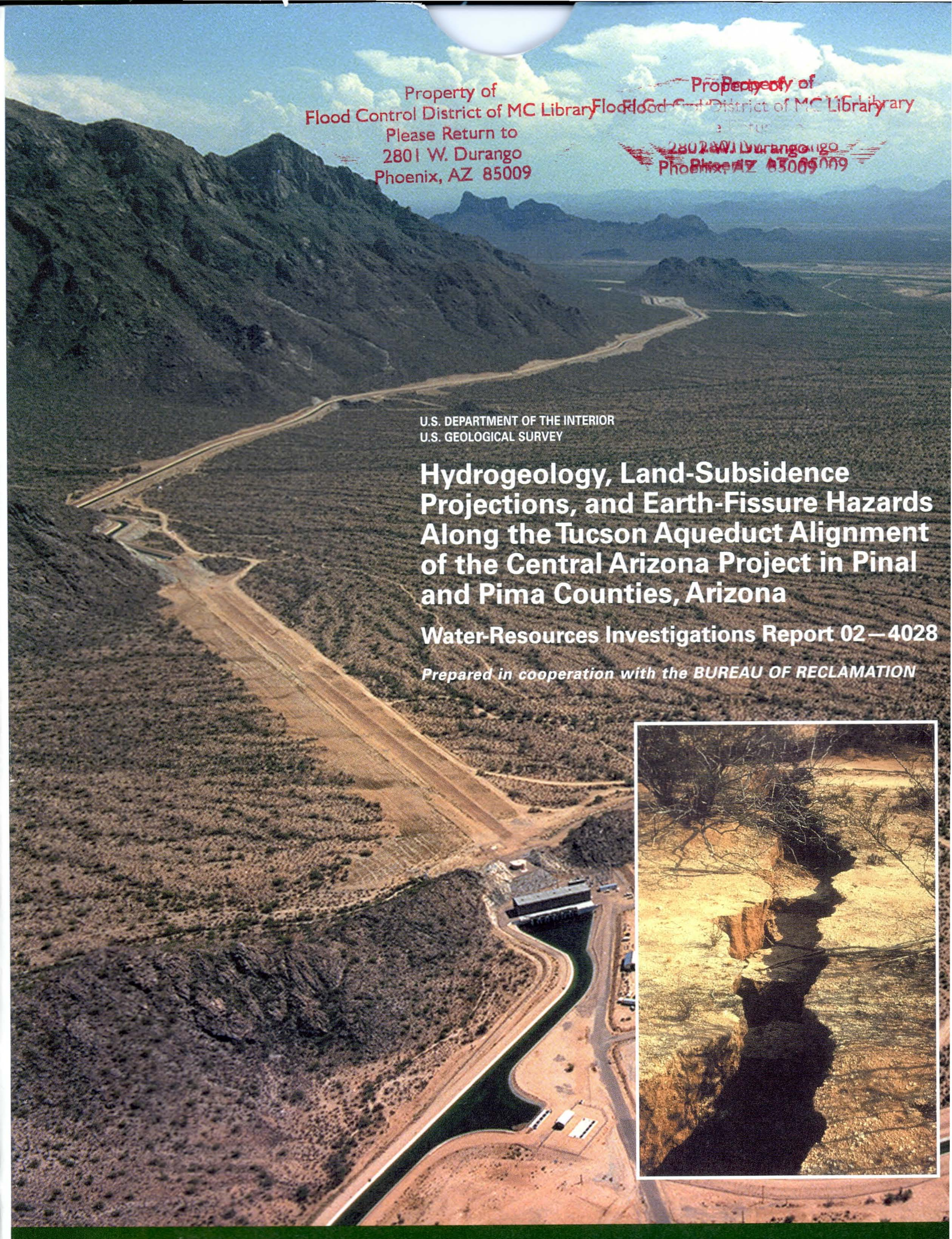


U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Hydrogeology, Land-Subsidence Projections, and Earth-Fissure Hazards Along the Tucson Aqueduct Alignment of the Central Arizona Project in Pinal and Pima Counties, Arizona

