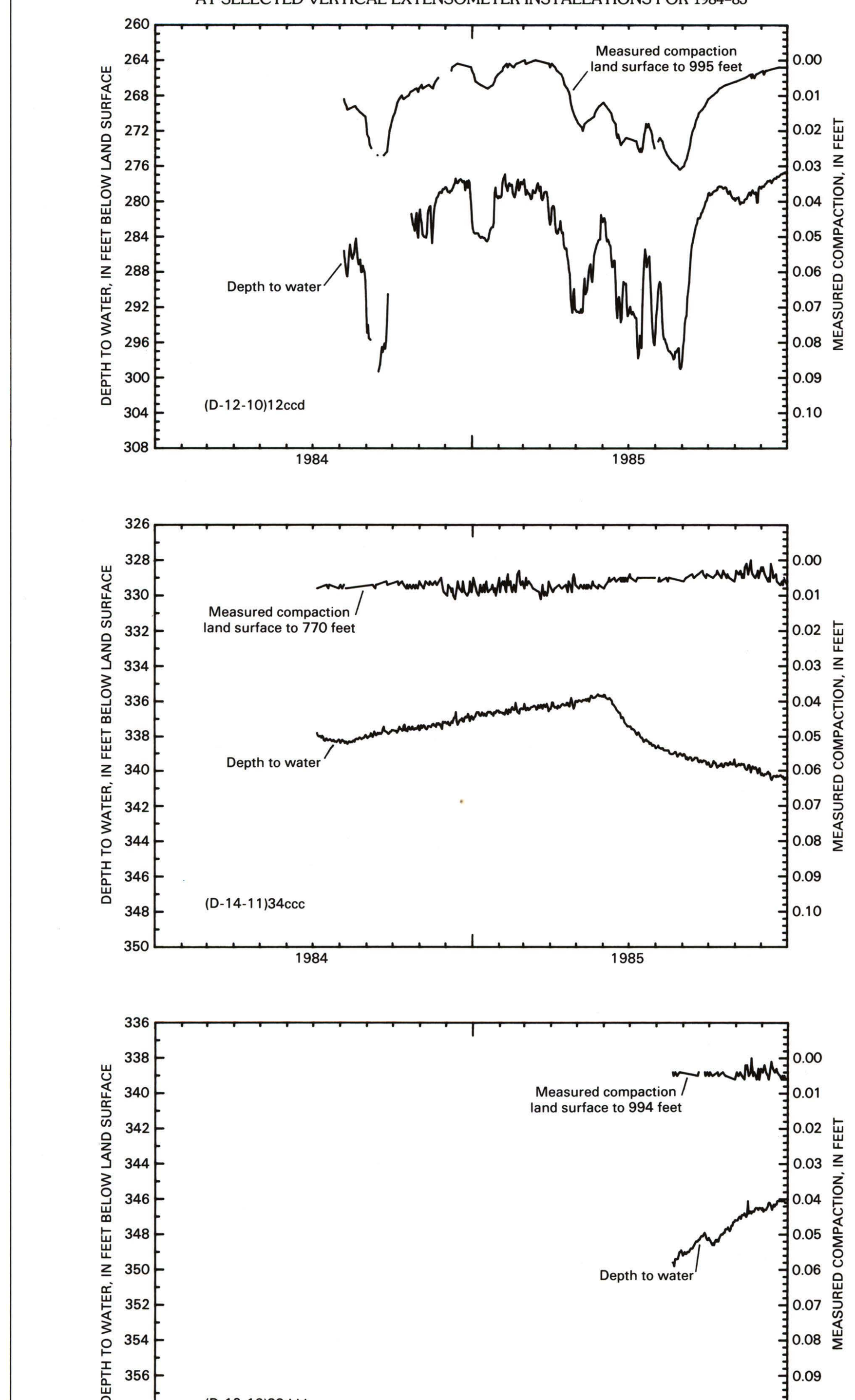
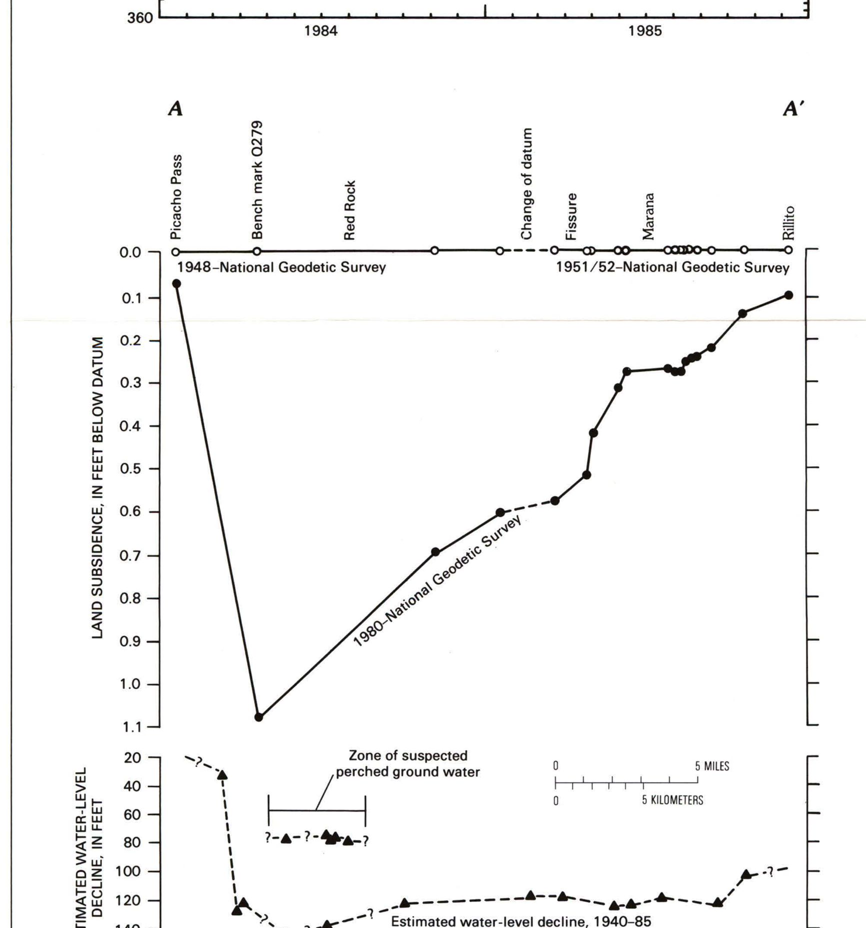
HYDROGRAPHS SHOWING DEPTH TO WATER AND MEASURED COMPACTION AT SELECTED VERTICAL EXTENSOMETER INSTALLATIONS FOR 1984-85





