GROUND-WATER RESOURCES – INFORMATION SERIES

REPORT 5

LAND SUBSIDENCE IN LAS VEGAS VALLEY, NEVADA, 1935–63

By
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Geologist

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Prepared cooperatively by the
Geological Survey, U.S. Department of the Interior

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FOREWORD

This is the fifth report in the Information Series of this Department. This series of reports is designed to make public timely information on subjects not usually included in the Water Resources Bulletins or the Reconnaissance Ground-Water Reports of this Department.

This report, which was prepared by Glenn T. Malmberg, geologist with the U. S. Geological Survey, gives the known information on land subsidence in Las Vegas Valley. It points out specifically the influence of the reduction in artesian head in the valley on land subsidence. This data is of value to many agencies and individuals concerned with developments such as houses, roads, streets, wells, pipe lines, and other facilities in the affected area.

Hugh A. Shamberger, Director,
Department of Conservation and Natural Resources.

June, 1964
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Glenn T. Malmberg

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ABSTRACT

Releveling of the Hoover Dam level network by the U. S. Coast and Geodetic in 1963 indicates that subsidence of the land surface from compaction has exceeded 2 feet in the vicinity of Las Vegas and North Las Vegas since 1935.

About 200 square miles in the central part of the valley has subsided largely as a result of a reduction in artesian head caused by large groundwater withdrawals. The area of subsidence is in part similar to the area of greatest artesian head decline. Reduction of artesian pressure removes part of the hydraulic support of the overlying beds thereby increasing the overburden load on the confined aquifer system which causes compaction of the compressible material in the ground-water reservoir.

The maximum rate of subsidence since 1950 has been about 0.1 foot per year or about twice the rate during the period 1935-50. Maximum subsidence occurs in the area about 2 1/2 miles east of the Las Vegas Valley Water District well field where about 50 percent of the total pumping in the valley is concentrated and where the greatest artesian head declines have occurred. This apparent inconsistency is interpreted to be due principally to the increase in clay and silt deposits in the area east of the Las Vegas Valley Water District well field, and in part to localized pumping of the North Las Vegas wells. Although the subsidence since 1952 has been accelerating the ratio between subsidence and decline in artesian head has been decreasing.

During 1935-63 approximately 30,000 acre-feet of ground water or about 4 percent of the total cumulative pumpage in Las Vegas Valley was obtained from a reduction in storage probably resulting from permanent rearrangement of the compactible material in the ground-water reservoir. Subsidence of the land surface resulting from compaction has caused and probably will continue to cause damage to wells and pumping equipment, buried pipe and sewer lines, streets and other engineering structures.
INTRODUCTION

Las Vegas Valley is a large structural depression in southern Nevada encompassing an area of 800 square miles and surrounded by mountains that reach heights of nearly 12,000 feet. It is bounded on the west by the Spring Mountains, on the north by the Sheep and Las Vegas Ranges, and on the south and east by River Range and Frenchman Mountain. The valley floor is underlain by unconsolidated and partially consolidated deposits of continental and lacustrine origin that are more than 1,000 feet thick.

In the vicinity of Las Vegas and North Las Vegas ground water contained in these deposits under confined and semiconfined conditions has been utilized extensively since about 1906 when the first successful wells were developed. Large ground-water withdrawals since that time have progressively lowered the artesian head more than 100 feet in some areas in the vicinity of Las Vegas and North Las Vegas, and because of the decline in artesian pressure, an area in the center of the valley of approximately 200 square miles has been subsiding. Additional subsidence has occurred due to the load imposed by the filling of Lake Mead and due to a regional southward tilting.

The purpose of this report is to show the area and magnitude of subsidence resulting from the artesian-head decline in Las Vegas Valley; to compute the volume of pore-space reduction in the ground-water reservoir resulting from subsidence; and to relate the rate of subsidence to the reduction in artesian head.

GENERAL GEOLOGY OF THE GROUND-WATER RESERVOIR

The rocks exposed in the mountains and underlying the alluviated basin include about 35,000 feet of marine and continental deposits lying upon the Precambrian basement complex. The rocks are dominately indurated, calcareous and clastic sedimentary deposits of Paleozoic and Mesozoic age that are overlain partly by rocks of volcanic origin and partly by unconsolidated deposits of sand, silt, and clay of Tertiary age. Most of the rocks of Tertiary age and older have been highly faulted and folded, and are deformed into a structural depression into which weathered material derived from the older rocks exposed in the surrounding mountains is being deposited.