Water-Resources Investigations Report 02–4028

Prepared in cooperation with the BUREAU OF RECLAMATION

PREPARED IN COOPERATION WITH THE
BUREAU OF RECLAMATION

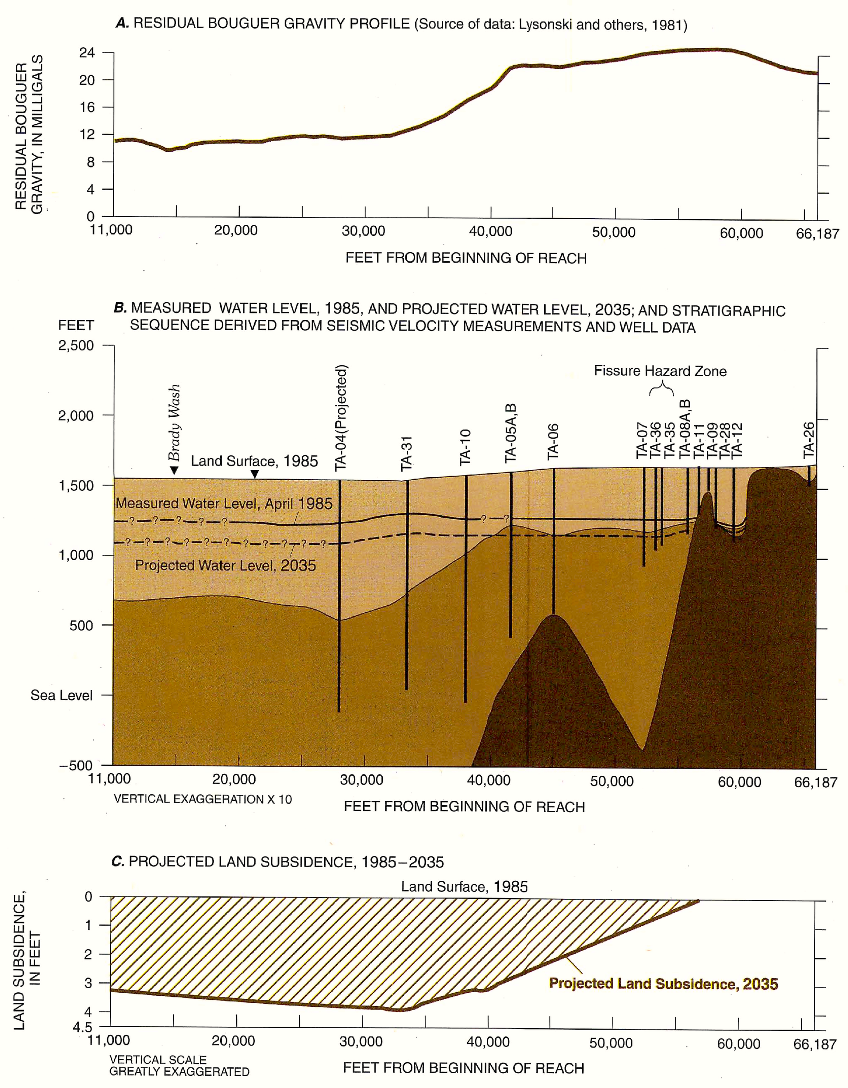
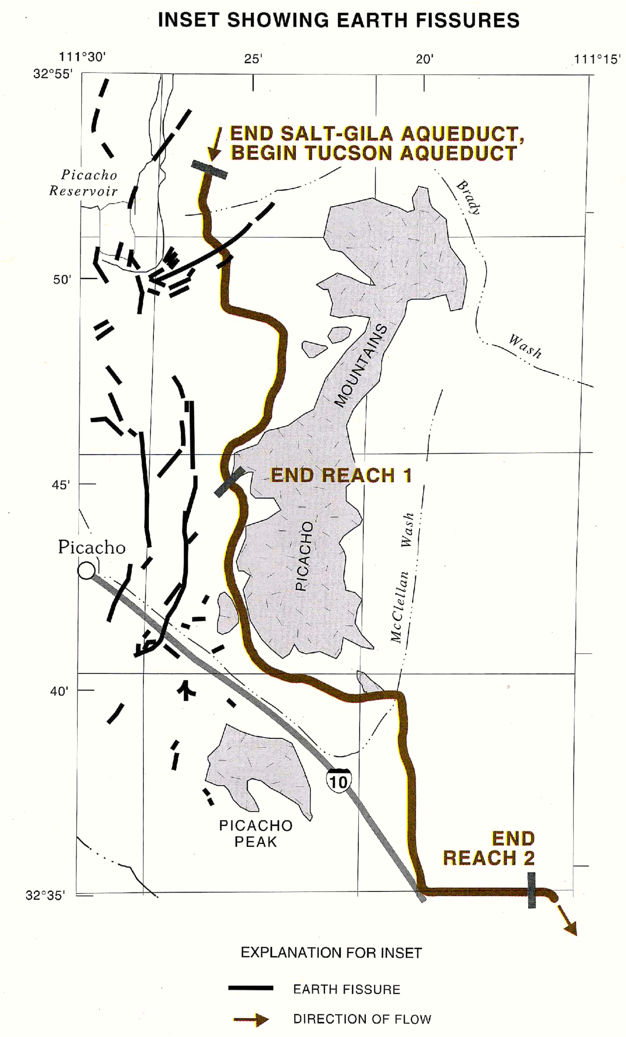


Figure 2. Vertical profile representations along **REACH 1** of the Tucson Aqueduct.



Index Map. Study area, alignment of Central Arizona Project aqueduct, and locations of upper and lower Santa Cruz Basins and Eloy Basin.

