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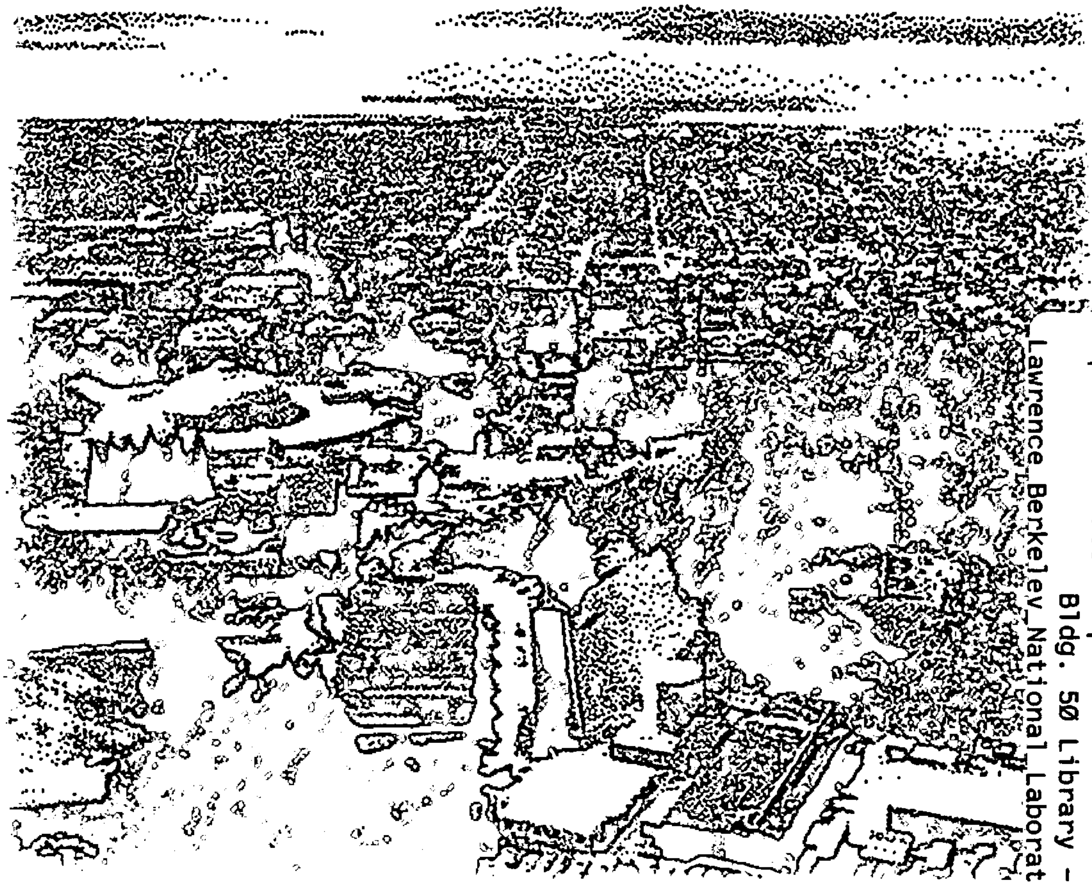

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PROTECTION OF SUBSURFACE AQUIFERS: A BROADER CONTEXT

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ABSTRACT

Large-scale groundwater extraction for municipal, irrigation, and industrial purposes became widespread throughout the world early in this century with breakthroughs in deep-well pump technology. Accelerated extraction soon led to declines in aquifer productivity, land subsidence, salt-water intrusion, and other adverse impacts. A consensus exists among earth scientists that aquifers are bounded, open systems that constitute the lower part of the hydrologic cycle. They are dynamically linked to the upper part of the hydrologic cycle, comprising the atmosphere and surface water bodies. Whereas surface water bodies respond rapidly to climatic changes, subsurface aquifers respond more slowly over long time periods. In order that we may continue to benefit from groundwater reservoirs into the indefinite future, aquifer management must be linked to management of surface water resources, taking due notice of the differences in the reaction times of surface water and groundwater bodies. An essential foundation to such management is sustained monitoring of the groundwater system and its linkages to the other components of the hydrologic cycle. Experience gained in the development of groundwater resources in the Santa Clara and the San Joaquin Valleys of California provides insights into the technical and human aspects of large-scale integrated development of groundwater resources.

Keywords: groundwater, aquifers, hydrologic cycle, protection, scales, integrated management, California

INTRODUCTION

On the eve of the 21st century there is a general awareness worldwide that the earth is a finite planet and its natural resources must be managed with great care. Within this overall context, the protection of subsurface aquifers from depletion and physical and chemical degradation is a topic of considerable importance. Equally important is the recognition that development of subsurface aquifers for water supply can, in turn, have significant impacts on the greater environment and ecosystems. Thus, it is relevant to simultaneously address both the issue of protecting ecosystems from the effects of aquifer development and that of protecting the aquifer resource. The challenge of water management and policy is to balance these impacts so that society may continue to benefit from its groundwater resources for long periods of time.

In this paper, the topic of subsurface aquifer protection is addressed from a generic, philosophical

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point of view. To give some form and substance to these theoretical concepts, examples of groundwater development are drawn from the state of California. Over the past century and a half, California has seen extraordinary developments in water through a combination of its abundant natural resources and its aggressive applications of technology and policy. The experiences that have been gained in California are of great value in providing insights into issues related to aquifer protection in general, regardless of geographic location.

This paper is divided into two parts. The first part on historical background presents observational experience from California to portray issues that are pertinent to subsurface aquifer protection. The second part is devoted to a discussion of scientific concepts relevant to such protection and implications for aquifer management.