The subsurface extent of the unconsolidated Tertiary deposits (Muddy Creek Formation) is not known accurately; however, it probably underlies most of the valley. Although the formation crops out at isolated points in the valley, it is buried about 700 feet below the land surface in the vicinity of Las Vegas (Maxey and Jameson 1948, p. 69). Where the unconsolidated Tertiary deposits occur at depth beneath the valley floor, they contain ground water and generally are considered to be part of the valley fill. Several hundred feet of unconsolidated to partially consolidated alluvial-fan and playa deposits of Quaternary age lie unconformably upon the older deposits. In general, the alluvial-fan deposits range from a thick sequence of lenses of
heterogeneous material consisting of boulders, gravel, sand, silt, and clay near the heads of the fans and alluvial apron to thinner more irregular and discontinuous lenses of better sorted sand and gravel at the toes of the fans. Near the center of the valley the coarse-grained material grades laterally into a thick sequence of alternating beds of fine sand, silt, and clay. Most of the deposits cannot be correlated over a wide area. The gross character of the lithology of the valley fill changes abruptly from predominantly coarse to mainly fine-grained material along the toe of the alluvial apron west of Las Vegas. Along the west side of the valley, gravel and sand deposits contain only minor amounts of silt and clay, whereas in the area to the east, silt and clay predominate. The geologic section from Red Rock to the base of Frenchman Mountain, shown in Nevada Water Resources Bulletin 5 (Maxey and Jameson 1948, plate 6) indicates a progressive decrease in sand and gravel and an increase in silt and clay toward the east.

The silt and clay deposits of moderately low permeability, which impede the vertical movement of ground water, occur as lenses or layers within the aquifers and act as semiconfining layers separating the principal artesian aquifers. Maxey and Jameson (1948, p. 82) divide the valley-fill deposits into three principal zones of aquifers, described as a upper zone ranging from about 250 to 450 feet below land surface, a middle zone ranging from about 500 to 700 feet below land surface, and a deep zone generally of unknown thickness below a depth of about 700 feet. Most of the semiconfining layer of silt and clay overlying the upper unit is saturated to within a few tens of feet of the land surface, but because of its low permeability, development of ground water in the upper 250 feet of valley fill has been limited largely to domestic wells having low yields. The most productive aquifers are the upper and middle zones of artesian aquifers along the toe of the alluvial apron west of Las Vegas where approximately 70 percent of the gross pumpage in the valley is obtained from wells having depths of less than 1,000 feet.

**VERTICAL CONTROL NETWORK**

The network of levels crossing Las Vegas Valley is a small segment of the Hoover Dam vertical control network. The network was originally established in 1935 to observe subsidence of the Lake Mead basin expected to result from the increased load on the earth's surface as the newly formed lake filled behind Hoover Dam. That part of the vertical-control network in Las Vegas Valley includes traverses totaling approximately 65 miles in length that consist of a northwest-southeast line approximately parallel to U.S. Highway 95 from the vicinity of the Tule Springs Ranch to Henderson, and a northeast-southwest line along the Union Pacific Railroad track from Apex to Arden, Nevada. The western end of the level line that extends from a point about 2 1/2 miles northeast of Nellis Air Force Base along Gypsum Wash to the Boulder Wash gage on the shore of Lake Mead is included in the level net in Las Vegas Valley (fig. 1)

3.
Figure 1.—Map of part of Las Vegas Valley showing a portion of the Hoover Dam level net.
Altitudes of bench marks in the Hoover Dam level network were determined by first order leveling in 1935, 1940-41, and 1949-50 by the U.S. Coast and Geodetic Survey.\(^1\) A compilation of the changes in altitude of the adjusted elevations during the successive intervening periods was published in a comprehensive report of the Lake Mead area by the U.S. Geological Survey (Longwell, D. R., 1960, pl. 3). In 1963 the Coast and Geodetic Survey reelevated much of the original Hoover Dam level net, including all of the level lines crossing Las Vegas Valley and added approximately 58 miles of new level lines to the original level network. The expansion of the net in Las Vegas Valley includes the extension of the original level lines to bedrock anchor points and additional lines across the principal areas of pumping.

