquite and cacti. Annual rainfall ranges from 11 to 16 inches on the valley floors to as much as 30 inches in the surrounding mountains. Higher rainfall volumes in the upper elevations of the mountains around the TAMA's margins support conifers and deciduous trees such as aspens, Douglas firs and oaks. In January, the mean daily maximum temperature is 66^{o} F and the mean daily minimum temperature is 40^{o} F. In July, the mean daily maximum temperature is 100^{o} F and the mean daily minimum is 74^{o} F (National Weather Service Forecast Office, 2016).

Precipitation occurs in the TAMA in two distinct seasons: a wet summer season from July to late September, referred to locally as the monsoon season, and a wet winter season from November to April *(See Figure 2-2*) (The Weather Channel). The summer rainy season of isolated, localized thunderstorms beginning in late June to early July provides a break from the dry spring season. Moisture drawn into southern Arizona from the Gulf of California and the Pacific Ocean combines with rising hot air to generate high-intensity, short-term thunderstorms. During the last stages of the summer rainy season, in September and October, dissipating tropical cyclones that originate in the Pacific Ocean off Mexico occasionally make their way into southern Arizona. The tropical cyclones generate large regional storm events that can cause intense precipitation and occasional flooding in southern Arizona. During the winter rainy season, from November to April, widespread low-intensity precipitation events are generated by large-scale regional low-pressure frontal systems. Individual winter precipitation events may not produce large rainfall totals locally, however, long duration winter storm events can produce substantial rainfall totals and severe flooding.

FIGURE 2-1
TUCSON ACTIVE MANAGEMENT AREA

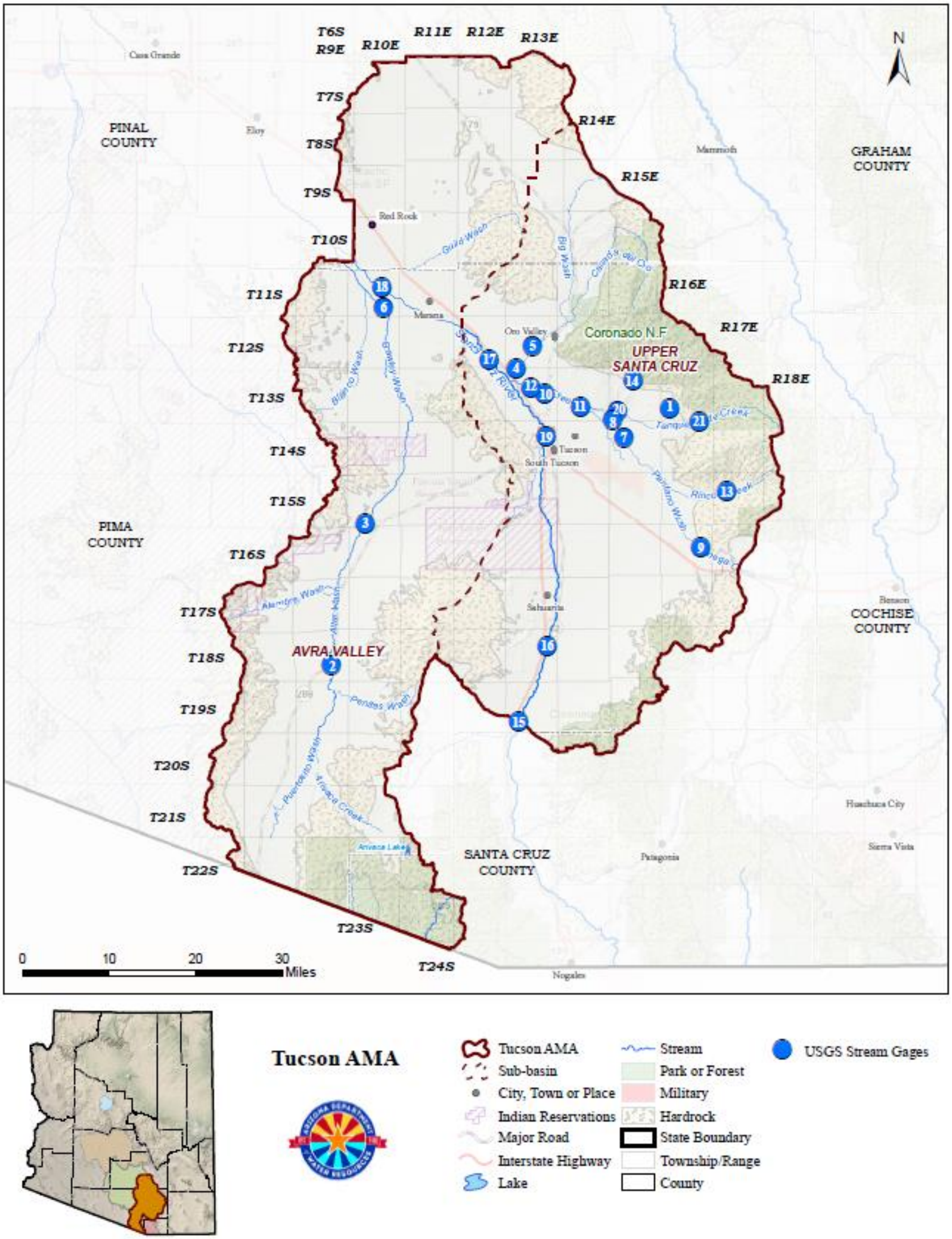
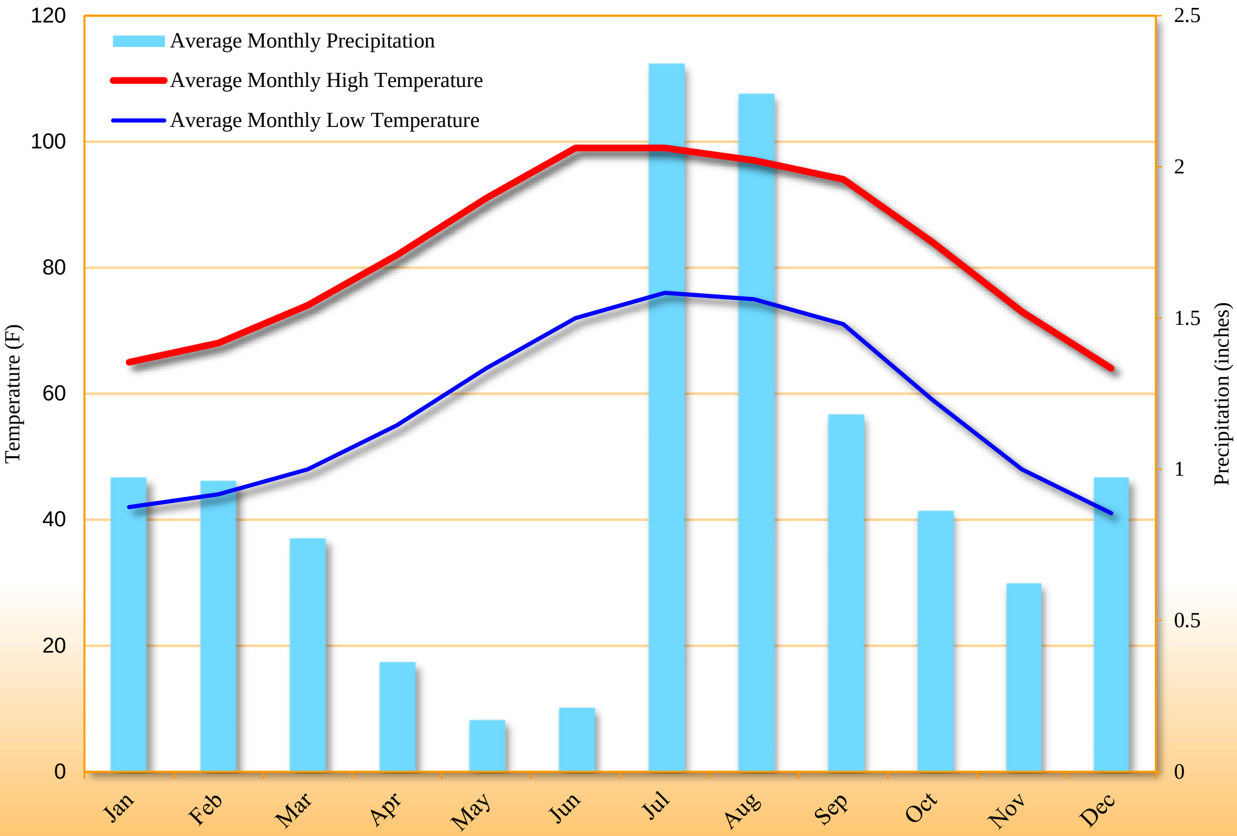


FIGURE 2-2
TUCSON AMA ANNUAL PRECIPITATION



2.3 SURFACE WATER RESOURCES

Most flows in the main surface water drainages in the TAMA are ephemeral and occur only in response to rainfall events or snowmelt. Individual flow events generated by direct precipitation falling in the valleys are usually of short duration, especially during the summer monsoon season. Some winter storms may last for several days and can generate substantial prolonged flow events. Stream infiltration from flow events provides an important component of the annual recharge to the TAMA regional aquifer.

The streambed of the Santa Cruz River occupies about 72 miles within the TAMA, entering from the south, flowing through both sub-basins, and exiting the TAMA in the northwest. Available US Geological Survey (USGS) stream gauge data for the Santa Cruz River show a very strong summer monsoonal flow signature with about 70 percent of annual flows occurring during July, August and September. Throughout most of the USC Sub-basin the Santa Cruz River is ephemeral, flowing only in response to local rainfall events. However, reclaimed water discharges into the riverbed from two Pima County Regional Wastewater Reclamation Department (PCRWRD) treatment plants have created a perennial reach downstream from the discharge points. Historically, reclaimed water discharges reached the TAMA - PAMA boundary between the Silver Bell and Picacho Mountains near the Santa Cruz River at Trico Road stream gauge *(See Figure 2-1*). Recent improvements in wastewater treatment facilities have improved the quality of the reclaimed water discharged, resulting in a higher percentage of the discharged water recharging, which has reduced or eliminated the flow of water across the AMA boundary into PAMA.

Major tributaries to the Santa Cruz River in the USC Sub-basin include Rillito Creek, Tanque Verde Creek, Sabino Creek, Pantano Wash and Cañada del Oro. USGS stream gauge data for the Rillito-Tanque Verde Creek system indicate a biannual flow distribution with a dominant winter flow regime from December to March and a fairly well defined summer monsoon flow signature. The one exception to this biannual distribution is Pantano Wash, which has a strong summer flow regime and a very weak winter flow signature.

In the Avra Valley Sub-basin, Altar Wash, Brawley Wash and Los Robles Wash form the main surface water drainages. Altar Wash drains the Altar Valley section of the Sub-basin. (Altar Wash is renamed Brawley Wash where it enters the Avra Valley part of the Sub-basin and is called Los Robles Wash just before it joins the Santa Cruz River in the northern part of the Sub-basin) *(See Figure 2-1)*. The available gauging data for Brawley Wash indicates that the system is dominated by short-duration, summer monsoon flows occurring mostly in July, August and September. These short-duration flow events tend to be localized and generally do not create flow throughout the entire drainage. Occasional long-duration flows from cyclonic events or winter frontal storms, usually from September to March, create flow events that affect the entire drainage. There are numerous years with either no significant flows or only small, local flows of very short duration in the flow record. Table 2-1 provides a summary of USGS stream gauges with flow data in and near the TAMA.

TABLE 2-1
TUCSON AMA GROUNDWATER MODEL
USGS STREAM DATA

Map Label	Gauge ID	USGS Station Name	Map Name	Gauge Records
1	9483200	AGUA CALIENTE WASH TRIB NEAR TUCSON	Agua Caliente	1965-1980
2	9486800	ALTAR WASH NEAR THREE POINTS	Altar	1966-2010
3	9487000	BRAWLEY WASH NEAR THREE POINTS	Brawley	1992-2010
4	9486350	CANADA DEL ORO BLW INA ROAD, NEAR TUCSON	Canada Del Oro #2	1995-2010
5	9486300	CANADA DEL ORO NEAR TUCSON	Canada Del Oro #1	1965-1978
6	9487250	LOS ROBLES WASH NEAR MARANA	Los Robles	1966-1983
7	9485450	PANTANO WASH AT BROADWAY BLVD AT TUCSON	Pantano #2	1998-2010
8	9485500	PANTANO WASH NEAR TUCSON	Pantano #3	1940-1977
9	9484600	PANTANO WASH NEAR VAIL	Pantano #1	1959-2010
10	9486000	RILLITO CR NEAR TUCSON	Rillito #2	1913-1975
11	9485700	RILLITO CREEK AT DODGE BLVD AT TUCSON	Rillito #1	1990-2010
12	9486055	RILLITO CREEK AT LA CHOLLA BLVD NEAR TUCSON	Rillito #3	1995-2010
13	9485000	RINCON CREEK NEAR TUCSON	Rincon	1993-2010
14	9484000	SABINO CREEK NEAR TUCSON	Sabino	1987-2010
15	9481770	SANTA CRUZ NR AMADO	Santa Cruz #1	2003-2009
16	9482000	SANTA CRUZ RIVER AT CONTINENTAL	Santa Cruz #2	1991-2010
17	9486500	SANTA CRUZ RIVER AT CORTARO	Santa Cruz #4	1993-2010
18	9486520	SANTA CRUZ RIVER AT TRICO RD NEAR MARANA	Santa Cruz #5	1989-2010
19	9482500	SANTA CRUZ RIVER AT TUCSON	Santa Cruz #3	1998-2010
20	9484500	TANQUE VERDE CREEK AT TUCSON	Tanque Verde #2	1940-2010
21	9483100	TANQUE VERDE CREEK NEAR TUCSON	Tanque Verde #1	1959-1974

2.4 HYDROGEOLOGIC UNITS AND AQUIFER CHARACTERISTICS

The TAMA is divided by block-faulted mountains into two separate groundwater sub-basins filled with alluvial sediments. The block-faulted mountains are composed of Precambrian through Tertiary age granitic, metamorphic, volcanic and consolidated sedimentary rock. The sedimentary deposits that fill the two sub-basins are collectively termed basin-fill deposits and make up the TAMA regional aquifer. The basin-fill deposits are composed of volcanic deposits and unconsolidated to consolidated sediments consisting of gravel, sand, silt and clay with minor amounts of gypsiferous and anhydrous sediments. The basin-fill sediments are generally coarse-grained along the basin margins, and grade into finer-grained and evaporite deposits in the central parts of the basins.

The thickness of the basin-fill deposits range from a thin veneer along the mountain-fronts to as much as 9,000 feet thick in the Avra Valley Sub-basin and 11,200 feet thick in the USC Sub-basin (Davidson, 1973)(Anderson, 1987)(Anderson, 1988)(Anderson, 1989)(Hanson, Anderson, & Pool, 1990)(Hanson & Benedict, 1994). The basin-fill deposits have been divided into a lower basin-fill unit and an upper basin-fill unit based on regional hydrogeologic characteristics and further sub-divided into stratigraphic units based on lithology and depositional environment (Pashley, 1966)(Davidson, 1973)(Pool, 1986)(Anderson, 1987)(Anderson, 1988)(Anderson, 1989). Generalized geologic cross-sections for each sub-basin are presented in Figures 2-3 and 2-4. The general characteristics of the basin-fill deposits are described below. For more information on the cross section locations shown in Figures 2-3 and 2-4, see modeling report number 13, "A Regional Groundwater Flow Model of the Tucson Active Management Area, Tucson, Arizona: Simulation and Application", found at:
http://www.azwater.gov/AzDWR/Hydrology/Modeling/Tucson_Home.htm.

2.4.1 Upper Basin-fill

The upper basin-fill unit ranges from several hundred feet to as much as 1,000 feet thick in both sub-basins. The unit consists mostly of semi-consolidated to unconsolidated gravel, sands and clayey silt. In the Avra Valley Sub-basin, the upper basin-fill consists largely of finer grained material in the north and central parts of the sub-basin (Moosburner, 1972)(Anderson, 1988). The upper basin-fill is generally coarser in the southern part of Avra Valley consisting of a thick sequence of coarse to medium sized sands. In the USC Sub-basin the upper basin-fill is generally coarser north of Township 13 South and finer grained throughout the rest of the sub-basin (Hanson & Benedict, 1994). The upper basin-fill has been divided into the upper Tinaja beds, the Fort Lowell Formation and the surficial alluvium deposits based on hydrogeologic properties.

The surficial alluvial deposits are composed of gravels, sands and silty sands and include alluvial-fan, terrace and stream-channel deposits. The surficial deposits are not hydrologically significant except for the stream-channel deposits, which are usually referred to as the Younger Alluvium. The Younger Alluvium is very permeable and ranges from 40 to 100 feet thick (Davidson, 1973).

The sediments of the Fort Lowell Formation are generally flat lying and are at most 300 feet to 400 feet thick (Davidson, 1973)(Anderson, 1988)(Anderson, 1989). The Fort Lowell Formation is generally unconsolidated to weakly cemented and composed of gravel, sands and clayey silt. In the northern areas of the USC Sub-basin the sediments of the Fort Lowell Formation are coarser-grained than in the central and southern parts of the sub-basin. In the Avra Valley Sub-basin the unit is generally more coarse-grained in the southern part of the sub-basin and finer-grained in the central and northern parts of the sub-basin.

The upper Tinaja beds are several hundred feet thick and consist of unconsolidated to slightly cemented gravels, sands and clayey silts. In the USC Sub-basin the sediments of the upper Tinaja beds are coarsest in the northern section of the sub-basin, becoming finer-grained in the central and southern sections of the sub-basin. The upper Tinaja beds are coarser in the central and southern parts of the Avra Valley Sub-basin and grade into finer grained deposits in the northern part of the sub-basin.