HISTORICAL BACKGROUND

Although the extraction of groundwater for beneficial use through wells and other structures dates back many thousands of years in Egypt, the excessive removal of water from underground, leading to pronounced deleterious impacts on other components of the environment, is little more than a century old. Extraction of groundwater from considerable depths at a scale large enough to drastically deplete the resource and lead to collateral effects such as land subsidence and salt-water intrusion commenced with the advent of drilling machines during the early part of the 19th century. Between 1850 (when California attained statehood) and 1900, there were numerous artesian belts in sedimentary basins throughout California. Free-flowing artesian wells reaching down to more than 300 meters below the land surface and producing in excess of 3,800 cubic meters per day were common in the Central Valley. Towards the end of the 19th century, the drilling of a large number of such wells for irrigation led to a gradual decline in flow rates, accompanied by the lowering of water levels to below the land surface and the subsequent cessation of flow in many wells. The earliest horizontal-shaft centrifugal pumps, operated by steam engines, appeared in California around 1880 [Freeman, 1968]. These were limited to lifting water from depths less than 10 meters below the land surface. With the construction of the first hydroelectric plant in 1893 in California, electric power became available to operate pumps by the early 1900s. Nevertheless, lifting water from depths greater than 10 meters remained a challenge to large-scale groundwater extraction.

A major breakthrough in pump technology, largely driven by the profitability of irrigation, occurred around 1901 when the first multi-stage vertical-shaft turbine pump was designed and tested in Chicago. This design soon underwent major improvements and the first turbine pump for irrigation went into operation in Chino in southern California in 1907 [Freeman, 1968]. A rapid increase in the use of such pumps throughout the California for irrigated agriculture soon followed. In the subsequent decades, this new technology contributed to unprecedented overdraft of water in many parts of the state. The nature of the overdraft and consequences are well illustrated by the history of subsurface aquifer development in the Santa Clara and San Joaquin Valleys.

Santa Clara Valley

The Santa Clara Valley is a small, topographically well defined basin situated at the south end of San Francisco Bay in California (Figure 1). Renowned worldwide for its prunes, apricots, and other orchard crops in the early twentieth century, this area is now known as the Silicon Valley due to its computer industry. The valley is underlain by over 600 meters of Late Tertiary to Recent sediments, which contain highly productive aquifers down to about 250 meters. Up to the turn of the 20th century, a belt of free-flowing wells existed in the lower, northern area of the valley close to the bay. These artesian wells, in addition to pumped wells, supported thriving and rapidly expanding irrigated agriculture. During the 1910s, the farmers in the valley began to adopt the turbine pump and increased their ability to lift water from great depths. Within a decade, the enormously accelerated withdrawal of groundwater led to rapidly declining water levels and productivity of wells, as shown in Figure 2. In 1931, a precision survey carried out by the U. S. Coast and Geodetic Survey [Rappleye, 1933] revealed that, between 1920 and 1931, an elevation benchmark in the city of San Jose had subsided by about 1.3 meters. A map of the region showing the extent of subsidence during 1935-36 is given in Figure 3. Based on field data, the correlation between land subsidence and groundwater overdraft came to be clearly established. The mechanism of subsidence was soon ascribed to the compaction of soft fine-grained sediments (aquitards) in response to declining water pressure [Meinzer, 1937].

The alarming increase in pumping costs resulting from the decline of water levels motivated the farmers of the Santa Clara Valley to commission a study by Fred Tibbetts and Stephen Kieffer, civil engineers, to find means of better managing the water resources of the valley as a whole. Based on intensive data gathering on physiography, geology, climate, surface water runoff, and well inventory, the report [Tibbetts and Kieffer, 1921] recommended coordinated water resources management involving storage of winter flood water, artificial recharge, and groundwater extraction. Although these recommendations were only partially implemented thirteen years later, the report largely inspired the subsequent integrated development of surface water and groundwater in the Santa Clara Valley.

By the 1950s, the growth of the electronics industry had transformed the valley into a growing metropolitan area. Land-use patterns in the valley began to change steadily from agriculture to urban and suburban. It became clear that the water resources of the local basin alone would be grossly insufficient to support the valley's growing water uses. A decision was made to bring water into the valley from outside.

Currently, water is imported into the valley from the rivers of the Sierra Nevada via three paths: the South Bay Aqueduct of the State Water Project, San Francisco's Hetch Hetchy Aqueduct (both on the northeast), and San Luis Reservoir on the California Aqueduct to the southeast. A map of the modern Santa Clara Valley water system is given in Figure 4. The current total water used by the valley is approximately 560 million cubic meters per year, or about 1.5 million cubic meters per day. About half of this is met by imported water. Most of the remainder comes from groundwater, with minor contributions from local surface water. Some wells supplying water for the city of San Jose can produce as much as 9.5 cubic meters of water per minute. Although groundwater pumpage could be increased, production is curtailed in wet years and increased during periods of drought. By limiting groundwater withdrawals and artificially recharging the aquifers, land subsidence has been brought under control.

The imported water, surface water reservoirs, and artificial recharge facilities are managed by the Santa Clara Valley Water District, which is overseen by the Santa Clara County government. Private companies and municipalities that pump groundwater under permit and purchase water from the Santa Clara Valley Water District at a wholesale rate carry out the actual distribution of water to communities and end users.