Profile A–A′.—Land subsidence and estimated water-level decline between Picacho Pass and Rillito.

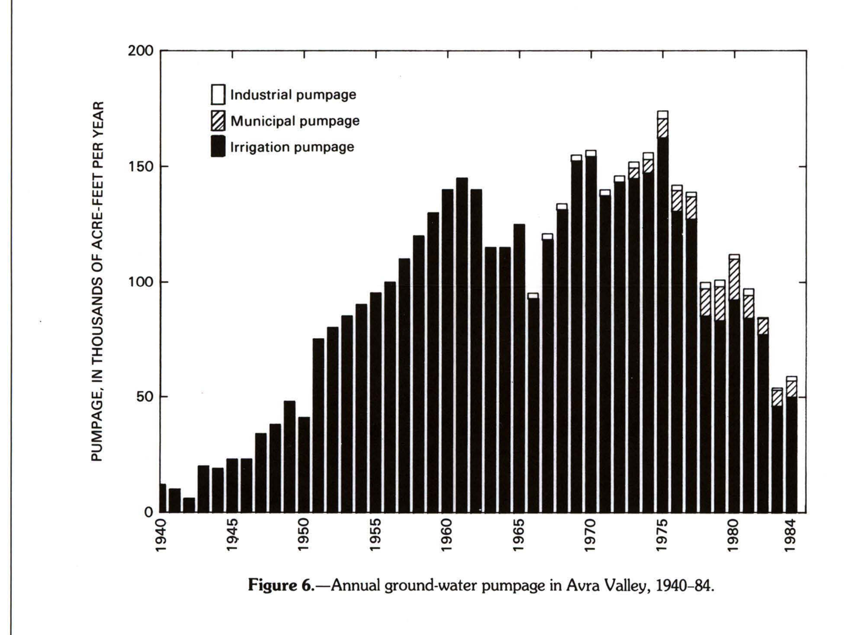


Figure 6.—Annual ground-water pumpage in Avra Valley, 1940–84.