FIGURE 2-3
AVRA VALLEY SUB-BASIN CROSS SECTION

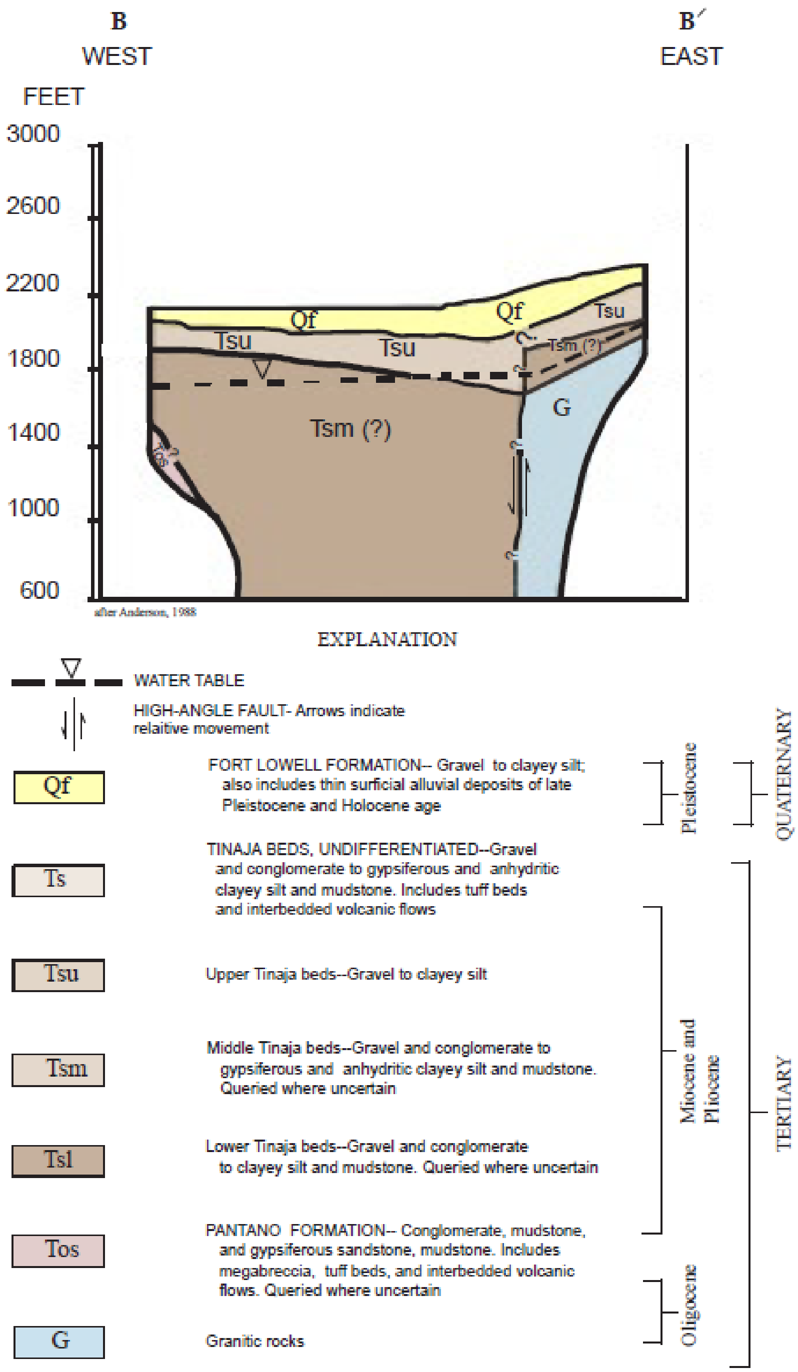
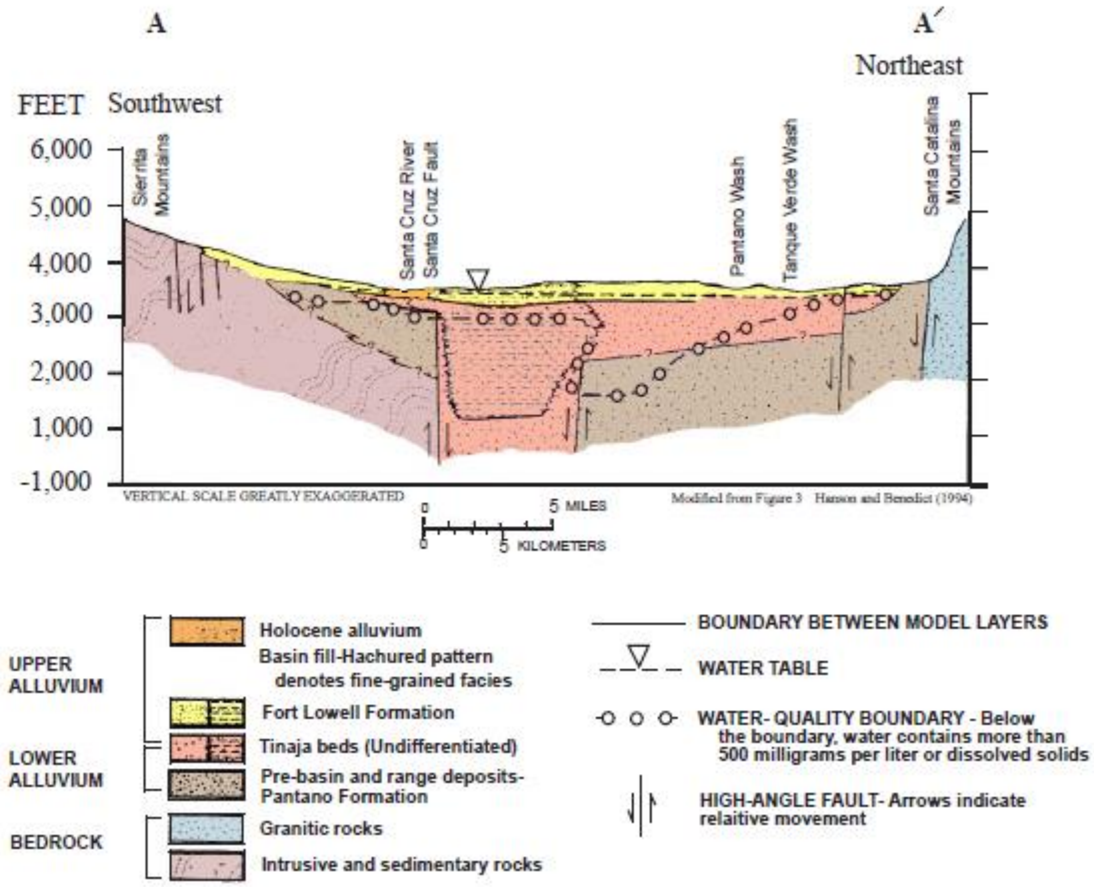


FIGURE 2-4
UPPER SANTA CRUZ SUB-BASIN CROSS SECTION



2.4.2 Lower Basin-fill

The lower basin-fill is several thousand feet thick and consists of conglomerates, gravels, sands, silts, anhydritic clayey silts and mudstones. In the Avra Valley Sub-basin the lower basin-fill grades from mostly sands, gravels and conglomerates in the southern part of the sub-basin to anhydritic clayey silts and mudstones in the central and northern parts of the sub-basin (Anderson, 1988), (Hanson, Anderson, & Pool, 1990). The lower basin-fill is more coarse-grained in the northern part of the USC Sub-basin with finer grained deposits, including extensive evaporite deposits, occurring in the central sections of the USC Sub-basin (Davidson, 1973)(Anderson, 1989)(Hanson & Benedict, 1994). The lower basin-fill has been divided into the middle and lower Tinaja beds and the Pantano Formation (Anderson, 1987)(Anderson, 1988)(Anderson, 1989).

The middle and lower Tinaja beds are several hundred to several thousand feet thick and their composition ranges from gravels and conglomerates to gypsiferous, anhydritic clayey silts and mudstones. The sediments of the middle and lower Tinaja beds are found in the downthrown blocks of the structural basins in the USC Sub-basin and the northern part of the Avra Valley Sub-basin. The middle Tinaja sediments are generally not present on the upthrown blocks, having been removed by erosion between periods of Basin and Range faulting (Anderson, 1987). In the downthrown blocks, the middle and lower Tinaja sediments are generally fine-grained and can contain thick deposits of gypsiferous and anhydritic clayey silts.

The Pantano Formation consists of semi-consolidated to consolidated conglomerates, sandstones, mudstones and gypsiferous mudstones (Davidson, 1973)(Anderson, 1987)(Anderson, 1988)(Anderson, 1989). The total thickness of the Pantano Formation is not known, but it is estimated to be several thousands of feet thick (Davidson, 1973). The unit is usually deeply buried by overlying Tinaja beds along the central axis of the USC Sub-basin in the downthrown structural blocks. Along the basin's margins, on the upthrown fault blocks, the Tinaja beds are much thinner, and the Pantano Formation is closer to the surface and sometimes exposed at the surface.

2.4.3 Aquifer Characteristics

Groundwater in the upper basin-fill generally occurs under unconfined or water table conditions. Localized perching conditions, caused by interbedded layers of fine-grained sediments, are known to exist in the USC Sub-basin in Township 15 South, Ranges 13 and 14 East, and in the northern sections of the Avra Valley Sub-basin *(See Figure 2-1*) (Babcock & Hix, 1981),(Anderson, 1988)(Anderson, 1989). The Fort Lowell Formation and upper Tinaja beds of the upper basin-fill are the most productive units within the regional aquifer. Most high capacity wells that provide water for municipal, industrial or irrigation uses are completed in one or the other of these units. Well yields and the hydrologic properties of the upper Tinaja beds and the Fort Lowell Formation are also generally similar and wells completed in these units are capable of producing 500 to 1,500 gallons per minute (Davidson, 1973)(Anderson, 1988)(Anderson, 1989).

The surficial alluvial deposits are not hydrologically significant except for the stream-channel deposits. The stream channel deposits are very permeable and prior to extensive groundwater development the stream channel deposits were probably partially-to-fully saturated along most of the Santa Cruz River and its tributaries. However, by the 1940s, water level declines from localized groundwater pumpage had drained much of the stream channel deposits along the Santa Cruz River and its tributaries. The stream channel deposits remain hydrologically important presently because they serve as a conduit for stream-flow recharge that infiltrates into the underlying regional aquifer.

The Fort Lowell Formation has significant saturated thickness throughout most of the USC Sub-basin and in the northern parts of the Avra Valley Sub-basin and is considered the main regional aquifer. However, the upper Tinaja beds have become a more important aquifer in areas where water level declines have reduced the saturated thickness of the Fort Lowell Formation. Throughout much of Avra Valley, the Fort Lowell Formation is either not saturated or has a smaller saturated thickness than in the USC Sub-basin. As a result, the upper Tinaja beds, along with the middle and lower Tinaja beds, are more significant aquifers in the Avra Valley Sub-basin. This is particularly true in the southern portions of the Avra Valley Sub-basin where the Fort Lowell Formation is unsaturated and the Tinaja beds consist of thick sequences of coarse-grained sand deposits. In this area, the Tinaja beds can be very productive and are the main water-bearing unit.

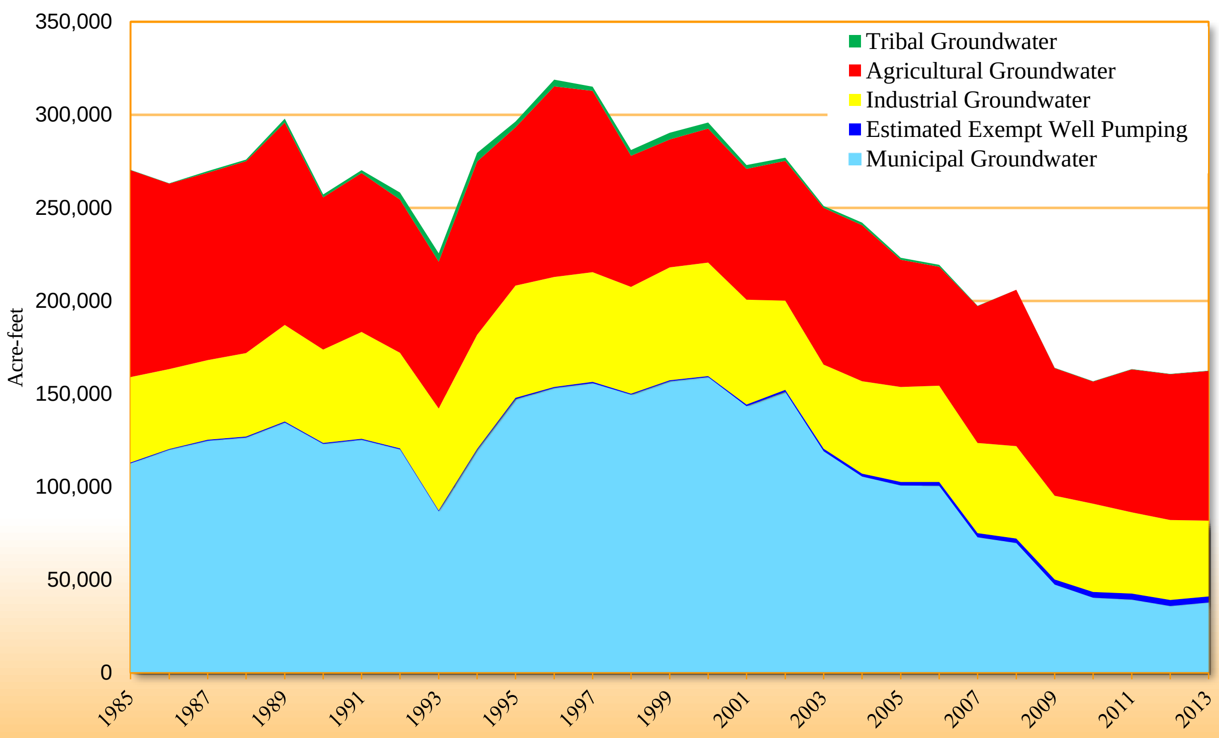
The middle and lower Tinaja beds and Pantano Formation of the lower basin-fill are generally not highly productive and have not been widely developed as a source of groundwater. This is due to several reasons, which may include depth of burial, increased consolidation and presence of large percentages of fine materials. Wells developed in the middle and lower Tinaja beds and Pantano Formation generally produce only small to moderate amounts of water. However, there are areas along the basin margins and in the southern sections of the Avra Valley Sub-basin where the middle and lower Tinaja and Pantano formation are an important source of groundwater.

2.5 GROUNDWATER RESOURCES

2.5.1 Historical Water Use

Groundwater pumpage for agricultural, municipal and industrial purposes is the single largest source of water withdrawals from the TAMA's regional aquifer. Groundwater pumpage has significantly impacted the groundwater system and water levels in many parts of the TAMA. Groundwater development for farming and to support the City of Tucson began as early as 1900. By the 1930s, estimated annual pumpage in the TAMA ranged from 30,000 to 45,000 ac-ft per year (Anning & Duet, 1994). By 1940, withdrawals increased to about 60,000 ac-ft per year, and since that time annual groundwater withdrawals have generally greatly exceeded annual natural recharge. In the mid-1970s, groundwater pumpage peaked at about 385,000 ac-ft per year (Mason & Bota, 2006). From 2000 to 2013, the average annual reported groundwater pumpage for the TAMA was approximately 214,000 ac-ft *(See Figure 2-5*). This figure does not include recovery of stored water from recovery wells.

FIGURE 2-5
TUCSON AMA GROUNDWATER PUMPING BY SECTOR, 1985-2013



Initially, most groundwater in the TAMA was used for irrigation, but by the mid-1970s, irrigation withdrawals began declining due to urbanization and farms being retired. At the same time, municipal and industrial demands began increasing along with population growth. By the mid-1980s, agricultural use and municipal water use were about equal, with each accounting for about 40 percent of the total groundwater withdrawn. Industrial use made up the remaining 20 percent. In 2013, municipal groundwater use was about 39,000 ac-ft, while agricultural groundwater use was about 81,000 ac-ft (not including in-lieu groundwater). However, total municipal withdrawals were greater than agricultural withdrawals because much of the municipal pumping was recovered annually or as long-term recharge credits, not groundwater. Total municipal demand in 2013 was 162,000 ac-ft whereas total agricultural demand was only 110,700 ac-ft. Industrial demand was 48,000 ac-ft and primarily consisted of groundwater. See Chapter 3 of this plan for more description of historical water uses by source of supply for each water use sector in the TAMA.

2.5.2 Avra Valley Sub-basin

Until the late 1970s, about 95 percent of groundwater withdrawals had been used for agricultural irrigation in the Avra Valley Sub-basin with the remaining five percent used by the municipal and industrial sectors. Farm acreage increased dramatically in the early to mid-1950s when agricultural development reached a peak of about 30,000 acres in production (White, Matlock, & Schwalen, 1966). The dominance of irrigation use has changed in the last 30 to 40 years due to urbanization and the retirement of farm lands within the sub-basin. In 2013, agricultural pumpage comprised 36 percent of total withdrawals in the sub-basin. Annual pumping in the sub-basin declined from a high of about 230,000 ac-ft in 1976 to about 117,000 ac-ft per year in 2013. Since about 2000, pumpage of recovered annual or long-term recharge credits for municipal use has increased, and in 2013 pumpage associated with recovery of recharge credits in the sub-basin was about 67,000 ac-ft.

