Prepared in cooperation with the
CITY OF TUCSON

GROUND-WATER PUMPAGE AND WATER-LEVEL DECLINE

Annual ground-water pumpage in the Tucson basin increased from about 48,000 acre-ft in 1940 to 269,000 acre-ft in 1975 (Davidson, 1973; Natalie White, Hydrologist, U.S. Geological Survey, oral commun., 1984) as shown in figure 6. Between 1975 and 1980, annual ground-water pumpage decreased from 269,000 to 202,000 acre-ft. Most of the ground water pumped prior to 1940 and through the mid- to late-1950's was used for irrigation. By 1980, ground water was used almost equally for irrigation, public supply, and industry.

The hydrologic system in the Tucson basin was in approximate equilibrium until 1940 (Anderson, 1972). Inflow to the aquifer was approximately equal to outflow and ground-water levels remained generally unchanged. In the Cortaro-Rillito area, however, ground-water pumpage prior to 1940 was greater than the natural recharge to the aquifer and as much as 30 ft of water-level decline occurred (Schwalen and Shaw, 1957). After 1940, ground-water pumpage exceeded recharge in many parts of the basin. By 1947, water levels had declined about 5 ft in the southern part of the Tucson metropolitan area, about 35 ft in the area near the confluence of the Santa Cruz River and Rillito Creek, more than 50 ft in the Cortaro-Rillito area, and about 10 to 20 ft near Sahuarita and Continental (University of Arizona, 1947). From 1947 to 1981, water levels declined more than 100 ft in the Tucson metropolitan area and 150 ft in the Sahuarita-Continental areas as shown in figure 7 (Babcock and Hix, 1982).

AQUIFER COMPACTION

Aquifer compaction in the Tucson basin 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 wall 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; some recordings at two installations were to the nearest 0.0002 ft. Depth to water is recorded to the nearest 0.1 ft.

The seven VEI's are located at wells *(D–14–14I22aab)*, *(D–14–14I23cab)*, *(D–14–14I29cbc)*, *(D–15–14I30cbc)*, *(D–17–14I3baa)*, *(D–13–14I31cac)* and *(D–15–14I19bac* (figs. 2, 3, and 7). The VEI's 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 water-supply and test wells owned by the city of Tucson. Much of the VEI network was constructed in 1979 and 1980 (Anderson and others, 1982). Vertical-extensometer installations at wells *(D–13–14I31cac)* and *(D–15–14I19bac* were constructed in 1982 and 1983, respectively (Babcock and others, 1984). Measured aquifer-compaction and depth-to-water values for these installations are shown in figure 7; future results will be published by the city of Tucson on an annual basis (R. Bruce Johnson, chief hydrologist, Tucson Water Planning Division, oral commun., 1985).

The amount of aquifer compaction at the wells 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. Compaction data from well *(D–14–14I22aab)* show the effects of many barometric fluctuations during winter months that appear to coincide with the passage of large storm fronts. Periods of missing record are shown as breaks in the graphs.

Net amounts of measured aquifer compaction increased at the seven installations during the period of record; however, the amounts were small (fig. 7). The largest net amount of compaction measured from 1980 to 1984 was about 0.06 ft at well *(D–15–14I30cbc)*. Prior to a sustained water-level recovery and accompanying expansion of the aquifer from 1982 to 1984, the rate of compaction at well *(D–15–14I30cbc* was about 0.02 ft/yr and the ratio of compaction to water-level decline was about 0.02 ft/ft.

