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Land Subsidence and its Relation to Past and Future Water Supplies in Antelope Valley, California

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Abstract

Extensive ground-water pumpage for agriculture during the period 1952 to 1968 played a significant role in the development of more than 6 ft of land subsidence measured between 1926 and 1992 in Antelope Valley, California. Since the 1970's, the reduction of irrigated agriculture in this arid, high-desert valley has paralleled dramatic increases in population and urban land use. Concurrently, ground-water pumpage has declined sharply, to the lowest levels in decades. Although currently less than at any time since the 1940's, annual ground-water extraction still exceeds the estimated mean natural recharge to the valley by nearly two-fold. As a result, ground-water levels, historically depleted throughout the central part of the valley, continue to decline in urban and isolated agricultural areas where ground-water use is high. The population of Antelope Valley is projected to grow from 260,400 in 1990 to 690,000 by 2010, and water demand is expected to exceed projected supplies by the year 2004. Ground-water supplies have satisfied 50 to 90 percent of the annual water demand in Antelope Valley during the period of development, and will constitute a substantial component of the future water supply. If ground-water levels are maintained at approximately their historic low levels, the subsidence presently observed may be only a modest fraction (perhaps 35 to 65 percent) of that which will ultimately occur. Past agricultural and mounting municipal- industrial demand for ground-water leaves future residents of the valley a legacy of ongoing aquifer-system compaction, land subsidence and related problems, and the challenge to manage the resource within beneficial limits.

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Introduction

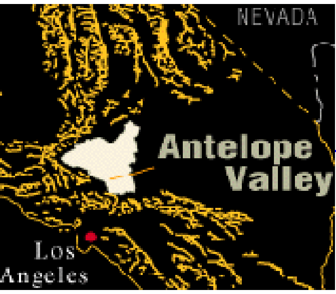


Fig. 1

Antelope Valley is an arid valley in the southwestern corner of the Mojave Desert, about 50 miles northeast of Los Angeles (Figure 1). The triangular-shaped valley is bounded on the south by the San Gabriel Mountains, on the northwest by the Tehachapi Mountains, and by lower hills, ridges, and buttes in the north and east. The valley is a topographically closed basin with surface-water runoff terminating in several playas. Average annual precipitation varies from 30 inches near the crests in the San Gabriel Mountains to 3 inches on the valley floor.

Antelope Valley overlies three large structural basins filled to depths of more than 5000 ft with Tertiary and Quaternary alluvial sediments eroded from the adjacent highlands. Water infiltrating the basin-fill sediments over the past million years or more has created a vast ground-water basin. The ground-water basin has been conceptually subdivided into 12 separate but variably connected, ground-water subbasins (Thayer, 1946), of which the Lancaster subbasin (Figure 1) is by far the largest and most developed. The Lancaster subbasin has been further subdivided into aquifer systems containing transmissive, water-bearing aquifers and relatively non-transmissive aquitards (Londquist and others (1993). The aquifer systems in the Lancaster subbasin contain two alluvial aquifers known locally as the principal aquifer and the deep aquifer. Both aquifer systems consist of interbedded layers of heterogeneous mixtures of clay, silt, sand, and gravel. The "principal aquifer" is partially confined by the interbedded, fine-grained sediments (aquitards) and is separated from the "deep aquifer" by laterally extensive, thick (>100 ft) lacustrine deposits that confine the "deep aquifer".

Mountain streams account for an estimated mean annual recharge between 31,300 and 59,100 acre-ft to the Antelope Valley ground-water basin (Steven P. Phillips, U. S. Geological Survey, written commun.). Before the development of irrigated agriculture in the early-to-mid 1900's, ground water flowed from recharge areas near the San Gabriel and Tehachapi Mountains toward meadows, marshes and springs (now dry) near the center of Antelope Valley where most of it discharged from the Lancaster subbasin via evapotranspiration. Figure 2 shows ground-water levels in the Lancaster subbasin representing the "principal aquifer" potentiometric surface in the year 1915, prior to significant ground-water development (Durbin, 1978). Since then, ground-water withdrawals far in excess of the estimated natural recharge have created problems of land subsidence caused by compaction of the aquifer- system that typically accompanies ground-water mining in alluvial basins.