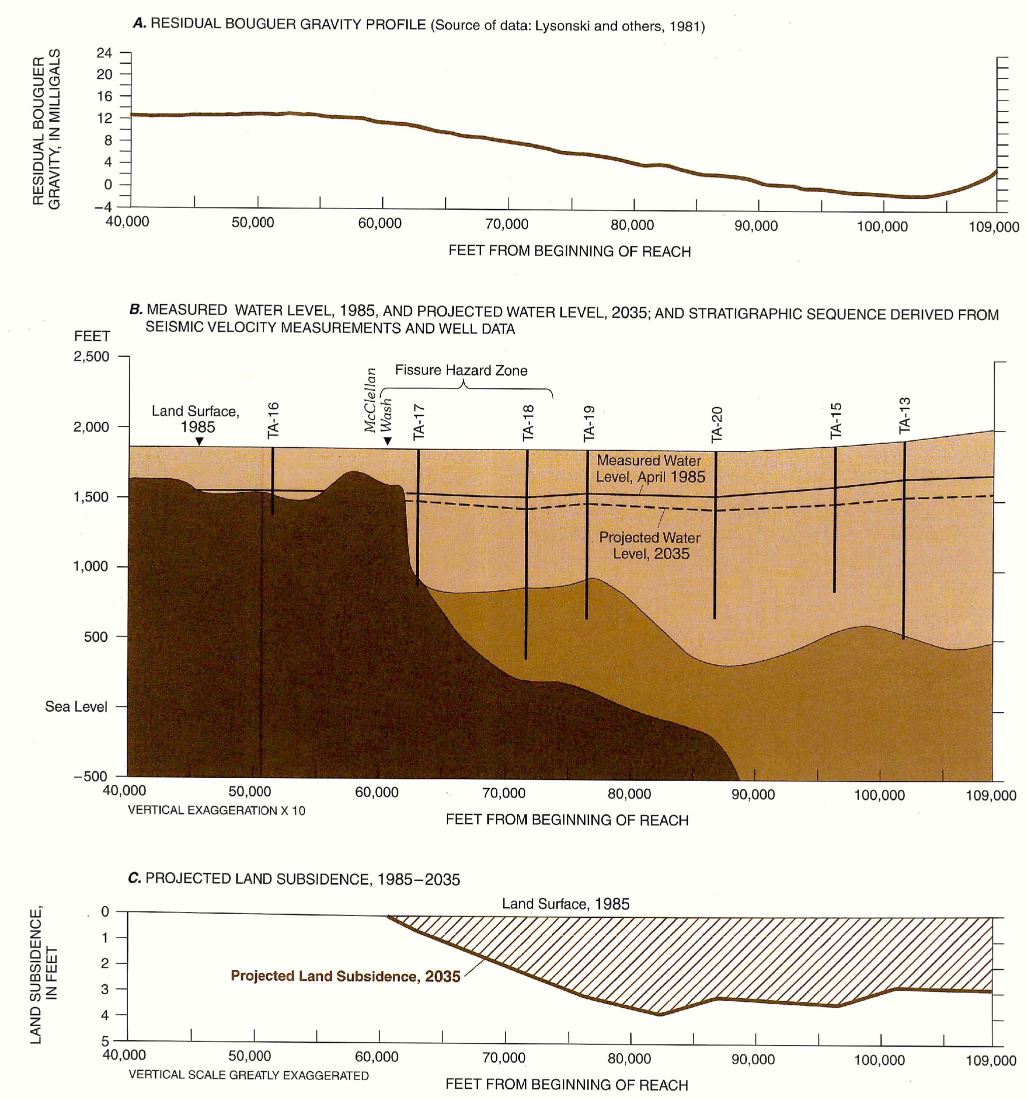


Figure 3. Vertical profile representations along **REACH 2** of the Tucson Aqueduct.

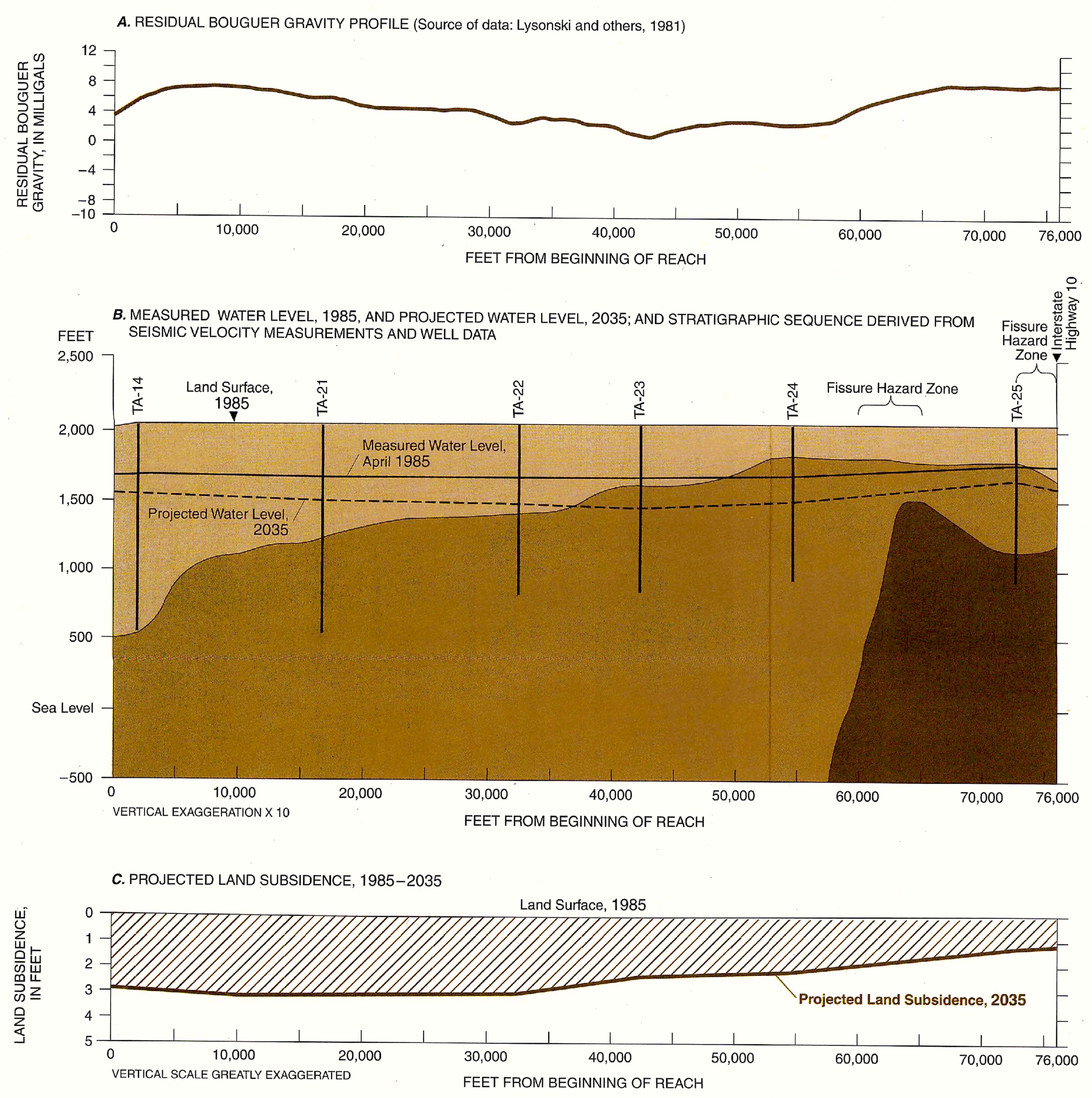


Figure 4. Vertical profile representations along **REACH 3** of the Tucson Aqueduct.