Groundwater recharge, flood control, wastewater reclamation, and public education are all integral to the overall management philosophy in the valley. This generally rational approach to integrate management has come into existence, among other reasons, because the unit of management is a self-contained physiographic and groundwater basin and because the local population had the will to judiciously manage its finite resources of water.

San Joaquin Valley

The San Joaquin Valley, the southern half of the Great Central Valley of California, provides an example of how the natural resources infrastructure can be impacted in different ways from water resources development. San Joaquin Valley is among the most productive agricultural regions of the world. Agricultural in this semi-arid region is sustained by irrigation with water imported from outside the basin and with pumped groundwater. In combination, the aridity, peculiar topography, and geology of this basin have combined to give rise to physical as well as chemical problems that greatly affect the groundwater and soil resources of the valley.

As can be seen in Figure 5, the Great Central Valley is a prominent intermontane valley, about 640 km long and 80 km wide. It is bounded on the east by the Sierra Nevada range and on the west by the Coast Ranges. At the southern extremity of the valley, the Sierra Nevada and the Coast Ranges are linked together by the Tehachapi Mountains. Because of peculiar sedimentary depositional conditions, the southern third of the San Joaquin Valley is an enclosed inland basin known as the Tulare Basin. The area north of the Tulare Basin is drained by the San Joaquin River, which flows to the north.

Throughout the San Joaquin Valley, productive aquifers with high quality water occur within the soft unconsolidated sedimentary formations down to depths of more than 600 meters. During the 19th century, a prominent artesian belt of flowing wells occupied the axis of the San Joaquin Valley and the lower parts of the Tulare Basin. This region coincided with swamps, marshes and wetlands, showing that it was the discharge area for regional groundwater flow systems of the intermontane basin. Clearly, regional forces from the Sierra Nevada on the east and the Coast Ranges on the west provided the force that sustained the upward movement of groundwater in the discharge area.

Following the availability of deep-well turbine pumps, the San Joaquin Valley experienced intensive pumping of groundwater for irrigation purposes starting from about 1910. Soon, the artesian wells stopped flowing and the artesian belt that occupied several thousand square kilometers disappeared Figure 6). Further pumping continued, especially on the westside, along the foothills of the Coast Ranges where surface water was too scant to support irrigation. By the 1950s, the groundwater overdraft resulted in a prominent belt of land subsidence parallel to the Coast Ranges (Figure 7), exceeding 8 meters at some locations. Groundwater withdrawal clearly could not go on at these excessive rates for long.

Since the 1950s, irrigated agriculture in the San Joaquin Valley has benefited greatly from two major multi-purpose water projects, the federal Central Valley Project and the State Water Project. The Delta-Mendota Canal of the Central Valley Project and California Aqueduct of the State Water Project move immense quantities of water uphill over several hundred kilometers from the basin of the Sacramento River in the north. The importation of this water significantly helped reduce groundwater withdrawals in the San Joaquin Valley, curtailing subsidence of the land.

Although the importation of large quantities of water from the Sacramento Basin helped to bring more acreage under cultivation and limit land subsidence, it gave rise to more serious problems of groundwater quality. The presence of the artesian belt and wetlands along the axis of the San Joaquin Valley indicates that these discharge areas are dominated by vertical movement of water with very low horizontal water movement. Thus the axis of the Valley is naturally vulnerable to gradual accumulation of salts present in the imported water. It has been estimated that between 1985 and 1994 salt was accumulating in the valley at an annual rate of about 800,000 metric tons [Orlob, 1990, 1999]. This excess salt cannot be easily drained out of the Valley both because the natural flows of the San Joaquin River and its tributaries have been drastically curtailed by the construction of many dams, and because horizontal groundwater velocities towards the north are extremely small.

To maintain agricultural productivity under these conditions, farmers have resorted to the use of agricultural drains to remove the excess salts from the root zone and transport the salts away. However, the salts remain within the San Joaquin Valley because no physically and politically feasible method of exporting the salts into the San Francisco Bay or the Pacific Ocean has been developed. In all, over 400,000 hectares of land in the San Joaquin Valley are affected by serious salinity problems and shallow water tables. Furthermore, roughly 2,000 hectares become uncultivable each year because of unacceptable salt accumulation.

At present, much remains to be understood about the potential long-term impact of irrigated agriculture and importation of irrigation water on the groundwater resources of the San Joaquin Valley. However, existing information indicates that groundwater and soils are gradually being degraded by the accumulation of salts. Although farmers are able to locally succeed in overcoming salinity through the installation of drains, it is doubtful if modern technology can successfully overcome the enormous forces of the regional groundwater system that ultimately dictate the accumulation of salts in the arid, poorly-drained San Joaquin Valley.

SUBSURFACE AQUIFER PROTECTION

Sustainability and Attributes of Aquifers

In a general sense, subsurface aquifer protection is part of the larger issue of the sustainability of the hydrologic cycle. For our purpose, an aquifer is a geologic entity that can produce economic quantities of water. The word *economic* is significant because it implies a value of water to human society and a dependence of society on the aquifer for its survival and well being. In this sense of economy and survival, society relies on aquifers for domestic and municipal water supplies, agriculture, and industry. As we have seen from the examples of the Santa Clara and San Joaquin Valleys of California, aquifers are vulnerable to physical as well as chemical damage from their development. The goal of modern groundwater resources engineering and policy is to manage aquifers judiciously so that the benefit they bring to society can continue for indefinitely long periods of time. This essentially is the notion of long-term sustainability of aquifers, which provides a basis to define subsurface aquifer protection and to devise means of its implementation.

