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ON THE DETERMINATION OF THE COMPRESSIBLE SOIL PROPERTIES REQUIRED TO MODEL SUBSIDENCE IN THE AREA OF HOUSTON, TEXAS

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ABSTRACT: One of the most important characteristics used to simulate the consolidation of an aquifer being pumped is the compressibility of the subsurface material. The present work, based on water level fluctuations and borehole extensometer data in the Houston area, determines, analyzes and compares the storage coefficient for either the elastic and inelastic ranges and the vertical hydraulic conductivity. Specifically coastal and inland areas are examined and values are recommended for use in modeling. In the coastal Houston area, data from Baytown, Clear Lake and the Johnson Space Center (NASA) taken each 28 days by the USGS since 1973 is analyzed. Similarly in the inland area, data from gages in the Southwest and Addicks areas are analyzed. The boreholes used for the extensometers at the Clear Lake, and Addicks sites were drilled to the base of the Evangeline aquifer. This is the deepest aquifer being pumped in most of the region. Since little or no water level decline has occurred below the aquifer, these extensometers measure total man-made consolidation (compaction). The extensometer at the Johnson Space Center is designed to measure compaction in the Chicot aquifer. This is the shallowest aquifer in the region; it overlies the Evangeline aquifer. The Clear Lake site was selected so that the information obtained there could be coupled with information from the Johnson Space Center. The results of the present analysis will be used to determine the percentage of subsidence for each of the aquifers being pumped in the region.

INTRODUCTION

Ground water in the Houston area is used for public supply, industry and irrigation. The use of ground water in this area slowly increased until 1973 when the industry started using surface water for its needs. Generally speaking, water levels in the Houston area (regional basis) declined from the beginning of development until 1977. The declines in water levels have caused pronounced regional subsidence of the land surface. The center of regional subsidence is the Pasadena area, where more than 2.7 m (9 feet) of subsidence occurred between 1906 and 1978. Localized centers of subsidence exist throughout in the region, especially in the Baytown-La Porte and Texas City areas (Gabrysch 1984).

Since late 1976, changes in the pumping distribution resulting from efforts to control subsidence and the introduction of surface water from Lake Livingston have altered the pattern of water level changes.The average daily withdrawals of ground water in Harris County and parts of Fort Bend and Waller Counties between 1975-1984 was 20 m^3/s (464 Mgal/day). The percentage of ground water to total average daily use during 1975-1984 was between 48 to 58% (Williams and Ranzau, 1987). During 1985-1989, the City of Houston's water supply averaged about 55% ground water. During 1985-1989, the City of Houston's ground water withdrawal decreased from 8.5 m^3/s (194 Mgal/day) in 1985 to 7.7 m^3/s (175.4 Mgal/day). During the decade 1980-1989 the average daily withdrawal of ground water in Harris County and parts of Fort Bend and Waller Counties was 19.26 m^3/s (439.77 Mgal/day).

The purpose of the present work is to present the analysis performed at four different places in the Houston area following the methodology described in Bravo, et.al., 1991.

BACKGROUND

The Houston-Galveston area has two major aquifers: the Chicot and the deeper Evangeline aquifer, with the Burkeville Confining layer below.

Recording borehole extensometers, which sometimes are called compaction monitors are holes drilled and cased to selected depths, into which smaller diameter standpipes are installed. Since 1979 the United States Geological Survey (USGS) has 11 boreholes extensometers in operation at 11 different sites in the Houston-Galveston region. These borehole extensometers continuously record the consolidation of the interval between the land surface and the bottom of the standpipe. Moreover, in the Houston-Galveston region, the United States Geological Survey (USGS) is collecting data on water level changes in different sand layers at the aquifers. From these data estimates of pressure change (stress change) at different depths for various time intervals may be made. Electrical logs are available for the places where the borehole extensometers are placed. These electrical logs can be used to identify the compressible and incompressible layers present either in the Chicot or the Evangeline aquifers.