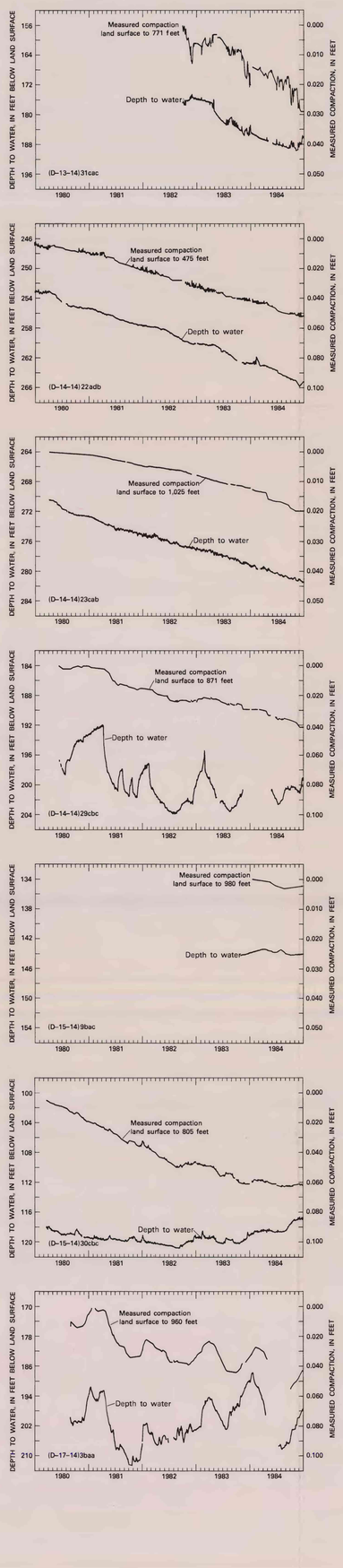
LAND SUBSIDENCE

Land subsidence is measured by releveling of a network or line of bench marks and is equal to the differences between releveled bench-mark elevations and the original elevations. The level lines *A-A'*, *B-B'*, and *C-C'* along which land subsidence was measured in the Tucson basin are shown in figure 7. Bench marks in the network were releveled in 1951–54 and 1979–80 by the National Geodetic Survey and in 1976 by the U.S. Geological Survey using first-order leveling methods (National Oceanic and Atmospheric Administration, 1974; Strange, 1983).

The amount of subsidence that occurred in the Tucson basin prior to 1951–54 is unknown but was probably insignificant on the basis of documented water-level changes. Land subsidence in the Tucson basin from 1951–54 to 1979–80 ranged from less than 0.1 ft to almost 0.5 ft; the largest amount occurred at bench mark B317 south of Davis-Monthan Air Force Base (fig. 7, profile *C-C'*). The rate of subsidence at bench mark B317 may have averaged about 0.05 ft/yr from 1976 to 1979–80 and appears to be accelerating. Subsidence generally was small in relation to water-level decline in the basin from 1951–54 to 1979–80; however, subsidence was large in relation to water-level decline from 1976 to 1979–80 at bench mark B317. Long-term data indicate a ratio of subsidence to water-level decline of generally less than 0.003 ft/ft in the basin from 1951–54 to 1979–80; short-term data, however, indicate a ratio as great as 0.02 ft/ft from 1976 to 1979–80 at bench mark B317.

The ratio of land subsidence to water-level decline may be increasing in some parts of the basin. For example, the ratio of compaction to water-level decline measured at well *(D–15–14I30cbc* from 1980 to 1982 is an order of magnitude larger than the long-term ratio of subsidence to water-level decline measured at this location (fig. 7, profile *B-B'*). A transition from elastic to virgin compaction may be occurring in parts of the aquifer; if so, the aquifer was naturally overconsolidated prior to ground-water pumping. Because of the limited data available in 1985, the magnitude of the threshold water-level decline was difficult to determine; however, the magnitude of the decline may be about 100 ± 50 ft as inferred by the long-term water-level declines at well *(D–15–14I30cbc* and bench mark B317.

