WATER-LEVEL DECLINES, LAND SUBSIDENCE, AND SPECIFIC COMPACTION NEAR APACHE JUNCTION, SOUTH-CENTRAL ARIZONA

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 86-4071

Tucson, Arizona
January 1987

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, the conversion factors for the inch-pound units used in this report are listed below:

Multiply metric unit	By	To obtain inch-pound unit
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

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 mean sea level.

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ABSTRACT

The alluvial-aquifer system near Apache Junction, Arizona, has been compacting since the early 1930's because of the continuing decline of ground-water levels. Near Powers Road and the planned Superstition Freeway, the ground-water level declined 120 meters between 1930 and 1980. The resulting land-surface subsidence, as defined by leveling surveys in 1933 and 1980, was 1.58 meters near Powers Road and Apache Trail. From 1933 to 1948, specific compaction was 0.0012 meter of subsidence per meter of head decline; this small value indicates elastic deformation. Between 1948 and 1964, specific compaction was 0.0093 meter of subsidence per meter of head decline. Between 1964 and 1980, specific compaction was about 0.025 meter of subsidence per meter of head decline. This larger value is characteristic of nonrecoverable, or virgin, compaction. Near Powers Road and Apache Trail, at least 22 meters of water-level decline occurred before the increased effective stresses exceeded the preconsolidation stresses within the aquifer system.

INTRODUCTION

Documented land subsidence and earth fissuring have occurred near Apache Junction, Arizona, since the mid-1960's, and land subsidence may have begun in the area as early as the late 1940's. Several geologic and hydrologic studies were started near Apache Junction in cooperation with the U.S. Bureau of Reclamation with the ultimate purpose of minimizing possible detrimental structural effects on the Central Arizona Project aqueduct in areas of subsidence and earth fissuring. Modeling of the deformation associated with subsidence over an irregular bedrock surface requires a valid stress-strain model and measurements of deformation and water-level fluctuation for calibration and validation. In addition, a history of deformation and water-level fluctuation is needed to establish initial conditions and other parameters for the model. This report presents the history of water-level fluctuations and subsidence as one of the many facets of the overall hydrogeologic study near Apache Junction.

The study area is in the eastern part of the Salt River Valley in the Basin and Range lowlands water province in south-central Arizona (fig. 1). Surface drainage is toward the southwest by discontinuous ephemeral streams originating in the Goldfield and Superstition Mountains. Quaternary and Tertiary deposits of unconsolidated to weakly consolidated alluvial sands, gravels, and silts overlie a highly irregular buried topography developed on competent metamorphic and igneous basement rocks (Lee, 1905). In the eastern part of the Salt River Valley, compressible alluvium comprising the upper and middle units ranges from 0 to more than 400 m in thickness. The saturated part of the alluvium ranges in thickness from 0 to more than 250 m (R. L. Laney and Mary Ellen Hahn, U.S. Geological Survey, written commun., 1983).

Purpose and Scope

The purpose of this report is to provide estimates of the values of specific compaction and the amount by which the preconsolidation stress exceeds the overburden stress in the compacting alluvial-aquifer system in subsiding areas near Apache Junction, Arizona. The report includes water-level data from the Salt River Project (Steven A. Smith, written commun., 1983) and the U.S. Geological Survey (B. L. Wallace, written commun., 1982). It also includes, in compact form, leveling data from the National Geodetic Survey, the Arizona Department of Transportation (Pat Church, written commun., 1982), and the U.S. Bureau of Reclamation (G. M. Tuttle, written commun., 1982). Subsidence profiles along Apache Trail and the planned Superstition Freeway, the time history of bench-mark subsidence, and available water-level data between Powers Road and Hawk Rock are also presented.

An objective of this study was to calculate the elastic and virgin values of specific compaction, the magnitude of initial overconsolidation, if any, and the history of induced stress increase for the Hawk Rock area. These data are needed in ongoing studies of the subsidence and related earth fissuring that are occurring immediately north and east of Hawk Rock. Specifically, determination of the horizontal strain at failure and the total horizontal strain in the fissured areas is dependent on a reconstruction of the history of aquifer-system compaction in reponse to head decline.

Because of the limited availability of leveling and water-level data in the immediate Hawk Rock area, the stated objective was not fully met. This report presents estimated specific-compaction and overconsolidation values for an area about 10 km west of Hawk Rock in the Salt River Valley. It also presents the recent history of head decline and subsidence near Hawk Rock and the virgin specific-compaction values derived from that history.

Causes of Subsidence

In a confined aquifer, compaction occurs when the potentiometric surface declines and causes a decrease in support for overlying materials and an increase in the vertical effective stress on the aquifer matrix. In an unconfined aquifer, water-level decline causes a decrease in buoyant support of the matrix in the dewatered zone. Subsidence of the land surface results from and is essentially equivalent to aquifer compaction. Specific compaction is defined as the decrease in thickness of deposits per unit increase in applied stress during a time period (Poland and others, 1972). Because the decline of water levels in wells is a direct measure of the increase in stress applied to the aquifer system, it is customary to express specific compaction in terms of change of thickness per unit of head decline.

Extensive studies in California (Riley, 1969; Poland and others, 1975; Helm, 1977; Ireland and others, 1984) have demonstrated that aquifer-system sediments deform elastically when subjected to water-level fluctuations that do not cause effective stresses to exceed the maximum values previously attained. The values of specific compaction under conditions of elastic deformation are relatively small. In the absence of site-specific data, elastic specific compaction may be estimated by multiplying the thickness of the stressed aquifer system in meters by $1 \times 10^{-5} m^{-1}$. This multiplier is a typical value, derived from the California studies, of the elastic compressibility of alluvial-aquifer systems comprising interbedded coarse- and fine-grained sediments.

The California studies also showed that if water-level declines are sufficient to cause effective stresses to exceed maximum past stresses, the resulting virgin compaction is largely nonrecoverable. The resulting values of specific compaction are relatively large, typically 10 to 50 times larger than the values for elastic deformation. The threshold value of effective stress at which the compaction response changes from elastic to nonrecoverable is known as the preconsolidation stress. Preconsolidation stress generally is interpreted to be the maximum antecedent stress to which a deposit has been subjected (Poland and others, 1972). If the preconsolidation stress at any depth within the aquifer system is greater than the existing overburden stress, the sediments at that depth are said to be overconsolidated by an amount equal to the difference between the preconsolidation and overburden stresses.

An examination of head decline and subsidence histories led Holzer (1981) to conclude that the aquifer system in the Eloy-Picacho area of south-central Arizona was initially overconsolidated by a stress equal to 30 m of water. In contrast, the alluvial aquifer near Bowie in southeastern Arizona compacted linearly with head decline, indicating little or no initial overconsolidation.