The wish that aquifers continue to provide benefits to society for long - and even indefinite - periods of time is based on the premise that aquifers are open systems subject to replenishment each year from the upper part of the hydrologic cycle. In addition, they also possess the important ability to store and release water. Because of these attributes, aquifer systems are rightfully recognized as dynamic groundwater reservoirs. These characteristics of annual replenishment and storage lie at the heart of issues related to subsurface aquifer protection.

The groundwater system has the ability to store a portion of the annual precipitation that infiltrates to the water table. In a simplistic sense, an aquifer is sustained if the average quantity of water extracted and naturally discharged annually approximately equals the annual replenishment. However, this approach is inadequate for various reasons. First, annual precipitation is subject to variability on several time scales. Periodic occurrences of several continuous years of below or above normal rainfall are a rule of nature. As a result, annual replenishment to the groundwater reservoir is remarkably variable. This is exacerbated by the fact that periods of highest groundwater demand coincide with those of low precipitation and recharge. Second, the ability of subsurface aquifer systems to store water is finite and small. Except for shallow unconfined systems, aquifers and associated aquitards can take into storage infiltrating meteoric water only through their ability to change porosity by very small amounts. Shallow unconfined aquifer systems, on the other hand, can take into storage much larger quantities of water through a change in saturation. Finally, the rate of recharge can be extremely slow, especially for deep aquifers. Because of these attributes, confined aquifers, which lie at greater depths than unconfined ones, are particularly vulnerable to rapid depletion. Unconfined aquifers, despite their larger ability to take water into storage, have limited sustained yields because they generally communicate directly with surface bodies and often contribute to base flow in streams. Because of this, overdraft of shallow aquifer systems can, in some cases, significantly affect neighboring terrestrial ecosystems through declines in the water table.

Therefore, subsurface aquifer systems can only play the role of dynamic storage reservoirs or buffers that help moderate the effects of uncertain climatic variations. In essence, groundwater storage must be judiciously managed to balance excess water available for recharge during years of above-normal rainfall with satisfying water demands during periods of drought. In the Santa Clara Valley, groundwater is managed in this way by using surplus water for artificial recharge and increasing groundwater extraction during years of surface water deficit. It must be noted, however, that Santa Clara Valley is presently able to meet its water uses because it is able to import the majority of its water from outside its own surface water and groundwater basins.

Protection of aquifers from overdraft thus entails integrated management of both surface water and groundwater over watersheds and groundwater basins. In regions where aquifer systems at great depth are involved, this management becomes challenging because the time lag between annual precipitation cycles and the response of deep aquifer systems is significant.

In the foregoing, we have devoted attention to the physical degradation of the productivity of aquifer systems. The chemical degradation of aquifers is a more profound issue in its long-term consequences. Groundwater quality is intimately linked with the chemistry of soils and aquifer materials, and is ultimately controlled by regional groundwater flow patterns. The time scales at which chemical reactions take place are generally larger than the time scales at which water levels and pressures change. As a consequence, once chemically degraded, it is extremely difficult or even impossible to restore water and soil quality. Such indeed is the salinity problem in the San Joaquin Valley. The regional flow patterns are such that the only way the problem of salinization can be solved is to export salts out of the valley, a politically impossible task. As agricultural technology the world over increases productivity through the addition of large quantities of fertilizers and pesticides, it becomes necessary to visualize the long-term response of regional groundwater systems to these massive inputs. Technology, it appears, is very efficient in solving short-term problems of crop productivity, isolated from potential impacts on other components of the natural system. Experience gained over the past several decades suggests that the time has come to seriously address the long-term consequences to hydrogeological systems arising from aggressive physical and chemical manipulations of natural resources.

Implications to Water Management

Aquifers are spatially and temporally complex, interconnected, difficult-to-predict open systems which are vulnerable to depletion, physical and chemical degradation, and the inducement of secondary environmental consequences. In order to sustain the benefits of aquifers over the long term, hydrogeologists and groundwater managers must expand their scales of consideration, account for uncertainty, and pursue aggressive data gathering policies.

In the preceding discussion, we noted that the hydrologic cycle operates at multiple temporal and spatial scales, and is interconnected with adjacent ecosystem components. The shift from simple resource exploitation to sustainable resource use is inherently a process of expanding the scales of concern. Instead of merely locating productive aquifers, pumping groundwater, and resolving disputes, groundwater management must now provide a reliable, sustainable supply of water of a certain quality while preventing and correcting any adverse environmental effects. The emphasis of management has to change so that the available resource is utilized in an efficient, sustainable, and equitable manner contributing to the social well-being of the broader community [Das Gupta, 1998]. In other words, the goal must be to sustain natural and social systems instead of a single variable, such as yield.

The logical place to begin to expand considerations is with spatial and temporal scales. Individual aquifers usually cross boundaries of management and jurisdiction. Furthermore, real aquifers are not the discrete boxes that managers and modelers may consider them to be. Hydrogeologic processes, such as regional groundwater flow and pumping-induced quality degradation, are not restricted to single aquifers and often occur over large spatial scales. Clearly, a basin-wide approach is an appropriate initial scale of operation. In a similar manner, the temporal scales of groundwater behavior do not conform to human conventions, span a broad range, and include very large scales. Consequently, groundwater managers and engineers must operate at a wide range of spatial and temporal scales that generally do not coincide with convenience.

Aquifer management must also enlarge its considerations from groundwater *per se* to larger natural and social systems; that is, we must expand our scale of knowledge. It is widely accepted among scholars of water resources that the study and management of groundwater and surface water must be integrated because alterations to one part of the greater hydrologic cycle will affect others. Furthermore, water resource planning should be coordinated with land use and economic planning, such as urban development and human health programs. One approach for this coordination is integrated water management, which is an attempt to formalize and model hydrological, ecological, administrative, social, and economic interrelations [Kuijpers, 1993]. However, its complexity and institutional barriers have hindered implementation.