Changes in altitude of the bench marks in the Hoover Dam level net are relative to the Cane Spring bench mark, about 60 miles northeast of Las Vegas which is assumed to be fixed zero datum. Elevations of the bench marks for the first three successive level runs used in the preparation of this report have been adjusted by the Coast and Geodetic Survey to be internally consistant by the method of least squares (Braaten and McCombs, 1963). The level data for 1963 are unadjusted field data and therefore may be subject to some correction.

**CAUSES OF SUBSIDENCE**

Subsidence in Las Vegas Valley is due to three principal causes; 1) regional subsidence and widespread tilting of the entire Lake Mead Reservoir and adjacent areas to the south resulting from tectonic activity; 2) subsidence of a broad basin-like depression centering in Boulder Canyon (about 12 miles upstream from Hoover Dam) resulting from the additional load imposed on the earth's surface by the impoundment of the Colorado River behind Hoover Dam; and, 3) local subsidence in Las Vegas Valley due to decline of artesian pressure and resulting compaction of the unconsolidated alluvial fill.

Successive reeleving of the Hoover Dam level net indicates a regional tilting of the entire Lake Mead Reservoir and the area to the south; it includes the depression and tilting of mountain ranges and intervening valleys. Longwell (1960, p. 36) surmised that the regional tilting is related to movement that may have been in progress prior to the construction of Hoover Dam.

Reeleving also indicated broad subsidence of the Lake Mead basin after impoundment of the Colorado River began in 1935. Since that time the combined subsidence due to tilting and basining resulted in depressing the bedrock floor beneath Lake Mead about a foot due principally to the weight of the water impounded in the principal area of storage of the reservoir of about 10 tons per square foot. (Longwell, C. R. 1960, p. 35). Subsidence of the rock beneath Lake Mead and adjacent areas may have resulted in several ways, including differential subsidence of the bedrock floor along old fracture zones, elastic yielding of the bedrock, or by plastic deformation at depth.

\(^1\) Leveling in 1935 was done during March and April. Successive reeleving spanned periods from Oct. 1940 to Apr. 1941; Dec. 1949 to July 1950; and May to July 1963.
The depression of the floor of Lake Mead and adjacent areas has affected an area of several thousand square miles around the lake. The cone of land subsidence, which centers in the area east of Boulder Canyon, extends outward 40 miles or more from the approximate center of gravity of the lake. Las Vegas Valley lies within the Lake Mead cone of depression, approximately 30 miles west of its center. Releveling of bench marks anchored in bedrock on the north, east, and south sides of Las Vegas Valley indicates that Las Vegas Valley has been depressed and tilted toward the east since the first survey in 1935. Releveling of the Hoover Dam level net indicates that areas of maximum subsidence of bedrock on the east side of the valley have been depressed about 0.4 foot (120 millimeters) during the period 1936-63. Extrapolation of the level data suggests that regional subsidence along the western margin of the valley was about 0.2 foot (60 millimeters) during the same interval. The tilting of Las Vegas Valley associated with the depression centered around Lake Mead in any event does not affect the hydraulic properties of the ground-water reservoir in the valley fill; therefore, in this report it is significant only insofar as it constitutes part of the total measured subsidence in Las Vegas Valley.

In addition to the regional tilting and subsidence of Las Vegas Valley, the unconsolidated valley-fill deposits locally have subsided largely because of compaction of the fine-grained deposits in the ground-water reservoir. Compaction occurs when that part of the overburden load supported by artesian pressure is transferred from the water to the porous material of the aquifer system as the artesian pressure is reduced. As the artesian head is reduced a pressure differential is established between the fine-grained material of the confining layers and interbeds and the coarse-grained material in the aquifer, because pore pressure in silt and clay adjusts more slowly to changes in artesian pressure than does the pore pressure in the coarse-grained material of the aquifers. The pressure differential causes water to move from the fine material in the confining layers into the coarse material. Thus, a reduction in artesian pressure causes a corresponding increase in the grain-to-grain load of the aquifer and the confining beds, causing permanent rearrangement and elastic compression of the compressible materials in the aquifers and the overlying confining beds and a consequent subsidence of the land surface. Direct evidence of compaction of the material in the ground-water reservoir is indicated by the protrusion of well casings above the land surface by as much as 2 feet or more.