Figure 1. Study area showing location of reaches, test holes, and seismic-refraction profiles along the Tucson Aqueduct.

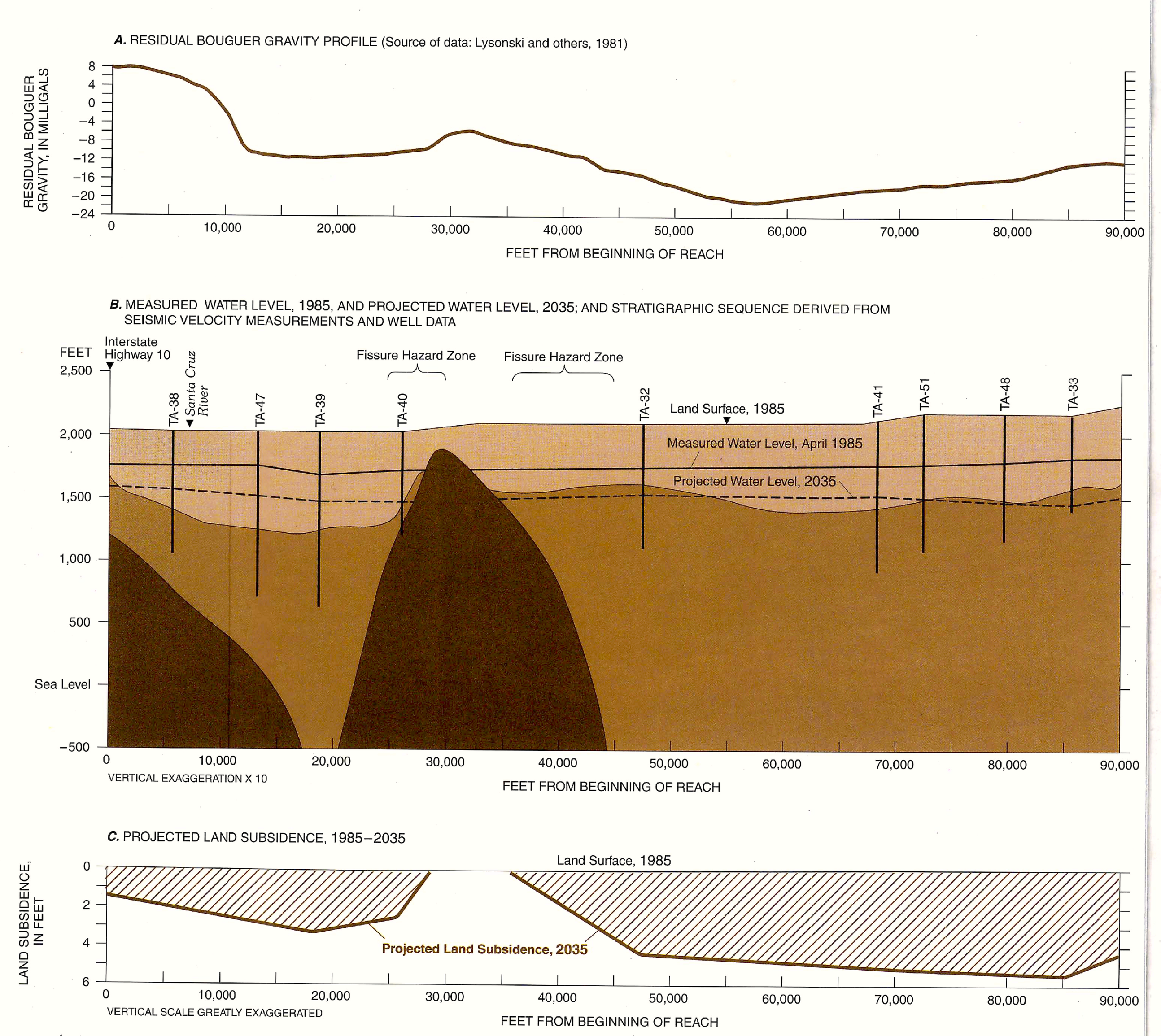
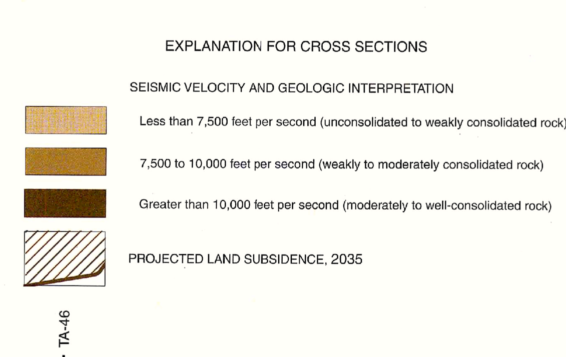


Figure 5. Vertical profile representations along **REACH 4** of the Tucson Aqueduct.