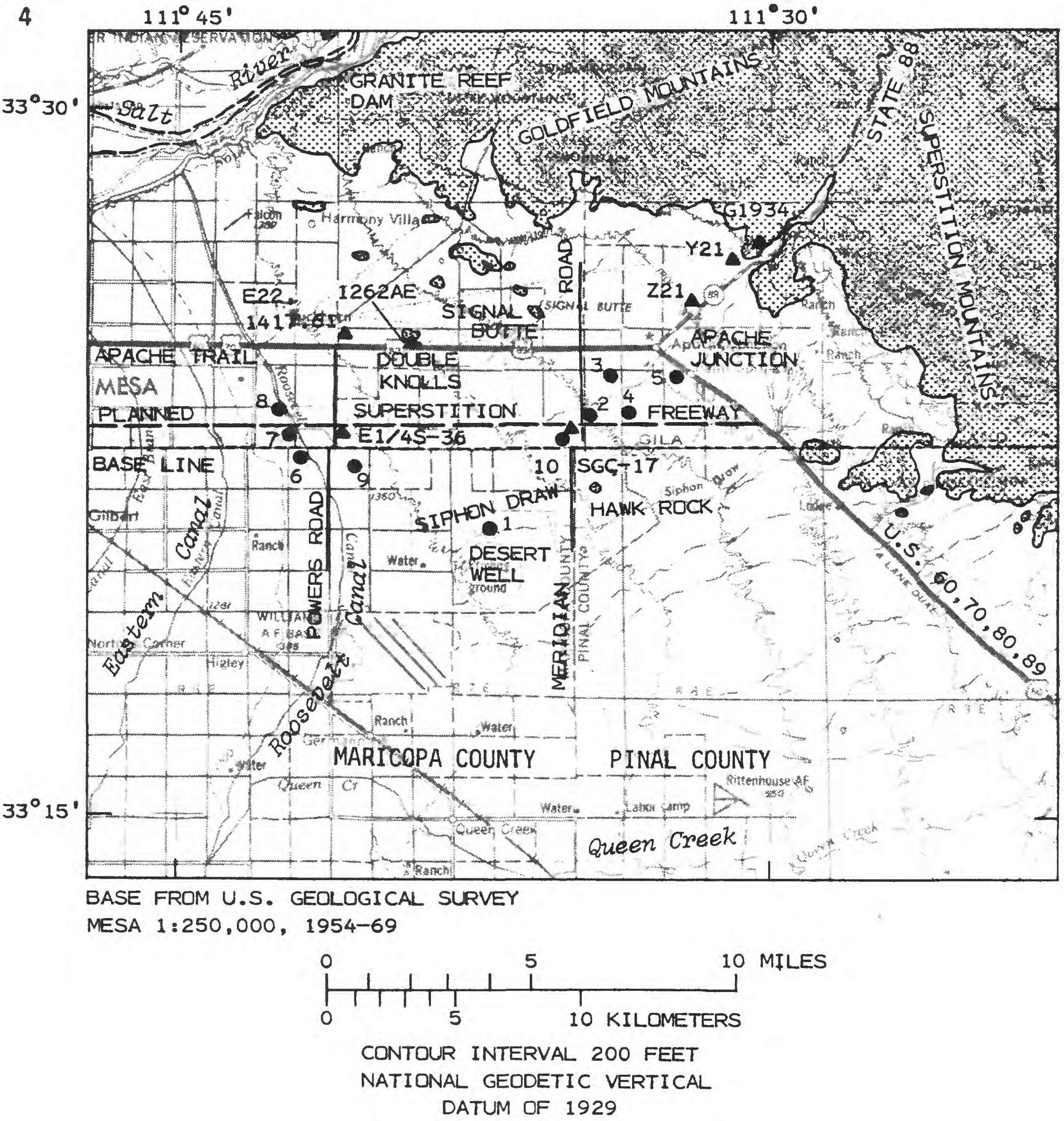


Figure 1.--Location of selected wells and bench marks.

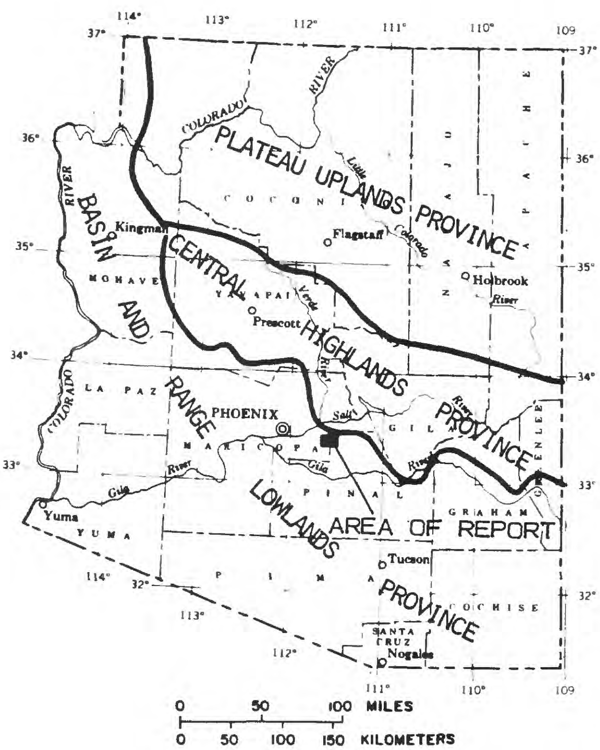
E X P L A N A T I O N

BEDROCK

● 10 WELL—Number, 10, is well identifier

1	(D-1-7)11dcc (Desert Well)
2	(A-1-8)31ccc
3	(A-1-8)30aaa
4	(A-1-8)32bba
5	(A-1-8)28abb
6	(D-1-6)1bad
7	(A-1-6)36cbb
8	(A-1-6)35aba
9	(D-1-7)6abb1
10	(A-1-7)36daa1

▲ Z21 BENCH MARK—Number, Z21, is bench-mark identifier. See tables 1, 2, and 3



INDEX MAP SHOWING AREA OF REPORT AND ARIZONA'S WATER PROVINCES.