HYDROGRAPHS SHOWING DEPTH TO WATER AND MEASURED COMPACTION AT VERTICAL EXTENSOMETER INSTALLATIONS FOR 1980–84



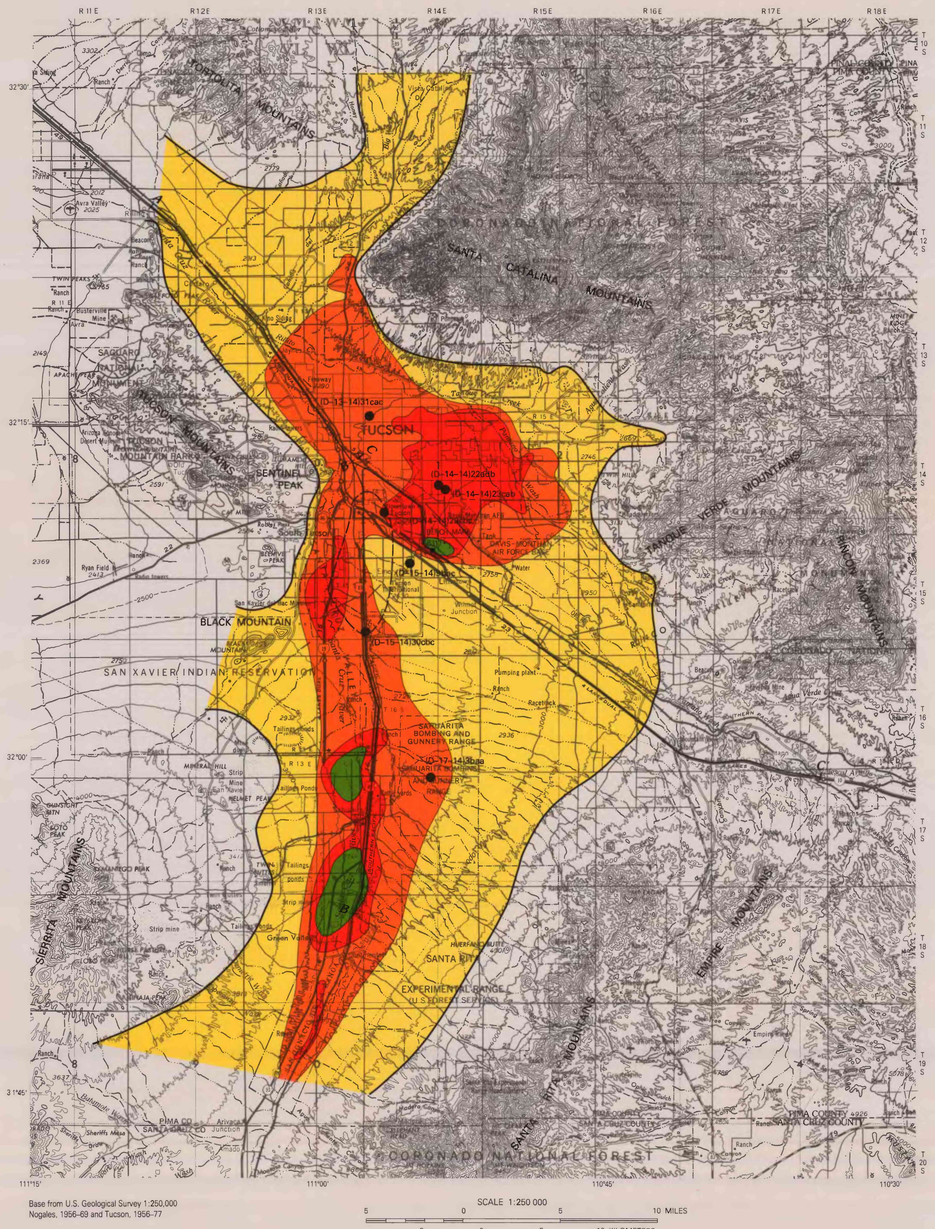


FIGURE 7.—Water-level decline, aquifer compaction, and land subsidence in the Tucson basin.

EXPLANATION

Water-level decline, 1947–81

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

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

(D–15–14I9bac **Well with vertical extensometer installation**—Number, (D–15–14I9bac, is well number. Hydrographs show depth to water and measured compaction at vertical extensometer installations for 1980–84

A — A' **Line of profile**—Coordinates, A–A', are level lines. Profiles show estimated water-level decline, 1940–81, and measured land subsidence, 1951–54 to 1979–80, at selected points