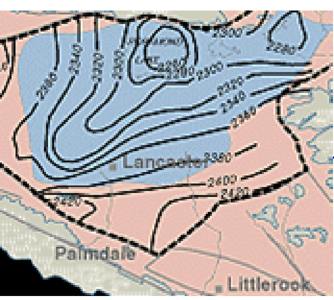


Fig. 2

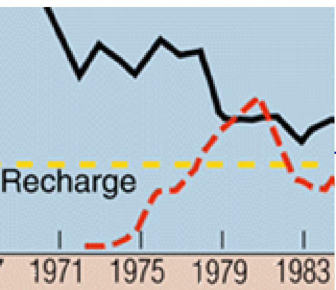
Problems related to land subsidence thus far have been subordinate to problems of ground-water supply. The costs of pumping ground water, which played a major role in the reduction of agricultural ground-water use, is not yet a limiting factor for the development of municipal-industrial ground-water supplies. The importation of surface water to Antelope Valley from northern California in 1972 via the State Water Project (SWP), California Aqueduct (Figure 1) has provided an alternate water resource that has sustained the growth of a municipal-industrial water demand that is fundamentally dependent on ground-water supplies. The limited storage and delivery capacity of the SWP and the high degree of annual variability in the supply due to climatologic and environmental factors related to diversions from the San Francisco Bay/Delta system, place reliance on the ground-water supply to sustain current and future levels of demand. The prospect for the continuing depletion of the aquifers looms large in the face of this growing demand. A legacy of land subsidence inherited by current and future users of the ground-water resource will become more burdensome under projected circumstances. The economic and environmental consequences of continued ground-water mining -- aquifer-system compaction and land subsidence -- pose challenges to users of the depleted resource and may play a role in limiting the development of municipal-industrial supplies.

This paper briefly addresses the historical context of ground-water use and concomitant land subsidence in Antelope Valley. We explore the transition of an agricultural-based water demand to a burgeoning municipal/industrial- based water demand. We discuss the essentially irreversible process of land subsidence in terms of the immediate challenges it presents to future managers of the ground-water resource in Antelope Valley.

Ground-Water Use in Transition

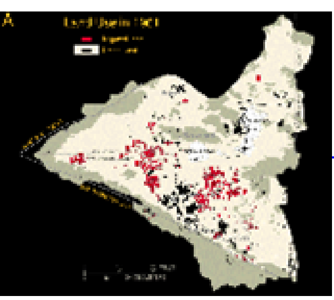
Prior to 1908, the early settlers in Antelope Valley drilled more than 300 flowing wells in the central and lower parts of the valley where it was possible to tap shallow artesian aquifers (Figure 2). Many of these wells were drilled to obtain patents to Government land; some were used to water livestock and crops (Johnson, 1911). The alkali soils in the region of flowing wells severely limited attempts to farm the land, and the quantity of water from flowing wells applied to irrigation was probably small (Thompson, 1929). Concurrently, diversions along the courses of mountain streams were used to irrigate primarily orchards on lands near the heads of alluvial fans along the south side of the valley.

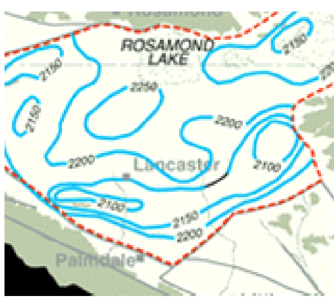
When the earliest irrigation systems, dependent on surface streams, failed to provide a stable and reliable water source for crop production, the ready accessibility of ground-water spurred a steady and strong development of irrigated agriculture, which began shortly after 1912. Initially, land was developed for alfalfa production near the margins of the area of artesian flow (Figure 2) where soil conditions were suitable and pumping lifts were low (Thompson, 1929). Alfalfa was the most important crop in Antelope Valley and by the early 1950's constituted about 60 to 75 percent of the irrigated acreage and 60 to 70 percent of the gross annual income from all crops (Snyder, 1955). Water demand for crop production reached peak levels in the 1950's when irrigated acreage was at its peak (Figure 3).



Figs. 3a and 3b

Ground-water pumpage was the principal source of water supply until the mid-1970's when imported SWP water was delivered via the California Aqueduct. By this time, irrigated acreage and ground-water pumpage for crop production were on a steady decline, decreasing to 20 percent of peak levels by 1991 (Figure 3). Meanwhile, during the decade of the 1980's, the population of Antelope Valley nearly doubled as the predominant land use shifted from irrigated agriculture to urban land use. Since about 1980, ground-water use has exceeded use of imported surface water and together they make up about 90 percent of the water supply; local surface-water sources constitute the remaining 10 percent.