Figure 1

WATER-LEVEL DECLINE

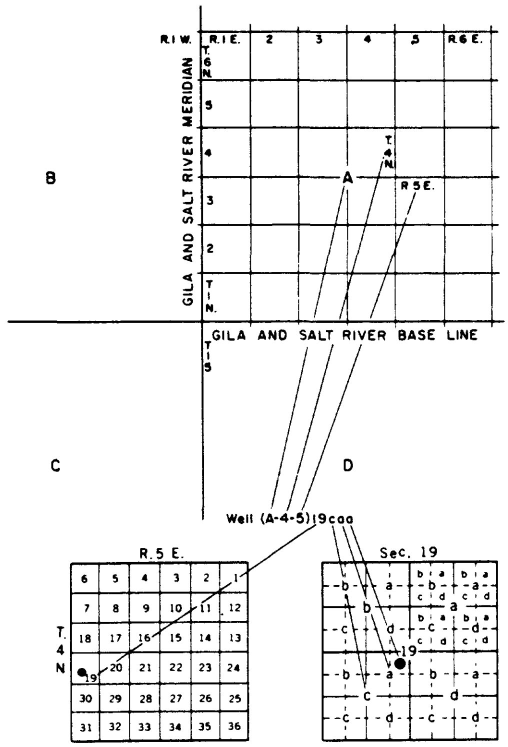
The altitude of the water table in the study area prior to major pumping ranged from about 365 m to about 395 m above sea level (wells A through E, figs. 2, 3). At Desert Well in 1905, the water level was 380 m above sea level (Lee, 1905). Near Baseline and Meridian Roads, the water level was reported to be about 360 to 370 m above sea level in the 1940's (Bert Perry, driller, oral commun., 1983). Variations in altitude of the water level do not appear to correlate with topographic slope or with proximity to recharging ephemeral streams.

Because water-level data prior to 1977 are lacking near Hawk Rock, data from four wells 10 km west of Hawk Rock were used to assemble a composite well hydrograph (fig. 3). These are the nearest wells with records that date from the 1930's and thus predate the period of major water-level decline. These wells are nearer areas of greater ground-water use than those near Hawk Rock (Anderson, 1968). They also are close to the Roosevelt Canal, which was initially concrete lined between 1924 and 1930 (Grant Ward, Roosevelt Water Conservation District, oral commun., 1982). The effects of agricultural use of ground water, recharge from the canal prior to lining, and irrigation from the canal offset each other in an indeterminable way. The composite hydrograph, therefore, is considered only approximately representative of water-level declines in the western part of the study area. Significant pumping near Apache Junction occurred later than pumping to the west of Apache Junction (fig. 3; Anderson, 1968). Rates of water-level decline near Powers Road estimated from slopes in figure 3 were about 1.3 m/yr from 1936 to 1948, 4.4 m/yr from 1948 to 1964, and 1.5 m/yr from 1964 to 1976. Total water-level decline from 1933 to 1980 was about 120 m. Near Meridian Road and the planned Superstition Freeway, the water level declined from 338 m in 1977 to 328 m in 1982 at a nearly constant rate of 2.0 m/yr.

LEVELING

Leveling was performed along Apache Trail in 1933, 1948, and 1980 (National Geodetic Survey, 1933; 1948; and 1980) (table 1; fig. 4). All National Geodetic Survey leveling data used in this report are unadjusted observed altitudes from Phase 1 abstracts. Because the starting altitude for each line of levels was arbitrary, it was necessary to adjust each line to a common datum. The adjustment was made by assuming that bench marks Z21, Y21, and G1934 were not subject to subsidence because they are on the periphery of the alluvial basin and were otherwise stable. The 1933 and 1948 lines were adjusted to the 1980 line. The 1933 adjustment is:

$$1/3\ [(1980\ \text{Altitude}_{Z21} - 1933\ \text{Altitude}_{Z21}) + (1980\ \text{Altitude}_{Y21} - 1933\ \text{Altitude}_{Y21}) + (1980\ \text{Altitude}_{G1934} - 1933\ \text{Altitude}_{G1934})] = 21\ \text{mm},$$



The well numbers used by the Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants. These quadrants are designated counterclockwise by the capital letters A, B, C, and D. All land north and east of the point of origin is in A quadrant, that north and west in B quadrant, that south and west in C quadrant, and that south and east in D quadrant. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. In the example shown, well number (A-4-5)19caa designates the well as being in the NE$\frac{1}{4}$NE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 19, T. 4 N., R. 5 E. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

Figure 2.--Well-numbering system in Arizona.

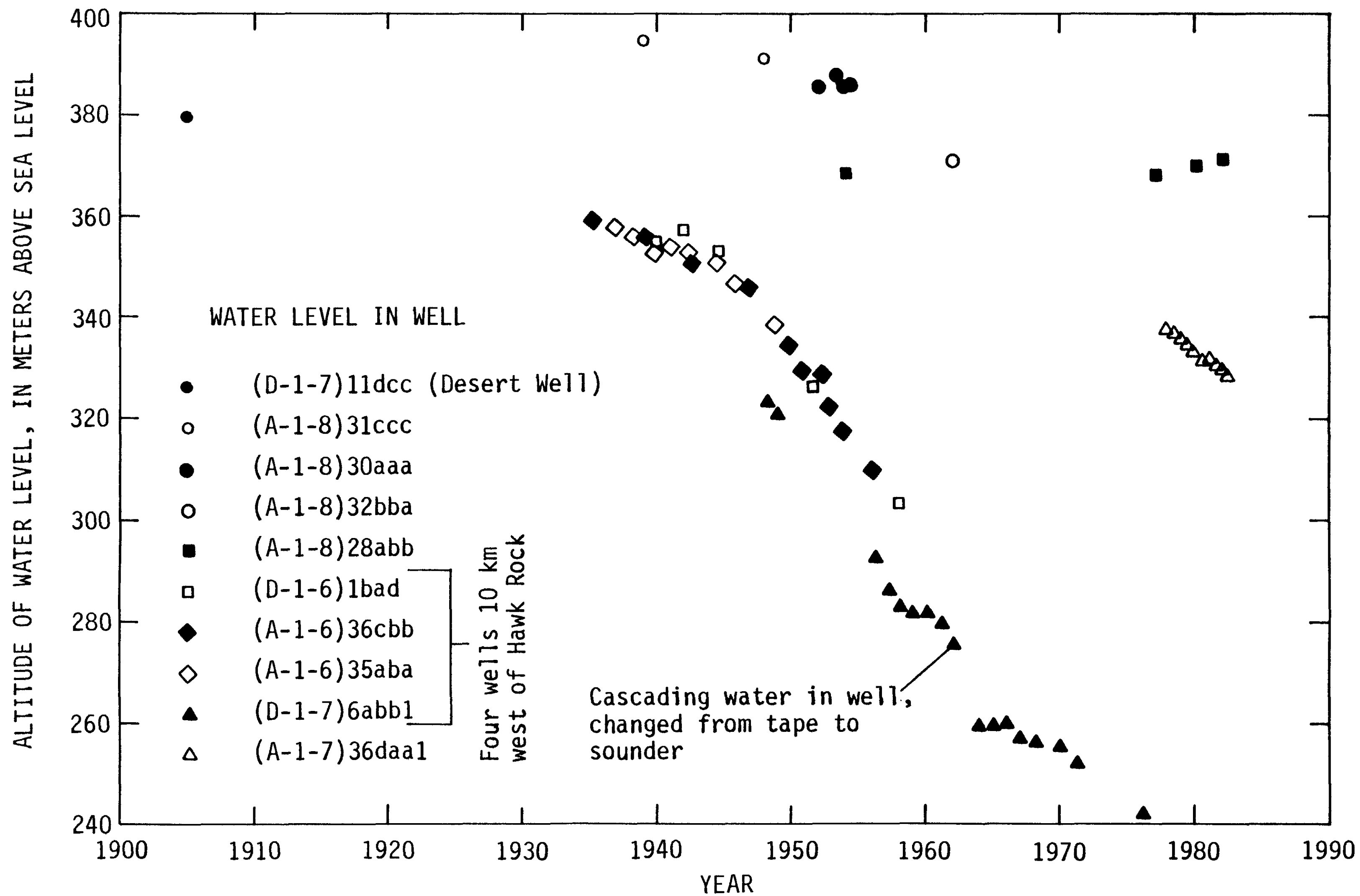


Figure 3.--Altitude of the water level in selected wells, 1905-84.