Boundary of aquifer

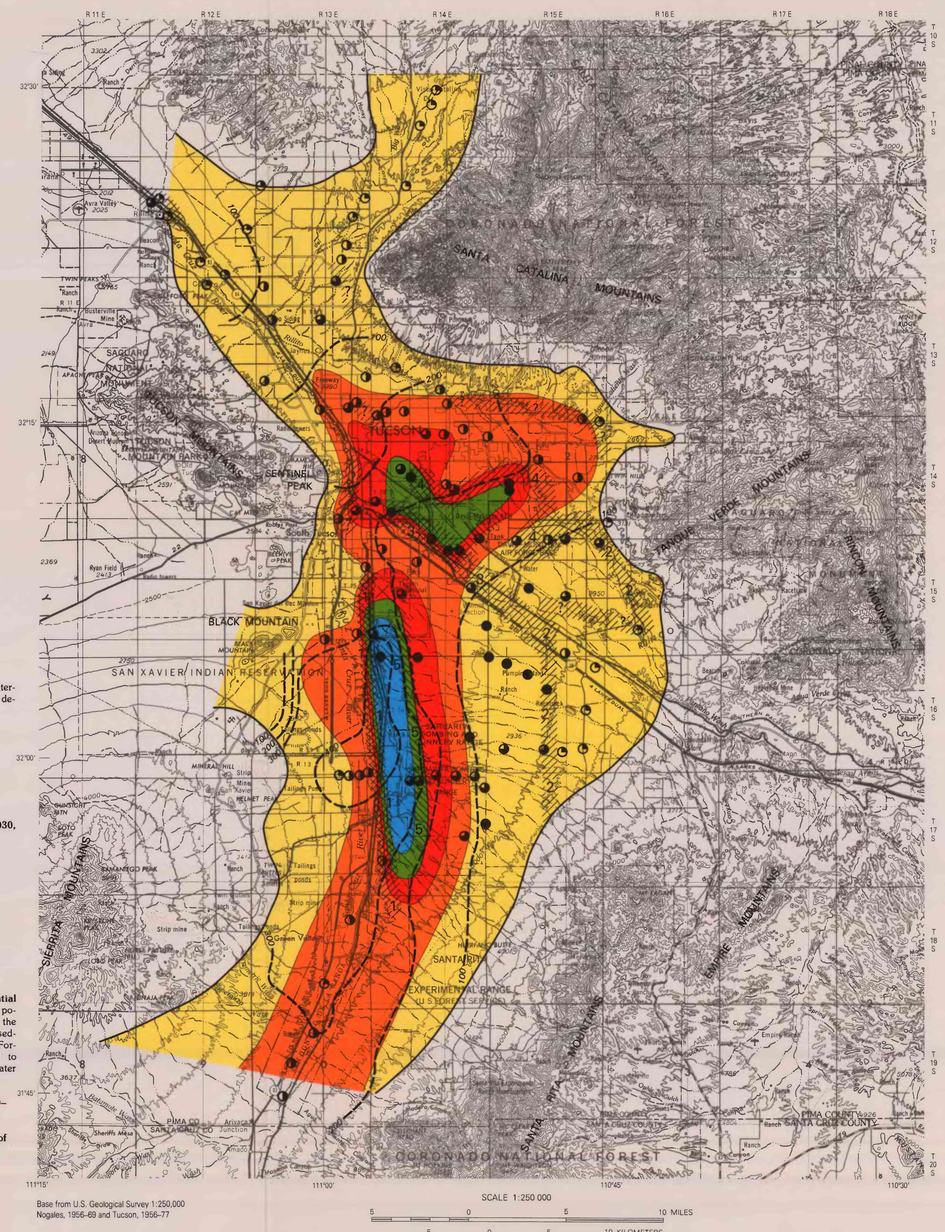


FIGURE 9.—Potential land subsidence and zones of potential severe localized differential land subsidence in the Tucson basin.

EXPLANATION

Potential land subsidence rate—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

—200— **Line of equal estimated water-level decline, 1940–2030, based on model simulation**—Interval 100 feet

Potential land subsidence, 1940–2030—In feet

- Less than 1
- 1 to 3
- 3 to 6
- 6 to 10
- More than 10

Major zones of potential severe localized differential land subsidence—Numbers indicate areas where potential land subsidence may be affected by: 1 the Santa Cruz fault; 2 and 3, unnamed faults; 4, the sediments of the upper Tinaja beds and Fort Lowell Formation grading abruptly from coarse-grained to fine-grained material; 5, localized ground-water withdrawals from fine-grained deposits

3 **Zones based on estimated water-level decline, 1940–2030.** Queried where uncertain

2 **Zones based on hypothetical water-level decline of 300 feet.** Queried where uncertain

Boundary of aquifer

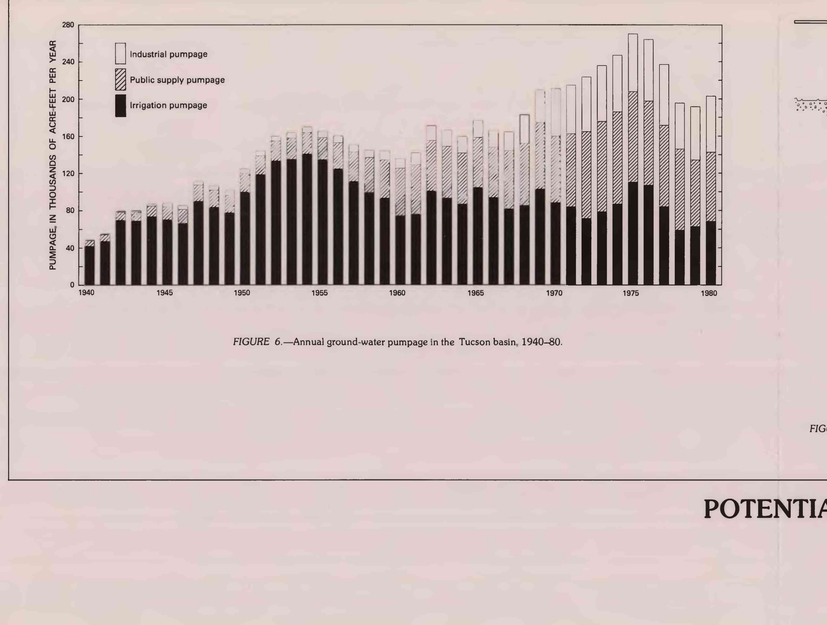


FIGURE 6.—Annual ground-water pumpage in the Tucson basin, 1940–80.