Management and modeling of groundwater resources must acknowledge and incorporate uncertainty and complexity [Quinodoz, 1998]. The first source of uncertainty, incomplete and inaccurate hydrologic characterization, can be reduced but not eliminated through data acquisition. Knowledge of the hydrogeologic system is critical because, as noted above, aquifers have finite and often small storage, and the rate of recharge is slow. The second source of uncertainty is the frequency and magnitude of external events. These are the forcing functions and boundary conditions in hydrogeologic models. Borrowing from ecology, adaptive management offers a framework to address the complexity and uncertainty of future events [Sophocleous et al, 1998].

These sources of uncertainly indicate the need for vigilant monitoring of aquifers. Integrated monitoring of water resources is an issue of infrastructure. The collection of meteorological data and stream discharge data are now readily accepted as part of society's need for basic data on natural resources. Yet the same recognition does not extend to the monitoring of groundwater systems, which need to be monitored over long periods of time. Attitudes of water managers need to change in regard to sustained monitoring of groundwater systems. All levels of government should take an active role in monitoring of resources and data distribution. This allows hydrogeologists and groundwater managers to upgrade their knowledge base of the system attributes, as well as to extrapolate the data for planning. However, we have seen that such planning may be limited to the short term.

This approach of expanding scales while acknowledging uncertainty, and gathering data while remaining flexible, will help prevent aquifer depletion, physical or chemical degradation, and secondary environmental impacts resulting from aquifer utilization. It represents an alternative to simple technological solutions, and addresses the reality of large scale, interconnected systems.

Acknowledgments

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References

Belitz, K. 1990: Character and evolution of the groundwater flow system in the central part of the western San Joaquin Valley, California, Water Supply Paper 2348, U. S. Geological Survey, 28 p.

Das Gupta, A. 1998: Strategic approaches towards sustainable groundwater resources development and management - *Water Resources Journal*, **42**, 1-7.

Division of Water Resources, State of California. 1933: Santa Clara Investigation, Bulletin 42, 265 p.

Erskine, M., Batow, A. and Lettis, W. 1992: Field guide to the tectonics of the boundary between the California Coast Ranges and the Great Valley of California, Amer. Assoc. Petroleum Geol., Pacific Section, Bakersfield

Freeman, V. 1968: *People - Land - Water: Santa Clara Valley and Oxnard Plain, Ventura County, California*. Lorrin L. Morrison, Los Angeles, 227 p.

Kuijpers, C. 1993: Integrated water management in the Netherlands: Myth of practice? - In *Water for Sustainable Development in the Twenty-First Century*, A. Biswas, ed. Oxford University Press, Delhi, pp. 116-125.

Meinzer, O. 1937: Land subsidence caused by pumping - *Engineering News Record*, **118**, 715.

Orlob, G. T. 1991: San Joaquin salt balance: Future prospects and possible solutions, in The Economics and Management of Water and Drainage in Agriculture, Kluwer Academic Publishers, Boston, pp. 143-168.

Quinodoz, A. 1998: Managing uncertainty in yield estimates - In *Perspective on Sustainable Development of Water Resources in Kansas*, M. Sophocleous, ed. Kansas Geological Survey Bulletin 239, pp. 200-209.

Rappleye, H. 1933: Recent areal subsidence found in releveling B *Engineering News Record*, **110**, 845.

Sophocleous, M., Buddemeier, R., and Buchanan, R. 1998: Evolving sustainability concepts: Modern developments and the Kansas experience In *Perspective on Sustainable Development of Water Resources in Kansas*, M. Sophocleous, ed. Kansas Geological Survey Bulletin 239, pp. 87-95.

Stohsnet, E. E., 1937: Santa Clara Valley subsidence has now reached 5 feet, - *Engineering News Record*, **118**, 479

Tibbetts, F. and Kieffer, S. 1921: *Report to Santa Clara Valley Water Conservation Committee on Santa Clara Valley Water Conservation Project*. Santa Clara Valley Water Conservation Project, San Jose, 243 p.

Figure 1: Relief map of Santa Clara Valley, California (From Stream Care Guide for Santa Clara Valley, Santa Clara Valley Water District, circa 1990)

Figure 2: Decline in water levels and groundwater draft in the Santa Clara Valley following the introduction of deep-well turbine pump (From Division of Water Resources, 1933)