Figs. 4a and 4b



Figs. 5a and 5b

The transition from a predominantly agricultural water demand to a municipal/industrial water demand began in the early 1960's and had become fully manifest in the early 1990's. Comparisons between the peak agricultural water-use periods of the early 1960's and the early 1990's show that irrigated acreage was reduced by 80 percent while urban land use was increased by more than 200 percent (Figure 4). Although the magnitude of ground-water pumpage in Antelope Valley was reduced dramatically from 1960 levels, by 1991 the shape of the regional aquifer-potentiometric surface showed little recovery in ground-water levels (Figure 5) as extraction more than kept pace with recharge (Figure 3a). In 1991, ground-water pumpage exceeded, by nearly two-fold, the estimated mean natural recharge to Antelope Valley. By 1991 ground-water pumpage had become more focused in the expanding urban areas of Lancaster and Palmdale, where additional ground-water level declines are evident (Figure 5b). Figure 6 shows the change in ground-water levels from 1915 to 1991 in the principal aquifer of the Lancaster subbasin.

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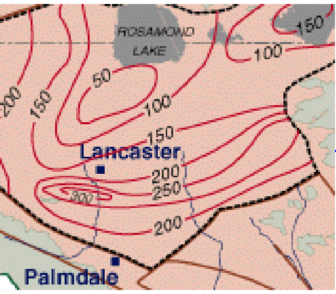
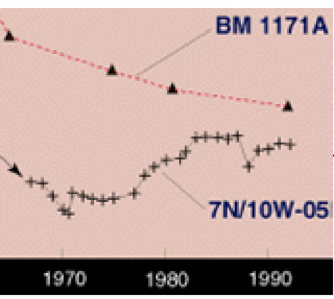


Fig. 6

Legacy of Land Subsidence

The earliest recognition and recording of land subsidence in Antelope Valley may have been made by the Office of the County Engineer of Los Angeles County, on the basis of surveys made during the period 1928 to 1960 (Mankey, 1963). Subsequent measurements made by the County in 1972 were used to compute elevation differences at selected benchmarks between 1935 and 1972 and rates of subsidence between 1967 and 1972 (McMillan, 1973). The relation between ground-water level declines and land subsidence in Antelope Valley was noted by Lofgren (1965), Lewis and Miller (1968), Poland (1984), Holzer (1986), and Prince and others (1995). Measurements relating ground- water level declines, land subsidence and aquifer-system compaction near Edwards Air Force Base were presented by Blodgett and Williams (1992), and Londquist and others (1993). The relation between regional land subsidence and ground-water level declines in central Antelope Valley was established on the basis of geodetic and hydrologic measurements made during the period 1926 to 1992 and reported by Ikehara and Phillips (1994).



Figs. 7a and 7b

More than 6 ft of subsidence, attributable to ground-water withdrawal has occurred since 1926 in parts of Antelope Valley. Figure 7 shows paired graphs of ground-water level changes in two wells and land subsidence calculated for two nearby benchmarks. The locations of the wells and benchmarks are shown on Figure 1. The distribution and magnitude of subsidence (Figure 8) reflects in part the changing shape and position of the aquifer potentiometric surfaces (Figure 6) and the areal distribution and aggregate thickness of compressible sediments. Altogether, 290 square miles have been affected by more than 1 foot of land subsidence in Antelope Valley (Ikehara and Phillips (1994).