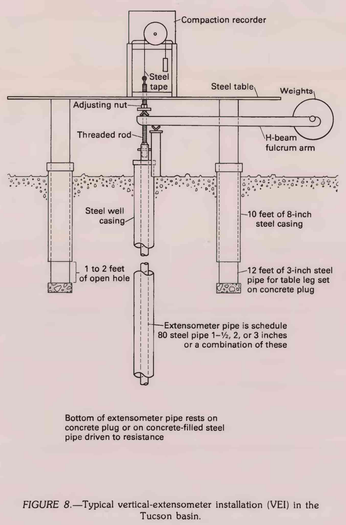
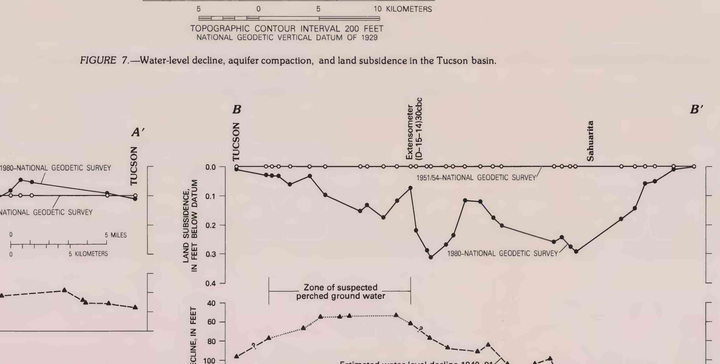
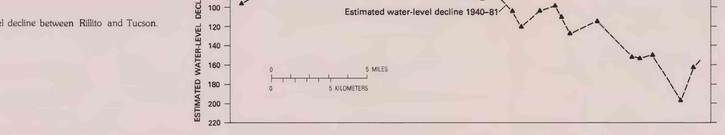


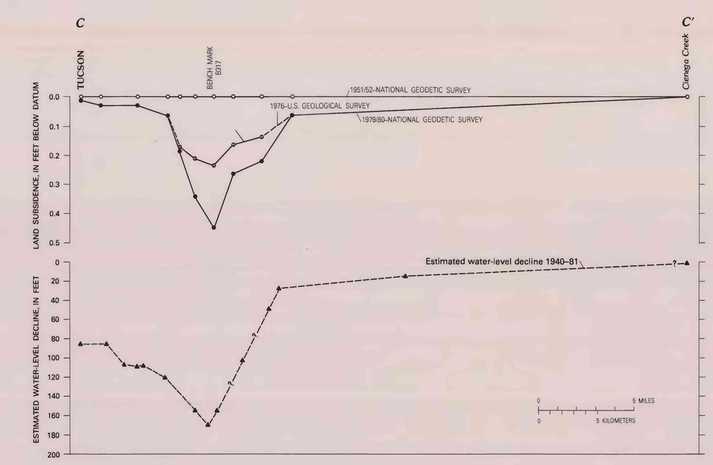
FIGURE 8.—Typical vertical-extensometer installation (VEI) in the Tucson basin.



PROFILE A-A'.—Land subsidence and estimated water-level decline between Rillito and Tucson.



PROFILE B-B'.—Land subsidence and estimated water-level decline between Tucson and south of Sahuarita.



PROFILE C-C'.—Land subsidence and estimated water-level decline between Tucson and Cienega Creek.

POTENTIAL LAND SUBSIDENCE

As of 1985, 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 the Tucson basin to observed water-level decline and subsidence in the Eloy-Picacho area. On the basis of observed and inferred geohydrologic similarities, the assumption is made that additional water-level decline in the Tucson basin 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 the Tucson basin is likely to result in similar increases.

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

Relation:

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

Assumptions:

1. The aquifer is naturally overconsolidated.
2. The ground-water system was in equilibrium until 1940.
3. Compaction and subsidence in the Tucson basin 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; virgin compaction occurs for a water-level decline of more than 100 ft.
5. Elastic specific unit compaction equals 1.0×10^{-5} ft^{-1}.
6. Virgin specific unit compaction equals 1×10^{-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 land subsidence per foot of water-level decline in excess of the threshold water-level decline is shown in figure 9. Potential land subsidence and zones of potential severe localized differential subsidence that may accompany two scenarios of future water-level decline—an estimated decline and a hypothetical decline—are also shown in figure 9. The estimated water-level decline is from model projections by W. R. Meyer (Hydrologist, U.S. Geological Survey, written commun., 1982). The decline represents the estimated change in ground-water levels from 1940 to 2030 assuming that the rates and distributions of all inflow to and outflow from the aquifer remain at about 1970–78 levels. The hypothetical decline is a uniform regional water-level decline of 300 ft that is similar in magnitude to the largest decline in the Eloy-Picacho area as of 1977 (Laney and others, 1978).