Electrical logs in the area indicate alternating sand and clay layers scattered throughout the vertical aquifer sections. Log interpretation made at Baytown, Clear Lake and Johnson Space Center (NASA), Southwest and Addicks sites indicates that aproximately 50% of the Chicot and Evangeline aquifers is composed of compressible materials.

BAYTOWN

Ground water pumping in the Baytown area slowly increased until 1973. During 1972, about 1.4 m^3/s (32 Mgal/day) was pumped while in 1978 a total of 0.95 m^3/s (21.6 Mgal/day) was pumped (Gabrysch 1984). Since 1972 the ground water pumping has decreased because industry increased its use of surface water. During 1973-1977, water levels rose as much as 6.1 m (20 feet) in wells in the Baytown area. The Baytown site, established in 1972, has two extensometers installed to depths of 131 m (431 feet) and 450 m (1475 feet) to measure the consolidation in two depth intervals. In addition piezometers at different depths were also installed. Data has been taken every 28 days since 1976. The wells where these devices are placed are numbered LJ-65-16-930 and LJ-65-16-931 respectively. The plot of the water level changes for both wells show that since 1976 the water has risen almost 37 m (120 feet) in the well LJ-65-16-930 and appears to remain stable since 1987 indicating that the system is reaching equilibrium. The water level in well LJ-65-16-931 has risen more than 24 m (80 feet) and the system also appears to be in equilibrium. The difference in these heads roughly depicts the change in effective stress.

Electrical logs in the Baytown area indicate alternating sand and clay layers scattered throughout the vertical aquifer sections. Log interpretation has 16 layers of compressible material that are present between 131 m (431 feet) and 450 m (1475 feet). The total clay thickness in this range is 155 m (510 feet) which represents 49% of the total thickness under study: 318 m (1044 feet).

CLEAR LAKE AND JOHNSON SPACE CENTER (NASA)

The Clear Lake and Johnson Space Center areas are located in the southern part of Harris County. During 1960, 0.05 m^3/s (1.2 Mgal/d) was pumped in the Johnson Space Center area. This pumping increased gradually until 1976, when 0.90 m^3/s (20.6 Mgal/d) was pumped for municipal supply and industrial use. During 1976 both of the mentioned areas began using some surface water from Lake Houston. During 1978, total ground water pumping decreased to 0.22 m^3/s (5.2 Mgal/d), of which 0.18 m^3/s (4.0 Mgal/d) was for municipal use (Gabrysch 1984). The history of the water level changes in the Johnson Space Center shows a decline of 76 m (250 feet) between 1943 and 1970. Later during 1973-1977, water levels rose as much as 20 feet (6.1 m) in the same area.

Alternating sand and clay layers are scattered throughout the vertical aquifer sections in this area. Log interpretation in the Clear Lake and Johnson Space Center, shown in Figure 1, has 21 layers of compressible material that are present between 235 m (770 feet) and 936 m (3072 feet) below land surface. The total clay thickness in this interval is 307 m (1007 feet) which represents 44% of the total thickness under study.