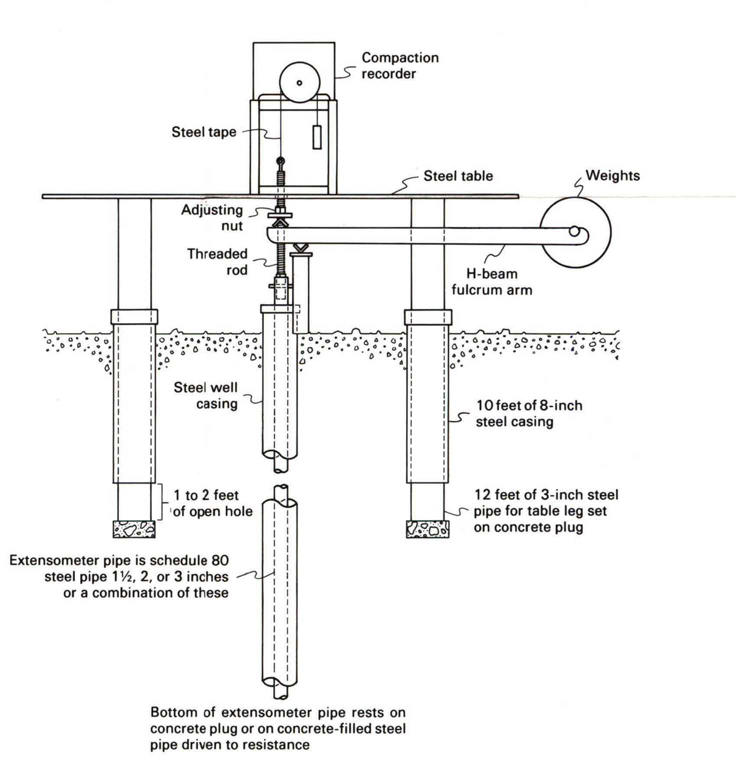
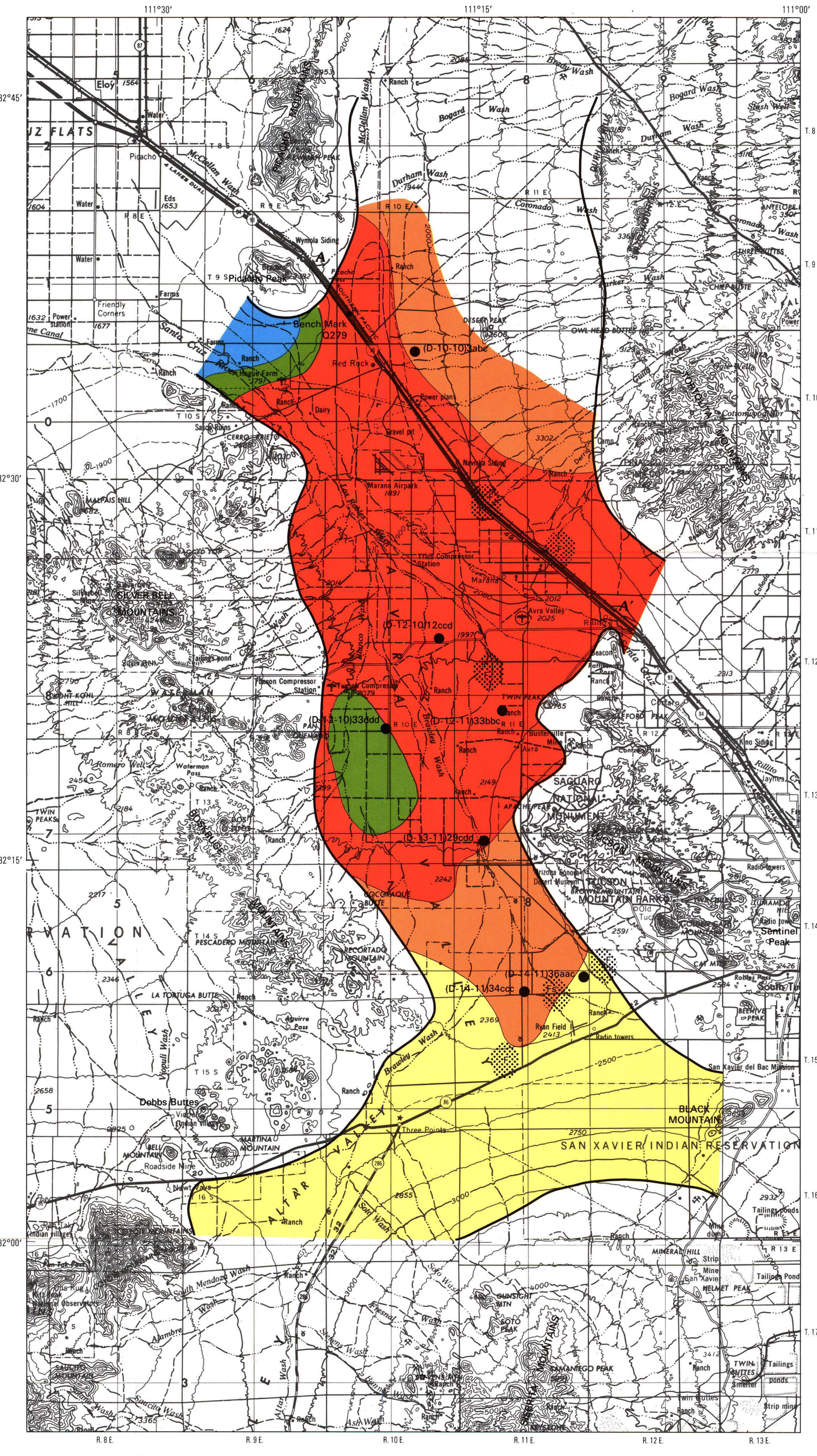