2.5.3 Upper Santa Cruz Sub-basin

Agricultural pumpage accounted for 80 to 90 percent of the total pumpage in the USC Sub-basin until the mid-1950s. Since the mid-1950s the percentage of municipal and industrial pumpage has increased and the percentage of agricultural pumpage has decreased. The decline in agricultural withdrawals in the USC Sub-basin reflects the shift in water use from farming to supplying municipal and industrial water to the growing population of the Tucson area. Withdrawals in the USC Sub-basin increased from about 50,000 ac-ft per year in 1950 to over 270,000 ac-ft per year by 1976. Since 1976, withdrawals have generally declined, and by 2013, pumping was just under 173,000 ac-ft per year. Pumpage by sector for 2013 in the USC Sub-basin was 22 percent municipal, 21 percent agricultural and 29 percent industrial. The remaining pumping was recovery of stored water (recovered water was used primarily by the municipal sector).

2.5.4 Groundwater Recharge and Discharge

2.5.4.1 Recharge

Groundwater recharge components in the TAMA include: 1) mountain-front, 2) stream recharge, 3) underflow, 4) incidental recharge and 5) artificial recharge. For the purposes of this document, incidental recharge is defined as water that recharges the TAMA's regional aquifer during the course of its use for agricultural, industrial or municipal purposes. This includes water that is: 1) recharged as a result of irrigation activities, 2) reclaimed water that is released into the Santa Cruz River or used for irrigation and 3) water infiltrating from mine tailings ponds. Artificial recharge is defined as water that is recharged at constructed or managed recharge projects permitted by ADWR.[1]

Historically, the largest source of recharge to the TAMA regional aquifer has been mountain-front recharge and streambed recharge along the Santa Cruz River and its major tributaries. Mountain-front recharge occurs along the margins of the TAMA where rainfall and snowmelt generate surface flows that infiltrate into the alluvial material and enter the regional aquifer. Based on results of the latest TAMA groundwater flow model, long-term average of mountain-front recharge is estimated to be 28,100 ac-ft per year (Mason & Hipke, 2012). Streambed recharge occurs during moderate to large flows along the Santa Cruz River and its major tributaries and, like stream flow, is highly variable. Historical annual stream-flow from gauges in the TAMA was analyzed and the resulting estimated annual stream recharge volumes were included in the updated Tucson groundwater flow model. The results of the model indicate that inclusion of annualized stream recharge pulses provide a better model calibration than using long-term average stream infiltration values. The stream-flow analysis and model calibration results suggest that from 1940 to 2013 stream

[1] A "managed underground storage facility means a facility . . . that is designed and managed to utilize the natural channel of a stream to store water underground pursuant to permits issued under this chapter through artificial and controlled release of water other than surface water naturally present in the stream" (A.R.S. § 45-802.01(12)). A "constructed underground storage facility means a facility that . . . is designed and constructed to store water underground pursuant to permits issued under this chapter." (A.R.S. § 45-802.01(4)).

recharge has varied from a low of 15,300 ac-ft per year to a high of 415,400 ac-ft per year. Annual rates of natural and incidental recharge and riparian demands for the years 1985 through 2013 are listed in Table 2-2.

TABLE 2-2
TUCSON AMA RATES OF ANNUAL NET NATURAL RECHARGE, 1985-2013 (ac-ft/year)

Year	Natural Recharge			Incidental Recharge		**Total Natural and Incidental Recharge**	Natural Discharge		Total Natural Discharge	**Net Recharge**
	Mountain front	Stream Channel*	Groundwater inflow	Canal Seepage	Lagged Ag Recharge		Riparian transpiration (GW)	Groundwater outflow		
1985	28,100	137,479	29,443	3,657	44,371	**243,050**	7,164	21,292	28,456	**214,594**
1986	28,100	113,599	29,790	3,657	45,469	**220,615**	6,920	22,597	29,517	**191,098**
1987	28,100	94,235	30,472	3,657	45,549	**202,013**	6,111	22,066	28,177	**173,836**
1988	28,100	75,898	29,838	3,657	44,942	**182,435**	4,032	19,771	23,803	**158,632**
1989	28,100	62,248	30,351	3,657	44,070	**168,426**	2,551	18,611	21,162	**147,264**
1990	28,100	94,773	30,757	3,657	43,236	**200,523**	2,761	21,244	24,005	**176,518**
1991	28,100	108,114	32,126	3,657	38,398	**210,395**	4,489	18,275	22,764	**187,631**
1992	28,100	113,067	31,503	3,657	39,212	**215,539**	5,850	18,539	24,389	**191,150**
1993	28,100	320,201	30,367	3,657	38,516	**420,841**	10,623	21,117	31,740	**389,101**
1994	28,100	91,285	32,012	3,657	35,402	**190,456**	7,762	20,120	27,882	**162,574**
1995	28,100	106,598	32,789	3,657	31,232	**202,376**	7,587	19,335	26,922	**175,454**
1996	28,100	61,162	32,320	3,657	30,069	**155,308**	3,872	18,499	22,371	**132,937**
1997	28,100	47,992	32,472	3,657	27,319	**139,540**	2,204	16,952	19,156	**120,384**
1998	28,100	118,228	32,291	3,657	25,774	**208,050**	3,877	15,798	19,675	**188,375**
1999	28,100	80,899	32,597	3,657	25,425	**170,678**	2,987	15,113	18,100	**152,578**
2000	28,100	171,267	31,399	3,657	25,457	**259,880**	2,581	13,633	16,214	**243,666**
2001	28,100	53,711	31,702	3,657	25,103	**142,273**	2,035	15,579	17,614	**124,659**
2002	28,100	46,386	32,109	3,657	23,093	**133,345**	1,103	16,072	17,175	**116,170**
2003	28,100	96,683	29,862	3,657	22,015	**180,317**	1,023	15,338	16,361	**163,956**
2004	28,100	75,049	29,806	3,657	23,173	**159,785**	1,254	14,788	16,042	**143,743**
2005	28,100	112,548	30,830	3,657	23,318	**198,453**	4,145	15,357	19,502	**178,951**
2006	28,100	144,088	31,865	3,657	26,072	**233,782**	5,397	15,859	21,256	**212,526**
2007	28,100	92,204	31,902	3,657	26,808	**182,671**	3,905	16,055	19,960	**162,711**
2008	28,100	87,745	32,028	3,657	23,245	**174,775**	4,065	14,542	18,607	**156,168**
2009	28,100	47,730	30,955	3,657	22,013	**132,455**	1,900	18,153	20,053	**112,402**
2010	28,100	87,766	31,885	3,657	23,039	**174,447**	3,470	18,035	21,505	**152,942**
2011	28,100	90,807	30,595	3,657	22,800	**175,959**	3,775	17,135	20,910	**155,049**
2012	28,100	114,848	30,400	3,657	24,150	**201,155**	3,890	17,560	21,450	**179,705**
2013	28,100	125,987	30,145	3,657	32,300	**220,189**	3,950	18,030	21,980	**198,209**

*Stream channel recharge includes the recharge of reclaimed water from the discharge points to the TAMA boundary with PAMA. Effluent discharge is included in the Stream channel recharge column for all years, except for the historical volumes that left the AMA prior to the recent improvements in the wastewater treatment facilities that resulted in higher quality water and a higher percentage of recharge.

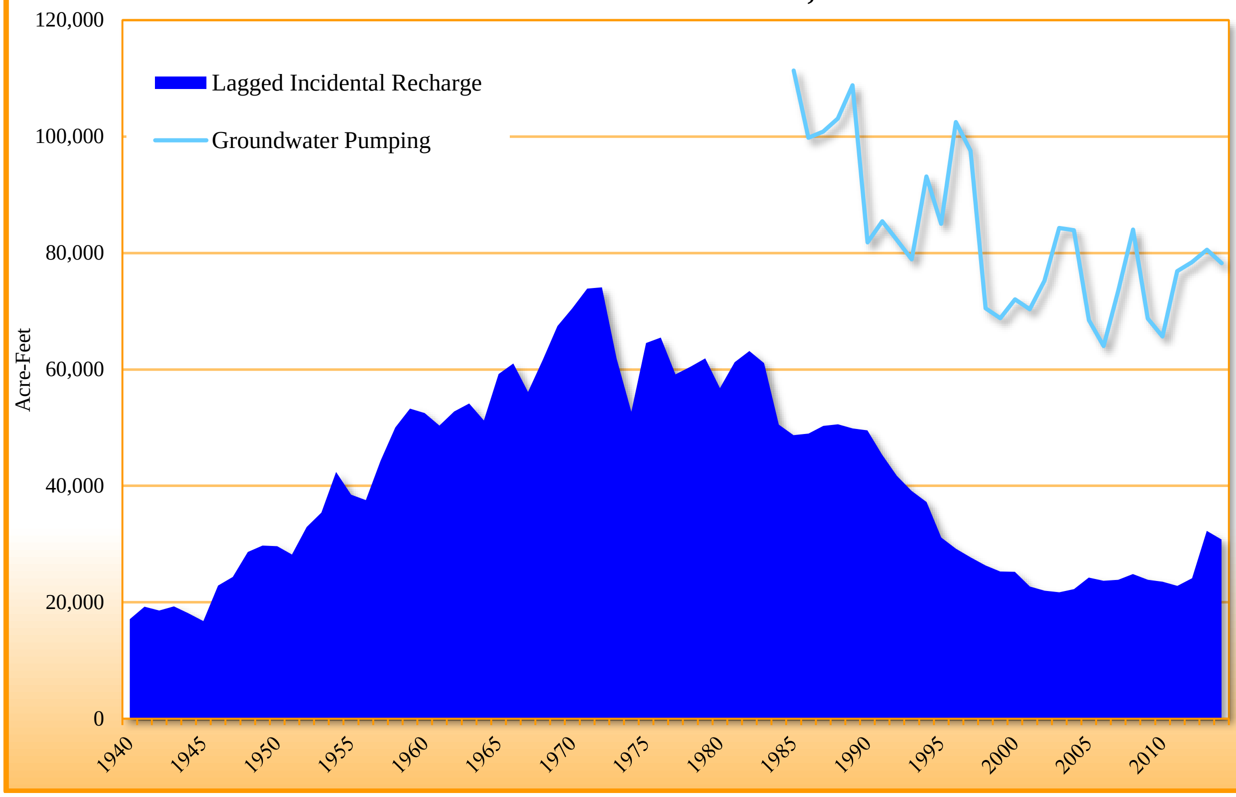
Artificial recharge is not shown in Table 2-2 because water that is artificially stored underground belongs to the storer, other than any cuts to the aquifer required by law (*See Chapter 8 of this plan*).

According to the USGS, underflow can be considered groundwater outflow from an area (a model, a basin, an aquifer), into another area that occurs within alluvial material that isn't measured at a stream gaging station *(See http://water.usgs.gov/wsc/glossary.html#G*). Underflow into the TAMA occurs from the south across the TAMA - SCAMA boundary and through bedrock gaps where Pantano Wash and Tanque Verde Creek enter the TAMA. Previous estimates of underflow into the TAMA from the SCAMA range from 5,600 ac-ft per year to 15,500 ac-ft per year (Mason & Bota, 2006). Groundwater underflow across the SCAMA – TAMA boundary has varied over time. Water level fluctuations caused by pumping on both sides of the boundary, infiltration of water from large stream flows and reclaimed water released from the Nogales International Wastewater Treatment Plant have impacted the underflow into the TAMA (Mason

& Bota, 2006), (Nelson, 2006). Groundwater model estimates of underflow into the TAMA range from 9,950 ac-ft per year to 22,545 ac-ft per year, and the average underflow from 1985 to 2010 is 21,045 ac-ft per year (Mason & Hipke, 2012). Estimates of underflow from Pantano Wash and Tanque Verde Creek into the study area are small and are included in mountain-front recharge estimates.

The Tucson groundwater flow model does not simulate groundwater flow in Altar Valley. The groundwater flow out of Altar Valley into southern Avra Valley is simulated as a constant flux along the model's boundary in southern Avra Valley. The underflow across the model boundary, located approximately at Township 17 South, is not believed to have changed greatly over time as evidenced by hydrographs in that area, which show fairly consistent water levels through time (Mason & Bota, 2006). The calibrated groundwater underflow into the model from Altar Valley is 10,270 ac-ft per year. This value is the sum of mountain-front recharge and stream-bed recharge for the Altar Valley portion of the Avra Valley Sub-basin.

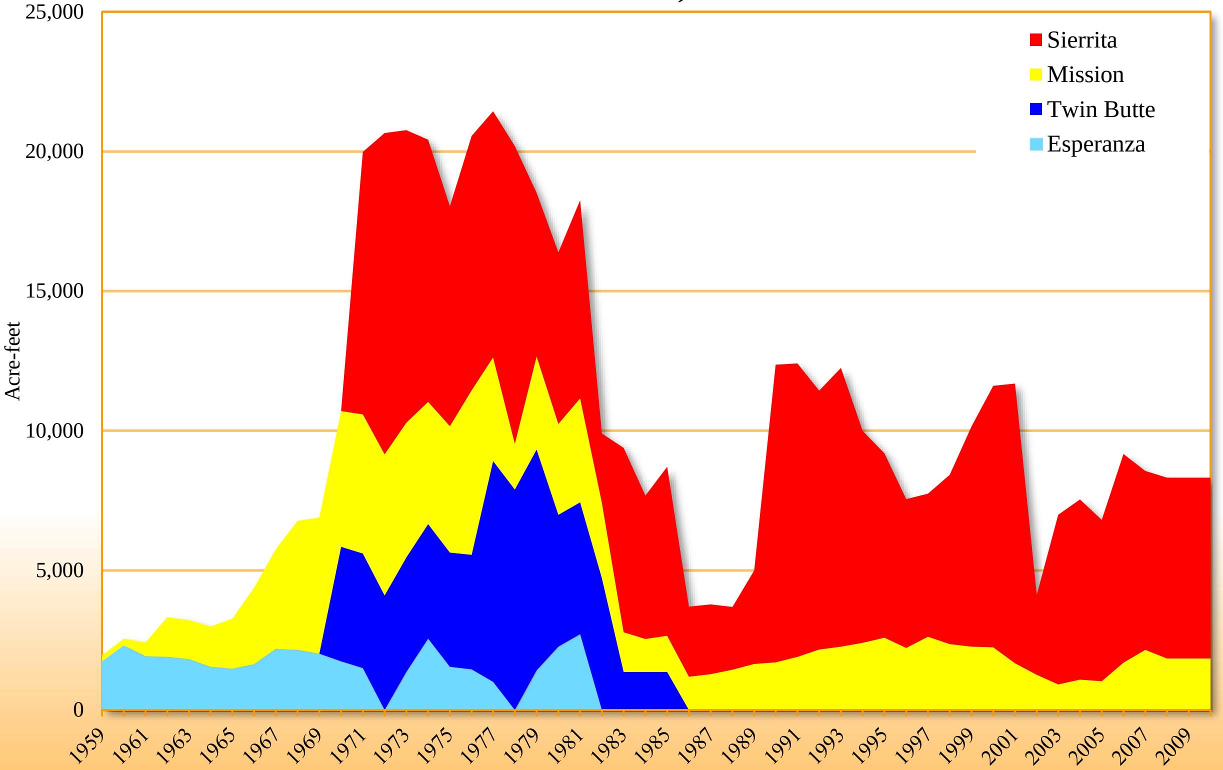
FIGURE 2-6
TUCSON AMA AGRICULTURAL GROUNDWATER DEMAND & LAGGED INCIDENTAL RECHARGE, 1940-2014



Incidental and artificial recharge have become a more important source of water to the regional aquifer as the TAMA's water resources have been developed. The Tucson groundwater flow model lags agricultural recharge based on an estimated rate of vertical movement and the depth to water through time. The result of the lagging is that agricultural recharge peaks during the early 1970s to the mid-1980s, and then declines. The agricultural recharge decline is offset in time but mirrors the decline in agricultural groundwater pumping (*See Figure 2-6)*.

Mine tailing recharge is water that is returned to the aquifer through seepage from tailing ponds associated with mining operations. Tailings pond recharge began in the early 1950s, soon after mining operations began and has generally varied annually along with various ore production. Estimates of tailing pond recharge volumes used in the Tucson groundwater flow model were developed based on information from the Arizona Department of Environmental Quality (ADEQ) reports and from reports provided to ADWR by Montgomery and Associates (Montgomery and Associates, 2009). The mine tailing recharge is limited to the southwestern portion of the USC Sub-basin. Figure 2-7 contains the model estimated annual mine tailings pond recharge values.

FIGURE 2-7
TUCSON AMA ESTIMATED MINE TAILINGS POND RECHARGE, 1959-2009



Reclaimed water from wastewater treatment plants (WWTP) has been used for irrigation in the Tucson area since the early 1900s (Schladweiler, 2001). From 1917 to 1969, reclaimed water was used to irrigate various city farmlands located within or near the city boundaries or delivered under contract to private farms. Direct delivery of reclaimed water for irrigation was discontinued in 1969, and since that time most reclaimed water from the Roger Road and the Ina Road WWTPs has been discharged directly into the Santa Cruz River. Note that the Roger Road WWTP was recently replaced by the Agua Nueva Water Reclamation Facility (WRF) and the Ina Road WWTP was extensively improved and renamed the Tres Rios WRF. Some reclaimed water continues to be used for agricultural and turf facility irrigation. The Cortaro-Marana Irrigation District (CMID) began receiving secondary treated reclaimed water for irrigation in 1977, and in 1984, the City of Tucson began operating a reclaimed water distribution system that supplies reclaimed water to turf facilities (parks, golf courses and cemeteries) within TAMA. From 2000 to 2013, discharges from the WWTPs into the Santa Cruz River bed have averaged 52,240 ac-ft per year. A portion of this water infiltrates and incidentally recharges the aquifer and is included in the total estimate of streambed recharge. The reclaimed water distribution system receives and distributes about 11,000 ac-ft per year. Table 2-3 shows the reclaimed water releases from 1950 to 2013.