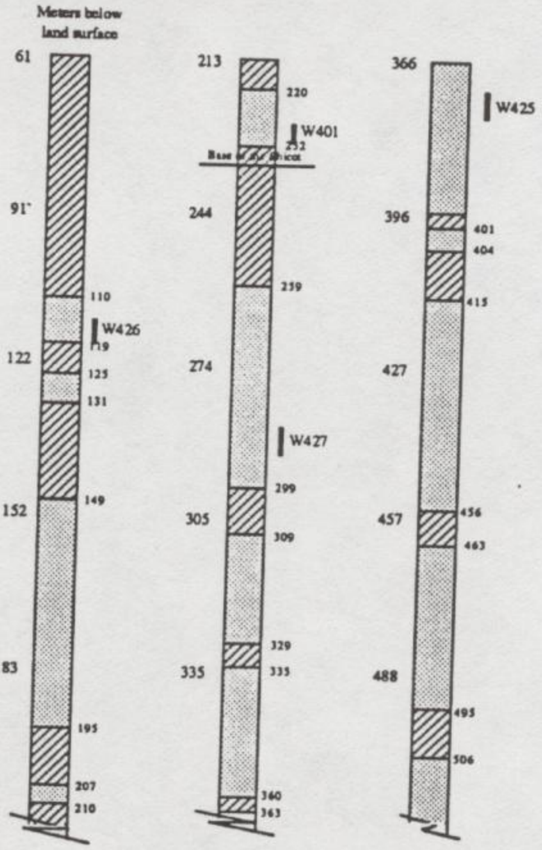

Figure 1(a) Soil profile: Clear Lake area. Solid vertical lines indicates the interval of well perforation.

The extensometer installed at the space center by the United States Geological Survey USGS in 1962 is the second extensometer installed and is the oldest in existence in the

Houston Galveston region. This borehole extensometer records the consolidation of the compressible layers between the land surface and 235 m (770 feet). It is designed to measure consolidation of the Chicot aquifer. Because additional information about consolidation and subsidence was required, the Houston Galveston Coastal Subsidence District funded the installation of two extensometers and three separate piezometers at the Clear Lake site in 1976. This site was selected so the information obtained could be coupled with information from the Johnson Space Center site. The deepest extensometer was completed at 936 m (3072 feet) in the Burkeville confining layer at the base of the Evangeline aquifer.

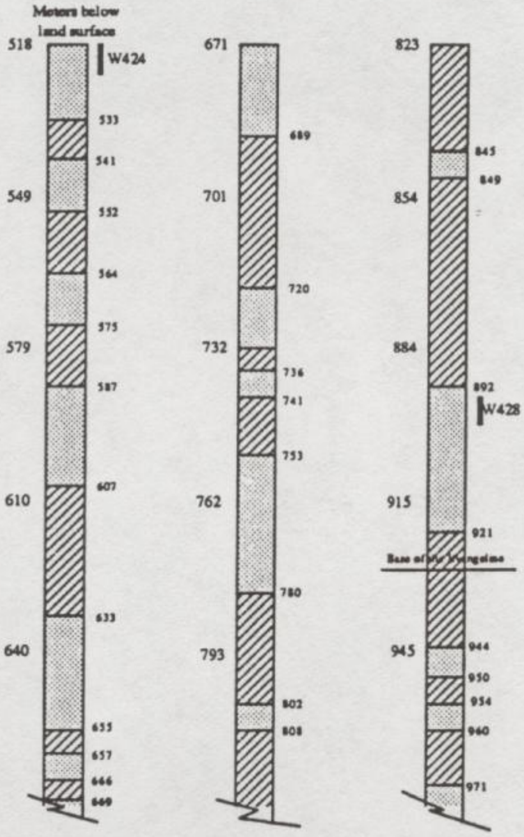

Figure 1(b) Soil profile: Clear Lake area. Solid vertical lines indicates the interval of well perforation.

Records of the water level changes from piezometers installed at different depths at the Clear Lake and Johnson Space Center sites are available. These data collected every 28 days since 1977 were used to determine the hydraulic head change or stress change acting on the different clay layers following the procedure described in Bravo, et.al., (1991).

The plot of the water level changes for the piezometer well installed at the Johnson Space Center, LJ 65-32-401 (235 m (770 feet) depth from 1977 to 1989) (Bravo, 1990) indicates that the water level during 1977-1979 rose about 8.0 m (25 feet) and only about 3.0 m (10 feet) during 1980-1989. Since 1987 there is a tendency towards an equilibrium.