Laboratory studies of aquifer material in the San Joaquin Valley in California (Inter-agency Committee on land subsidence in the San Joaquin Valley, 1958) indicate that the most compressible materials in that valley are the highly porous lacustrine clay and to a lesser extent the silty clay, silt, and sandy silt. The inter-agency report (1958, p. 152) also indicates that the materials near the base of the water-bearing deposits generally are less compressible than those from shallower depths. Therefore, insofar as the data for subsidence in the San Joaquin Valley is applicable to Las Vegas Valley it is suggested that the most significant subsidence in Las Vegas Valley may be occurring in the playa and lacustrine clay and silt beds in the upper and middle zones of artesian aquifers and in the intercalated semiconfining beds.
The area of land subsidence resulting almost wholly from artesian-head decline and compaction of the valley-fill deposits in Las Vegas Valley extends from Tule Springs Ranch southeast about 18 miles to Hidden Hills Ranch and eastward to the base of Sunrise Mountain—an area of about 200 square miles. The area of subsidence is generally concordant with the area of extensive ground-water withdrawals in the central part of the valley, and is underlain principally by coarse-to-fine-grained alluvial-fan deposits interbedded with playa and lacustrine material.

Subsidence of the land surface may have started at the time of the initial decline in artesian head after the first successful flowing wells were developed in 1906. The extent and magnitude of subsidence prior to the establishment of the Hoover Dam level net in 1935 is unknown; however, in some parts of the valley the magnitude may have been on the order of a foot or more, based on the ratio of artesian-head decline to land subsidence (p. 8).

Figures 2, 3, and 4 show the magnitude and extent of the land subsidence in Las Vegas Valley during the periods 1935-41, 1935-50, and 1935-63. The contours connecting points of equal change in altitude of the land surface are based on the change in altitude of bench marks in the Hoover Dam level network corrected for regional tilting toward Lake Mead. Corrections for regional subsidence and tilting were obtained by difference between regional subsidence contours projected across Las Vegas Valley and the total measured change in altitude of the bench marks. The difference in altitude between the projected and observed surfaces approximates the amount of subsidence resulting principally from compaction of the unconsolidated valley-fill deposits. Accordingly, corrections ranging from zero along the west side of Las Vegas Valley to about 0.15 foot along the base of Frenchman Mountain are subtracted from the total measured decline in altitude of the bench marks during 1935-41. Corrections similarly applied to the data for periods 1935-50 and 1935-63 indicate cumulative adjustments in the measured altitude of the bench marks ranging from about 0.3 foot to 0.25 foot along the western margin of the valley to about 0.5 foot along the eastern side of the valley. Figures 2, 3, and 4 show the subsidence of the land surface resulting principally from compaction of the valley-fill deposits for the periods indicated. The three illustrations show the progressive enlargement both vertically and laterally of the cone of subsidence.

From 1935 to 1941 maximum subsidence was about 0.25 foot (80 mm) at bench mark K169 at the Las Vegas Post Office. Land subsidence during this 5 1/2-year interval included an area of about 35 square miles underlying most of the Las Vegas-North Las Vegas urban area. Maximum subsidence occurred approximately 2 1/2 miles east of the Las Vegas Valley Water District well field and about a mile and a half south of the North Las Vegas municipal wells in an area underlain predominately by clay and silt. The volume of subsidence and the consequent reduction in pore space during this interval was about 2,000 acre-feet.
Figure 2.—Land subsidence in Las Vegas Valley, Nevada, due to artesian-head decline, 1935-1941
Figure 3.—Land subsidence in Las Vegas Valley, Nevada, due to artesian-head decline, 1935-1950
Figure 4.—Land subsidence in Las Vegas Valley, Nevada, due to artesian-head decline, 1935-1963
Maximum subsidence from 1935 to 1950 was about 0.8 foot at bench mark L169 near the Bonanza Street underpass. During the 9-year interval from 1941 to 1950, the average rate of subsidence of about 0.05 foot per year continued, but the center of maximum subsidence shifted from the vicinity of the Post Office near the center of town approximately a quarter of a mile northwest. The area of subsidence was enlarged to about 145 square miles by 1950 and the volume increased to about 14,000 acre-feet.