Figure 8.—Typical vertical-extensometer installation (VEI) in Avra Valley.



Base from U.S. Geological Survey 1:250,000 Nogales, 1956–69 and Tucson, 1956–77

Figure 7.—Water-level decline, aquifer compaction, land subsidence, and earth fissures in Avra Valley.

SCALE 1:250 000

TOPOGRAPHIC CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

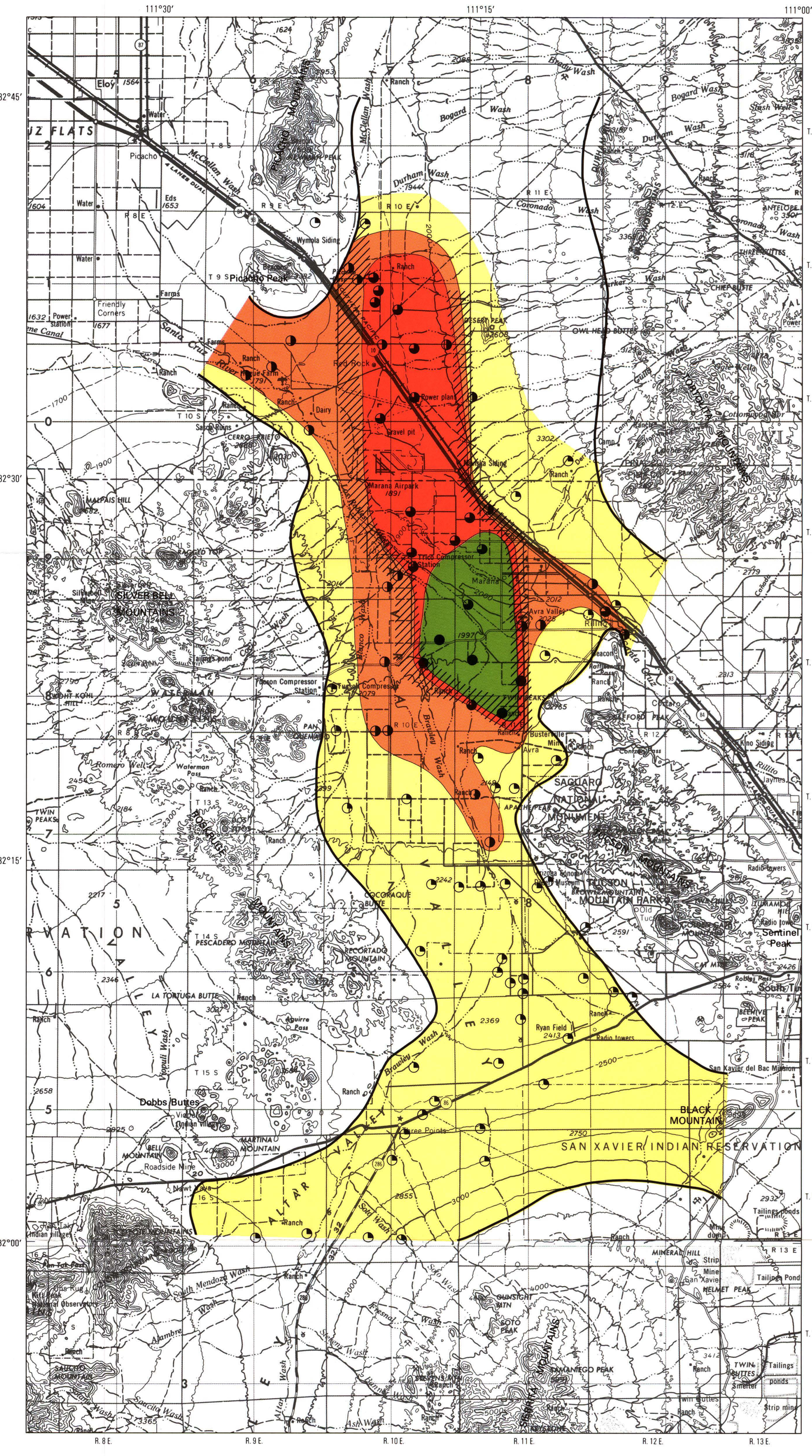


Figure 9.—Potential land subsidence in Avra Valley.