Artificial recharge facilities have become significant sources of recharge to the TAMA regional aquifer since 2000. Artificial recharge has comprised over 50 percent of total recharge simulated in the Tucson groundwater flow model since 2005. CAP surface water and reclaimed water are both stored underground at constructed or managed artificial recharge projects called Underground Storage Facilities (USFs) that are permitted by ADWR. CAP surface water was introduced to the TAMA in 1993 and is utilized in several ways. The largest proportion of CAP water is recharged at artificial recharge facilities. A small amount of CAP water is used directly for agricultural irrigation and by the industrial sector. The CAP water used for agricultural irrigation is either CAP pool water, in which case no recharge credits are earned, or as *in-lieu* water. In-lieu water is stored at a Groundwater Saving Facility (GSF). A GSF is a facility, such as an irrigation district or specific farm, to which a renewable supply is delivered to a recipient who agrees to curtail groundwater pumping and use the renewable supply in-lieu of that groundwater. Typically, a separate entity holds the Water Storage Permit to store the in-lieu water (and has the legal right to the renewable supply) and accrues long-term storage credits for each acre-foot of water used in-lieu of the groundwater.

TABLE 2-3
TUCSON AMA RECLAIMED WATER RELEASES, 1950-2013, (ac-ft)*

Fiscal Year	Model Year	Ina Rd WPCF Discharge	Roger Rd WWTF Discharge	Tres Rios WRF Discharge	Average Discharge
1950-51	1951		798		798
1951-52	1952		4,182		4,361
1952-53	1953		4,539		4,252
1953-54	1954		3,966		4,410
1954-55	1955		4,854		3,207
1955-56	1956		1,559		786
1956-57	1957		12		11
1957-58	1958		9		5
1958-59	1959				
1959-60	1960				9
1960-61	1961		18		9
1961-62	1962				
1962-63	1963				
1963-64	1964				
1964-65	1965				
1965-66	1966				
1966-67	1967				
1967-68	1968				
1968-69	1969				
1969-70	1970		29,952		14,976
1970-71	1971		29,952		31,327
1971-72	1972		32,702		34,792
1972-73	1973		36,882		36,067
1973-74	1974		35,252		33,778
1974-75	1975		32,303		32,808
1975-76	1976		33,313		34,712
1976-77	1977	6,138	29,974		36,359
1977-78	1978	9,207	27,399		38,166
1978-79	1979	12,276	27,451		39,000
1979-80	1980	13,810	24,463		40,832

Fiscal Year	Model Year	Ina Rd WPCF Discharge	Roger Rd WWTF Discharge	Tres Rios WRF Discharge	Average Discharge
1980-81	1981	15,344	28,047		43,114
1981-82	1982	15,515	27,320		42,505
1982-83	1983	15,400	26,776		41,894
1983-84	1984	14,755	26,858		43,077
1984-85	1985	16,317	28,223		44,608
1985-86	1986	15,746	28,929		46,367
1986-87	1987	17,655	30,403		48,102
1987-88	1988	18,346	29,800		48,308
1988-89	1989	18,812	29,658		48,305
1989-90	1990	17,652	30,488		47,655
1990-91	1991	21,053	26,116		47,896
1991-92	1992	20,721	27,902		49,342
1992-93	1993	21,608	28,452		49,894
1993-94	1994	22,526	27,203		52,036
1994-95	1995	25,180	29,164		53,688
1995-96	1996	25,440	27,592		53,116
1996-97	1997	24,379	28,822		53,668
1997-98	1998	24,845	29,289		53,448
1998-99	1999	24,618	28,143		53,376
1999-00	2000	26,083	27,908		53,991
2000-01	2001	26,083	27,908		52,045
2001-02	2002				53,124
2003	2003	26,408	30,754		57,162
2004	2004	27,925	26,985		54,910
2005	2005	24,552	29,188		53,740
2006	2006	24,968	28,374		53,342
2007	2007	27,864	24,495		52,359
2008	2008	31,546	21,691		53,237
2009	2009	28,528	23,567		52,095
2010	2010	28,821	22,094		50,916
2011	2011	27,368	22,985		50,354
2012	2012	24,391	24,487		48,878
2013	2013		18,988	27,954	46,942

*As reported by Pima County Wastewater

2.5.4.2 Discharge

Groundwater is discharged from the TAMA's regional aquifer through pumpage, underflow and evapotranspiration (ET). Groundwater pumpage has been discussed above, and until about 2000, has far exceeded annual recharge (Mason & Hipke, 2012). Groundwater underflow exits in the TAMA and into the PAMA through the gap between the Silverbell and Picacho Mountains in the northwest corner of the TAMA (*See Figure 2-1*). Underflow out of the TAMA has varied through time due to changing water levels along the TAMA-PAMA boundary. The results of the Tucson groundwater flow model indicate that underflow out of the TAMA ranges from 14,200 to 35,700 ac-ft per year (Mason & Hipke, 2012). ET loss is a result of water utilized by phreatophyte plants. ET losses are primarily from riparian corridors located along the Santa Cruz River and its major tributaries where groundwater is shallow enough to support phreatophyte plants. Groundwater discharge estimates from the Tucson groundwater flow model are presented in Table 2-2 under groundwater outflow.

2.6 GROUNDWATER CONDITIONS

Groundwater conditions in an aquifer can be monitored by collection of water level measurements from the aquifer. The water level in an aquifer reflects the cumulative inflow and outflow stresses that have been applied to the aquifer. Groundwater level measurements also provide important information on long-term and short-term water level trends and on aquifer storage changes. Water level data have been collected from wells within the TAMA since the early 1900s.

The ADWR Hydrology Division's Field Services Unit collects water level data using both conventional field methods (electric sounders or steel tapes) and pressure transducers at automated sites. A selected group of wells, called index wells, are measured annually to monitor on-going groundwater conditions. Between 2000 and 2010, ADWR collected an average of 229 water levels per year in the TAMA. In addition to the annual index well data, ADWR also does AMA-wide water level sweeps where water levels are measured in as many wells as possible. AMA-wide water level sweeps completed in 1999-2000 and 2009-2010, resulted in 1,685 and 2,300 water level measurements, respectively. ADWR utilizes water level data collected by other entities in the TAMA that is submitted to ADWR and water level data entered into ADWR's Groundwater Site Inventory (GWSI) database that is collected by the ADWR Field Services Unit.

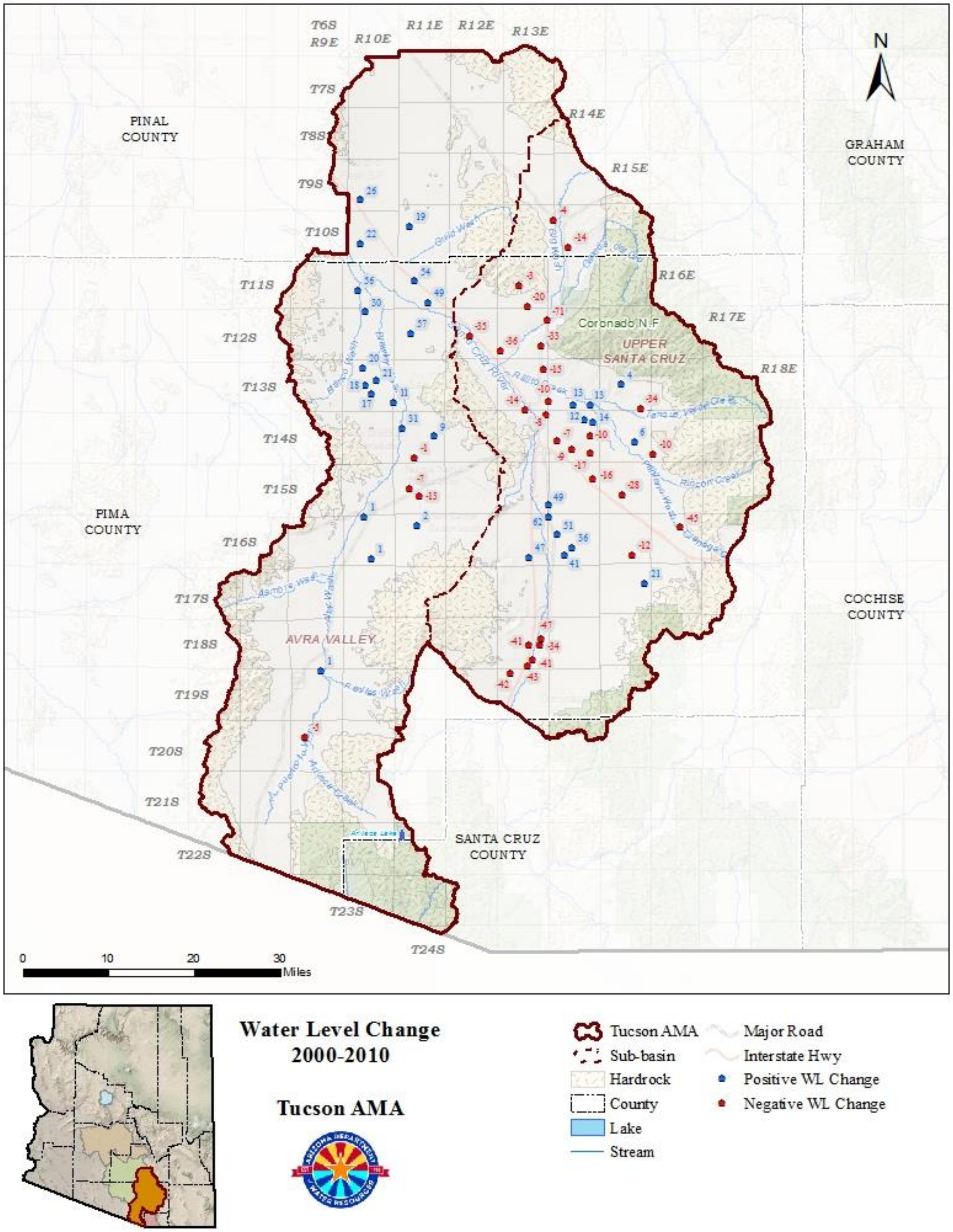
2.6.1 Water Level Trends, 1940-2010

Water level declines from the period 1940 to 2010 have had a large impact on the TAMA regional aquifer. Widespread water level declines of 100 feet to 250 feet have occurred in both the Avra Valley and USC Sub-basins, reducing overall aquifer storage and transmissivity. Water level declines due to the withdrawal of groundwater from storage has resulted in aquifer compaction and associated land subsidence in both sub-basins. Water level declines associated with pumping centers have created large cones of depression, changing the groundwater flow paths. Water level declines have also isolated shallow aquifers in some areas creating perched zones (*Figure 2-8*). *(See Tucson Model Report Appendix E for a map of hydrograph locations and hydrograph figures:* *http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf)*.

2.6.2 Upper Santa Cruz Sub-basin

Water levels in many areas of the USC Sub-basin have exhibited a long-term downward trend. Groundwater withdrawals in the north central area of the USC Sub-basin have resulted in water level declines of between 50 and 225 feet since the 1940s, as well as the formation of a large cone of depression in the metropolitan Tucson area. This is an area referred to as the central well field, where a large concentration of high-capacity wells provides water to the City of Tucson. Many of the wells in this area have experienced steep, long-term declines *(See hydrographs USC-7, USC-15, USC-19 and USC-21 in the Tucson Model Report Appendix E for a map of hydrograph locations and hydrograph figures:* *http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf)*. Four of the hydrographs in the modeling report form a line that roughly transects the central well field from northwest to southeast. The hydrographs all show the long-term water level declines of 100 to 200 feet and are typical of water level declines observed in the central well field area. The shift of City of Tucson pumpage from the central well field area to recharge facilities in Avra Valley has resulted in either stabilization of water levels or water level recoveries in the central well field since the year 2000.

FIGURE 2-8
TUCSON AMA WATER LEVEL CHANGES, 2000-2010



Several smaller, localized cones of depression have formed in certain areas, reflecting localized groundwater withdrawals. In the Green Valley-Sahuarita area, located in the southern part of the USC Sub-basin, a cone has formed that parallels the Santa Cruz River, reflecting localized pumping. Water levels in the Green Valley-Sahuarita area declined about 100 to 150 feet between 1940 and the early 1980s. However, water levels in some areas have shown recoveries of 50 to 75 feet from the late 1980s to 2010. The recovery is due in part to reduced groundwater withdrawals, infiltration of flood flows in the Santa Cruz River and artificial recharge at the Pima Mine Road Recharge Facility *(See hydrographs USC-40 through USC-42 and USC-48 through USC-55 in the Tucson Model Report Appendix E: http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf)*. Other cones of depression have formed in the north-eastern part of Township 12 South, Range 13 East, and in the eastern section of the USC Sub-basin in the northern part of Township 14 South, Range 15 East *(See hydrographs USC-22, USC-23, and USC-24 in: http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf)*. These smaller cones have been created by groundwater pumping needed to meet local demands.

2.6.3 Avra Valley Sub-basin

Water levels in the northern part of the Avra Valley Sub-basin have declined by 150 feet to 200 feet from 1940 to the mid-1970s. Since the mid-1970s, water levels in some areas have stabilized or recovered by 75 to 100 feet *(See hydrographs AV-1 through AV-12 in: http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf)*. The water level recovery is due to several factors, which include a large decrease in agricultural pumpage in the northern Avra Valley since the mid-1970s. This decrease was due to a combination of a reduction in irrigated acreage and increased use of renewable supplies. Other factors leading to water level recovery include agricultural recharge that has reached the water table after percolating through the unsaturated zone and recharge from artificial recharge facilities. Well hydrographs in northern Avra Valley all exhibit the U-shape of water level declines from the 1940s to mid-1970s, followed by the water level recovery beginning in the mid-1970s.

The water level declines in central Avra Valley, though less dramatic than in northern Avra Valley, have also stabilized and begun recovering. The recharge and recovery of CAP surface water at artificial recharge projects in central Avra Valley have contributed greatly to the observed water level recoveries from 2000 to 2010 *(See hydrographs AV-13 through AV-18 in: http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf)*. Two groundwater mounds are developing around the recharge facilities located in Township 14 South, Range 11 East, and the mounds are beginning to coalesce. Hydrographs for wells AV-16 and AV-17 in: *http://www.azwater.gov/AzDWR/Hydrology/Modeling/documents/Tucson%20Model%20Report_No_24_AppendixE.pdf* are located immediately adjacent to the major CAP recharge projects and show the impacts of the facilities on local groundwater levels.

2.6.4 2010 Water Level Elevation and Depth to Water Map

The 2010 water level elevation map for the TAMA is shown in Figure 2-9. The water level elevation map shows the elevation of the water table above mean sea level. The general direction of groundwater flow in an aquifer can be determined by the orientation of the water table contours. The general rule of thumb is that water flows at right angles to the water level elevation contours and from areas of high elevation to lower elevation.

The depth-to-water in 2010 is shown in Figure 2-10. The depth-to-water map shows the depth of the water table below land surface. The direction of groundwater flow is not easily determined from a depth-to-water map. Depth-to-water maps are generally used for well location, design and hydrologic interpretation.