The plot of the water level changes for the piezometer well installed at Clear Lake, LJ 65-32-428 (937 m (3072 feet) depth from 1977 to 1989) indicates that the water level has dropped 4.0 m (13 feet) between the period 1977-1979, and rose almost 12.0 m (40 feet) from 1980 to 1987. During 1988, the water level did not change. Afterwards, the water level dropped again.

Data from the extensometers installed at the bottom of the Chicot and Evangeline aquifer were also available. The consolidation and difference in consolidation at the

Johnson Space Center and Clear Lake sites is shown in Figure 2. The plot shows that during late 1978 and early 1979 the subsurface material expanded. More expansion occurred in the Evangeline and Chicot aquifers than in the Chicot alone. In early 1979 both aquifers resumed consolidating. The consolidation of the Chicot aquifer between 1977 and 1989 has been about 122 mm (0.40 foot) and the consolidation of the clay layers in the same period of time between the land surface and the bottom of the Evangeline aquifer was 178 mm (0.58 foot). Of the 44 mm (0.145 foot) of subsidence that occurred from January 1977 to September 1978, 33 mm (0.109 foot) was the subsidence of the Chicot aquifer so the remaining 11 mm (0.036 foot) of subsidence was in the Evangeline. These numbers imply that 75% of the total consolidation (between the land surface and the bottom of the Evangeline aquifer) was due to the consolidation of the Chicot aquifer. The other 25% was due to the consolidation of the Evangeline aquifer. Therefore one can conclude that the clay layers present in the Chicot aquifer are more compressible than the clay layers present in the Evangeline aquifer.

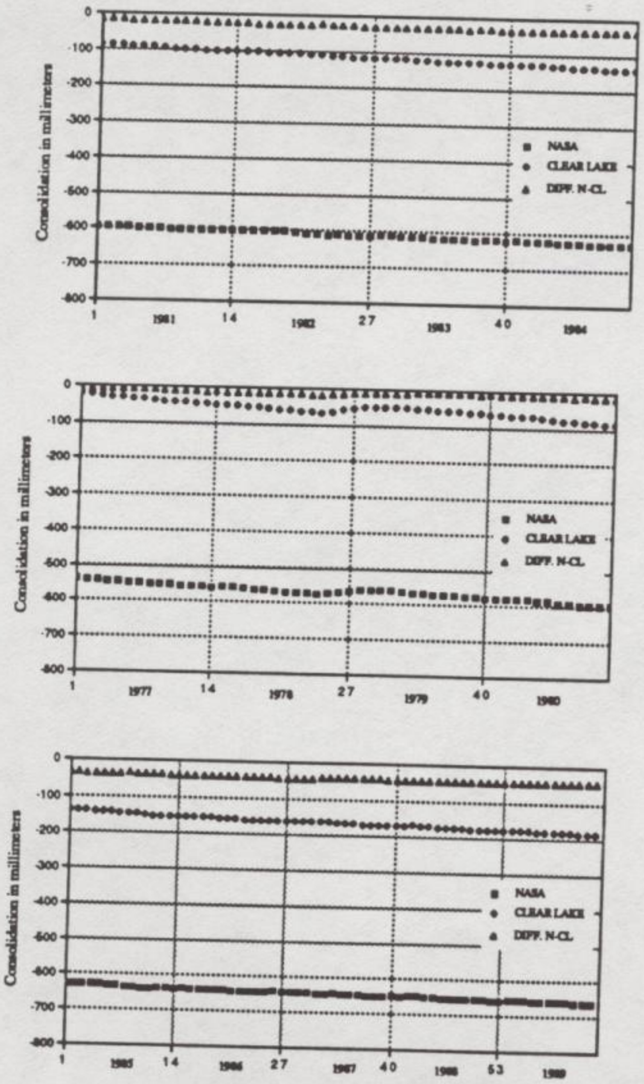

Figure 2 Cumulative consolidation: Clear Lake and NASA areas

Further analysis for the period 1978-1989, assuming no significant expansion has occurred since 1978, indicated that 131 mm (0.43 foot) was the total consolidation; 97.5

mm (0.32 foot) was consolidation of the Chicot aquifer, and 33.5 mm (0.11 foot) was the consolidation of the Evangeline aquifer. Again 75% of the total subsidence in this area was due to the clays present in the Chicot aquifer while only 25% was due to clays in the Evangeline aquifer.