EXPLANATION

Water-level decline, 1940–85

- **Less than 50 feet**
- **50 to 100 feet**
- **100 to 150 feet**
- **150 to 200 feet**
- **More than 200 feet**

Zone of suspected perched ground water—Indicates shallow water table or cascading water in wells

(D-12-10)12ccd **Well with vertical extensometer installation**—Number, (D-12-10)12ccd, is well number. Hydrographs show depth to water and measured compaction at selected vertical extensometer installations for 1984–85

A — A′ **Line of profile**—Coordinate, *A–A′*, is a level line. Profile shows estimated water-level decline, 1940–85, and measured land subsidence, 1948/52 to 1980, at selected points

Approximate location of observed or reported earth fissures as of 1986—Letters, Fs, indicates Snyder Hill Road fissure

Boundary of aquifer

EXPLANATION

Potential land subsidence—In feet per foot of water-level decline in excess of the threshold water-level decline

- **Less than 0.01**
- **0.01 to 0.03**
- **0.03 to 0.06**
- **More than 0.06**

Potential land subsidence—In feet, based on a hypothetical water-level decline of 300 feet

- **Less than 2**
- **2 to 5**
- **5 to 10**
- **More than 10**

Major zones of potential severe localized differential land subsidence—Based on a hypothetical water-level decline of 300 feet

Boundary of aquifer

GROUND-WATER PUMPAGE AND WATER-LEVEL DECLINE

Annual ground-water pumpage in Avra Valley increased from about 12,000 acre-ft in 1940 to 174,000 acre-ft in 1975 (Whallon, 1983; Cuff and Anderson, 1987) as shown in figure 6. Between 1975 and 1984, annual ground-water pumpage decreased from 174,000 to 59,000 acre-ft. Most of the ground water pumped from the aquifer during 1940–84 was used for irrigation. In 1984, agricultural ground-water use was about 85 percent of the total withdrawal. The significant reduction in pumpage from 1975 to 1984 (fig. 6) was due largely to the purchase and retirement of agricultural land by the City of Tucson (Whallon, 1983). These purchases have given the city the legal right to pump and transport ground water from Avra Valley to the Tucson urban area. As of 1984, water pumped for public supply from retired agricultural lands was much less than was formerly pumped for irrigation. In some areas, pumping has ceased from lands retired from cultivation.

The hydrologic system in Avra Valley was in approximate equilibrium until about 1940 (Moosburner, 1972; Whallon, 1983). Inflow to the aquifer was approximately equal to outflow and ground-water levels remained generally unchanged. Ground-water pumpage for irrigation began near Marana in 1937; by 1954, more than 100 irrigation wells were being pumped in the northern and central parts of the valley (White and others, 1966; Whallon, 1983). Ground-water levels declined in these areas throughout the period because pumpage from the aquifer was greater than recharge.

From 1940 to 1952, water levels declined about 25 ft near Marana, about 20 to 50 ft in the area along the Santa Cruz River south of Picacho Peak, and less than 10 ft in the central part of the basin. Water levels generally remained unchanged in the areas south of T. 13 S. from 1940 to 1952 (University of Arizona, 1952). From 1952 to 1981, water levels declined by more than an additional 100 ft throughout a large part of the valley (Babcock and Hix, 1982). According to Cuff and Anderson (1987), ground-water levels declined from 50 to 150 ft throughout much of Avra Valley from 1940 to 1985 (fig. 7). Declines of greater than 150 ft occurred in the area along the Santa Cruz River south of Picacho Peak and in the west-central part of the valley. Declines of less than 50 ft occurred in the southern part of the valley near Three Points from 1940 to 1985.

AQUIFER COMPACTION

Aquifer compaction in Avra Valley is measured by a network of seven vertical extensometer installations (VEI's). The main part of a VEI is a free-moving extensometer pipe that is located inside a well casing; the pipe rests on a concrete plug or other base in the bottom of the well (fig. 8). Aquifer compaction causes the free-moving pipe to move vertically upward in relation to the land surface. Vertical movement of the pipe is measured graphically by a recorder mounted on a table that is isolated from the instrument-house floor. A weighted fulcrum arm with a leveling adjustment is used to counterbalance a significant part—generally about 70 percent—of the pipe weight. Counterbalancing straightens the pipe and reduces friction between the pipe and casing. Each VEI in the network is also instrumented to measure water-level change. Aquifer compaction is recorded to the nearest 0.001 ft. Depth to water is recorded to the nearest 0.1 ft.