The potential land subsidence per foot of water-level decline may be greatest in the central part of the basin from near Davis-Monthan Air Force Base to south of Sahuarita; the rate may be greater than 0.06 ft/ft of water-level decline in some places (fig. 9). The potential land subsidence that may accompany the estimated water-level decline may be more than 10 ft in some areas of the basin. The distribution of potential land subsidence from 1940 to 2030 indicates several areas where localized differential land subsidence may be severe. Estimates of potential land subsidence that may accompany a hypothetical water-level decline of 300 ft indicate that significant additional areas of the basin are susceptible to severe localized differential land subsidence.

Major zones of potential severe localized differential land subsidence that may accompany the two scenarios of water-level decline are shown in figure 9. The zones are in areas where subsurface conditions and land subsidence caused by ground-water pumping may result in large and abrupt changes in the slope of the land surface. Zones 1–3 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 side of the faults where the upper Tinaja beds are thickest (fig. 9). Zone 4 is an area where the sediments of the upper Tinaja beds and Fort Lowell Formation grade abruptly from coarse-grained to fine-grained material (figs. 4 and 5). The potential for compaction is much greater on the basinward side of the depositional feature where the aquifer sediments are richer in clay and silt (fig. 9). Zone 5, which is east of the Santa Cruz fault and south of Davis-Monthan Air Force Base, shows the potential effects of localized ground-water withdrawals from fine-grained deposits. The delineation of zone 5 is based on the estimated water-level decline. Similar zones could accompany future localized ground-water withdrawals from other parts of the basin, especially in the area east of zone 5.

EARTH FISSURES

Subsidence fissures have not been observed in the Tucson basin as of 1985; the likelihood of undetected fissures is slight because only small amounts of aquifer compaction and land subsidence have been measured. Some localized ground failure and fissuring have occurred in the basin but these probably are the result of hydrocompaction and desiccation. Hydrocompaction and desiccation are mentioned in this report because the effects of these processes are occasionally detrimental and sometimes mistakenly attributed to compaction of the aquifer.

Hydrocompaction of near-surface sediments in the Tucson basin was suggested by Davidson (1973). Many parts of the basin are susceptible to the effects of hydrocompaction. Ground failure and fissuring related to wetting and near-surface compaction are most likely to occur on fans and flood plains and in newly irrigated areas that contain low-density soils (Davidson, 1973). Ground failures and shallow fissures have been observed in such areas, and some have been observed in the basin adjacent to nonsubsiding bench marks. These features are attributed to hydrocompaction. The effects of hydrocompaction may be detrimental in some urbanized areas. Many foundation failures that occur in the basin may be related to wetting and near-surface compaction (Platt, 1963; Lacy, 1964; Davidson, 1973). Although this type of ground failure may initially cause damage, the potential for secondary damages resulting from gullying of fissures is low.

Probable desiccation fissures were observed during this study in an uninhabited area southeast of Black Mountain near the Santa Cruz River. The fissures, which form crude polygonal patterns, are shallow and filled with sediment. On the basis of the morphology, the fissures are old and inactive (Anderson, 1978). The area in which the fissures are located was once heavily forested by mesquite (Tinkham, 1941) and underlain by a shallow ground-water table (Schwalen and Shaw, 1957). A lowering of the water table and the subsequent removal of moisture by mesquite probably resulted in desiccation of the near-surface sediments in the zone drained by water-level decline (Anderson, 1978). The probable desiccation fissures southeast of Black Mountain are no longer of any consequence. Similar fissures are unlikely to form elsewhere in the basin unless locally saturated sediments that are susceptible to desiccation lie above the regional ground-water table and within the reach of phreatophytes such as mesquite.

On the basis of the Eloy-Picacho analogy, the potential for the development of subsidence fissures in the basin is great. When and where subsidence fissures may first occur, however, is uncertain. On the basis of the estimated water-level decline and potential accompanying subsidence, localized differential land subsidence may be more severe in parts of the Tucson basin—especially in zone 1 (fig. 9)—by the year 2030 than it was before 1977 in some areas of observed fissuring in the Eloy-Picacho area. The projection of ground-water pumping and the Eloy-Picacho analogy strongly indicate that subsidence fissures may occur in the Tucson basin by the year 2030, and perhaps sooner. Some fissures may show vertical offset. Erosion of fissures and faults may result in severe gullying.

Subsidence fissures are most likely to occur in major zones of potential severe localized differential land subsidence delineated in figure 9. If sufficient localized differential subsidence occurs, however, fissures may form also in some areas mountainward of the Santa Cruz fault and the segmented subparallel fault system opposite it on the north and east edges of the basin (figs. 2, 3, and 9). Subsidence-related faulting is most likely to occur in zones 1–3. With the exception of zones 4 and 5, the subsurface conditions in the areas delineated in figure 9 appear similar to known or inferred subsurface conditions in areas of observed fissuring and faulting in the Eloy-Picacho area. The potential for earth-fissure formation in zones 4 and 5 is tenuous but is indicated by the potential severity of localized differential subsidence in these zones. Zone 1, which parallels a 15-mile segment of the Santa Cruz fault from south of the Tucson International Airport to southeast of Sahuarita, may be the most seriously affected by fissuring and faulting.