Table 1.--Leveling along Apache Trail by the National Geodetic Survey

Bench mark	Distance east of E22[1] (kilometers)	Adjusted altitude, 1933[2] (meters)	Adjusted altitude, 1948[2] (meters)	Adjusted altitude, 1980[2] (meters)	Subsidence, 1933-48 (meters)	Subsidence, 1948-80 (meters)
E22	0.00	433.118	433.095	431.534	0.023	1.561
1436.79	.75	-------	438.177	436.800	-----	1.377
1451.67	1.48	-------	442.735	441.770	-----	.965
1455.93	1.66	-------	444.032	443.361	-----	.671
1465.42	2.01	-------	446.926	446.903	-----	.023
1472.81	2.39	-------	449.160	449.150	-----	.010
1262AE	2.58	-------	-------	451.031	-----	-----
D22	3.01	453.402	453.389	-------	.013	-----
1489.18	3.09	-------	454.160	454.158	-----	.002
1497.24	3.38	-------	456.592	456.601	-----	-.009
1505.69	3.70	-------	459.174	458.957	-----	.217
1510.56	3.92	-------	460.653	460.280	-----	.373
Q269	4.04	-------	460.317	459.904	-----	.413
1542.26	5.16	-------	470.329	470.322	-----	.007
1549.47	5.44	-------	472.526	472.516	-----	.010
1562.00	5.94	-------	476.339	476.282	-----	.057
C22	6.20	478.565	478.552	-------	.013	-----
1583.97	6.98	-------	483.023	482.938	-----	.085
1586.68	7.20	-------	483.850	483.790	-----	.060
1594.67	7.60	-------	486.278	486.236	-----	.042
1612.85	8.59	-------	491.803	491.780	-----	.023
1617.70	8.85	-------	493.283	493.265	-----	.018
1626.01	9.22	-------	495.814	495.793	-----	.021
1632.39	9.49	-------	497.748	497.744	-----	.004
B22	9.66	498.728	498.721	-------	0.007	-----
BB100	9.95	-------	501.748	501.727	-----	.021
1649.26	10.14	-------	502.899	502.885	-----	.014
1654.61	10.33	-------	504.518	504.504	-----	.014
1667.27	10.78	-------	508.390	508.375	-----	.015
1685.99	11.47	-------	514.089	514.080	-----	.009
1693.94	11.80	-------	516.511	516.502	-----	.009
Z21[3]	14.43	545.661	545.664	545.663	-.003	.001
Y21[3]	16.92	577.303	577.305	577.305	-.002	.000
G1934[3]	18.02	589.429	589.423	589.426	.006	-.003

[1]1948 Phase 1 Abstract.

[2]Adjustments are observed altitude +27 mm for 1933, observed altitude +59 mm for 1948, and observed altitude +6 mm for 1980.

[3]Bench marks Z21, Y21, G1934 are along State Road 88 northeast of Apache Junction.