The seven VEI's are located at wells (D-10-10)03abc, (D-12-10)12ccd, (D-12-10)33ddd, (D-12-11)33bbc, (D-13-11)29cdd, (D-14-11)34ccc, and (D-14-11)36aac (figs. 2, 3, and 7). The VEI's at wells (D-12-10)12ccd, (D-12-10)33ddd, and (D-14-11)34ccc were constructed in 1984 and 1985 by the U.S. Geological Survey in cooperation with the city of Tucson (Babcock and others, 1986). Extensometers at wells (D-10-10)03abc, (D-12-11)33bbc, (D-13-11)29cdd, and (D-14-11)36aac were constructed in 1985 by the U.S. Geological Survey in cooperation with the U.S. Bureau of Reclamation (Wrege and others, 1985). The VEI's built in cooperation with the city of Tucson were installed in areas where the potential for land subsidence and (or) differential land subsidence was thought to be high; the placement of VEI's in these areas was determined by the availability, condition, and location of unused irrigation wells owned by the city of Tucson. Extensometers constructed in cooperation with the U.S. Bureau of Reclamation are located along the alignment of the Central Arizona Project Tucson Aqueduct. Measured aquifer compaction and depth-to-water values for wells (D-12-10)12ccd, (D-12-10)33ddd, and (D-14-11)34ccc are shown in figure 7. Future data from wells (D-12-10)12ccd, (D-12-10)33ddd, and (D-14-11)34ccc will be published on an annual basis (R. Bruce Johnson, chief hydrologist, Tucson Water Planning Division, oral commun., 1985).

The amount of aquifer compaction at wells (D-12-10)12ccd, (D-12-10)33ddd, and (D-14-11)34ccc prior to installation of extensometers is unknown; therefore, measured amounts of compaction presented are referenced to the least amount of compaction measured during the first year of extensometer operation. Small diurnal fluctuations that resulted from barometric changes and perhaps earth tides and thermal effects were observed in the records. Periods of missing record are shown as breaks in the graphs.

Net compaction at wells (D-12-10)12ccd, (D-12-10)33ddd, and (D-14-11)34ccc was less than 0.01 ft during the period of record shown; however, fluctuations as large as 0.03 ft occurred in 1984 and 1985 in response to water-level changes at well (D-12-10)12ccd (fig. 7). Measurements indicate that the aquifer generally was unresponsive to yearly water-level fluctuations in the range of 2 to 4 ft at wells (D-12-10)33ddd and (D-14-11)34ccc during 1984 and 1985. Measurements indicate that the aquifer was highly responsive to yearly water-level fluctuations of about 20 ft at well (D-12-10)12ccd. The ratio of compaction/expansion to water-level change at well (D-12-10)12ccd was about 0.001 ft/ft during 1984 and 1985. Early compaction/expansion and water-level change relations at well (D-12-10)12ccd indicate elastic compaction of the aquifer.

LAND SUBSIDENCE

Land subsidence is measured by releveling of a network or line of bench marks and is equal to the differences between releveled bench-mark elevation and the original elevations. The level line *A–A′* along which land subsidence was measured in Avra Valley is shown in figure 7. Bench marks along the line were releveled in 1948/52 and 1980 by the National Geodetic Survey using first-order leveling methods (National Oceanic and Atmospheric Administration, 1974; Strange, 1983). Additional basinwide leveling to supplement the measurements along profile *A–A′* is planned.

The amount of land subsidence that occurred in Avra Valley prior to 1948/52 is unknown but probably was insignificant on the basis of documented water-level changes. Land subsidence in Avra Valley from 1948/52 to 1980 ranged from less than 0.1 ft to about 1.1 ft; the largest amount occurred at bench mark Q279 southeast of Picacho Peak (fig. 7, profile *A–A′*). The long-term ratio of subsidence to water-level decline at bench mark Q279 is about 0.01 ft/ft, which is ten times larger than the 0.001 ft/ft measured along profile *A–A′* near Rillito. The larger ratio of subsidence to water-level decline at bench mark Q279 may indicate an acceleration of subsidence rates related to early virgin compaction of the aquifer southeast of Picacho Peak. Additional monitoring will be required to substantiate this inference and to evaluate the magnitude and possible variation of aquifer overconsolidation and threshold water-level decline in the valley.

As of 1986, compaction, subsidence, and water-level relations in Avra Valley are similar to those measured in the adjacent Tucson basin (Anderson, 1987a). The aquifer in the Tucson basin appears to be overconsolidated and the threshold water-level decline may be about 100 ±50 ft.