The subsidence in Las Vegas Valley from 1935 to 1963 resulting principally from the compaction of sediments has been slightly more than 2 feet at bench mark L169, or an increase of about 1.3 feet since the previous releveling of the Hoover Dam level network in 1950. The average rate of subsidence since 1950 increased to about 0.1 foot per year, or about twice the average rate from 1935 to 1950. The total area of subsidence remained about the same as in 1935-1950 but the volume of subsidence increased to about 30,000 acre-feet. The area of maximum subsidence enclosed by the 2-foot contour expanded northward about a mile from bench mark L169, and in 1963 included some of the North Las Vegas municipal wells adjacent to the Union Pacific Railroad track.

Figure 5 shows three profiles of land subsidence along the two principal level lines of the Hoover Dam level net in Las Vegas Valley. Line A-A' (fig. 5) extends from bench mark Z17 about 14 miles northwest of Las Vegas to bench mark Z51 about 16 miles southeast of Las Vegas; line B-B' (fig. 5) extends from bench mark K, 13 miles southwest of Las Vegas to bench mark V about 15 miles northeast of Las Vegas. The profiles, which are based on the Coast and Geodetic Survey leveling and corrected for regional subsidence and tilting, show the amount of subsidence at the time of the successive relevelings compared to the 1935 base and, by difference, indicate the amount of subsidence during the interval between level runs.

RELATION OF SUBSIDENCE TO DECLINE IN ARTESIAN HEAD AND GROUND-WATER WITHDRAWALS

The principal area of decline in artesian head has been in the vicinity of the Las Vegas Valley Water District well field, about 2 1/2 miles west of Las Vegas where approximately 50 percent of the total pumping in the valley is concentrated. Significant artesian-head declines also have occurred in the vicinity of North Las Vegas, in the area about 3 miles long along U.S. Highways 91 and 466 south of Las Vegas known as "The Strip", and in several other more localized areas around highly pumped wells. Figure 6 shows the areal extent and magnitude of decline of artesian pressure in Las Vegas Valley between 1944 and 1963.

The decline in head in the vicinity of the Las Vegas Valley Water District well field between 1944 and 1963 shown in figure 6 is about 100 feet. Water-level measurements in a few scattered wells near the Water District well field indicate that between 1935 and 1944 the artesian head declined about 20 feet. Therefore, the total decline in artesian head at the Water District well field between 1935 and 1963 was about 120 feet.
Figure 5.—Profiles of land subsidence due to artesian-head decline, 1935-63
Figure 6.—Map of part of Las Vegas Valley showing approximate net change in the piezometric surface between 1944 and 1963.
A comparison of the area of net change in artesian head since 1944 (fig. 6) and the area of land subsidence (figs. 2, 3, and 4) indicates that the area of maximum land subsidence is not coincident with the area of maximum head decline, but is about 2 1/2 miles east of it. If the stratification and lithology of the principal zones of artesian aquifers were fairly uniform over a wide area, the maximum subsidence would occur near the centers of greatest head decline. But the lithology does change. East of the Las Vegas Valley Water District well field there is a rapid transition from predominately coarse to predominately fine material within a distance of about 2 miles. For example, in Las Vegas Valley Water District well field the deposits to a depth of about 1,000 feet are composed of approximately 40 percent silt and clay, whereas in the vicinity of the Las Vegas Post Office about 2 1/2 miles east of the well field the valley-fill deposits to a depth of about 800 feet are composed of about 75 percent silt and clay. Inasmuch as subsidence is more pronounced for a given lowering of artesian head in areas underlain by sediments composed predominantly of clay and silt than in those predominantly sand and gravel, the apparent inconsistency between the area of maximum reduction in artesian head and the area of maximum subsidence can be explained perhaps by this eastward increase in fine-grained compressible material. Undoubtedly part of the subsidence is due to a local lowering in artesian head and subsequent compaction of the valley fill deposits in the vicinity of the North Las Vegas municipal wells. However, the reasons for the limited area and relative stability of the area of maximum land subsidence are unknown.