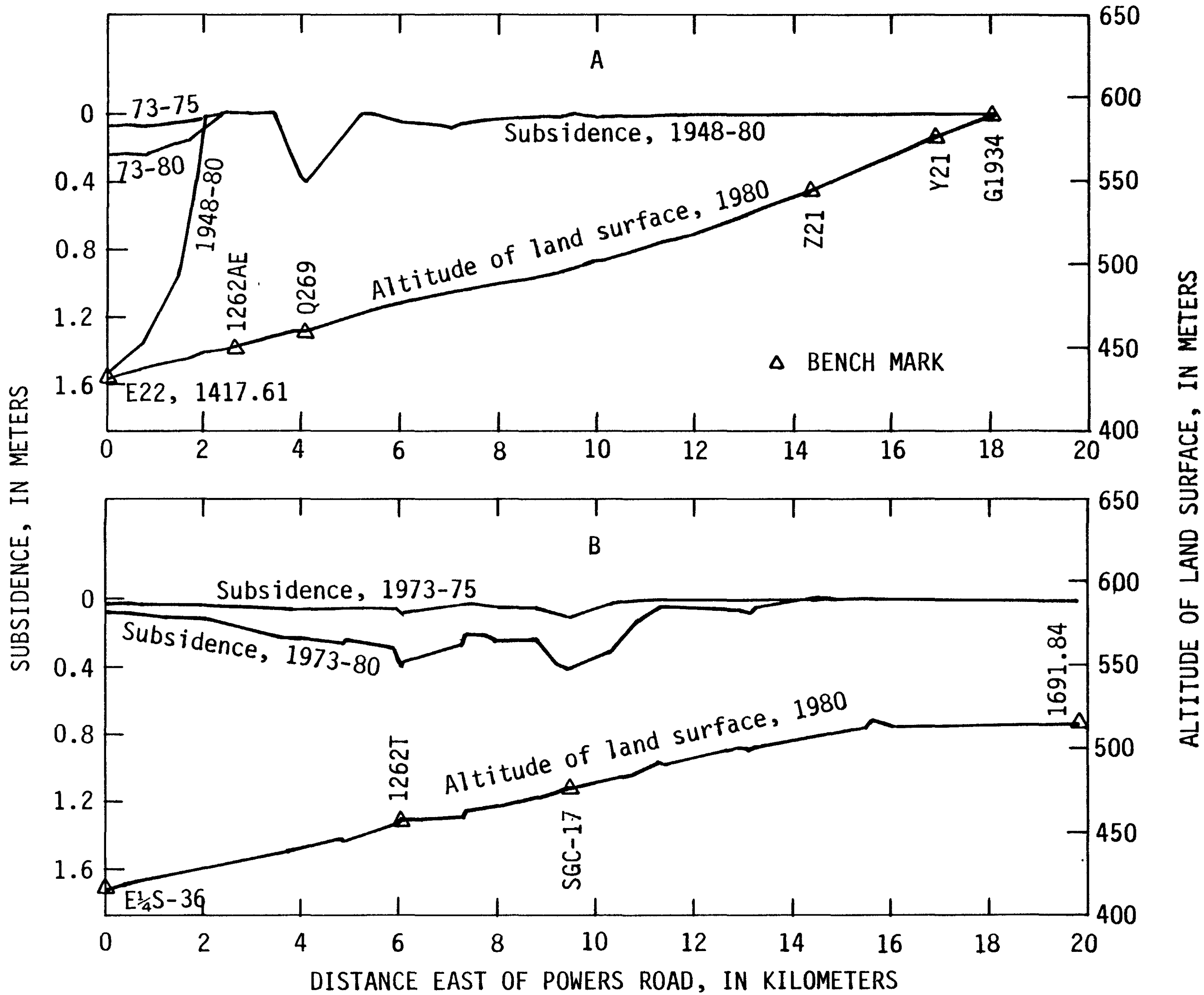


Figure 4.--Subsidence along (A) Apache Trail and (B) planned Superstition Freeway.

which was added to the observed 1933 altitude for each bench mark to obtain the 1933 adjusted altitude. The 1948 line was similarly adjusted by adding 53 mm. The largest deviation of the three bench marks for 1933 or 1948 from the adjustment is 6 mm (table 1). This deviation is about twice the nominal accuracy of 1.5 mm $\sqrt{K}$, where K is the distance between points in kilometers, for 1st Order, Class 1 leveling (Federal Geodetic Control Committee, 1974, p. 12). For these bench marks, nominal accuracy is 2.8 mm. Selectively eliminating G1934 from the adjustment would have reduced the deviation. This was not done because available leveling notes lacked any indication of instability of G1934 and the sample population for the adjustment was judged too small to discard a deviant point. Nominal 1st Order, Class 1 accuracy for the distance between G1934 and E22 is 6.4 mm, which is comparable to the observed deviation of the three adjustment bench marks.

The Arizona Department of Transportation performed 2d Order, Class 1 leveling with a nominal accuracy of 3 mm $\sqrt{K}$, along the planned Superstition Freeway in 1973, 1975, and 1980 (fig. 4; tables 2 and 3). That leveling was tied along Powers Road and Apache Trail to bench mark 1262AE set in bedrock at Double Knolls. The adjusted altitude of this point is based on bench marks set in bedrock northeast of Apache Junction and at Granite Reef. The altitude of 1262AE is 451.031 m, which is the datum selected for this report. An additional adjustment of +6 mm was applied to all three runnings of the National Geodetic Survey lines on Apache Trail to obtain compatibility with this datum.

Table 2.--Leveling along Apache Trail by the Arizona Department of Transportation

Bench mark	Distance east of 1417.61 (kilometers)	Adjusted altitude, 1973[1] (meters)	Adjusted altitude, 1975[1] (meters)	Adjusted altitude, 1980[1] (meters)	Subsidence, 1973-75 (meters)	Subsidence, 1973-80 (meters)
1417.61	0.000	431.052	430.972	430.797	0.080	0.255
1447+62	.804	435.450	435.369	435.195	.081	.255
1453.31	1.706	442.357	442.305	442.203	.052	.154
1469.62	2.413	447.937	447.938	447.940	-.001	-.003
1262AE	3.250	451.031	451.031	451.031	.000	.000

[1]Adjustments are observed altitude -2 mm for 1973, and observed altitude +1 mm for 1975 and 1980.

Altitude history since 1971 of bench mark SGC-17 (fig. 1) was provided by the U.S. Bureau of Reclamation from 2d Order, Class 1 leveling, performed annually since 1974 along the planned Central Arizona

Table 3.--Leveling along Superstition Freeway by the Arizona Department of Transportation

Bench mark	Distance east of E¼S-36 (kilometers)	Adjusted altitude, 1973[1] (meters)	Adjusted altitude, 1975[1] (meters)	Adjusted altitude, 1980[1] (meters)	Subsidence, 1973-75 (meters)	Subsidence, 1973-80 (meters)
E¼S-36	0.000	415.486	415.450	415.396	0.036	0.090
1262-P-1	.418	419.071	419.037	418.976	.034	.095
1262-P-2	.804	421.646	421.606	421.542	.040	.104
1262-P-3	1.191	424.026	423.983	423.906	.043	.120
1262-Q1	2.027	428.953	428.908	428.829	.045	.124
98.4A	3.636	439.045	438.972	438.809	.073	.236
1262-R-1	3.990	441.969	441.902	441.724	.067	.245
102-4-A	4.843	447.463	447.407	447.196	.056	.267
1262-S	4.891	446.086	446.031	445.833	.055	.253
107A	5.921	456.159	456.092	455.855	.067	.304
1262T-2	6.050	458.882	458.789	458.480	.093	.402
1262T	6.095	458.016	457.933	457.637	.083	.379
110A	7.289	460.808	460.773	460.531	.035	.277
1262T-1	7.337	463.316	463.289	463.097	.027	.219
1262T-4	7.627	465.600	465.565	465.384	.035	.216
113A	8.013	467.087	467.034	446.830	.053	.257
1262U-1	8.785	472.514	472.456	472.270	.058	.244
1262U-2	9.236	475.659	475.561	475.259	.098	.400
SGC-17	9.461	478.027	477.917	477.609	.110	.418
1262V-2	10.298	483.058	483.032	482.740	.026	.318
121-A	10.458	483.883	483.865	483.617	.018	.266
1222+46.79	10.845	487.035	487.027	486.906	.008	.129
1262-W	11.263	492.378	492.375	492.319	.003	.059
124	11.392	491.151	491.149	491.107	.002	.044
W¼S-33	12.872	500.978	500.969	500.906	.009	.072
129A	13.142	500.980	500.970	500.901	.010	.079
1262X-1	13.290	502.371	502.363	502.314	.008	.057
1262-Y	14.545	508.350	508.347	508.356	.003	-.006
1262Y-2	15.543	513.818	513.814	513.817	.004	.001
1262-Z	15.672	516.924	516.917	516.917	.007	.007
140A	16.154	513.575	513.571	513.573	.004	.002
141A	16.283	513.642	513.639	513.641	.003	.001
1691.84	20.080	515.835	515.830	515.831	.005	.004

[1]Adjustments by Arizona Department of Transportation.

Project aqueduct (table 4). Datum for this leveling is bench mark Hawk at Hawk Rock, which was established using stable points at Granite Reef and northeast of Florence (G. M. Tuttle, oral commun., 1982). U.S. Bureau of Reclamation altitudes of bench mark SGC-17 are consistent with Arizona Department of Transporation leveling along Superstition Freeway.