The effective stress acting in each of the 21 layers of clay in the Johnson Space Center and Clear Lake areas was determined using water level data changes from the multilevel piezometers. This information was coupled graphically with the corresponding soil deformation which was assumed to be proportional to the thickness of the layer. In Figure 3 the stress versus deformation for the Clear Lake and NASA area layer II, is presented to illustrate the loops used to determine the soil properties by the method described in Bravo,et.al.,1991.

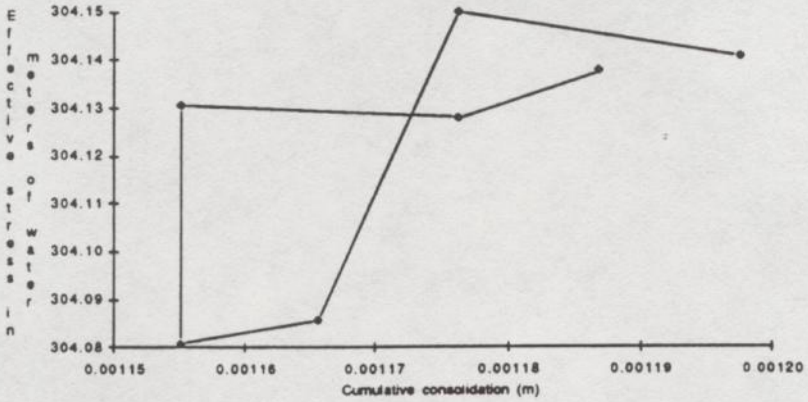

Figure 3 Stress deformation: Clear Lake & NASA areas, layer II, 1984

SOUTHWEST

The southwest site is located inside the Houston loop freeway area, where ground water withdrawals increased from 4.3 m^3/s (98 Mgal/d) during 1960 to 9.9 m^3/s (227 Mgal/d) during 1978. About 83% of the water being pumped in this area was used by the City of Houston. The increase in ground water use can be considered as fairly uniform. By 1976 even though the city had periodically increased the use of surface water, the rapidly increasing population required more water. Ground water was the only available supply so that by 1978, water use in the city was 14.6 m^3/s (333 Mgal/d), of which 8.3 m^3/s (189 Mgal/d) was ground water and 6.3 m^3/s (144 Mgal/d) was surface water from Lake Houston. The pumping stress on the aquifer was barely reduced.

In the Houston area, most pumping is from the Evangeline aquifer. In the southwestern part of the Houston area during 1973-1977, water levels declined as much as 6.1 m (20 feet), which reflects an increase in pumping during this period of time (Gabrysch 1984).

During 1980 a borehole extensometer, 710 m (2330 feet) depth was installed in the southwest part of Houston, at the intersection of Newcastle and West Park, South of Highway 59. There are also 5 piezometers installed at the same location.

Alternating sand and clay layers are scattered throughout the vertical aquifer sections in this area as well. Interpretation of electrical logs in the southwest site indicates 17 layers of compressible material are present between 74 m (243 feet) and 710 m (2330 feet) below the land surface. The total clay thickness in this interval is 247 m (810 feet) which is 39% of the total thickness under study.

Water level in the piezometer well installed at the Southwest site (LJ 65-21-226) rose in 1980, dropped 8.0 m (25 feet) until 1983 when the water level rose again, regaining the 8.0 m (25 feet) lost earlier.

The consolidation in the southwest area does not present as much a rebound as in the other two places already analyzed. The subsidence measured from 1980 to 1989 is about 427 mm (1.4 feet).