SELECTED REFERENCES

Anderson, T.W., 1972, Electrical-analog analysis of the hydrologic system, Tucson basin, southeastern Arizona: U.S. Geological Survey Water-Supply Paper 1939-C, 34 p.

Anderson, S.R., 1978, Earth fissures in the Stewart area of the Willcox basin, Cochise County, Arizona: University of Arizona master's thesis, 72 p.

Anderson, S.R., Schumann, H.H., and Wallace, B.L., 1982, Progress report on measurement of aquifer compaction in the Tucson basin, *in* Babcock, J.A., and Hix, G.L., 1982, Annual static water level basic data report, Tucson basin and Avra Valley, Pima County, Arizona, 1981, 1982: City of Tucson, Tucson Water Planning Division report, 21 p.

Babcock, J.A., and Hix, G.L., 1982, Annual static water level basic data report, Tucson basin and Avra Valley, Pima County, Arizona—1981: City of Tucson, Tucson Water Planning Division report, 21 p.

Babcock, J.A., Cameron, J.A., Andrews, John, 1984, Annual static water level basic data report, Tucson basin and Avra Valley, Pima County, Arizona, 1983: City of Tucson, Tucson Water Planning Division report, 65 p.

Bates, R.L., and Jackson, J.A., eds., 1980, Glossary of geology, 2d edition: Falls Church, Virginia, American Geological Institute, 749 p.

Casagrande, A., 1936, The determination of the pre-consolidation load and its practical significance, *in* Proceedings of the First International Conference on Soil Mechanics and Foundation Engineering: Cambridge, Harvard University, v. 3, p. 60–64.

Cooper, J.R., 1973 (1974), Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–745, scale 1:48,000.

Davidson, E.S., 1973, Geohydrology and water resources of the Tucson basin, Arizona: U.S. Geological Survey Water-Supply Paper 1939–E, 81 p.

Drewes, Harald, 1980, Tectonic map of southeast Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–1109, scale 1:125,000.

———1981, Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 96 p.

Eberly, L.D., and Stanley, T.B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921–940.

Feth, J.H., 1951, Structural reconnaissance of the Red Rock quadrangle, Arizona: U.S. Geological Survey open-file report, 32 p.

Helm, D.C., 1978, A postulated relation between granular movement and Darcy's law for transient flow: Proceedings of Conference on Evaluation and Prediction of Subsidence, S.N. Saxena, ed., American Society of Civil Engineers, p. 417–440.

Holzer, T.L., 1977, Ground failure in areas of subsidence due to ground-water decline in the United States, *in* 2d International Conference on Land Subsidence, Anaheim, Calif., 1976, Proceedings: International Association of Hydrological Sciences Publication 121, p. 423–433.

———1978, Results and interpretation of exploratory drilling near the Picacho fault, south-central Arizona: U.S. Geological Survey Open-File Report 78–1016, 41 p.

———1981, Preconsolidation stress of aquifer systems in areas of induced land subsidence: Water Resources Research, v. 17, no. 3, p. 693–704.

Holzer, T.L., and Davis, S.N., 1976, Earth fissures associated with water-table declines [abs.]: Geological Society of America Abstracts with Programs, v. 8, no. 6, p. 923–924.

Holzer, T.L., Davis, S.N., and Lofgren, B.E., 1979, Faulting caused by groundwater extraction in south-central Arizona: Journal of Geophysical Research, v. 84, no. B2, p. 603–612.

Jachens, R.C., and Holzer, T.L., 1979, Geophysical investigations of ground failure related to ground-water withdrawal—Picacho basin, Arizona: Ground Water, v. 17, no. 6, p. 574–585.

Kam, William, 1965, Earth cracks—A cause of gullying, *in* Geological Survey Research 1965: U.S. Geological Survey Professional Paper 525–B, p. B122–B125.

Lacy, W.C., 1964, Geological causes of foundation failures in the area of Tucson, Arizona: Society of Mining Engineers Transactions, v. 229, p. 40–44.

Laney, R.L., 1972, Chemical quality of the water in the Tucson basin, Arizona: U.S. Geological Survey Water-Supply Paper 1939–D, 46 p.

Laney, R.L., Raymond, R.H., and Winikka, C.C., 1978, Maps showing water-level declines, land subsidence, and earth fissures in south-central Arizona: U.S. Geological Survey Water-Resources Investigations 78–83, 2 sheets.

Lofgren, B.E., 1971, Significant role of seepage stresses in compressible aquifer systems [abs.]: EOS Transactions, American Geophysical Union, v. 52, no. 11, p. 832.