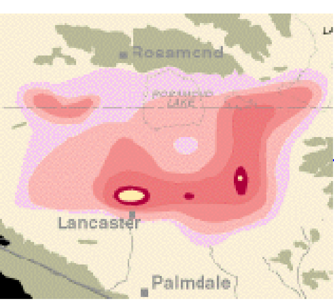


Fig. 8

It must be recognized that Figure 8 represents only a snapshot of an ongoing process that inevitably lags the depletion of artesian pressures in the aquifer systems. The rate at which the aquifer systems are presently compacting, and the extent of their progression toward the ultimate compaction required by the current state of ground-water level drawdowns are largely unkown. They are determined, predominantly, by the various thicknesses, vertical permeabilities, and compressibilities of the individual aquitards within the aquifer systems (Poland, 1984). These parameters have not yet been closely examined in Antelope Valley, and recent rates of compaction and their relation to ground-water level changes are known at only one site, near the southern end of Rogers Lake (Londquist and others (1993). Nevertheless, reasonable extrapolations from similar areas (Ireland and others, 1984; Poland and Ireland, 1988) suggest that the subsidence presently observed may be only a modest fraction (perhaps 35 to 65 percent) of that which will ultimately occur, if ground-water levels are maintained at approximately their historic low levels. Furthermore, that fraction may be expected to vary substantially from place to place within the basin as a function of the local geology and history of water-level decline. The data presently available are not adequate to support a reliable estimate of the magnitude of ground-water level recovery that would be required to virtually eliminate additional subsidence.

Differential land subsidence has altered surface drainage gradients, contributing to erosion and flooding problems, particularly evident on Rogers Lakebed where flooding and tensional earth fissures have caused the closure of runways once used to land the Space Shuttle (Blodgett and Williams, 1992). Linear engineered structures are particularly susceptible to damage, including canals, sewers, water delivery systems, drainage works, flood-control facilities, transportation grids, and well casings. No strict accounting has been made to date of private or public damages incurred as a result of land subsidence in Antelope Valley.

Past agricultural uses and increasing municipal-industrial demands for ground water leave future users of the resource a legacy of aquifer-system compaction, land subsidence, earth fissures and flood-control problems. Ground-water withdrawals have been reduced by importation of surface water to the most prominent subsidence areas in California (Bertoldi, 1992), including Antelope Valley. In some of these areas subsidence has been stopped by a substantial recovery of artesian pressures. However, increasing and conflicting demand on the developed surface-water supply and extended drought periods resulting in increased ground-water withdrawals provide reasons for concern about potential renewed or continuing land subsidence.

Ground water continues to be an important component of the water supply in Antelope Valley, constituting about 85 percent of the total supply in 1992 (Templin and others, 1995). 1992 was the sixth year of the 1987-1992 drought in California. In non-drought years, ground-water constitutes about 60 percent of the total water supply in Antelope Valley (Templin and others, 1995). Variabilities in annual hydrologic cycles and deliveries of surface-water supply from the SWP underscore the importance of managing the local ground-water resources in the effort to meet current and future demands.

Managing the Resource

Blomquist (1992) defines ground-water basin management as representing "... a deliberate effort to derive greater benefits from the use of this resource while avoiding its depletion and the associated human welfare costs." One of the human welfare costs is the damage caused by land subsidence. In the past and currently, the private cost of using the ground-water resource has not reflected the cost to society of ameliorating the consequences of subsidence. The optimal use of the ground-water resource would approximate a balance between supply and demand to minimize depletion of the resource, while maximizing its beneficial use and minimizing social costs. One challenge facing the developing Antelope Valley is to quantify and monitor the benefits and true costs of using the ground-water resource.

In 1991, in response to growing concerns of ground-water depletion and related land subsidence problems, the ad hoc Antelope Valley Water Group (AVWG) formed to provide a forum for communication and cooperation between valley agencies with an interest in water. The group currently includes representatives from the member agencies, Antelope Valley-East Kern Water Agency (AVEK), Antelope Valley United Water Purveyors, City of Lancaster, City of Palmdale, Edwards Air Force Base, Los Angeles County Waterworks Districts, County Sanitation Districts of Los Angeles County, Palmdale Water District, and Rosamond Community Services District. The group's primary mission is to address the future of the valley's water resources through the conjunctive use of available surface-water and ground-water supplies. Taken together, the AVWG represents virtually all of the surface-water deliveries, imported and local, and more than half of the ground-water pumpage in the valley.

In Antelope Valley and elsewhere, the hazards and economic costs associated with land subsidence depend on its proximity to populations and manmade structures, among other factors. Mapping programs are recognized as an important element in efforts to identify and manage subsidence problems (National Research Council, 1991). The AVWG completed two studies that mapped current (early 1990's) and historical land and water use (Templin and others, 1995), and land subsidence related to ground-water withdrawal (Ikehara and Phillips, 1994). A third, companion study assessed water supply and demand issues in the context of the valley's water resources (Takaichi, 1995). The results of this study included a proposed "Basic Water Resource Protection Strategy" and specific recommended actions for implementing the strategy.