The effective stress acting in each of the 17 layers of clay in the Southwest area was determined using water level data from the piezometers. This information was coupled graphically with the corresponding soil deformation, which was assumed to be proportional to the thickness of the layer. Stress and deformation loops were used to determine the soil properties following the method described by Bravo,et.al.,1991.

ADDICKS

The Addicks site also belongs to the Houston area or region.

Alternating sand and clay layers are scattered throughout the vertical aquifer sections in this area. Interpretation of electrical logs in the Addicks site indicates 18 layers of compressible material between 15 m (50 feet) (497 m (1630 feet) below the land surface). The total clay thickness in this interval was 287 m (940 feet), which is 59% of the total thickness under study.

Consolidation monitoring at the Addicks site began in 1974 with installation of an extensometer to the top of the Burkeville confining layer at a depth of 549 m (1802 feet). Piezometers also were installed in 1974 and 1978. These piezometers (numbered as LJ-65-12-725, LJ-65-12-728, LJ-65-12-729, LJ-65-12-726) were placed at 15 m (49 feet), 47 m (153 feet), 72 m (237 feet) , and 503 m (1650 feet) respectively.

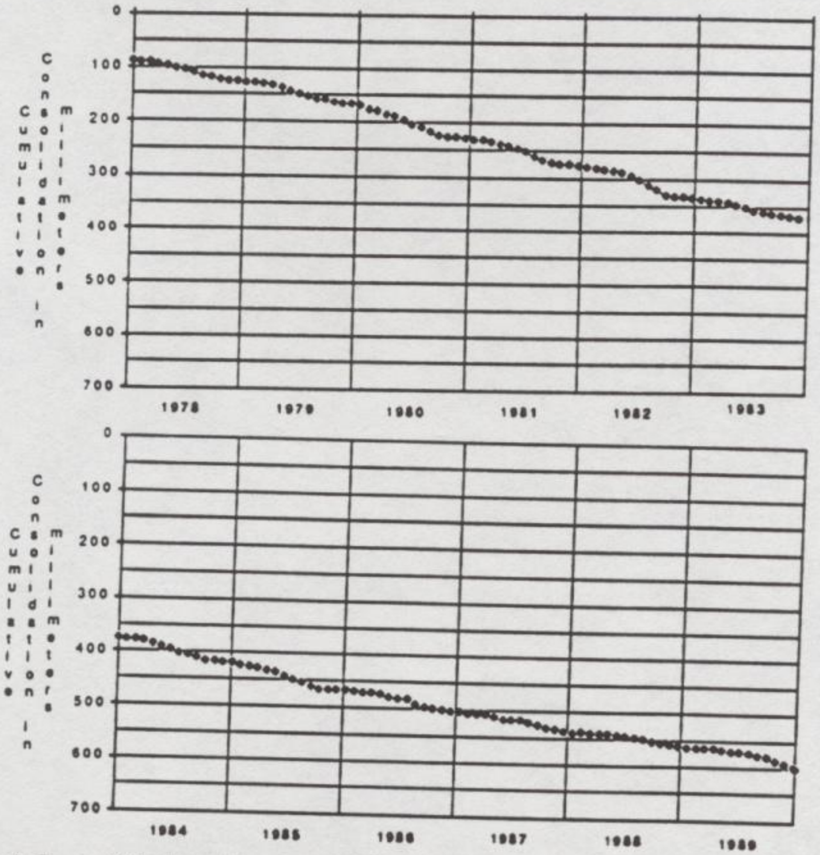

Figure 4 Consolidation history: Addicks area.

The water level in the piezometer well, LJ-65-12-729, installed at the Addicks site, was dropping more or less uniformly from 1978 to 1984. A sudden rise occurred in 1985, then the water level continued dropping, which indicates that the aquifer is still under the load process. Between 1978-1989 the water level in this well has dropped about 5.5 m (18 feet).