SUBSIDENCE

Data for determination of subsidence rates in the study area are sparse prior to 1973 (fig. 5). The rate of subsidence near Apache Trail and Powers Road, as determined using bench marks E22 and 1417.61, was 1.5 mm/yr from 1933 to 1948 (table 1), 41 mm/yr from 1948 to 1973 (tables 1 and 2), and 36 mm/yr from 1973 to 1980 (table 2). In contrast, E¼S-36 near Powers Road and planned Superstition Freeway subsided at a rate of only 13 mm/yr from 1973 to 1980 (table 3). SGC-17 near Meridian Road and planned Supersitition Freeway subsided at a rate of 62 mm/yr from 1971 to 1980 (table 4). The rates of subsidence near Apache Trail and Powers Road and near Meridian Road and planned Superstition Freeway are the highest in the study area, on the basis of the available data. The east-west profiles of subsidence along Apache Trail and planned Superstition Freeway (fig. 4) indicate a striking variability of subsidence in the eastern part of Salt River Valley. Such variations may be caused by local differences in water-level decline, aquifer thickness, aquifer compressibility, or a combination of these factors. Subsidence studies in south-central Arizona (R. L. Laney, U.S. Geological Survey, written commun., 1982; Jachens and Holzer, 1979; Raymond and others, 1979) have noted a close correspondence between rate of subsidence and aquifer thickness as controlled by bedrock topography. Drilling and geophysical studies near Hawk Rock confirm that the local area of rapid subsidence near bench mark SGC-17 (fig. 4) corresponds to a local trough in bedrock topography (Hassemer and Dansereau, 1980). In 1980, the maximum thickness of saturated alluvium at this location was about 245 m.

SPECIFIC COMPACTION

Dividing the rate of subsidence by the rate of water-level decline gives a mean specific compaction (Poland and others, 1972) for each locality for each time period for which both rates are known. This approach is necessary when beginning and ending times for water-level records do not coincide exactly with leveling surveys. In addition, the method tends to minimize errors due to fluctuations in water-level declines.

The summary of specific-compaction values is given in table 5. The estimates of specific compaction may be affected by measurement errors in leveling and variations in water levels among wells used in a composite well hydrograph. The calculated root mean square error for

Table 4.--Altitude history of bench mark SGC-17

[Arizona State Plane Grid Coordinates, Central Zone N868, 103.49 E602, 301.12. After G. M. Tuttle, U.S. Bureau of Reclamation, written commun., 1982]

Date	Altitude, in meters	Subsidence since 1971, in meters
1971		
fall/winter	478.124	0.000
1973		
fall/winter	478.027	.097
1974		
fall/winter	477.990	.134
1975		
fall/winter	477.917	.207
1976		
fall/winter	477.832	.292
1977		
fall/winter	477.771	.353
1978		
November 14	477.713	.411
December 13	477.701	.423
1979		
January 8	477.701	.423
February 12	477.701	.423
March 16	477.689	.435
April 5	477.683	.441
July 18	477.658	.466
1980		
February 26	477.625	.499
May 20	477.600	.524
August 8	477.600	.524
December 16	477.576	.548
1981		
March 6	477.576	.548
April 22	477.545	.579
July 24	477.533	.591
September 25	477.509	.615
1982		
February 24	477.503	.621

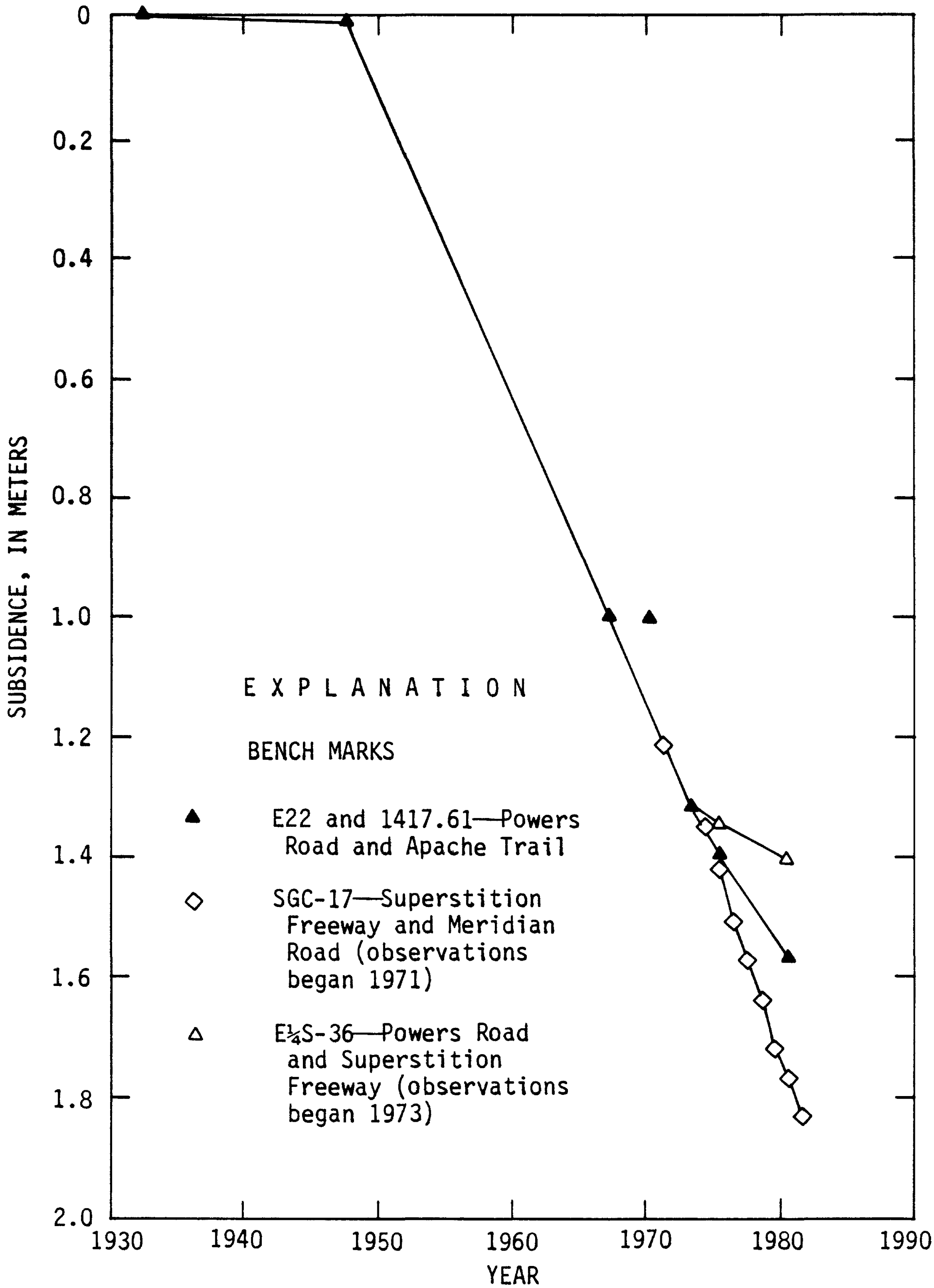


Figure 5.--Subsidence history at selected bench marks.