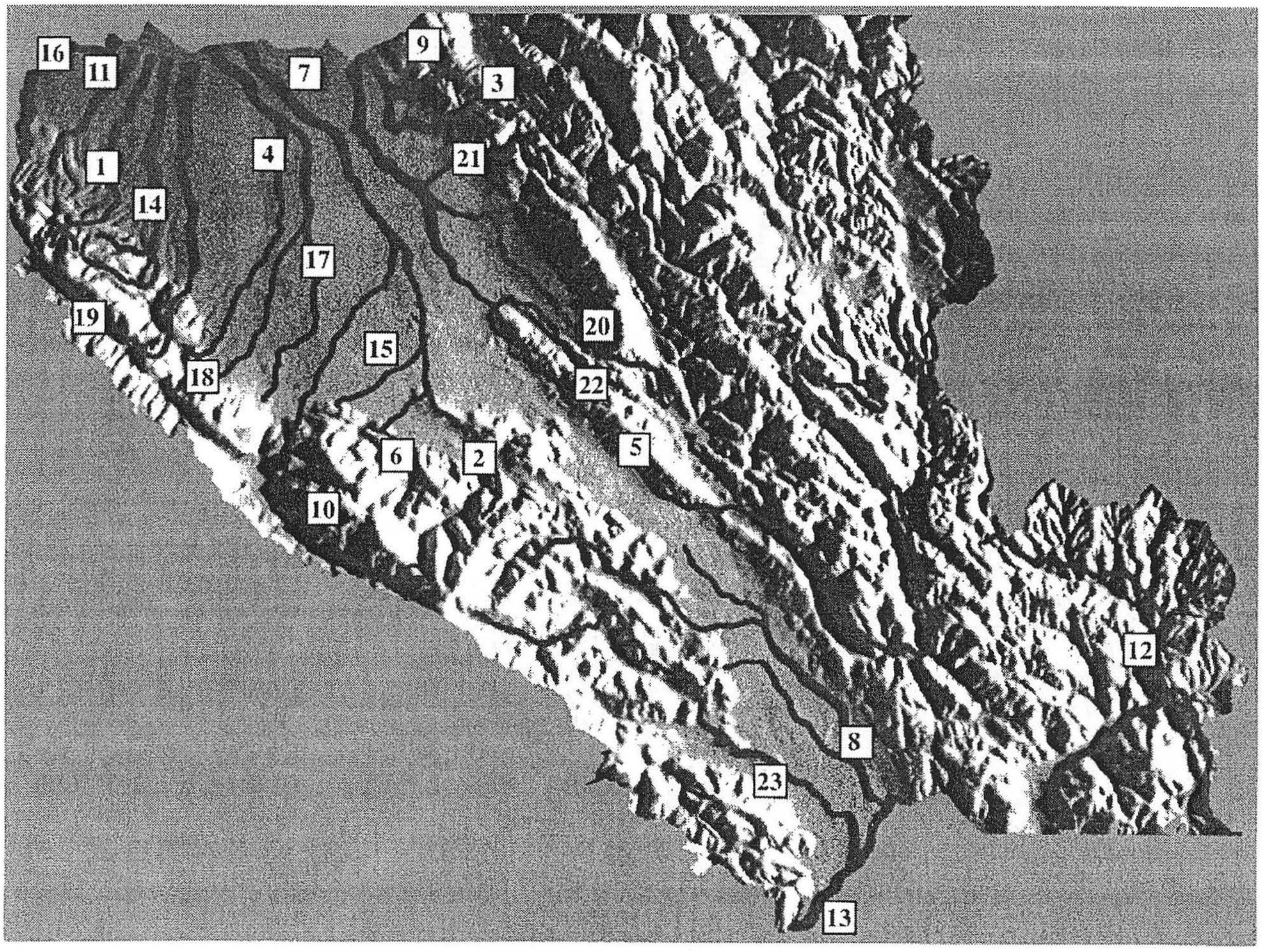
Figure 3: Land subsidence near San Jose in Santa Clara Valley, California, 1935-36 (From Stohsnet, 1937)

Figure 4: The Santa Clara Valley water supply system, California (From Discover Water, Santa Clara Valley Water District, 1991)

Figure 5: General map of the Great Central Valley, with the San Joaquin Valley occupying the southern half. Stippled area indicates the Sierra Nevada Range. Dotted line delineates the valley basin (From Erskine et al., 1992)

Figure 6: A memorial to the artesian belt that once occupied the San Joaquin Valley. It disappeared due to groundwater over draft

Figure 7: Land subsidence on the west side of the San Joaquin Valley, 1926-1972 (From Belitz, 1990)



1. Adobe Creek
2. Alamitos Creek
3. Berryessa Creek
4. Calabazas Creek
5. Coyote Creek
6. Guadalupe Creek
7. Guadalupe River
8. Llagas Creek
9. Los Coches Creek
10. Los Gatos Creek
11. Matadero Creek
12. Pacheco Creek
13. Pajaro River
14. Permanente Creek
15. Ross Creek
16. San Francisquito Creek
17. San Tomas Aquino Creek
18. Saratoga Creek
19. Stevens Creek
20. Thompson Creek
21. Upper Penitencia Creek
22. Upper Silver Creek
23. Uvas-Carnadero Creek