FIGURE 2-9
TUCSON AMA WATER LEVEL ELEVATIONS, 2010

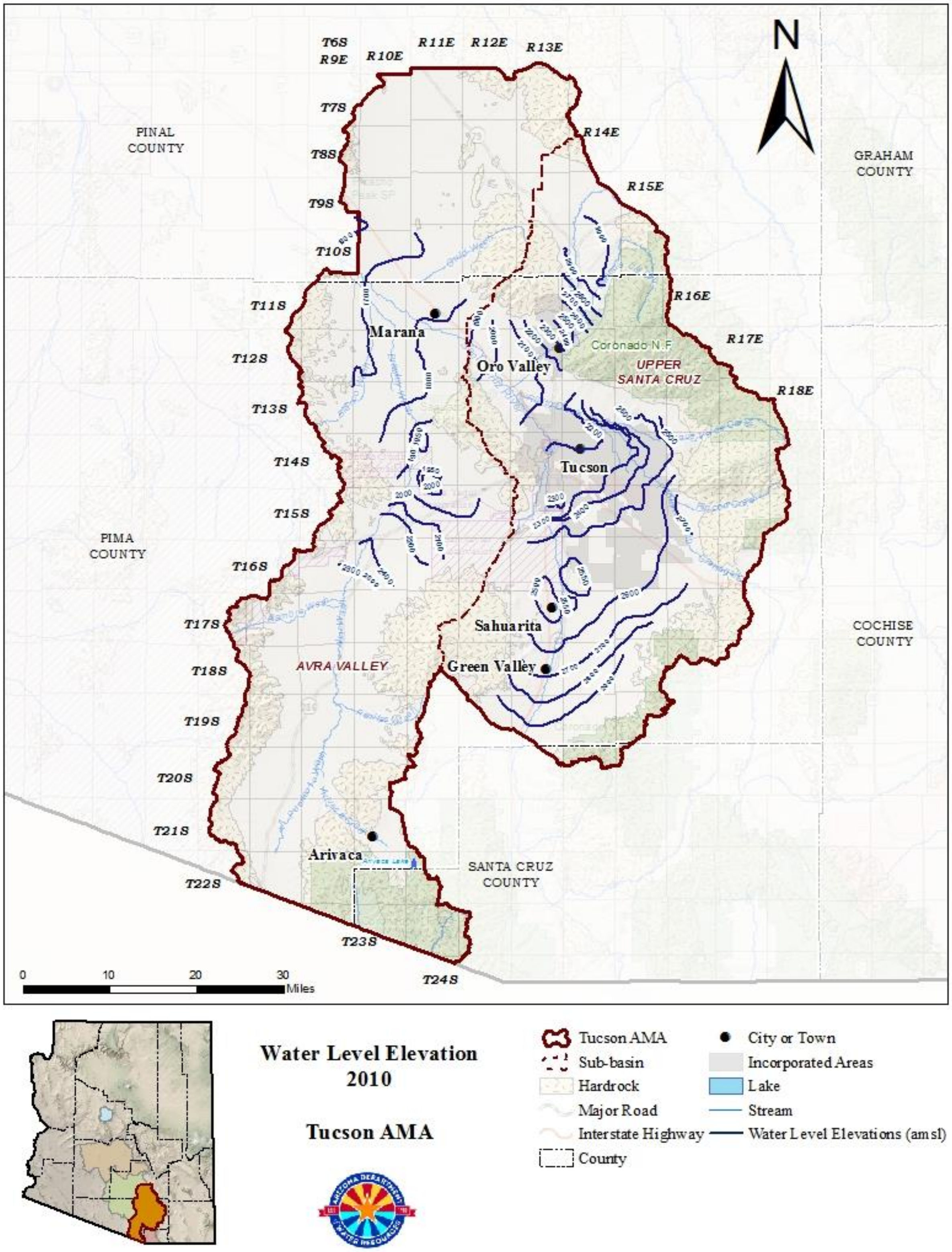
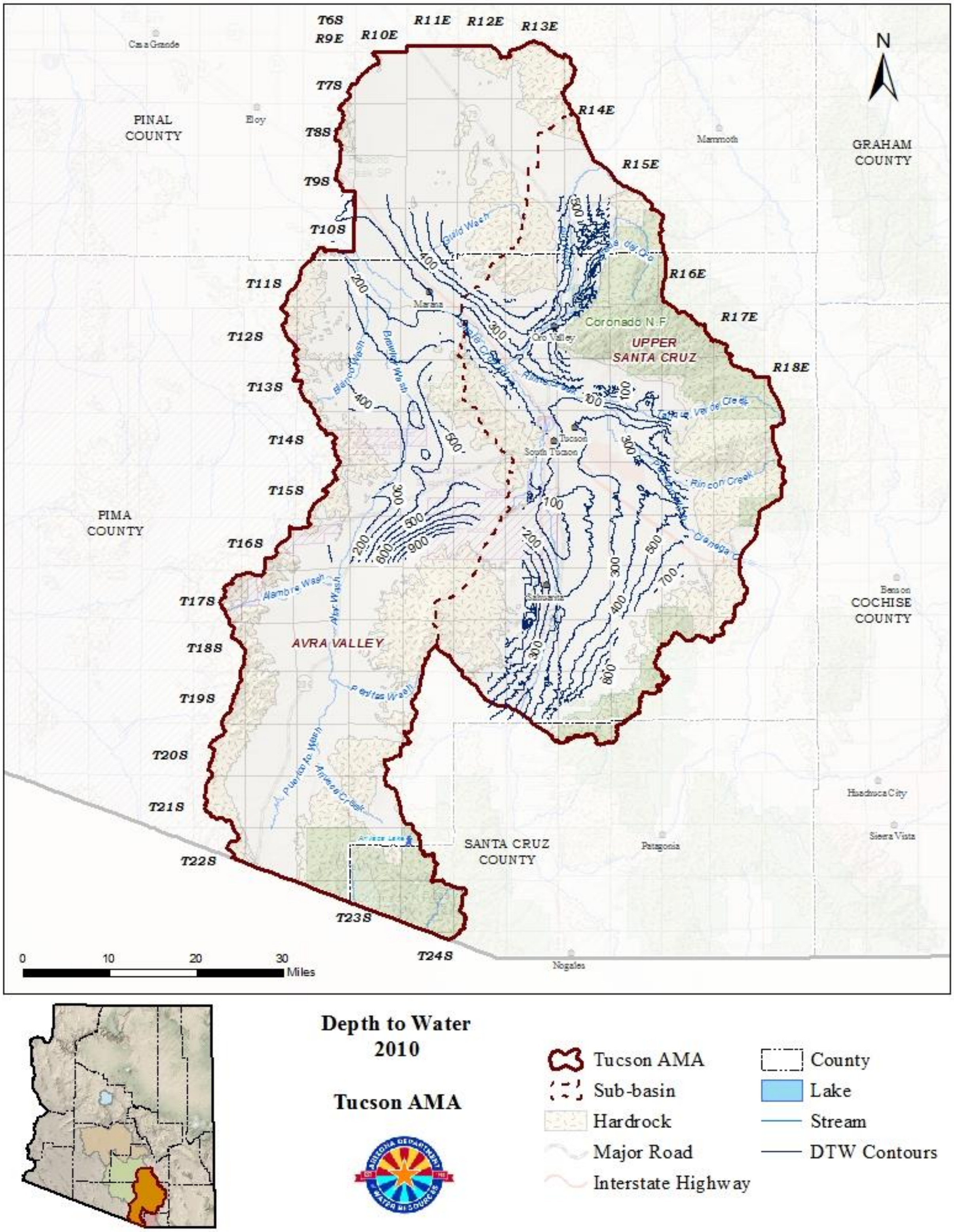


FIGURE 2-10
TUCSON AMA DEPTH TO WATER, 2010



2.6.4.1 Estimated Groundwater-in-storage and Change-in-storage

Information on aquifer thickness, depth-to-water and aquifer storage properties can be used to estimate the volume of water in storage in an aquifer. The estimated groundwater-in-storage to 1,000 feet below land surface for the area covered by the Tucson groundwater flow model in 2010 is 49.3 million ac-ft (*See Table 2-4)*. The USC Sub-basin groundwater-in-storage is estimated to be 32.9 million ac-ft and the groundwater-in-storage for the Avra Valley portion of the Avra Valley Sub-basin is estimated at 16.3 million ac-ft (Mason & Hipke, 2012).

TABLE 2-4
TUCSON AMA GROUNDWATER IN STORAGE
ESTIMATE FLOW MODEL

Sub- Basin	Groundwater Storage estimated ac-ft
Upper Santa Cruz	32,929,700
Avra Valley	16,330,800
Pinal AMA	787,100
Santa Cruz AMA	282,200
TOTAL	**50,329,800**

Overdrafting of the TAMA regional aquifer since the 1940s and the accompanying water level declines resulted in a long-term loss in the volume of groundwater stored in the regional aquifer. The storage loss in the regional aquifer since 1940 has been estimated to range from 6 to 8 million ac-ft (ADWR, 1999). The Tucson groundwater flow model simulated a storage loss in the model domain from 1940 to 2010 of 6.6 million ac-ft (Mason & Hipke, 2012).

The loss of aquifer storage, or negative change-in-storage, has been reversed in the Avra Valley Sub-basin since 1995. Results of the Tucson groundwater flow model indicate that the aquifer in Avra Valley has recorded a net increase in storage of about 358,000 ac-ft since 1995. The positive change is primarily due to large volumes of CAP surface water applied at recharge facilities in northern and central Avra Valley. The aquifer storage recovery is supported by the observed water level recovery in many wells in the sub-basin. The USC Sub-basin aquifer has recorded a continuous net loss of aquifer storage since 1940. Recharge at the Pima Mine Road Recharge Facility (PMRF) has helped reduce the overall change-in-storage losses since 1995. The net loss of storage in the USC Sub-basin from 1995 to 2010 simulated by the Tucson groundwater flow model is 1.5 million ac-ft (Mason & Hipke, 2012).

2.7 LAND SUBSIDENCE

Land subsidence can occur when groundwater is withdrawn to such a degree that portions of an aquifer become dewatered and, due to the weight of overlying land, this material becomes compacted. This results in a drop in elevation at the land surface and can result in cracks and earth fissures at the land surface.

Land subsidence can cause considerable damage to sewer, water and gas pipelines, canals, wells, roads, buildings and other infrastructure. In addition, when aquifer material compacts several characteristics of the aquifer can change. The pore space available to store water is reduced. This in turn could reduce the ease with which water moves through the aquifer material and the productivity of wells in the area of compaction. If these changes occur, they are generally irreversible.

If land subsides at the same rate over a large area, there is less impact to the land surface and a decreased potential for damage to infrastructure than if adjacent land subsides at different rates. Such "differential subsidence" can occur when subsurface geologic conditions change over distance. This can occur near bedrock, around faults, and in areas where the composition of subsurface sediments changes abruptly. In the TAMA, there is some evidence of aquifer compaction and associated land subsidence attributed to aquifer dewatering. Fissuring, aquifer compaction, and subsidence have been observed in northern Avra Valley. In 1988, an earth fissure in Avra Valley damaged the CAP aqueduct, costing about $50,000 in repairs (Slaff, 1993). Sink holes have been reported near the Santa Cruz River within the San Xavier District (Hoffman, Pool, Konieczki, & Carpenter, 1997). These sinkholes are not directly related to regional subsidence but may be related to localized water level declines.

TABLE 2-5
TUCSON AMA LAND SUBSIDENCE, 1980-2009
(based on USGS Vertical Extensometer data)

	USGS Vertical Extensometer	Total Compaction (ft)	Compaction Rate (ft/year)
06/1980 - 09/2011	B76	0.51	0.016
12/1979 - 09/2011	C45	0.465	0.015
01/1981 - 09/2011	D61	0.324	0.011
12/1979 - 12/2009	SC17	0.202	0.007
09/1982 - 09/2011	WR52	0.238	0.008
11/1983 - 07/2009	WR53	0.072	0.003

Aquifer compaction and associated land subsidence of nearly 0.5 feet had occurred south of Davis-Monthan Air Force Base from the 1940s to 1980 (Anderson, 1988) *(See Table 2-5).* Subsidence monitoring has been conducted since the early 1980s by the City of Tucson (Tucson Water) and the USGS using extensometers to measure aquifer compaction *(See Figure 2-11*). In the northern Avra Valley Sub-basin, subsidence has been measured at 1.1 feet (Anderson, 1989). Measurement of compaction at specific locations in the time period between 1980 and 1995 were reported in the Tucson Water Annual Static Water Level Report for 1995 (Tucson Water, 1997). Results indicated compaction of from 0.02 feet to 0.18 feet at seven locations in the USC Sub-basin and from 0.01 feet to 0.11 feet at seven locations in the Avra Valley Sub-basin. City of Tucson elevation survey data in the Tucson central well-field area from the early/mid 1990s to 2011 indicate subsidence as much as 0.9 feet *(See Figure 2-12*).

Based on the maximum subsidence potential projected in earlier USGS modeling studies (Hanson & Benedict, 1994), it appears the depth of land subsidence could vary from 2 feet to 10 feet in the vicinity of downtown Tucson by 2025 and from 2 feet to 14 feet in the central area of Avra Valley by 2025 (Hanson, Anderson, & Pool, 1990). The USGS land subsidence modeling studies used a one-dimensional model and a limited dataset. The USGS has since compiled an extensive dataset on groundwater change, aquifer storage change and land subsidence which should greatly improve any future land subsidence modeling/estimation projects for the TAMA. However, historical and current land subsidence data for the TAMA indicate the smaller USGS land subsidence estimates for the Avra Valley and downtown Tucson areas are more likely, especially considering the recent water level rises or stabilization measured in those areas.

Recent ADWR land subsidence monitoring and land subsidence maps are published annually on ADWR's website, *http://www.azwater.gov/AzDWR/Hydrology/Geophysics/LandSubsidenceInArizona.htm*. These maps provide further evidence of land subsidence in the TAMA, particularly in two areas in and near the Tucson central well-field area, which correlates to features identified by the USGS and Tucson Water; and a third area within the Town of Sahuarita. Land subsidence in the Avra Valley area no longer appears to be active.