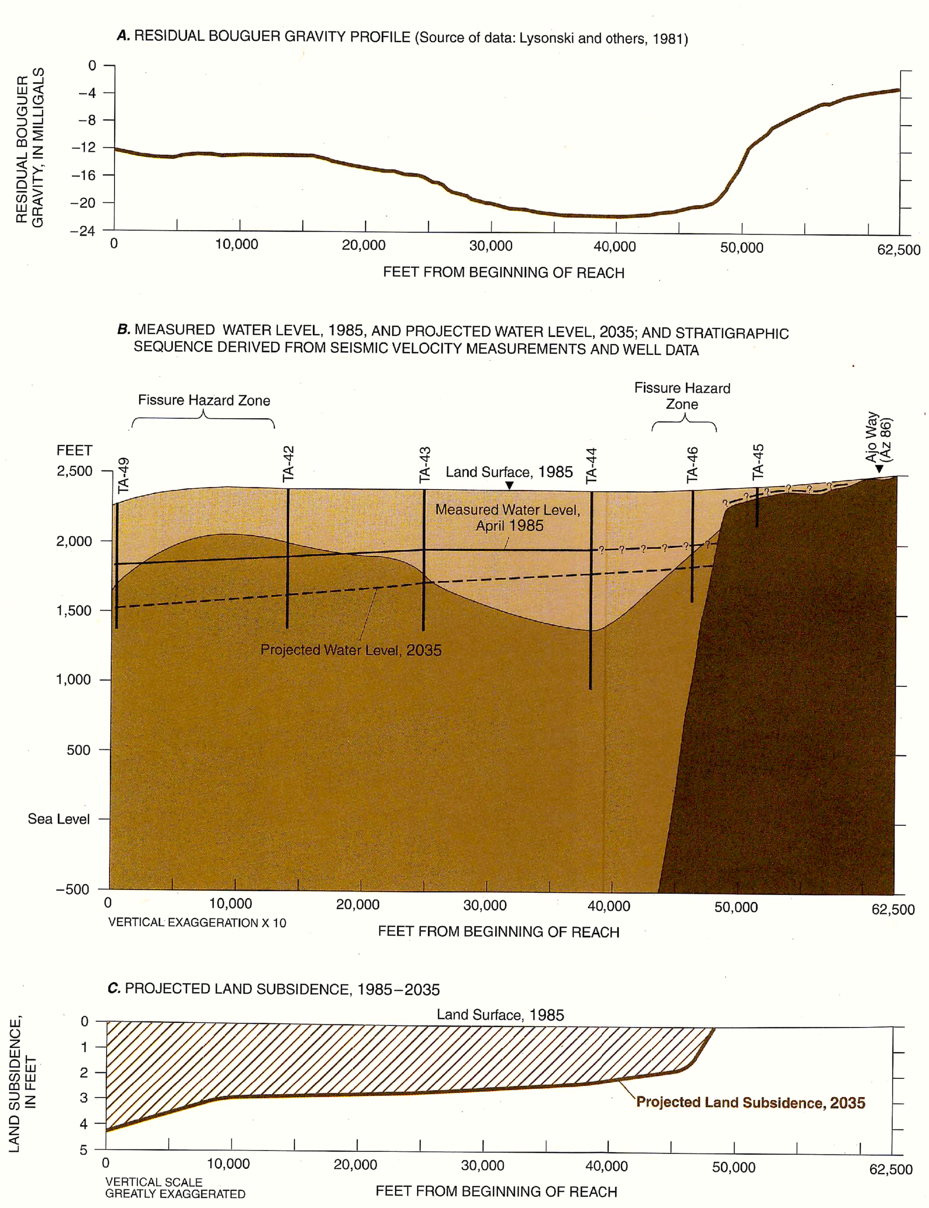


Figure 6. Vertical profile representations along **REACH 5** of the Tucson Aqueduct.

Hydrogeology, Land-Subsidence Projections, and Earth-Fissure Hazards Along the Tucson Aqueduct Alignment

By
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2002

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INTRODUCTION

The design and location of the Tucson Aqueduct of the Central Arizona Project (CAP) required information on the existing and potential land-subsidence and earth-fissure hazards along the aqueduct route through parts of Pinal and Pima Counties in south-central Arizona (fig. 1). The CAP includes a series of aqueducts and pumping plants constructed to bring water from the Colorado River into south-central Arizona to meet future water demands and to reduce ground-water overdraft. A study was conducted by the U.S. Geological Survey in cooperation with the Bureau of Reclamation (BOR), from 1979 to 1986, to evaluate land-subsidence and earth-fissure hazards along the proposed Tucson Aqueduct route and to provide design data for the construction of the aqueduct. As the study progressed, the BOR used the data and interpretations to help guide engineering designs and placement of the aqueduct. Construction of the CAP by the BOR was completed in 1993.

The term "land subsidence" refers to the vertical downward movement of the land surface; however, small horizontal movements also may be present. Land subsidence is a geologic process that has been accelerated in south-central Arizona by human activities, primarily by overdraft of ground water from the alluvial aquifers. Ground-water depletion has caused the aquifer material to compact, and aquifer compaction has caused large-scale land subsidence (Schumann and others, 1986).

Land subsidence and related earth fissures have caused millions of dollars in damage to engineering structures and present geologic and environmental hazards in parts of southern Arizona. By 1977, land subsidence and earth fissures had adversely affected about 675 mi^2 in the Eloy-Picacho area of western Pinal County (Schumann and others, 1986). The Tucson Aqueduct crosses the eastern edge of that area (fig. 1).