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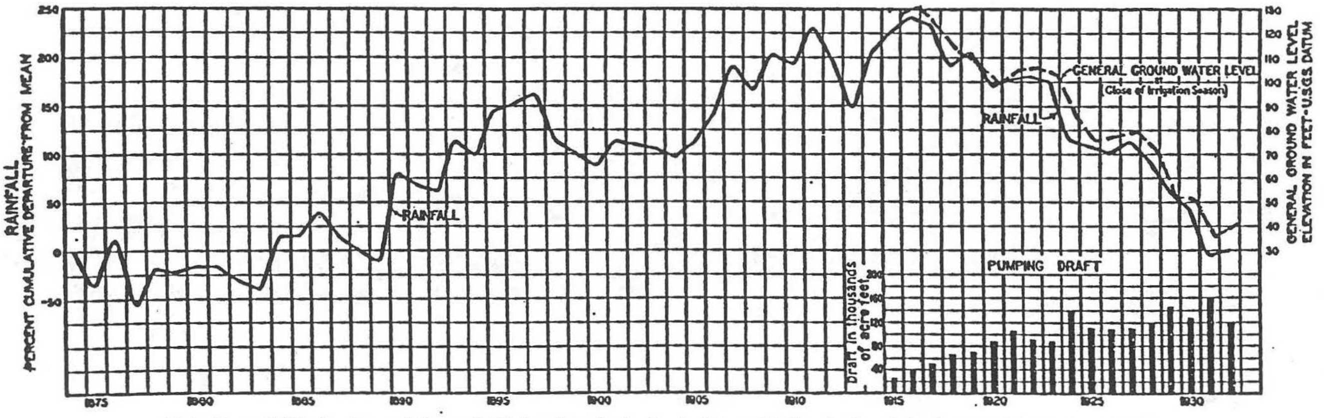
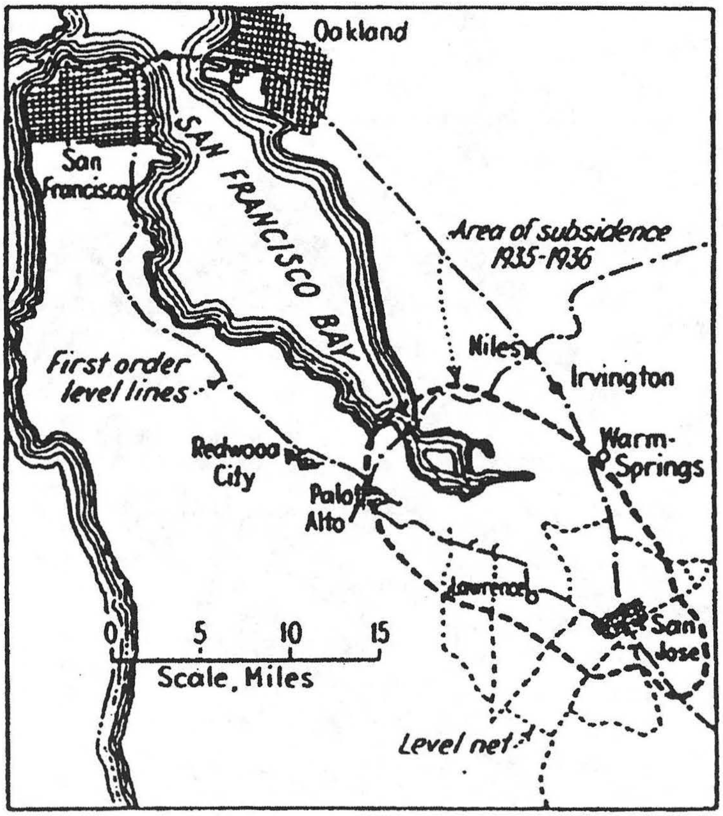


Relation of Fluctuation of Ground Water Levels in Santa Clara Valley to Precipitation and Pumping Draft.

Figure 2: Decline in water levels and groundwater draft in the Santa Clara Valley following the introduction of deep-well turbine pumps (From Division of Water Resources, 1933)

FIG. 1—LOCATION of the subsiding area is in the Santa Clara Valley at the southern end of San Francisco Bay.



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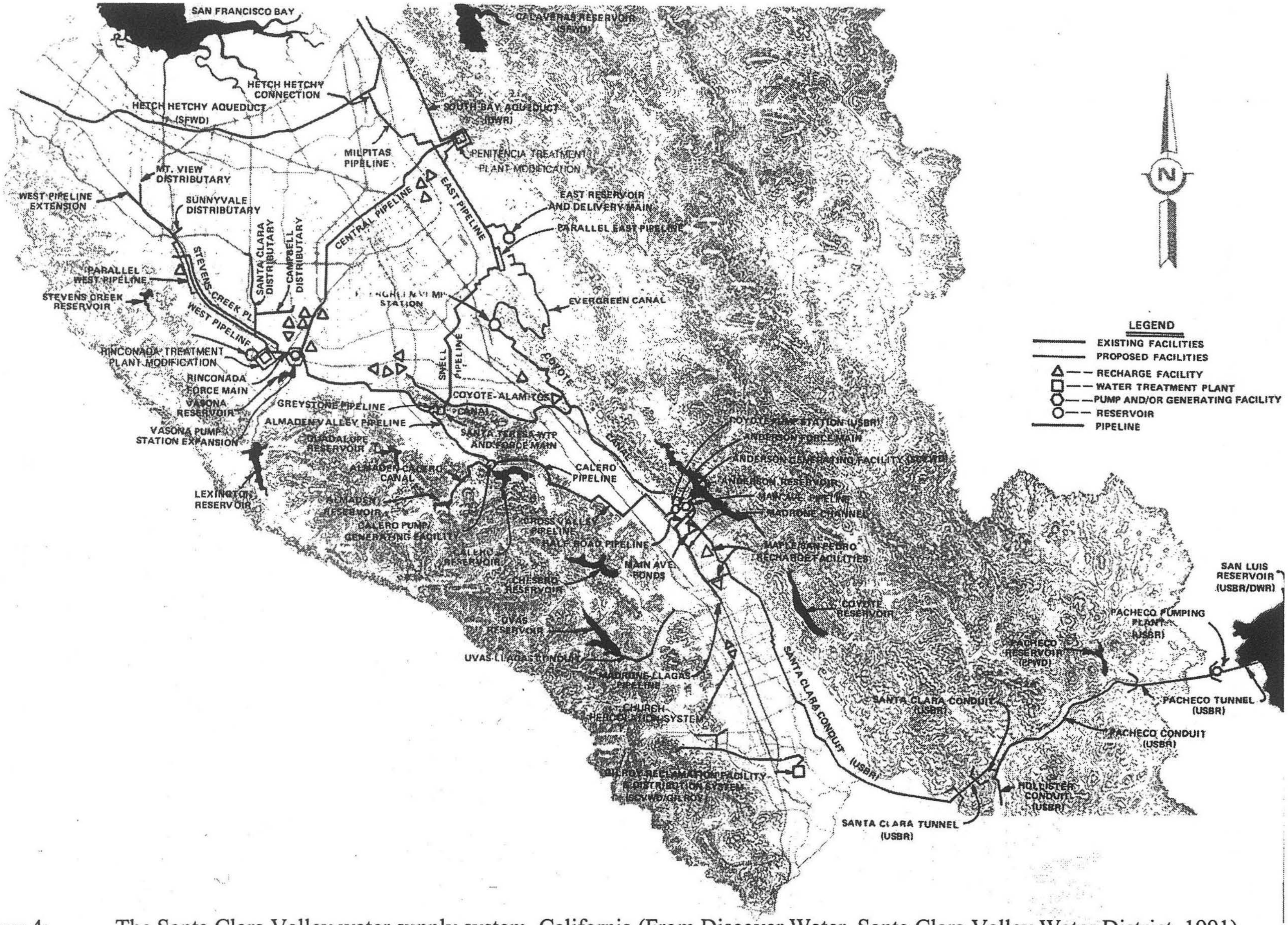