A relationship between land subsidence and reduction in artesian pressure is illustrated in figure 7. Comparison of subsidence at bench mark L169 at the Las Vegas Post Office with the change in artesian head in the Craner well (S20/61-34accl), which is about a quarter of a mile to the south, suggests that the overall rate of subsidence has been about 1 foot for each 20 feet of decline in artesian head. The annual high artesian head in the Craner well declined irregularly from about 38 feet above land surface in December 1938 to about 8 feet above land surface in January 1960. Between 1938 and 1952 the average annual rate of decline of the artesian head in the well was about half a foot per year. After January 1952 the average annual rate of decline accelerated to about 3 feet per year. The approximate subsidence of bench mark L169 indicated by the graph in figure 7 during corresponding periods of time were about 0.8 foot and 0.9 foot respectively. The rate of subsidence between 1938 and 1952 was about .06 foot per year and since 1952 it has increased to about 0.1 foot per year.

The ratio between subsidence of bench mark L169 and decline in artesian head at the Craner well is about 1:8 during the interval from January 1939 to January 1952. From January 1952 to January 1960 this ratio decreased to about 1:30. Comparison of the change in artesian head in the Craner well or the Haggard well with bench mark K169 (figure 7) during a somewhat shorter period of time similarly shows a decrease in the ratio between subsidence and change in artesian head.
Figure 7.—Change in altitude of bench marks L-169 and K-169 in Las Vegas and decline of the artesian head in two nearby wells
The data indicate that the amount of subsidence per unit of decline in artesian head since 1952 is about a quarter to a half less than during the period prior to 1952, even though the subsidence since 1952 has accelerated. The reason for the decrease in the ratio between subsidence and change in artesian head is not known and is generally inconsistent with the findings in California (Poland, J. F., written communications 1963).

Compaction of the fine-grained confining beds and interbeds begins immediately after a reduction in head but lags behind the pressure decline. It may continue for weeks, months, or years, depending on the time required for the internal fluid pressure in the silt and clay members to reach equilibrium with the reduced pressure in the more permeable sand and gravel aquifers which adjust to pressure change rapidly. Consequently, the amount of water that will be yielded from the ground-water reservoir per unit change in artesian head will increase with time in proportion to the amount of water "squeezed" from the compacted material. Therefore, values for the coefficient of storage derived from pumping tests may represent only a small part of the available water that will eventually be removed from storage (Poland, J. F., 1961, p. B-53).

The cumulative pumpage from the artesian aquifers during the period 1935-40 was about 100,000 acre-feet. The volume of subsidence during this same interval was about 2,000 acre-feet. Therefore, approximately 2 percent of the water pumped during this period was derived from storage as a result of reduction in pore space caused by compaction of the ground-water reservoir. During the periods 1935-50 and 1935-63, the cumulative pumpage from the artesian aquifers increased to about 370,000 and 970,000 acre-feet respectively. The volumes of subsidence during these same periods were about 14,000 and 30,000 acre-feet. Therefore, over the longer intervals of time, approximately 3 to 4 percent of the water pumped from the artesian aquifers was obtained from a reduction in storage resulting from compaction.

If it is inferred that compaction was caused principally by permanent rearrangement of the grains in compactible material in the ground-water reservoir, most of the reduction in pore space that has occurred would be permanent and the amount of water thereby forced from storage would be available only once. As overdraft on the ground-water reservoir continues, which it undoubtedly will until additional surface water can be imported from Lake Mead, the artesian pressure will be reduced and compaction of the aquifer system and subsidence of the land surface will continue. If the annual pumping rate continues to increase, as it has in the past few years, the rate of decline of artesian pressure and consequently the rate of subsidence of the land surface can be expected to increase.
EFFECTS OF SUBSIDENCE

Structures of man are sometimes damaged as a result of subsidence of the land surface. Another effect—not so apparent—is the compaction of the ground-water reservoir, which reduces the interstitial pore space and diminishes storage capacity of the reservoir.

The most noticeable damage to engineering structures in Las Vegas Valley resulting from subsidence has been the protrusion of well casings above the land surface. Associated damage commonly includes cracking and differential movement of the concrete pads or floors of well houses, cracking of walls in masonry structures, rupture of pipe lines leading from the wells, damage to pumping equipment both above and below land surface, and deformation and failure of well casings. Subsidence also has caused, and undoubtedly will continue to cause, damage to underground sewage lines, water distribution systems, gas lines, and storm drains. Tension, which may be associated with the subsidence, has caused fractures in buildings, severed gas and water lines, and cracked curbs and streets.

REFERENCES


Inter-Agency Committee on land subsidence in the San Joaquin Valley, 1958, Progress report on land-subsidence investigations in the San Joaquin Valley, California, through 1957: 160 p., 45 pls.