Table 5.--Mean specific compaction by locality

$$\left[\frac{\text{Subsidence in meters per year}}{\text{Water-level decline in meters per year}} = \text{Specific compaction}\right]$$

Interval (years)	Specific compaction		
	Powers Road and Apache Trail (E22 and 1417.61)	Powers Road and Superstition Freeway (E¼S-36)	Meridian Road and Superstition Freeway (SGC-17)
1933-48	$\frac{0.0015}{1.3} = 0.0012$	-----	-----
1948-64	$\frac{0.041}{4.4} = 0.0093$	-----	-----
1964-73	$\frac{0.041}{1.5} = 0.027$	-----	-----
1973-80	$\frac{0.036}{1.5} = 0.024$	$\frac{0.013}{1.5} = 0.0087$	$\frac{0.062}{2.0} = 0.031$

subsidence of bench mark E22 is 9 mm if bench mark G1934 is held constant. For 1933-48, this value is 39 percent of the calculated subsidence but less than 1 percent for 1948-80 (table 1). Similarly, if 1262AE at Double Knolls is held fixed for 1973-80, nominal accuracy of E¼ S-36 is 10 mm or 10 percent of measured subsidence (table 3). If bench mark Hawk is held fixed for 1973-80, nominal accuracy of SGC-17 is 6 mm or 1 percent of measured subsidence (table 4). In a similar manner, a 5-meter error in water-level decline, as estimated from the range of water levels in wells (D-1-6)1bad, (A-1-6-)36cbb, and (A-1-6)35aba in the western part of the study area (fig. 3), has a greater percentage effect during periods of smaller water-level decline such as 1930-48 and 1964-80.

A plot of subsidence versus water-level decline constitutes a form of stress-strain curve. The inverse slopes of the curve represent specific-compaction values during the intervals between paired measurements. The relation between subsidence near Apache Trail and Powers Road and the water-level decline determined from the composite hydrograph (fig. 3) of four wells near Powers Road and planned Superstition Freeway is shown in figure 6. Significant possibilities for error in determining specific compaction arise because bench-mark subsidence was, of necessity, plotted for a point 4 to 5 km from the four wells. The inverse slopes give specific-compaction values of 0.0012 for 1933-48, 0.0093 for 1948-64, 0.027 for 1964-73, and 0.024 for 1973-80. Because typical elastic compressibility is 10^{-5} per meter of head decline per meter of saturated thickness and the aquifer system is at least 150 m

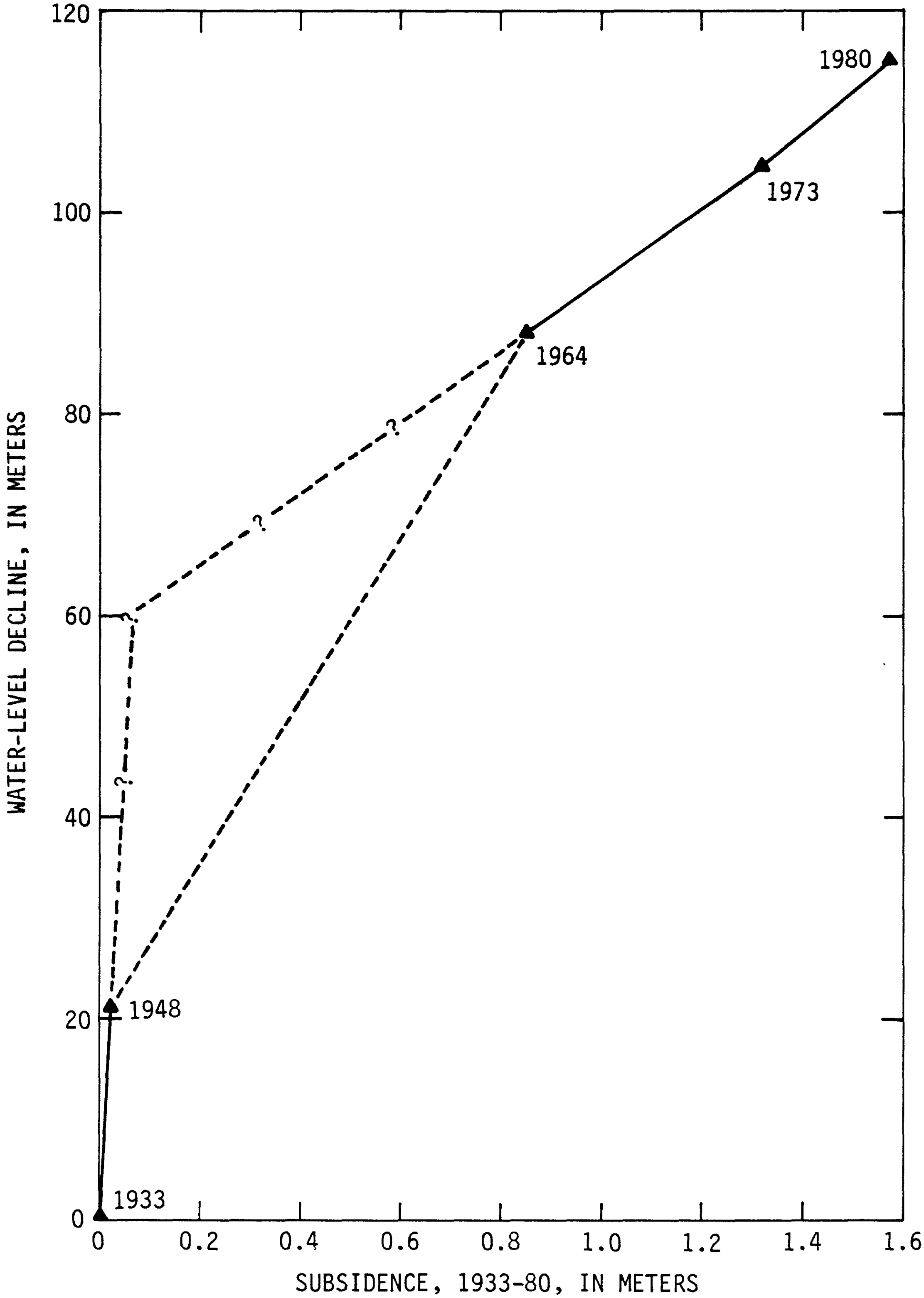


Figure 6.--Stress-strain curve for bench marks E22 and 1417.61.

thick, the value for 1933-48 must represent essentially elastic compaction. (The product of compressibility times thickness yields an estimate of 0.0015 for elastic specific compaction.) The post-1964 value represents an increase in specific compaction by a factor of about 22, which indicates a change to conditions of virgin compaction. The intermediate value results from straight-line interpolation between 1948 and 1964 and fails to provide any useful definition of the process of transition from elastic to virgin compaction.