POTENTIAL LAND SUBSIDENCE

As of 1986, compaction and subsidence had not yet occurred in sufficient amounts to enable reliable prediction of potential subsidence on the basis of measurement data from the compaction- and subsidence-monitoring networks (fig. 7). In this report, therefore, the potential for subsidence is based on an analogy that relates potential water-level decline and subsidence in Avra Valley to observed water-level decline and subsidence in the Eloy–Picacho area (Anderson, 1987a). On the basis of observed and inferred geohydrologic similarities, the assumption is made that additional water-level decline in Avra Valley will result in compaction and subsidence that are similar to the compaction and subsidence in the Eloy–Picacho area. The rate of compaction and subsidence per foot of water-level decline increased by an order of magnitude in the Eloy–Picacho area when water-level decline exceeded a threshold of about 100 ft (Holzer, 1981). Continued water-level decline in Avra Valley is likely to result in similar increases.

The following relation and assumptions were used to evaluate the potential for land subsidence in Avra Valley (fig. 9). The relation is defined as specific unit compaction by Meyer and Carr (1979) and Poland and others (1972).

Relation:

$$\frac{\text{Aquifer compaction (ft)}}{\text{water-level decline (ft)} \times \text{clay-silt thickness (ft)}} = \text{Specific unit compaction } (ft^{-1})$$

Assumptions:

1. The aquifer is naturally overconsolidated.
2. The ground-water system was in equilibrium until 1940.
3. Compaction and subsidence in Avra Valley will be similar to compaction and subsidence in the Eloy–Picacho area.
4. The threshold water-level decline equals 100 ft; elastic compaction occurs for a water-level decline of less than 100 ft, and virgin compaction occurs for a water-level decline greater than 100 ft.
5. Elastic specific unit compaction equals 1.0×10^{-5} ft^{-1}.
6. Virgin specific unit compaction equals 1.5×10^{-4} ft^{-1}.
7. The clay-silt thickness of the aquifer at any one place equals the thickness of the saturated deposits of the upper Tinaja beds and Fort Lowell Formation multiplied by the average percent of clay and silt (figs. 3–5).
8. Similarly fine-grained intervals of the Fort Lowell Formation and upper Tinaja beds are equally compressible.

The potential for land subsidence is greatest in the central and northern interior parts of the valley and least in the areas south of T. 13 S. (fig. 9). If water levels continue to decline, subsidence may, in time, exceed 0.06 ft/ft of water-level decline in the northern half of the valley (fig. 9). Subsidence ultimately may exceed 10 ft in parts of Ts. 11 and 12 S. if water levels decline by 300 ft or more. Subsidence of 10 ft or more is likely to be accompanied by areas of severe localized differential subsidence and the formation of earth fissures.

The potential for severe localized differential land subsidence in Avra Valley is shown in figure 9. Zones of potential differential subsidence delineated in figure 9 show areas of the valley where subsurface conditions and land subsidence caused by ground-water withdrawal may result in large and abrupt changes in the slope of the land surface. Zones are based on a hypothetical uniform regional water-level decline of 300 ft that is similar in magnitude to the maximum regional water-level decline in the Eloy–Picacho area as of 1977 (Laney and others, 1978). Zones of severe localized differential land subsidence (fig. 9) are near major subsurface faults that greatly influence the thickness of the upper Tinaja beds (figs. 2 and 3). The potential for compaction is much greater on the downthrown sides of the faults where the upper Tinaja beds are thicker. Additional zones not shown in figure 9 are possible. Analysis of the adjacent Tucson basin (Anderson, 1987a) indicates a potential for severe differential compaction and subsidence along the edges of abrupt depositional discontinuities in the aquifer and perhaps along the boundaries of some localized cones of depression in the water table. Continued monitoring of compaction and subsidence networks will eventually provide a better basis for evaluating these potential effects of ground-water withdrawal in the valley.

EARTH FISSURES

Several fissures and related gullies have been observed in Avra Valley (Caito and Sogge, 1982; H.H. Schumann, hydrologist, U.S. Geological Survey, oral commun., 1985). The approximate locations of these features, some of which are no longer visible, are shown in figure 7. The most prominent fissure gully observed in the valley as of 1986 was first noticed July 12, 1981, after a heavy rainstorm (Caito and Sogge, 1982). The fissure gully, which was subsequently backfilled by a road maintenance crew before it could be adequately studied, opened approximately parallel to Snyder Hill Road in the northernmost part of sec. 2, T. 15 S., R. 11 E. Other fissures and gullies have been observed in the vicinity of the Snyder Hill Road fissure and in areas near Marana (fig. 7). These features may be the result of aquifer compaction and land subsidence; however, some are situated in areas where the potential for compaction and subsidence is low and therefore may be the result of processes unrelated to compaction of the aquifer.