FIGURE 2-11
METROPOLITAN TUCSON USGS EXTENSOMETERS AND GROUNDWATER MONITORING WELLS IN

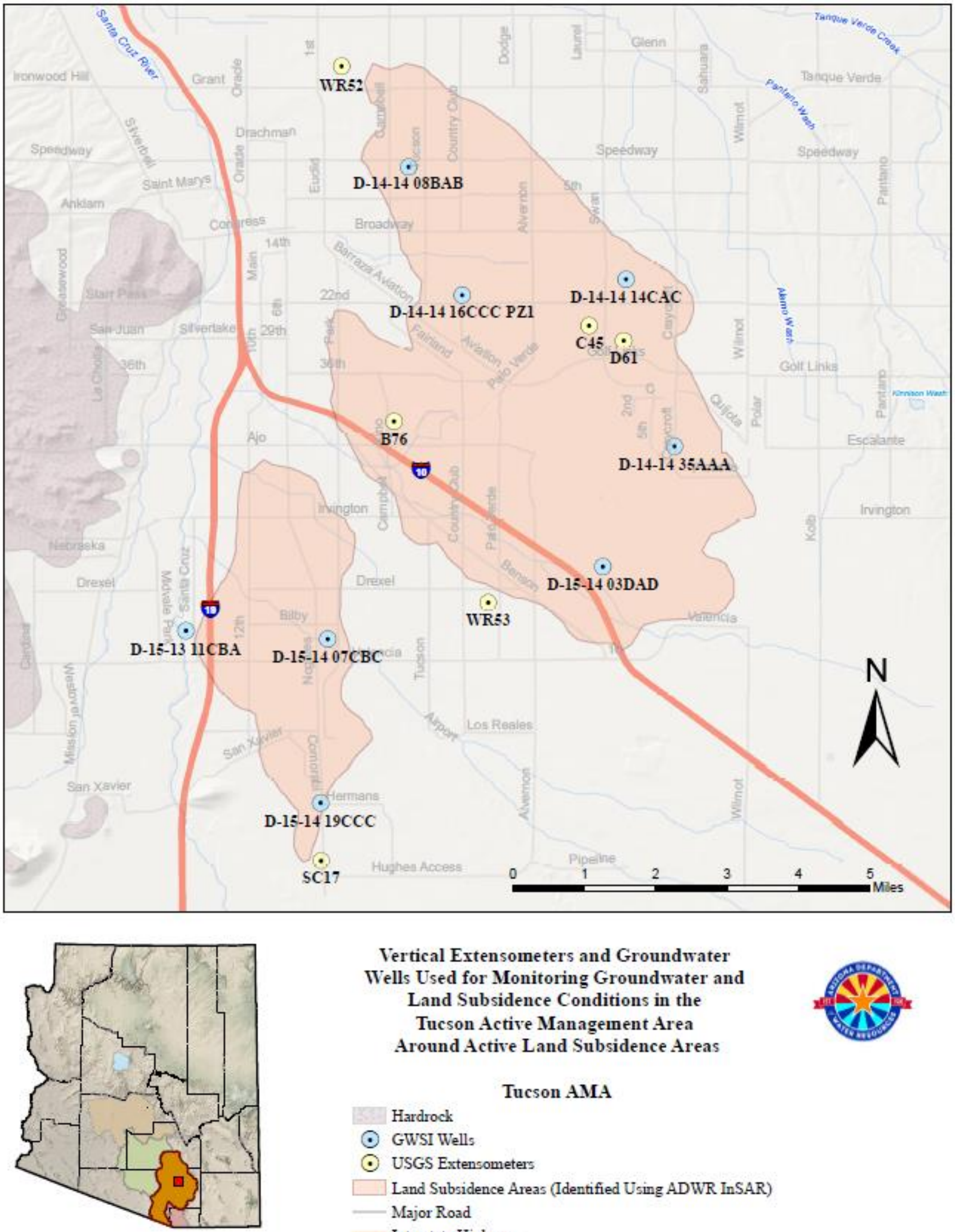


FIGURE 2-12
CITY OF TUCSON ELEVATION SURVEY DATA

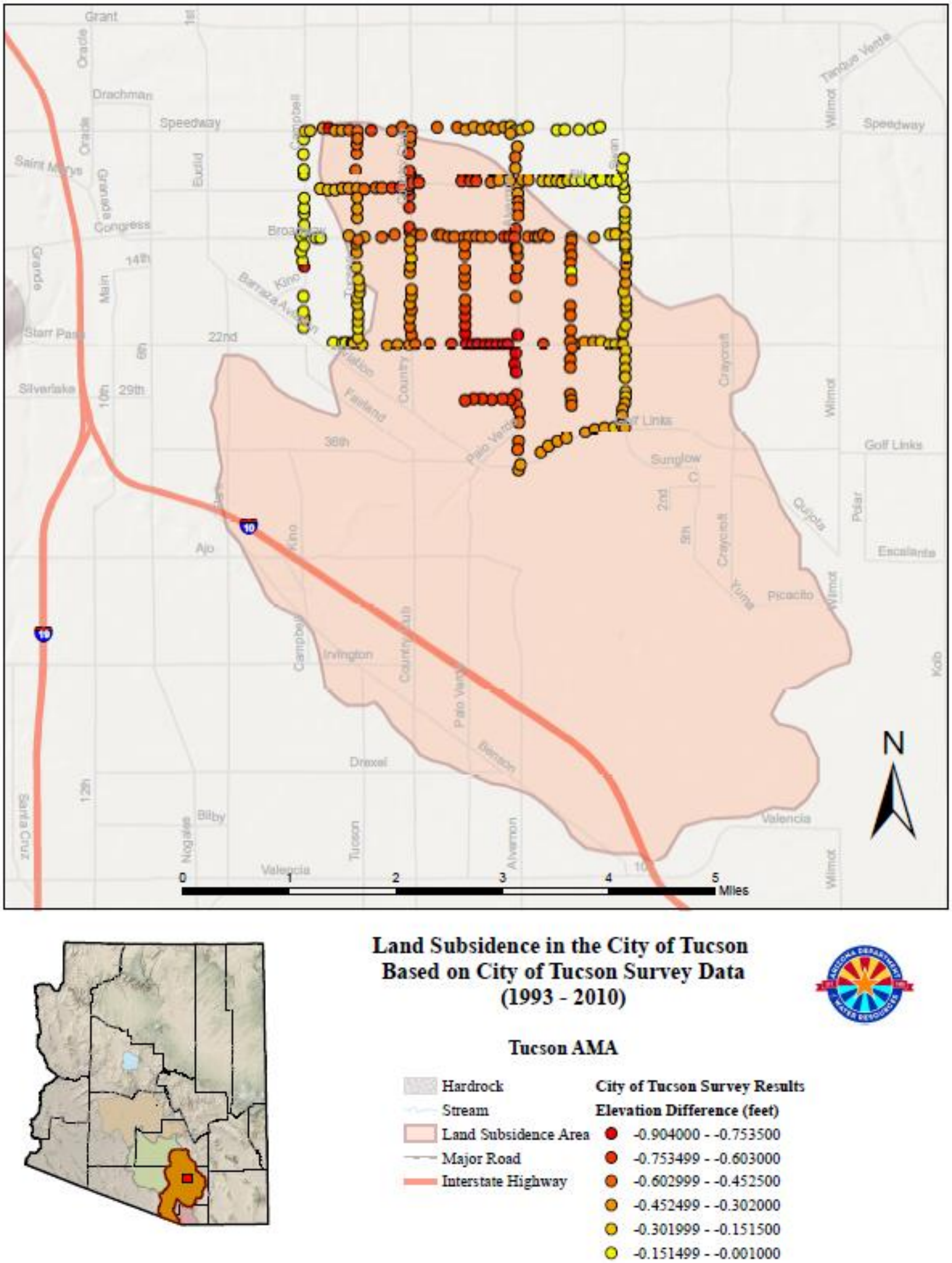
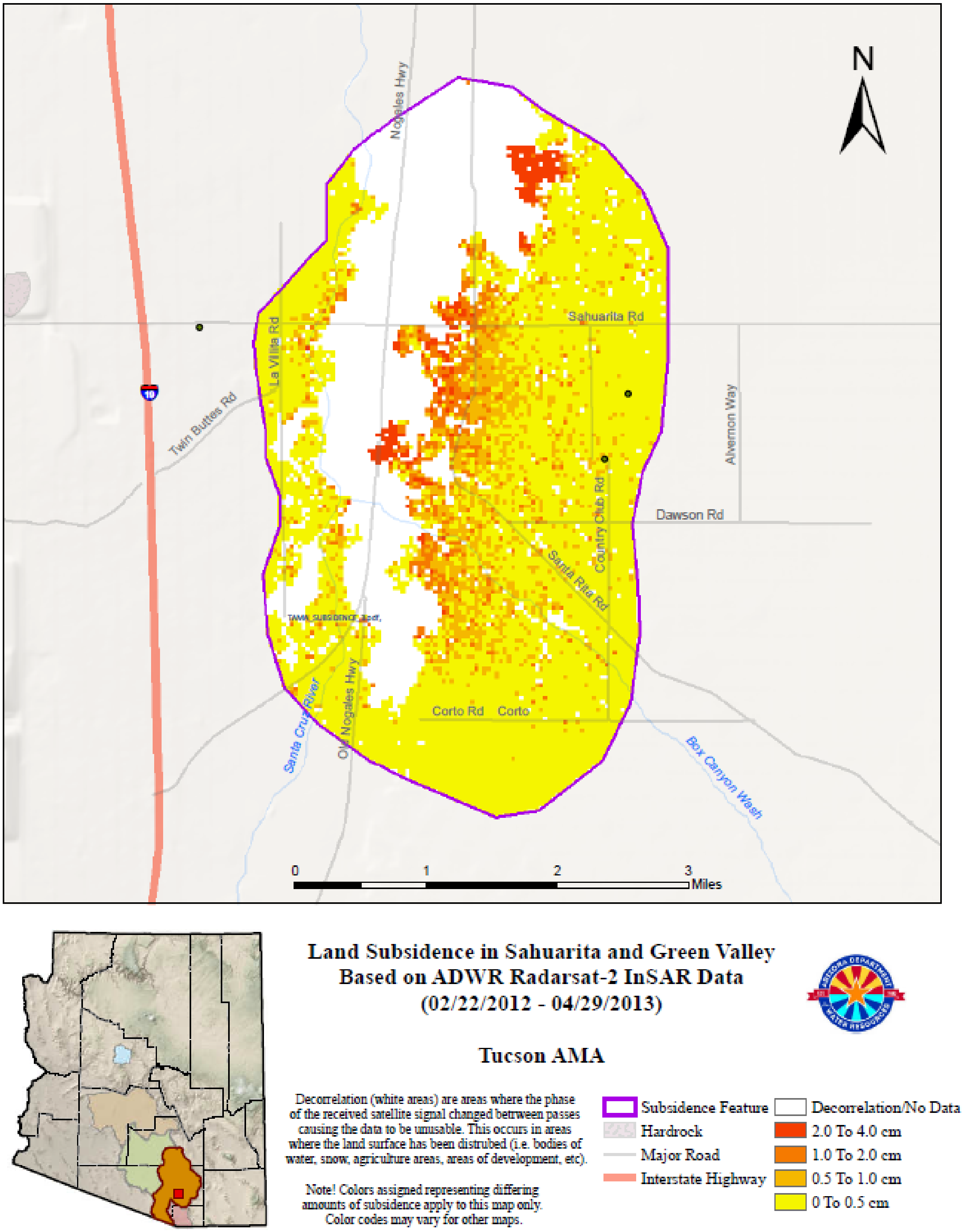


FIGURE 2-13
SAHUARITA AREA LAND SUBSIDENCE, FEB 2012 – APR 2013



ADWR has been monitoring land subsidence in the majority of the TAMA using a satellite-based remote-sensing system since 2005, collecting, processing and analyzing Interferometric Synthetic Aperture Radar (InSAR) data *(See Table 2-6*). Three separate land subsidence features have been detected in the TAMA using InSAR data. Two land subsidence features are located in the Tucson metropolitan area; the first feature is centered near Tucson's central well field near Alvernon Way and Golf Links Rd and the second is centered near Nogales Hwy. and Valencia Rd. The third feature is located in the Town of Sahuarita and is centered near Sahuarita Rd. and Old Nogales Hwy. The feature located in Sahuarita, referred to as the Green Valley Land Subsidence Feature by ADWR, is dominated by an elastic aquifer system and has seasonal deformation (uplift and subsidence). There had been times historically when the seasonal deformation was in equilibrium, resulting in no land subsidence (March 2008 to February 2009; and January 2010 to April 2011); and times when the subsidence was greater than the uplift *(See Figure 2-13*), resulting in land subsidence (February 2007 to March 2008, September 2010 to January 2010, and April 2011 to May 2012).

ADWR has processed archived and regularly scheduled InSAR data for the periods November 1993 to September 2000; February 2003 to January 2010; and May 2010 to April 2012 for the TAMA. The rate of land subsidence has decreased at the two Tucson metropolitan areas described above when comparing these sets of InSAR results *(See Figures 2-14 through 2-16).* Total compaction and subsidence rates for the three land subsidence areas are listed in Table 2-6.

TABLE 2-6
TUCSON AMA LAND SUBSIDENCE
(based on ADWR INSAR data)

	Valencia Feature Subsidence (ft)	Highest Rate-Valencia (ft/year)	Central Well Field Feature Subsidence (ft)	Highest Rate-Central Well (ft/year)	Green Valley Feature Subsidence (ft)	Highest Rate-Green Valley (ft/year)
11/1993 - 09/2000	0.79	0.11	0.43	0.06	ND	ND
02/2003 - 01/2010	0.33	0.05	0.26	0.04	ND	ND
05/2010 - 04/2012	0.02	0.01	0.06	0.03	ND	ND
04/2011 - 05/2012	ND	ND	ND	ND	0.13	0.12
Total Subsidence	**1.14**	**ND**	**0.74**	**ND**	**0.13**	**ND**

NOTE: ND means no measurement was recorded for that area.

Groundwater levels have been slowly rising in the areas around the Tucson well field and the Valencia land subsidence features since the early 2000s. (*See Figure 2-17(A-H) for hydrographs and Figure 2-18 for a map showing the location of the hydrograph wells.*) The groundwater level increase is most likely the cause for the decrease in land subsidence rates in the Tucson metropolitan area when comparing ADWR InSAR results. A number of groundwater monitoring wells *(See Table 2-7)* are measured annually, providing ADWR with accurate groundwater level change data that is analyzed with current and historical land subsidence data. Residual land subsidence may continue to occur even with the continued recovery of groundwater levels. Land subsidence will only ease and cease once the groundwater system reaches equilibrium. Even though groundwater levels may recover to previously high levels after land subsidence occurs, because the aquifer material has been compacted, the space available for groundwater storage is reduced so less groundwater is available for pumping. Also, once land subsidence has occurred, the addition of water to the subsurface cannot return the land to its full original elevation (Slaff, 1993).

TABLE 2-7
TUCSON AMA, TUCSON METRO AREA
GROUNDWATER MONITORING WELLS NEAR LAND SUBSIDENCE

Groundwater Monitoring Well	01/1994 - 02/2011 Water level Change (ft)	12/1993 - 01/2012 Water level Change (ft)	02/1994 - 12/2009 Water level Change (ft)
B-14-14 08BAB	-14		
B-14-14 16CCC PZ1		-19.5	
B-14-14 35AAA		-26.5	
B-14-14 14CAC			-26.5
B-15-14 03DAD		-6	
B-15-14 07CBC	15.2		
B-15-14 19CCC	18.3		
B-15-13 11CBA	-22.8		

Note: A positive value represents rising water levels and a negative value represents dropping water levels)

Continued lowering of groundwater levels could result in additional land subsidence. Because there is potential for significant damage due to land subsidence in the TAMA, mitigation of groundwater overdraft in subsidence-prone areas continues to be a groundwater management issue for the TAMA. ADWR will continue to monitor land subsidence in the TAMA using regularly scheduled InSAR data collection and analysis.

2.8 GROUNDWATER QUALITY LIMITATIONS ON SUPPLY

Most groundwater supplies in the TAMA are of acceptable quality for most uses. However, human activity and natural processes have resulted in the degradation of groundwater quality in some areas to the extent that it is unusable for many purposes without treatment. The extent and type of contamination varies by location and land use activities. Contaminated groundwater in the TAMA has generally been caused by human activity. Volatile organic compounds (VOCs) are a predominant contaminant in the TAMA and limit the direct use of some groundwater. Remedial processes are used to treat VOC contaminated water to drinking water quality standards, making this water available for either current or future direct potable use. Water supplies contaminated with other constituents must also be properly treated prior to use for drinking water supplies. Beneficial end uses of lower quality water can be identified but are only likely to take place if they are economically feasible. For more information on water quality in the TAMA, see Chapter 7 of this plan.