The nearly equal values of specific compaction for 1964-73 and 1973-80, in response to roughly constant rates of head decline, indicate that after 1964 the average excess pore pressures in the fine-grained units of the aquifer system dissipated at a rate equal to the rate of head decline in the coarser units (Holzer, 1981). Under these conditions, the observed constant value of specific compaction (0.026) is representative of the product of the thickness of compacting sediments multiplied by their virgin compressibility. Thus, this specific compaction is conceptually and numerically equivalent to the skeletal, or matrix, component of the nonreversible confined storage coefficient under conditions of virgin compaction. Because this skeletal component is much larger than the component from expansion of pore water, the skeletal component may be considered to be, for practical purposes, the confined storage coefficient for continuing drawdown under virgin conditions.

The essentially linear relation between head decline and subsidence at SGC-17 near Hawk Rock (table 4, fig. 3) from 1977 to 1982 defines a virgin specific compaction of 0.031, which is also the apparent confined storage coefficient under virgin conditions. Because the aquifer thickness here is known to be about 245 m, the virgin compressibility, expressed as specific storage, may be calculated to be about 0.00013 m^{-1}.

PRECONSOLIDATION

Holzer (1981) has shown that stress-strain curves that are clearly bilinear and define two relatively constant and substantially different specific-compaction values can be used to infer the existence of preconsolidation in an undisturbed aquifer. The curves can be used to estimate the magnitude of stress increase (water-level decline) required to exceed the preconsolidation stress. In the simplest case, this stress increase is the water-level decline at the intersection of the two curve segments that define the elastic and virgin values of specific compaction. The minimum amount by which the preconsolidation stress exceeds the overburden stress as determined from the curve in figure 6 is 22 m of water-level decline. An estimate of the maximum amount by which the preconsolidation stress exceeds the overburden stress of 60 m of water is given by the intersection of the extrapolation of the early and late time segments in figure 6. The actual curve path probably would be inside the dashed triangle because this type of stress-strain (drawdown-compaction) curve is commonly convex upward owing to the time-lag inherent in hydrodynamic consolidation (Holzer, 1981). This curvature would generate continuously increasing values of specific compaction during the transient period of time-lag adjustment.

DISCUSSION

The long time intervals between early leveling surveys and the shortage of long-term water-level records limit the accuracy of specific-compaction values and impose a large uncertainty on the estimated amount by which the preconsolidation stress exceeds the overburden stress. Initial conditions of land-surface altitude and water table are not known within the accuracy available for later data and are entirely lacking for the Hawk Rock area. Repeated leveling and water-level measurements prior to water-level decline and subsidence are desirable in order to determine noise levels in the data. If leveling had been started before 1933 and had been done more frequently before 1967, the hinge of the subsidence curve (fig. 5) would be better defined. In addition, if the water-level history were better known, the hinge of the stress-strain curve (fig. 6) also would be better defined.

This analysis assumes that the 1933 land-surface altitude and the 1930 water-level altitude were actual initial conditions. A higher initial land-surface altitude would cause the value of elastic specific compaction to be higher and have little or no effect on the amount by which the preconsolidation stress exceeds the overburden stress. A higher water-level altitude would cause the value of elastic specific compaction to be lower, but the amount by which preconsolidation stress exceeds overburden stress would increase 1 m for every meter of increase in initial water-level altitude.

The plot of stress versus compaction (subsidence) might be expected to be concave upward because of diminishing saturated thickness with time and diminishing compressibility with increased stress. However, opposing effects that may predominate in the study area include hydrodynamic and viscoelastic time lag and an increase in depth of sediments affected by head decline. This increase might be caused by an increase in average depth of new wells or the gradual vertical propagation of head decline into deeper unpumped parts of the alluvium. If the hydrodynamic time constant of the system is long, the transition between elastic and virgin compaction generates a relatively long curve segment that is convex upward (Holzer, 1981; Riley, 1969). The linear segment of the virgin stress-strain curve, stabilized under conditions of a constant rate of continuing head decline, is then offset in the direction of higher stress. Extrapolating the resulting offset slope to the zero virgin-compaction line gives a head-decline intercept that is substantially larger than the actual amount by which the preconsolidation stress exceeds the overburden stress. The 60-meter intercept indicated in figure 6 would be valid only if the time constant were relatively short. A substantial thickness of unpumped, poorly permeable alluvium involved during the early stages of compaction can cause a long time constant because the time constant is proportional to the square of the effect of the thickness of the draining unit (Ireland and others, 1984). In the absence of data to constrain the time constant, the 60-meter value cannot be dismissed.

SUMMARY AND CONCLUSIONS

The few available data indicate that the undisturbed ground-water levels in the study area were at an altitude of about 380 ±15 m. In the western part of the study area, the water table declined 120 m from 1933 to 1980; the greatest rate of decline occurred from about 1948 to 1964. Water-level declines in the eastern part of the study area lagged those in the western part. Near Meridian Road and Baseline, the water level altitude declined from 338 m in 1977 to 328 m in 1982.

Leveling surveys coincided approximately with the earliest water-level records in 1933 and the major change in rate of water-level decline in 1948. Near Powers Road and Apache Trail at bench marks E22 and 1417.61, subsidence was 0.022 m from 1933 to 1948, 1.306 m from 1948 to 1973, 0.80 m from 1973 to 1975, and 0.175 m from 1975 to 1980. Near Powers Road and planned Superstition Freeway at bench mark E¼S-36, subsidence was 0.036 m from 1973 to 1975 and 0.055 m from 1975 to 1980. Near Meridian Road and planned Superstition Freeway at bench mark SGC-17, subsidence was 0.621 m from 1971 to 1982.

Near Powers Road and Apache Trail, the mean specific compaction in meters of subsidence per meter of water-level decline was 0.0012 for 1933 to 1948, 0.0093 for 1948 to 1964, 0.027 for 1964 to 1973 and 0.024 for 1973 to 1980. The value for 1933-48 is probably an elastic value. The intermediate 1948-64 value may be a consequence of the transition from elastic to virgin compaction. Post-1964 values probably represent virgin compaction. Additional values obtained for virgin specific compaction for 1973 to 1980 are 0.0087 near Powers Road and planned Superstition Freeway and 0.031 near Meridian Road and planned Superstition Freeway. For the known subsidence and water-level decline, the minimum amount by which preconsolidation stress exceeded overburden stress near Powers Road and Apache Trail was 22 m of water-level decline. The maximum amount probably did not exceed 60 m of water-level decline at that location.

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