Differential land subsidence has caused extensive areas of earth fissures in the alluvial sediments, mainly along the periphery of the subsiding areas. Locally, deep gullies formed along earth fissures have adversely affected urban and agricultural land use. Other environmental concerns caused by land subsidence and earth fissures include accelerated soil erosion, increased flood hazards, and an increased potential for ground-water contamination (Schumann and Genualdi, 1986).

This study, done in cooperation with the BOR from 1979 to 1986, was undertaken to identify areas along the then-proposed route of the Tucson Aqueduct that were susceptible to land subsidence and earth fissuring and to estimate the amount of land subsidence that would occur in the future.

PURPOSE AND SCOPE

The purpose of this report is to present a summary of the results of the cooperative study with the BOR to define and describe the potential for land subsidence and earth-fissure development along the Tucson Aqueduct route in Pinal and Pima Counties. Relations among land surface, rock units, water-level altitudes in 1985, and test holes are shown in vertical profile representations of the five reaches of the aqueduct. Projections of land subsidence and delineations of earth-fissure hazard zones are based on water-level measurements for 1985 and projected water-level altitudes for 2035, which is the end of the designed life of the aqueduct.

HYDROGEOLOGIC SETTING

The study area is characterized by rugged northward- to northwestward-trending mountain blocks separated by wide, gently sloping valleys. The present-day mountains and valleys are largely the result of episodes of major block-faulting (Eberly and Stanley, 1978).

The sedimentary units that fill the basins and underlie the valley floors consist mainly of alluvial, lacustrine, and evaporite sequences of Quaternary to Tertiary age that locally contain interbedded volcanic rocks (Wilson and others, 1969). These basin-fill sediments are porous, store large quantities of ground water, and constitute the alluvial aquifer system in each basin. The basin-fill deposits may be more than 3,000 ft thick in the central parts of the basins (Hardt and Cattany, 1965).

The upper part of the basin fill is unconsolidated to weakly consolidated and contains ground water under unconfined conditions near the mountain fronts and under semiconfined to confined conditions in the central parts of the basins. This unit yields moderate to large volumes of water to wells where sufficient saturated thicknesses are penetrated; however, ground-water depletion has drained the upper part of the basin fill in parts of the area.

The lower part of the basin fill is weakly to moderately consolidated, stores ground water, and yields small to moderate quantities of water to wells where sufficient saturated thicknesses of this unit are penetrated.

The alluvial aquifer system is the principal source of water for the area. The system is recharged by infiltration of streamflow along the major streams, by infiltration of precipitation along the mountain fronts, and by ground-water underflow from adjoining basins. Seepage from Picacho Reservoir (fig. 1), infiltration of surface water from unlined irrigation canals, and return irrigation flow probably provide significant amounts of recharge east of Casa Grande and north of Picacho (Hardt and Cattany, 1965). The return of ground water withdrawn for the irrigation of crops is only a recycling of ground water and is not an addition of new water to the aquifer system. Little or no recharge is thought to result from direct precipitation on the valley floors because the precipitation amounts are small and the potential for evapotranspiration is large.

Many millions of acre-feet of ground water have been pumped from the alluvial aquifer system to irrigate crops and for municipal and industrial use (Anning and Duet, 1994). Pumping rates have greatly exceeded recharge rates, and a general depletion of water in the alluvial aquifer system is indicated by the general decline in water levels throughout most of the area. Water-level declines have caused the alluvial aquifer materials to compact and the land surface to subside in places (Schumann and Poland, 1970).

Ground water is removed from the study area mainly by evapotranspiration losses of water pumped for the irrigation of crops and by underflow out of the area (Hardt and Cattany, 1965). Some of the water withdrawn in Avra Valley is transported into the Tucson Basin by pipeline for municipal and industrial use (Cuff and Anderson, 1987).

Extensive areas of earth fissures occur in the alluvial sediments in parts of Pinal County. The fissures first appear as long, narrow, linear features, generally less than 1 in. wide, or as a line of small-diameter holes. Newly opened fissures have nearly vertical sides, exhibit little or no lateral or vertical movement, range from a few feet to as much as 1 mi in length, and appear to be tensional failures.

The earth fissures generally occur on the periphery of the subsiding basins, roughly parallel to surface contours, and transect natural drainage paths. Differential land subsidence along the edges of the basins cause a flexure or bending of the alluvial sediments near the mountain fronts and produce tensile stresses. When the tensile stress exceeds the tensile strength of the alluvial sediments, tensional breaks will occur. Several investigators have observed that many earth fissures form over buried ridges, fault scarps, or other irregularities in the consolidated rock surfaces beneath unconsolidated to weakly consolidated alluvium (Feth, 1951; Robinson and Peterson, 1962; Schumann and Poland, 1970; Jachens and Holzer, 1979).

GROUND-WATER DEVELOPMENT AND GROUND-WATER MOVEMENT

Large-scale pumping of ground water in the Eloy-Picacho area began in about 1914 when shallow irrigation wells were drilled near Toltec in the lower Santa Cruz River Basin. As recently as 1923, the alluvial-aquifer system was assumed to be in dynamic equilibrium; on average, recharge was equal to discharge (Hardt and Cattany, 1965). Large floodflows and small-scale pumping may have produced local short-term fluctuations in the water table. Ground-water withdrawals in the entire lower Santa Cruz Basin increased sharply in 1930 when about 40,000 acres were irrigated in Pinal County (fig. 1).

Withdrawal of ground water for the irrigation of crops exceeded the natural rates of recharge by the mid-1930s. Widespread lowering of water levels in wells in parts of the Eloy-Picacho area occurred (Smith, 1940), and the cost of pumping water increased significantly. Between 1923 and 1942, water levels in wells near Eloy had declined as much as 30 ft (Hardt and Cattany, 1965).