FIGURE 2-14
TUCSON METROPOLITAN AREA LAND SUBSIDENCE, NOV 1993 – SEPT 2000

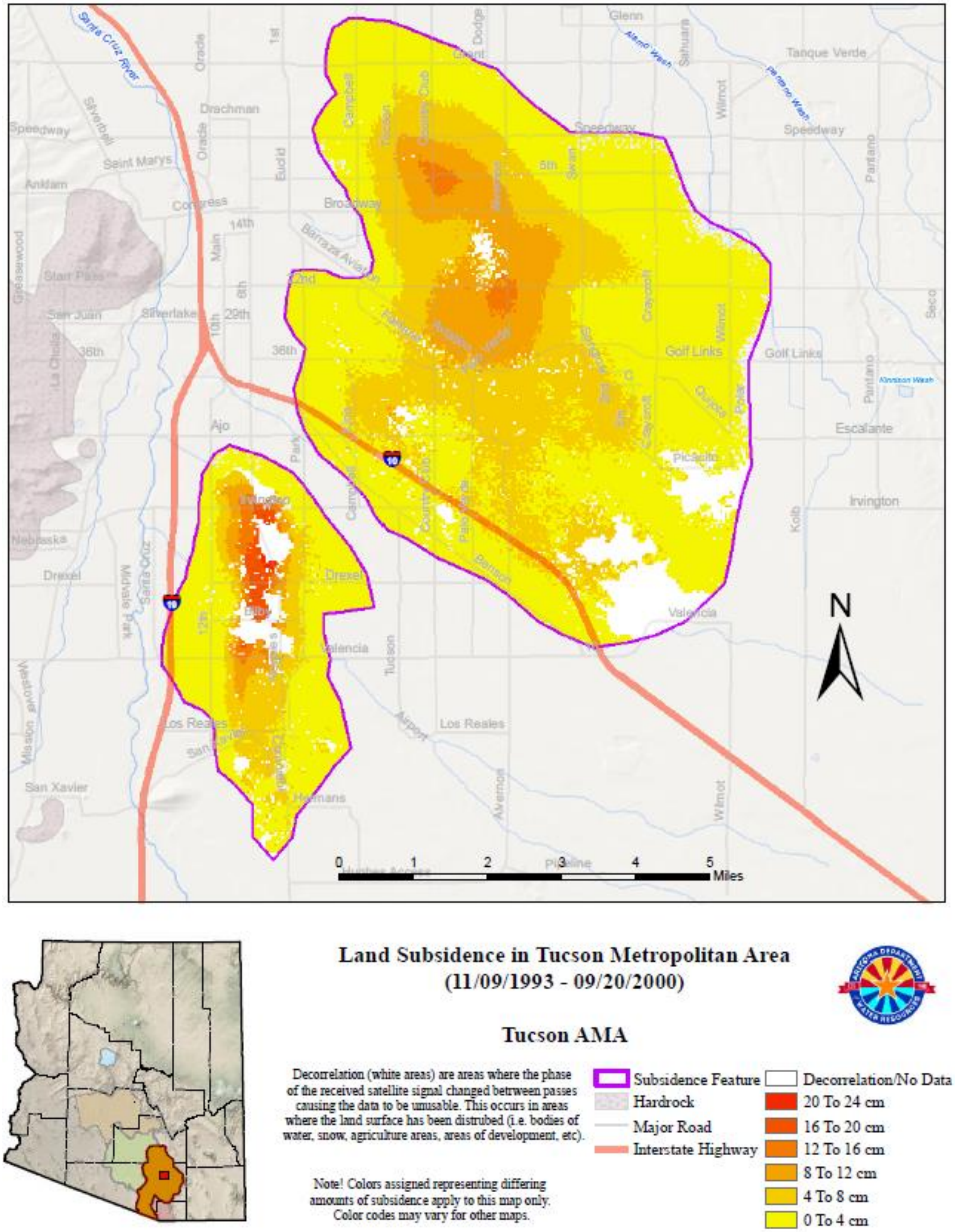


FIGURE 2-15
TUCSON METROPOLITAN AREA LAND SUBSIDENCE, FEB 2003 – JAN 2010

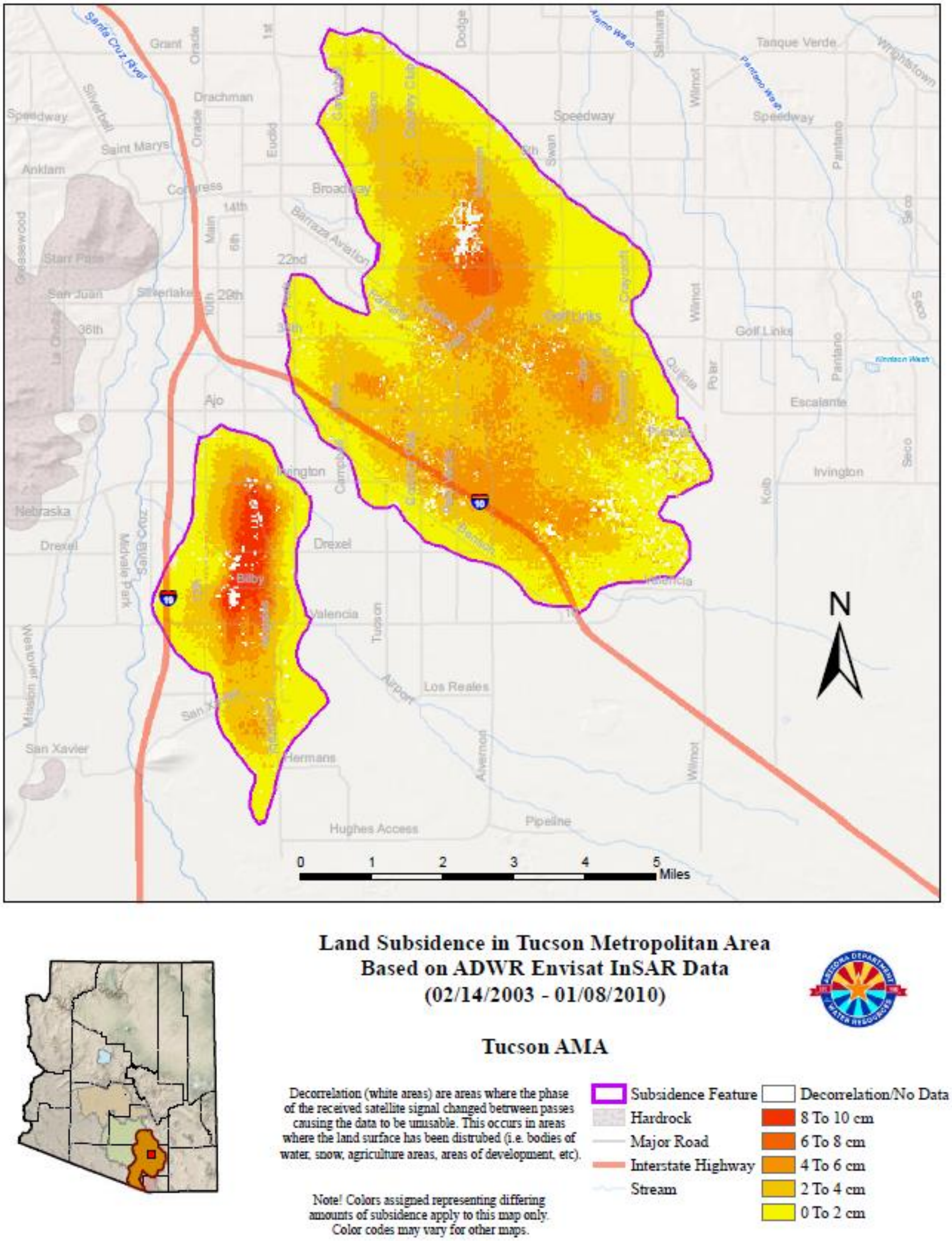


FIGURE 2-16
TUCSON METROPOLITAN AREA LAND SUBSIDENCE, MAY 2010 – APR 2012

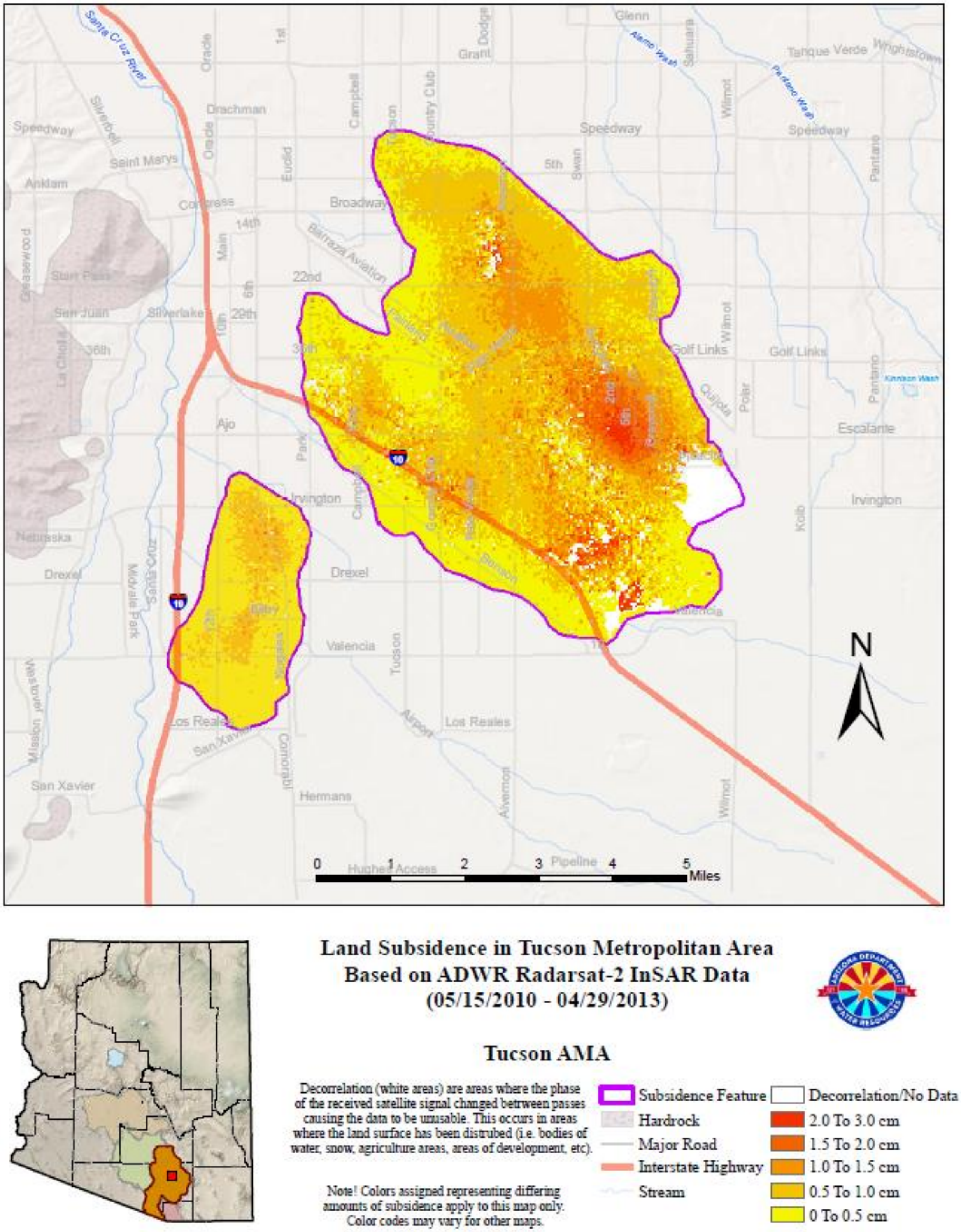


FIGURE 2-17 (A)
HYDROGRAPH FOR GW MONITORING Well 55-620173 D-14-14-08-BAB
in TUCSON AMA

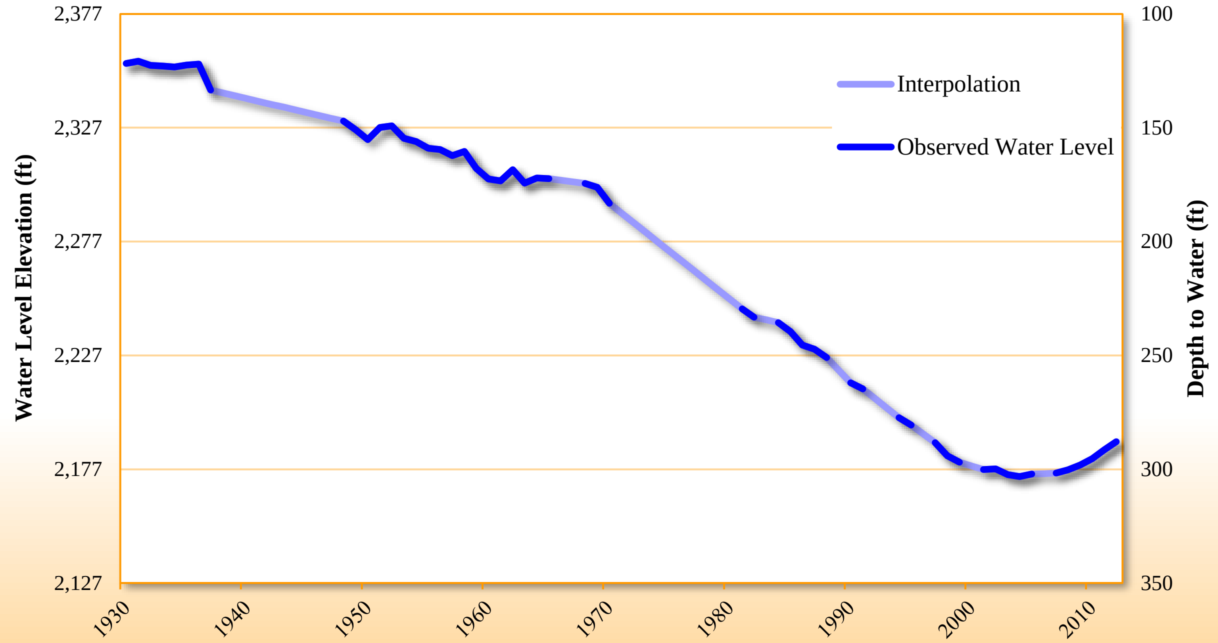


FIGURE 2-17 (B)
HYDROGRAPH FOR GW MONITORING Well D-14-14-16-CCC PZ1-2
in TUCSON AMA

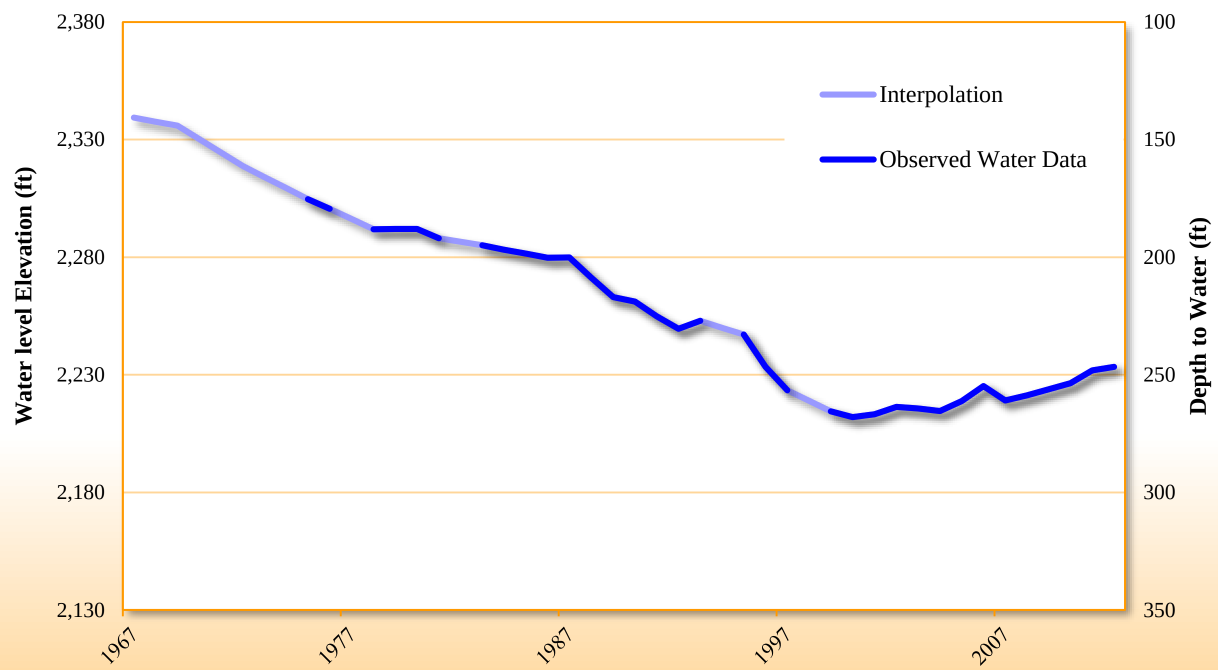


FIGURE 2-17 (C)
HYDROGRAPH FOR GW MONITORING Well 55-620042 D-14-14-14-CAC in TUCSON AMA

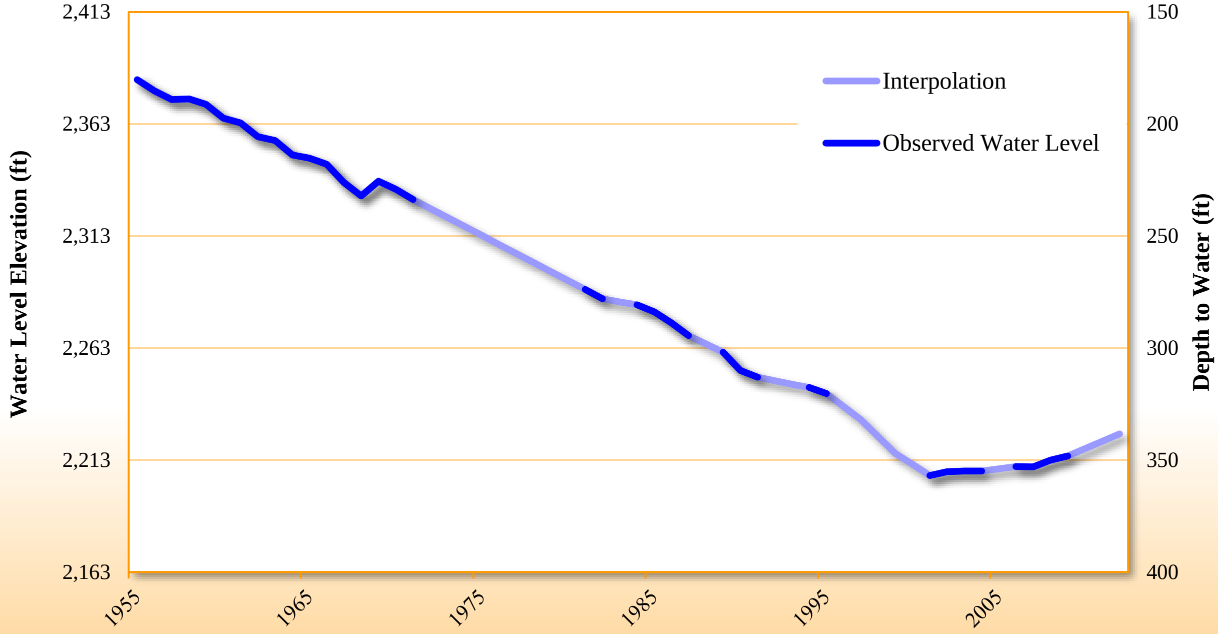


FIGURE 2-17 (D)
HYDROGRAPH FOR GW MONITORING Well 55-621581 D-14-14-35-AAA in TUCSON AMA

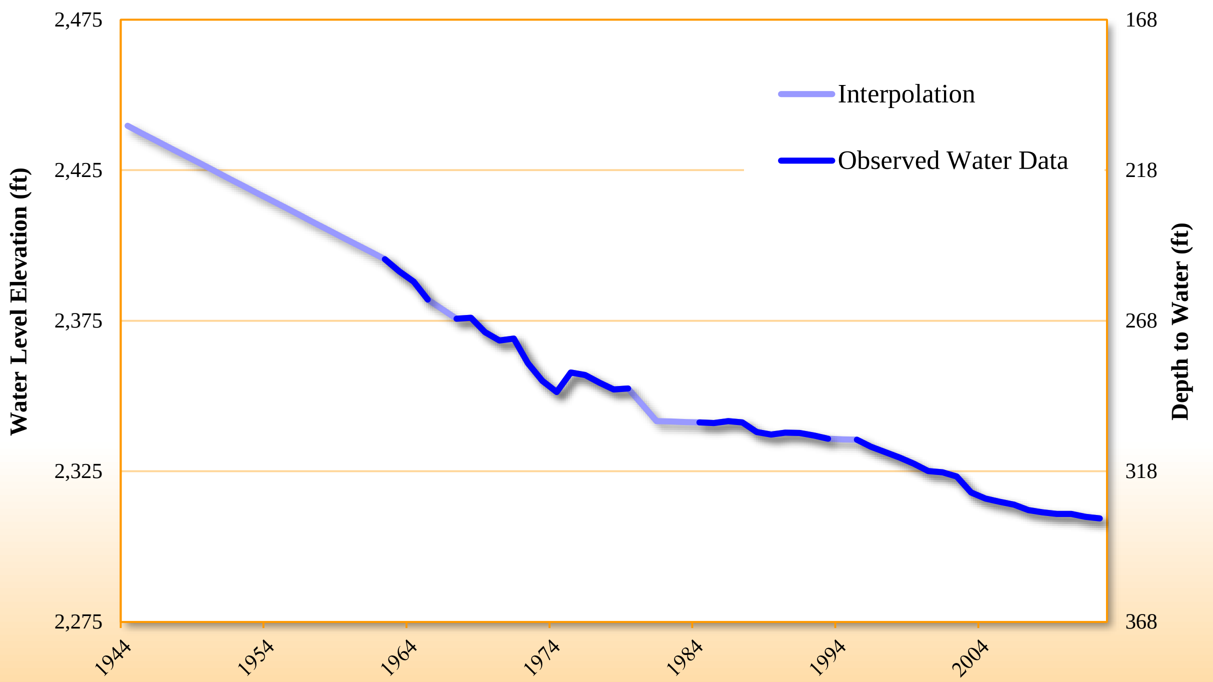


FIGURE 2-17 (E)
HYDROGRAPH FOR GW MONITORING Well 55-611361
D-15-14-03-DAD in TUCSON AMA

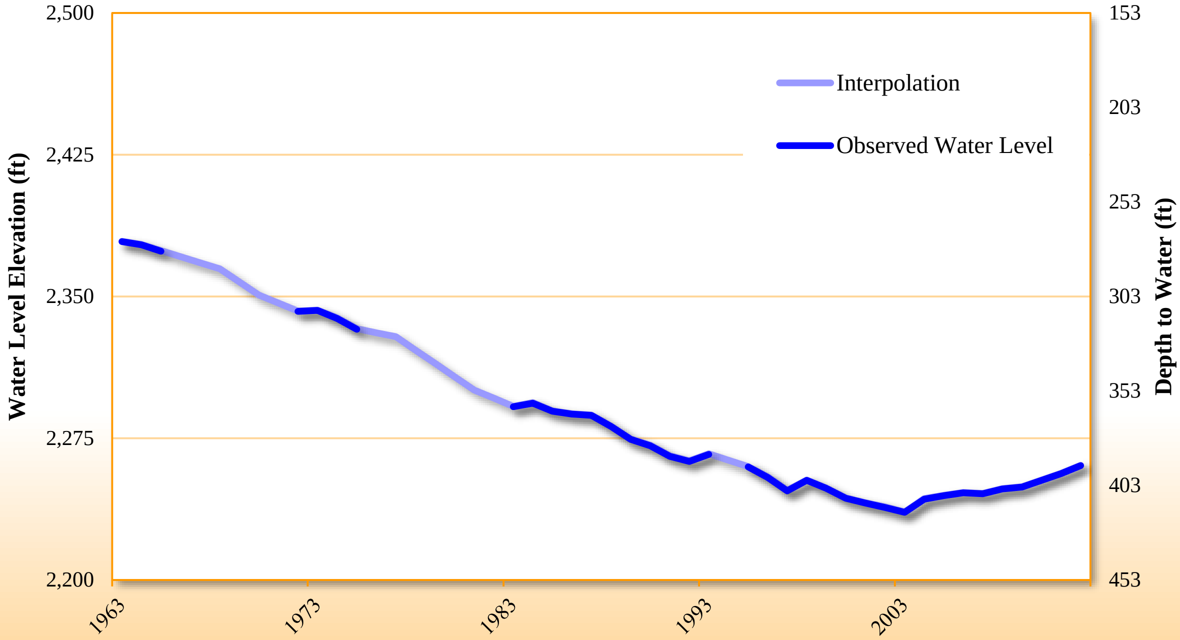


FIGURE 2-17 (F)
HYDROGRAPH FOR GW MONITORING Well 55-620003
D-15-14-07-CBC in TUCSON AMA

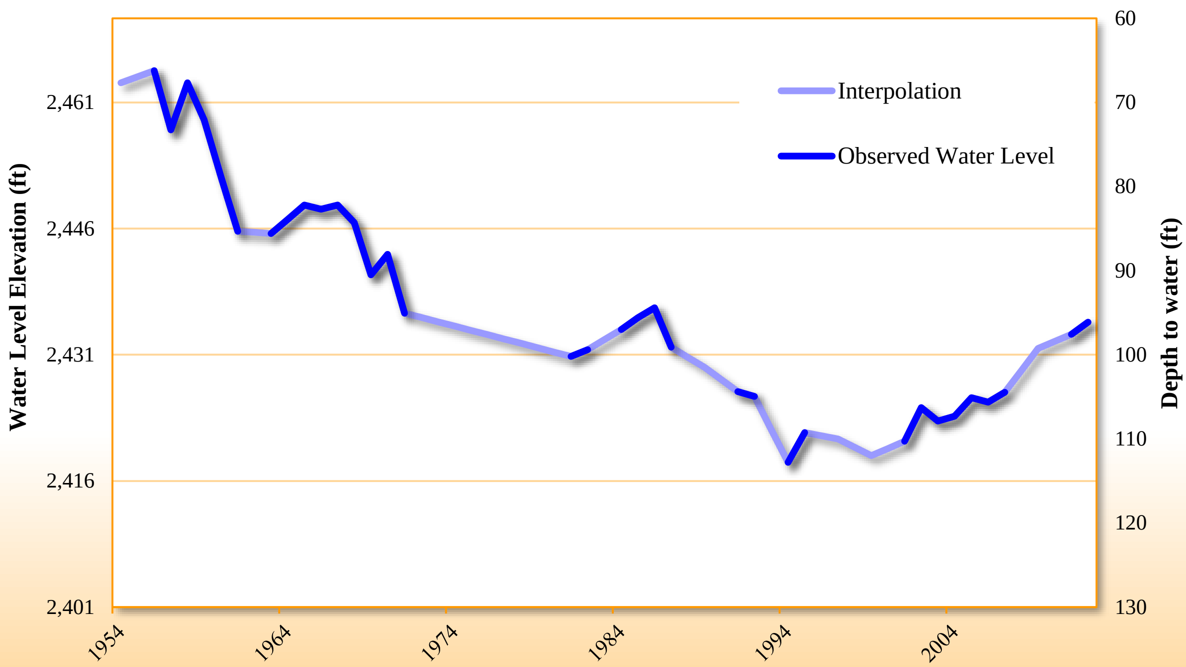


FIGURE 2-17 (G)
HYDROGRAPH FOR GW MONITORING Well 55-619881 D-15-14-19-CCC
in TUCSON AMA

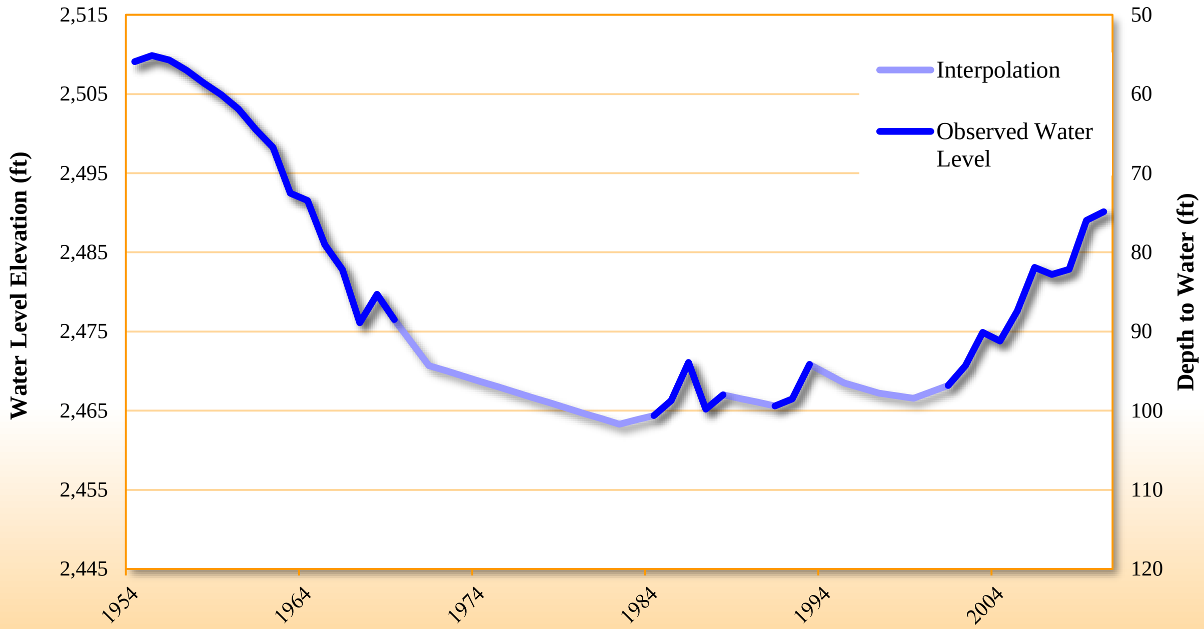


FIGURE 2-17 (H)
HYDROGRAPH FOR GW MONITORING Well 55-619918 D-15-13-11-CBA
in TUCSON AMA

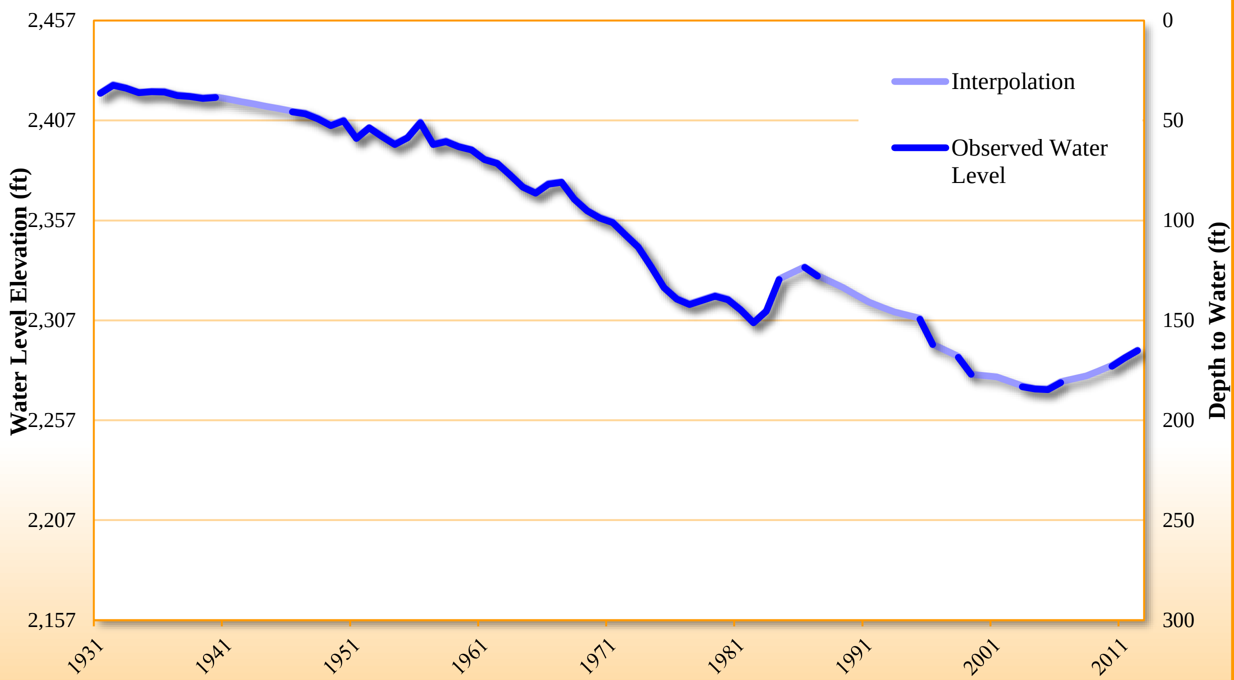
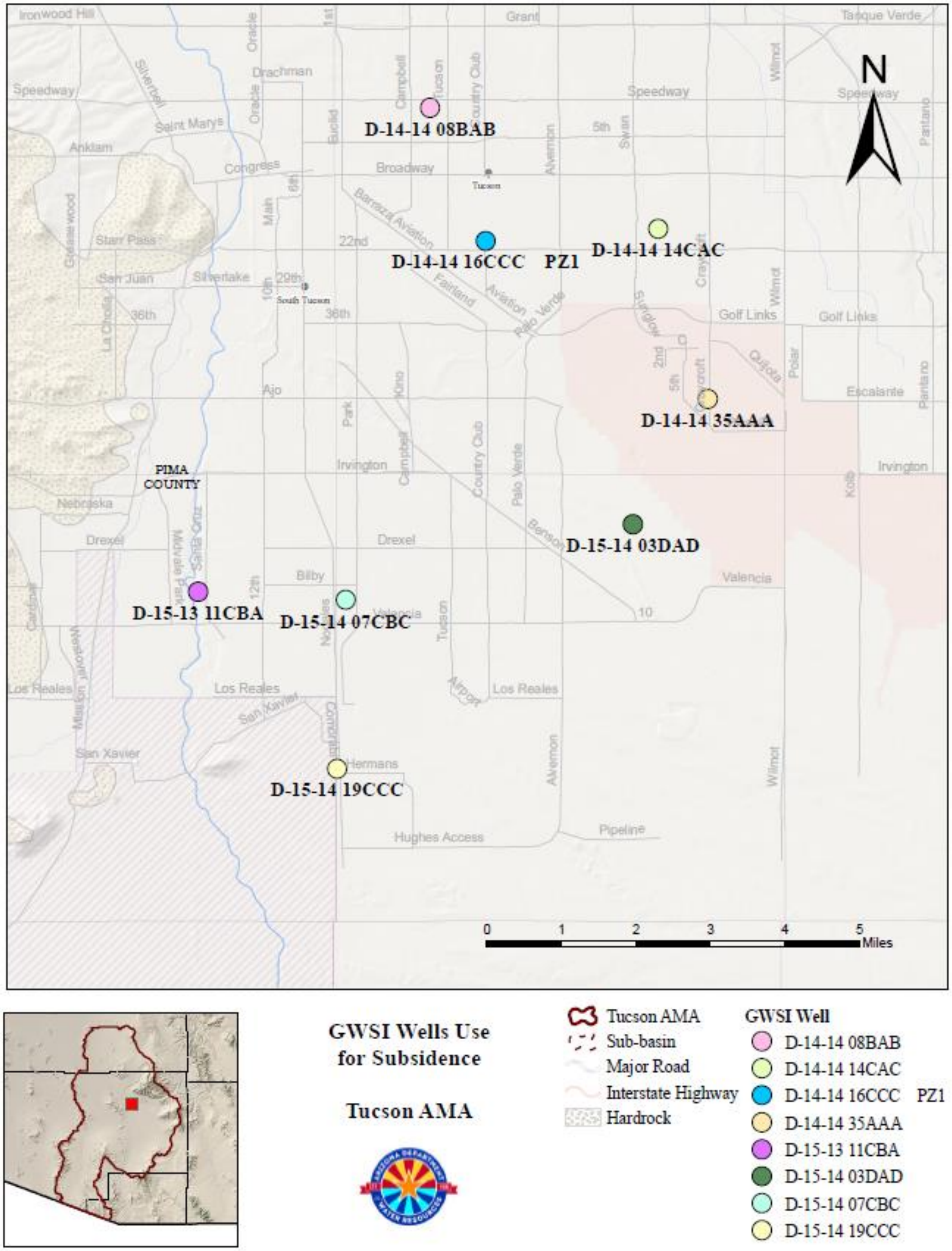


FIGURE 2-18
LOCATION OF HYDROGRAPHS, FIGURES 2-17 (A-H)



2.9 AVAILABLITY AND UTILIZATION OF RENEWABLE SUPPLIES

To achieve safe-yield in the TAMA by 2025, groundwater reliance must be reduced and renewable water supply use increased. Treated reclaimed water and CAP surface water are the currently available renewable supplies in the TAMA. The continued ability to effectively utilize CAP surface water and reclaimed water throughout the TAMA will significantly affect the TAMA's ability to reach safe-yield. The historical direct use of renewable supplies is described in detail in Chapter 3.

2.9.1 Reclaimed Water

In 2013, the total reclaimed water production for all wastewater treatment plants in the TAMA was 67,320 ac-ft (Pima County Regional Wastewater Reclamation Department, 2013). The majority of this reclaimed water was treated by Pima County Wastewater Management at two regional treatment plants located along the Santa Cruz River at Tres Rios WRF (Ina Road) and Agua Nueva WRF (Roger Road). Smaller amounts of reclaimed water were treated at a number of smaller capacity sub-regional plants. The majority of the reclaimed water is discharged into the Santa Cruz River where it infiltrates into the regional aquifer as a component of streambed recharge. Discharge to the river averaged 52,240 ac-ft per year between 2000 and 2013. Some of the reclaimed water generated at the regional plants is diverted into the Tucson Water's reclaimed water system for delivery to turf facilities throughout the Tucson metro area. Deliveries to the reclaimed water system from 2000 to 2013 averaged 13,150 ac-ft per year. A small portion of the reclaimed water is recharged at constructed underground storage facility sites or at on-site seepage basins at the sub-regional treatment facilities. For additional information on the volumes of reclaimed water stored and recovered in the TAMA, please see Chapter 8 of this plan. In the future, the reuse and recharge of reclaimed water would reduce the need to pump groundwater and help to minimize water level declines.