Meade, R.H., 1968, Compaction of sediments underlying areas of land subsidence in central California: U.S. Geological Survey Professional Paper 497–D, 39 p.

Meinzer, O.E., 1923, Outline of ground-water hydrology, with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p.

Menges, C.M., 1981, The Sonoita Creek basin—Implications for late Cenozoic tectonic evolution of basins and ranges in southeastern Arizona: Tucson, University of Arizona master's thesis, 239 p.

Menges, C.M., and McFadden, L.D., 1981, Evidence for a latest Miocene to Pliocene transition from Basin-Range tectonic to post-tectonic landscape evolution in southeastern Arizona, *in*, Stone, Claudia, and Jenney, J.P., eds., Arizona Geological Society Digest: Tucson, Arizona Geological Society, v. 13, p. 151–160.

Meyer, W.R., and Carr, J.E., 1979, A digital model for simulation of ground-water hydrology in the Houston area, Texas: Texas Department of Water Resources Report LP–103, 26 p.

National Oceanic and Atmospheric Administration, 1974, Classification, standards of accuracy, and general specification of geodetic control surveys: U.S. Department of Commerce, 12 p.

Neal, J.T., 1972, Playa surface features as indicators of environment in Neal, J.T., ed., Playas and dried lakes—Occurrence and development, Benchmark Papers in Geology, v. 20: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, Inc., p. 363–388.

Neal, J.T., and Motts, W.S., 1967, Recent geomorphic changes in playas of western United States, *in* Neal, J.T., ed., Playas and dried lakes—Occurrence and development, Benchmark Paper in Geology, v. 20: Stroudsburg Pennsylvania, Dowden, Hutchinson and Ross, Inc., p. 327–342.

Pashley, E.G., Jr., 1961, Subsidence cracks in alluvium near Casa Grande, Arizona: Arizona Geological Society Digest, v. 4, p. 95–101.

Platt, W.S., 1963, Land-surface subsidence in the Tucson area: University of Arizona master's thesis, 38 p.

Poland, J.F., and Davis, G.H., 1969, Land subsidence due to withdrawal of fluids, *in* Varnes, D.J., and Kersch, G., eds., Reviews in engineering geology: Geological Society of America, v. 2, p. 187–269.

Poland, J.F., Lofgren, B.E., and Riley, F.S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geological Survey Water-Supply Paper 2025, 9 p.

Pool, D.R., 1984, Aquifer geology of alluvial basins of Arizona, *in* Replogle, J.A., and Renard, K.G., eds., Water today and tomorrow: Specialty Conference: 1984 Irrigation and Drainage Division of the American Society of Civil Engineers, Flagstaff, Arizona, July 24–26, 1984, Proceedings, p. 683–690.

Riley, F.S., 1969, Analysis of borehole extensometer data from central California, *in* Tison, L.J., ed., Land Subsidence: Tokyo, International Association of Scientific Hydrology Publication 89, v. 2, p. 423–431.

Scarborough, R.B., and Peirce, H.W., 1978, Late Cenozoic basins of Arizona, *in* Callender, J.F., Wilt, G.C., and Clemons, R.E., eds., Land of Cochise: New Mexico Geological Society Guidebook, 29th Field Conference, p. 253–259.

Schumann, H.H., and Poland, J.F., 1970, Land subsidence, earth fissures, and ground-water withdrawal in south-central Arizona, U.S.A., *in* Land Subsidence: Tokyo, International Association of Scientific Hydrology Publication 88, v. 1, p. 295–302.

Schwalen, H.C., and Shaw, R.J., 1957, Ground-water supplies of the Santa Cruz Valley of southern Arizona between Rillito Station and the international boundary: Arizona University, Agricultural Experiment Station Bulletin 288, 119 p.

Sellers, W.D., and Hill, R.H., eds., 1974, Arizona climate 1931–72: Tucson, University of Arizona Press, 616 p.

Shafiqullah, M., Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas, *in* Jenney, J.P., and Stone, Claudia, eds., Studies in western Arizona: Arizona Geological Society Digest, v. 12, p. 201–260.

Simons, F.S., 1974, Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–762.

Strange, W.E., 1983, Subsidence monitoring for State of Arizona: National Oceanic and Atmospheric Administration report, 74 p.

Tinkham, E.R., 1941, An ecological study of the western white-winged dove *melopelia asiatica mearnsi* in the Sahuaro-Palo Verde, mesquite, and oak zones of Pima County in south central Arizona: Arizona Game and Fish Commission report, 90 p.

University of Arizona, 1947, Water level losses from year indicated to 1947, Santa Cruz basin near Tucson: University of Arizona, Agricultural Engineering Department Map, 1 sheet.

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By
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