Ground-water development increased significantly after World War II. By 1952, more than 120 ft of water-level decline had been measured near Eloy (Halpenny and others, 1952). Annual volumes of ground-water withdrawal decreased after a record 1.4 million acre-ft was pumped in the lower Santa Cruz Basin in 1953.

Large-scale development of ground water in Avra Valley began in 1937 when six irrigation wells were drilled near Marana to augment the supply of water that was being transported from the Cortaro area to irrigate about 6,000 acres of crops. Ground-water withdrawal after 1940 resulted in a general lowering of the water table throughout Avra Valley. By 1942, about 170,000 acres were irrigated in response to a large increase in the demand for agricultural products that occurred at the beginning of World War II (Hardt and Cattany, 1965). Between 1940 and 1965, water levels in wells had declined more than 100 ft near Marana and in the northwestern part of the valley (Moosburner, 1972). Between 1940 and 1985, water levels had declined more than 150 ft in the west-central part of the valley and more than 200 ft south of Picacho Peak in the northwestern corner of the valley (Cuff and Anderson, 1987). Since the mid-1960s, about 2,600 acre-ft/yr of ground water has been pumped for mining operations in the Silver Bell Mountains in the northwestern part of Avra Valley. Between 1973 and 1983, the city of Tucson pumped and transported 3,600 to 18,000 acre-ft/yr of water from Avra Valley into the Tucson area for municipal and industrial use (Cuff and Anderson, 1987). By 1984, a total of more than 3.9 million acre-ft had been withdrawn from the alluvial-aquifer system in the valley (U.S. Geological Survey, 1984), and continued ground-water overdraft had produced more than 350 ft of water-level decline southeast of Eloy (Thomsen and Baldys, 1985).

In 1900, before large-scale pumping began, the general direction of ground-water movement in the eastern part of the Eloy-Picacho area of the lower Santa Cruz Basin was to the west and northwest (Thomsen and Baldys, 1985). In 1940, ground water in Avra Valley generally moved northwestward into the lower Santa Cruz Basin between Picacho Peak and the Silver Bell Mountains (White and others, 1966). By 1983, after many years of large-scale pumping, ground water in the western part of the Eloy-Picacho area moved toward two large cones of depression (Thomsen and Baldys, 1985). One cone of depression was northwest of Toltec, and a second, larger cone of depression was southeast of Picacho. In 1985, ground-water movement in Avra Valley remained generally in a northwestern direction. In the extreme western part of Avra Valley, however, the direction had changed from northwest trending to almost due west trending.

METHODS OF STUDY

Hydrogeologic studies and geophysical surveys were used to determine the conditions that may produce land subsidence and earth-fissure hazards along the Tucson Aqueduct route. Methods included installation of test wells and analysis of well data, borehole-geophysical surveys, surface-geophysical surveys, measurement of water levels, analysis of existing gravity data, leveling surveys, use of the Global Positioning System (GPS), and analysis of aerial photographs.

Test drilling, borehole-geophysical surveys, and surface-geophysical surveys were used to determine the physical properties of the rocks and sediments in the subsurface along the Tucson Aqueduct route. Layers having similar physical and geophysical properties were grouped together into highly generalized hydrogeologic units. The hydrogeologic units, thus defined, do not necessarily correspond to chronostratigraphic or lithostratigraphic units.

A series of 50 deep test holes with an average spacing of about 1.5 mi were drilled along the Tucson Aqueduct route (fig. 1) to determine the thickness and physical characteristics of the alluvial aquifer materials and the lithology of the underlying consolidated rock units (Wrege and others, 1985). Locations for test holes were selected on the basis of available surface and subsurface geologic data and surface-geophysical surveys. Air and mud-rotary drilling techniques were used to drill test holes that ranged from 135 to 1,970 ft deep along and near the Tucson Aqueduct route (Wrege and others, 1985). Twenty-nine of the test holes were equipped with one or more piezometers to allow water-level measurements at selected depths within the alluvial aquifer. Five test holes (TA-10, -13, -32, -33, and -44) were instrumented with vertical extensometers to monitor compaction of the water-bearing units. Water-level and compaction data are recorded continuously at these sites (Evans and Pool, 2000).

Borehole-geophysical logs were collected in the test holes drilled along the aqueduct route to help determine the thickness and physical characteristics of the materials penetrated. A typical suite of geophysical logs collected included caliper, electric, natural gamma, gamma-gamma, neutron, and sonic velocity (Wrege and others,1985).

Gravity maps by Peterson (1968) and Hassemer and Dansereau (1980) and residual Bouguer gravity-anomaly maps prepared by Lysonski and others (1981) were used to evaluate the general configuration of the basins and to identify areas of suspected earth-fissure hazards. Gravity surveys also were used to help select drill sites and to design the seismic-refraction programs using a generalized depth-to-consolidated rock map compiled from gravity data by Oppenheimer and Sumner (1981).

Seismic-refraction profiles were used to help define the configuration of subsurface geologic features such as scarps, benches, or peaks that may control the location of earth-fissure hazards along the Tucson Aqueduct route (fig. 1). The seismic lines were laid out to transect areas of suspected subsurface geologic faults and to help define the configuration of the buried consolidated rock surface beneath the route. Data from about 75 mi of seismic profiles were collected along 39 seismic lines oriented along and at approximately right angles to the alignment of the Tucson Aqueduct. Thicknesses of the seismic-velocity layers were derived from seismic-refraction profiles.