The strategy developed by the AVWG includes institutional, engineering, financial, and public-education components. It focuses on minimizing the growth of water demand, and developing additional water resources to meet future demand while optimizing the use of existing water resources. Specific elements of the "Basic Water Resource Protection Strategy" include:

- Improved utilization of available water supplies -- focuses on use of reclaimed water, stormwater, and imported water, in lieu of ground water.

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- Ground-water basin management -- emphasizes balancing ground-water extractions with the safe-yield of the ground-water basins, and advocates implementing artificial ground-water recharge programs.
- Protection of ground-water quality.
- Reduction in long-term water demand -- proposes specific programs of water conservation for the Cities of Palmdale and Lancaster, and the Community of Rosamond.
- Improved SWP reliability -- promotes active participation in the issues involved in SWP allocations, such as environmental concerns in the Bay-Delta and SWP financing.
- Acquisition of additional imported water supplies.

The AVWG report (Takaichi, 1995) recommends that the following actions be taken to implement the strategy:

- Create an institutional framework to manage the development and use of water supplies.
- Determine the safe yield of the Antelope Valley ground-water basins.
- Continue the current ground-water monitoring program and publish an annual report on basin conditions.
- Develop a program to optimize the use of available water supplies.
- Develop water conservation, reclaimed water, stormwater management, and aquifer storage and recovery programs.
- Actively encourage the California Department of Water Resources to complete the State Water Project and/or improve its reliability.
- Obtain additional imported water supplies.
- Develop a revenue plan to implement the recommended programs.
- Initiate a public education program.

In order to address components of the "Basic Water Resource Protection Strategy" relevant to the ground-water flow system and land subsidence, the AVWG is developing a regional ground-water flow and aquifer-system compaction model for Antelope Valley. A separate study begun in April, 1996, is evaluating a pilot program for aquifer storage and recovery in Lancaster. Approximately 3000 acre-ft of treated, imported surface water will be injected in two existing production wells to recharge the principal aquifer. The pilot program will evaluate the aquifer hydraulics and mechanics involved in storing and recovering treated, surplus water from the SWP in the local aquifer.

The population of Antelope Valley is projected to grow from 260,400 in 1990 to 690,000 by the year 2010 (Calif. Dept. of Finance, 1992). Meanwhile, total water demands are expected to triple by the year 2010 because of continued urban development, placing more reliance on local ground-water resources and exacerbating problems of ground-water depletion and land subsidence. With the recommended water conservation programs in place, assuming 100 percent delivery of available water supplies and that ground-water extractions do not exceed 59,100 acre-feet per year, it is anticipated that the water demands will exceed the available supplies by the year 2002 (Takaichi, 1995). Implementing the recommended system for utilizing reclaimed water would satisfy the anticipated water demands for another two years, until 2004.

Clearly, actions to reduce water demand and increase locally available surface-water supplies will not meet anticipated water demands, even in the near-term. In the absence of a substantially increased allocation from the SWP or other non-local sources, the growing municipal-industrial water demand can be met only through increased ground-water pumpage. Experience suggests that the continued mining of ground water from the Lancaster subbasin will cause additional aquifer- system compaction. The future of ground-water use in Antelope Valley is linked to continuing compaction of the aquifer system and additional land subsidence. The hydrogeologic complexities of the linkages and the associated ground-water basin management challenges will continue to confront AVWG and other future users of this crucial resource in the arid, high-desert valley.

Acknowledgments

The authors acknowledge the pioneering efforts of the Antelope Valley Water Group (AVWG) in organizing the self-governing, collective action to address the critical and complex issues confronting future users of the scarce Antelope Valley water resources. The AVWG Technical Advisory Committee, on which we (U. S. Geological Survey) serve with representatives of AVWG, has been the driving force and focal point of that effort. We are grateful to our colleagues and mentors, Gilbert L. Bertoldi and Francis S. Riley, Scientists Emeritus, U. S. Geological Survey, for their thoughtful suggestions and comments that have improved the usefulness and completeness of this manuscript. We are especially grateful to Louisa D. Boyd for her input on improving the readability of the companion page on the world-wide-web, URL http://water.wr.usgs.gov/poland/index.html.

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