The water level in the piezometer well LJ-65-12-726, dropped almost 30 m (100 feet) between the period 1978-1979, which again is an indication that the compressible layers in this area are still compacting.

The consolidation history of the Addicks site, is shown in Figure 4. Between the surface and 549 m (1802 feet) it was 518 mm (1.7 feet). The consolidation appears constant with a rate equal to 61 mm/year (0.2 foot per year).

RESULTS AND CONCLUSIONS

The data described here was used to determine the vertical hydraulic conductivity $K_{z\ system}$, and the elastic and inelastic storage coefficients ($S_{ske\ system}$, $S_{skv\ system}$) using the methodology described by Bravo, et.al., (1991).

The calculated values are shown in Table 1. These values are consistent with other published values as shown in Tables 2 and 3.

There are seven other places where one could perform the same kind of analysis. Future work includes the study of these additional sites. These results can improve any regional or local modeling of ground water flow and land surface subsidence.

TABLE 1 Calculated parameters for the Houston area.

	Baytown	Clear Lake & NASA	Southwest
$K_{z\ system}$	4.36×10^{-5} m/day	1.10×10^{-5} m/day	0.73×10^{-5} m/day
$S_{ske\ system}$	9.00×10^{-4} m^{-1}	1.70×10^{-3} m^{-1}	2.95×10^{-5} m^{-1}
$S_{skv\ system}$	5.90×10^{-3} m^{-1}	1.30×10^{-3} m^{-1}	2.85×10^{-4} m^{-1}

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TABLE 2 Comparison of Clear Lake & NASA calculated storage coefficients and vertical hydraulic conductivities with published values.

Source	S_{ke}	S_{ske} (m^{-1})	S_{kv}	S_{skv} (m^{-1})	K_z (m day^{-1})
Bravo, et.al. (1991)	$1.25x10^{-1}$	$1.70x10^{-3}$	$4.01x10^{-1}$	$1.30x10^{-3}$	$1.10x10^{-5}$
Gabrysch, R.K. (1984)	$1.86x10^{-2}$ $4.60x10^{-1}$	$2.70x10^{-5}$ $6.60x10^{-4}$			
Meyer and Carr. (1979)		$4.90x10^{-5}$ $2.85x10^{-4}$	$3.00x10^{-4}$ $3.50x10^{-2}$		$3.90x10^{-5}$ $1.40x10^{-3}$
Jorgensen, D.G (1975)			$5.00x10^{-3}$ $3.00x10^{-2}$		
Riley, F.S.* (1969)	$1.0x10^{-3}$	$9.20x10^{-6}$	$5.70x10^{-2}$	$4.60x10^{-4}$	$2.40x10^{-6}$

TABLE 3 Comparison of Southwest calculated storage coefficients and vertical hydraulic conductivities with published values.

Source	S_{ke}	S_{ske} m^{-1}	S_{kv}	S_{skv} m^{-1}	K_z m day^{-1}
Bravo,et.al. (1991)	$1.38x10^{-2}$	$3.00x10^{-5}$	$5.06x10^{-2}$	$2.85x10^{-4}$	$7.30x10^{-6}$
Gabrysch, R.K. (1984)	$1.86x10^{-2}$ $4.60x10^{-1}$	$2.70x10^{-5}$ $6.60x10^{-4}$			
Meyer and Carr (1979)		$5.00x10^{-5}$ $2.85x10^{-4}$	$3.00x10^{-4}$ $3.50x10^{-2}$		$3.65x10^{-5}$ $1.40x10^{-3}$
Jorgensen, D.G. (1975)			$5.00x10^{-3}$ $3.00x10^{-2}$		
Riley, F.S.* (1969)	$1.00x10^{-3}$	$9.20x10^{-6}$	$5.70x10^{-2}$	$4.60x10^{-4}$	$2.40x10^{-6}$

* Values obtained for a cyclical load in Central California.