Surface- and subsurface-geophysical surveys were used to provide indirect information on selected physical properties of the subsurface geologic units. A rough approximation of the compressibility of the subsurface materials can be inferred from the unit's seismic velocity. All rocks having a seismic velocity of more than 10,000 ft/s (3.0 km/s) were considered to be moderately to well consolidated and were not considered to be compressible. Sedimentary units that have a seismic velocity between 7,500 to 10,000 ft/s (2.3 to 3.0 km/s) were considered to be weakly to moderately consolidated and were considered to be only slightly compressible. Sedimentary units having a seismic velocity less than 7,500 ft/s (2.3 km/s) were considered to be unconsolidated to weakly consolidated and moderately to highly compressible. The seismic-refraction profiles were calibrated with the use of acoustic-velocity logs obtained at the deep drill sites.

Land subsidence generally was measured by periodically surveying a network of bench marks using first- or second-order conventional leveling techniques. These bench-mark networks include ties to stable reference bench marks usually located on consolidated rock along the perimeter of the ground-water basins. Land subsidence was determined by a comparison of altitudes of bench marks obtained from successive level surveys.

The feasibility of using GPS data to measure subsidence was evaluated in the Eloy Basin during spring 1984. The test was done in cooperation with the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA). Relative positioning accuracies of one part per million (ppm) or less over distances of 1 mi to thousands of miles are possible using the GPS data. The GPS test in 1984 included conventional first-order leveling along the NGS level line and GPS measurements at selected bench marks along the level line in eastern Pinal County. This test indicated that repeated GPS measurements can be used to monitor land subsidence that occurs after the initial GPS survey with an accuracy of about ±0.05 ft. Subsidence monitoring has continued to the present (2002) at selected locations within the study area by using networks of differential GPS stations, extensometers, and satellite-derived interferograms (Evans and Pool, 2000; Pool and others, 2001).

Earth fissures along the Tucson Aqueduct route were mapped by analyzing aerial photographs taken from helicopters and fixed-wing aircraft. The fissures then were drawn on 1:24,000-scale topographic maps. Earth-fissure hazard zones were delineated along the aqueduct route on the basis of subsurface geologic conditions as determined from borehole data and surface-geophysical surveys.

LAND-SUBSIDENCE PROJECTIONS AND EARTH-FISSURE HAZARDS

Data from Bouguer gravity profiles, seismic-refraction profiles, well cuttings, and well logs were assembled into vertical profile plots for five reaches along the Tucson Aqueduct route. The profile plots are shown together with the water levels for 1985 and the projected water levels for 2035 in figures 2–6.

Historical water-level declines and subsidence at selected points within the study area were extrapolated to predict the future subsidence that might occur in the area of the aqueduct. The maximum reported ratio of land subsidence (12.5 ft) to water-level decline (275 ft) was 0.045 (Laney and others, 1978) from the area west of the town of Picacho near the center of the Eloy Basin (fig. 1 and index map). This part of the basin has large thicknesses of fine-grained sediments (Hardt and Cattany, 1965) and represents the most compactible sediment column within the study area. Sediments near the basin margins, more representative of those underlying the aqueduct route, have a much smaller percentage of fine-grained materials and experience much less compaction per unit of water-level decline than do sediments near the basin center. Several ratios were used to project amounts of land subsidence along the aqueduct route.

Estimates of future water-level declines for the study area and period of interest were extrapolated from results of long-term projections published by the Arizona Water Commission (1978). Projected water-level declines of 50 to 400 ft resulted in the projected land-subsidence profiles shown in figures 2–6. No correlations were determined between water levels at various depths in the aquifer and the potential for land subsidence.

Abrupt changes in the surface of the moderately to well-consolidated rocks that occur within about 1,000 ft of the land surface were the primary criteria used to identify earth-fissure hazard zones along the aqueduct route. The presence of earth fissures in adjacent areas or along the same structural trend was another important criterion. Historical and projected land-subsidence amounts and distributions were considered in the delineation of the earth-fissure hazard zones.

SUMMARY

This report describes the areas along the Tucson Aqueduct route that were believed to be subject to subsidence and earth-fissure hazards. Aerial photographs and aerial reconnaissance were used for mapping of earth fissures and other geologic features. Gravity maps were used to evaluate the general configuration of the basins and to identify areas of suspected earth-fissure hazards. Deep test holes, borehole-geophysical surveys, and surface-geophysical surveys along the Tucson Aqueduct route were used to determine the distributions and physical properties of the rocks and sediments that occur in the subsurface.

Eight earth-fissure hazard zones were identified along the proposed route of the aqueduct. Water-level elevations and land subsidence amounts along each of the five reaches of the aqueduct were projected for 2035. The ranges of subsidence projections for the five reaches of the aqueduct generally are 0 to 4 ft for reaches 1 and 2, 1 to 3 ft for reach 3, 0 to more than 5 ft for reach 4, and 0 to 4 ft for reach 5 (figs. 2–6).

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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Schumann, Wrege, and Meehan—HYDROGEOLOGY, LAND-SUBSIDENCE PROJECTIONS, AND EARTH-FISSURE HAZARDS ALONG THE TUCSON AQUEDUCT ALIGNMENT OF THE CENTRAL ARIZONA PROJECT IN PINAL AND PIMA COUNTIES, ARIZONA—U.S. Geological Survey Water-Resources Investigations Report 02–4028

Cover photograph of the Tucson Aqueduct courtesy of the Bureau of Reclamation.
Inset photograph of an earth fissure by Michael Carpenter, U.S. Geological Survey.