2.9.2 CAP Surface Water

CAP surface water is the most abundant renewable water supply in the TAMA. CAP allocations available to the TAMA total more than 260,000 ac-ft. The City of Tucson holds the highest share of the allocated water with 144,172 ac-ft. See Chapter 8 of this plan for a listing of CAP allocations in the TAMA and a map of the locations of the recharge facilities. Table 2-8 lists the Underground Storage Facilities (USFs) in the TAMA. The majority of the CAP water is delivered to underground storage facilities in the Avra Valley Sub-basin where the water is recharged to the regional aquifer. Six permitted recharge facilities are located in the USC Sub-basin; however, only the Pima Mine Road facility may store CAP water in this sub-basin. Between 2000 and 2013, approximately 1.9 million ac-ft of CAP water was recharged at permitted underground storage facilities in the TAMA.

TABLE 2-8
TUCSON AMA UNDERGROUND STORAGE FACILTIES

USF Permit Number	USF Permittee	USF Name	USF Type	Type of Water Recharged
71-564896	Metro Water District	Avra Valley Airport USF	Constructed	CAP
71-578806	Tucson Water	Central Avra Valley Storage & Recovery Project	Constructed	CAP
71-211284	Pima County RWRD	Corona De Tucson	Constructed	Reclaimed
71-591928	Tucson Water, Marana, CMID, AVIDD, Pima County, et al	Lower Santa Cruz Managed	Managed	Reclaimed
71-561366	Pima County FCD CAWCD	LSCRP-Constructed	Constructed	CAP
71-563876	Pima County FCD Town of Marana	Marana High Plains	Constructed	Surface & Reclaimed
71-577501	CAWCD	Pima Mine Rd	Constructed	CAP

USF Permit Number	USF Permittee	USF Name	USF Type	Type of Water Recharged
71-581379	Robson Ranch Quail Creek	Quail Creek-Robson Ranch	Constructed	Reclaimed
71-595209	Town of Sahuarita	Sahuarita WWTP	Constructed	Reclaimed
71-520083	Tucson Water	Santa Cruz-Sweetwater	Constructed	Reclaimed
71-211276	Tucson Water	Southern Avra Valley Storage & Recovery Project	Constructed	CAP
71-545944	Tucson Water	Santa Cruz River Managed	Managed	Reclaimed
71-221721	Saddlebrooke Utility Company	Saddlebrooke Water Reclamation Plan	Constructed	Reclaimed
71-222410	JPAR LLC	Project Renews	Constructed	CAP

In addition to its use at recharge facilities, some CAP water is used directly by the agricultural and industrial sectors. Agricultural use includes water that is provided to farms participating in ADWR's Groundwater Savings Facility (GSF) Program. At GSFs, CAP water is used in lieu of groundwater and the water storer receives credit for the groundwater "saved," which can then be used by the water storer in the future. From 2000 to 2013, CAP water use at GSFs has averaged more than 20,000 ac-ft. per year. CAP surface water is also supplied to the San Xavier District of the Tohono O'odham Nation for agricultural purposes. The total CAP water supplied to the Nation for agricultural purposes from 2000 to 2013 was approximately 203,300 ac-ft.

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