Fissures and gullies resulting from hydrocompaction and desiccation have been observed in the adjacent Tucson basin (Anderson, 1987a) and in other parts of the State. Hydrocompaction and desiccation may occur in certain geohydrologic environments in Avra Valley and may be accompanied by localized damage to manmade structures. Many foundation failures that occur in the Tucson basin may be related to wetting and near-surface compaction, which is most likely to occur on fans and flood plains and in newly irrigated areas that contain low-density soils (Davidson, 1973). Desiccation fissures are most likely to occur in areas where ground water is shallow enough to be tapped by the roots of phreatophytes such as mesquite (Anderson, 1978; Anderson, 1987a). In these areas, a lowering of ground-water levels is thought to be accompanied by desiccation and fissuring resulting from evapotranspiration in the zone drained by water-level decline.

To what extent hydrocompaction and desiccation have occurred in Avra Valley as of 1986 is uncertain. Several narrow arcuate fissures were observed just south of the Snyder Hill Road fissure site during a field inspection of the site in the summer of 1983. These fissures, which had the appearance of desiccation fissures observed elsewhere in the State, were located amongst a heavy growth of mesquite and creosote. In addition, several narrow arcuate to concentric fissures were observed along the Tucson aqueduct alignment northeast of Marana in November 1985 (Herbert Schumann, hydrologist, U.S. Geological Survey, oral commun., 1985). These fissures, many of which were offset vertically by several inches and were adjacent to small closed depressions in the land surface, probably resulted from the application of water to previously undisturbed soil. Other areas of Avra Valley may be susceptible to fissuring resulting from hydrocompaction and dessication of near-surface sediments, but additional study will be required in order to fully evaluate the potential for these types of fissures in the valley.

As of 1986, the cause of observed fissures in Avra Valley is uncertain. Caito and Sogge (1982) concluded that observed fissures in the southern part of Avra Valley (fig. 7) may have resulted from differential land subsidence induced by ground-water withdrawal. The analysis in this report, however indicates that the fissures may have resulted from other processes such as hydrocompaction or desiccation. These fissures are in areas where the long-term water-level decline is less than 50 ft and the potential for subsidence is low on the basis of subsurface geologic conditions (figs. 7 and 9).

In contrast to fissures in the southern part of the basin, the observed fissure northwest of Marana (fig. 7) lies in an area of the basin where the potential for severe localized differential subsidence is great on the basis of subsurface geologic conditions (fig. 9). The proximity of the fissure to profile *A–A′* (fig. 7) suggests a relation between water-level decline, differential subsidence, and fissuring. On the basis of available data, long-term water-level decline and subsidence near the fissure are greater than 100 ft and about 0.5 ft, respectively (fig. 7). Bench-mark elevations measured in 1948/52 and 1980 indicate the development of a zone of differential subsidence across the fissure. From 1948/52 to 1980, the land surface 2 mi northwest of the fissure subsided about 0.5 ft more than the land surface 2 mi southeast of the fissure (fig. 7). The probable subsidence fissure northwest of Marana was first reported in 1977 and by 1985 was largely filled with sediment. Continued water-level decline and subsidence may eventually result in renewed fissuring near the site.

The potential for the development of subsidence fissures, faults, and gullies in Avra Valley is great on the basis of the Eloy–Picacho analogy. The potential is dependent on subsurface geologic conditions and the rate and distribution of ground-water withdrawals from the aquifer. The greatest potential for subsidence fissures, faults, and gullies is along the central and northern edges of the valley in and near the major zones of potential severe localized differential subsidence delineated in figure 9. If water-level decline and differential subsidence are relatively large, fissures may occur also in some areas mountainward of these zones.

The zone of potential differential subsidence crossed by profile *A–A′* (figs. 7 and 9) east of Picacho Peak is of particular interest. Differential subsidence across the zone was about 1 ft in 1980 (fig. 7). The trend of the zone (fig. 7) and the subsurface fault on which it is based (fig. 2) are conspicuously parallel to the Picacho subsidence fissure-fault (Laney and others, 1978; Holzer and others, 1979) that lies to the east and northwest of the peak. Fissures and gullies probably will form in and near the area east of Picacho Peak if water levels continue to decline; faulting may occur across the zone if declines reach the magnitude of declines west of the peak. As of 1977, water levels west of Picacho Peak had declined by as much as 300 ft (Laney and others, 1978). As of 1985, water-level declines east of the peak in Avra Valley were only half as much (fig. 7).

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By
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