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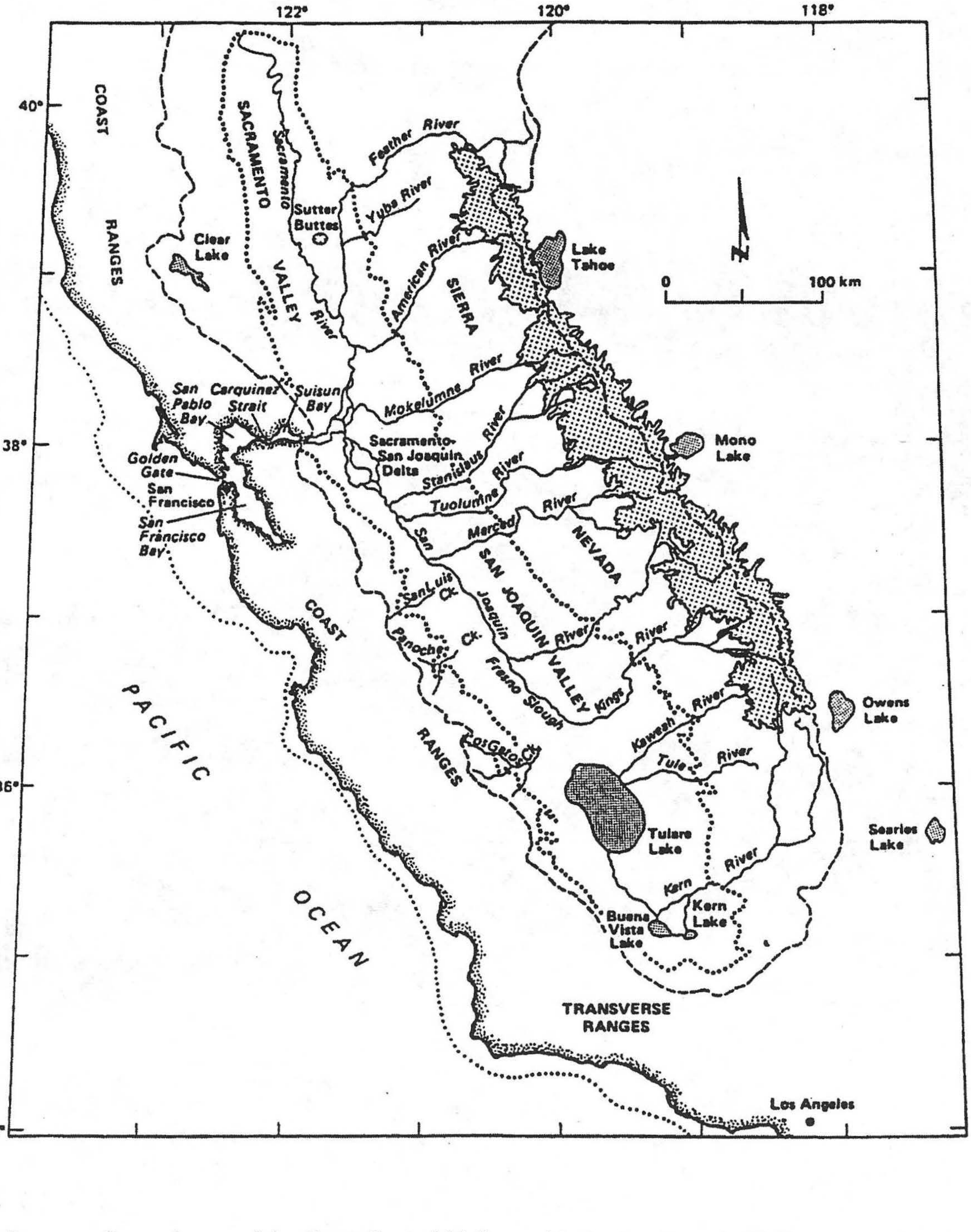

Figure 5: General map of the Great Central Valley, with the San Joaquin Valley occupying the southern half. Stippled area indicates the Sierra Nevada Range. Dotted line delineates the valley basin (From Erskine et al., 1992)

ARTESIAN WELLS

AT THIS SITE AND IN THE CLOSE VICINITY TO THE WEST, SEVERAL ARTESIAN WELLS WERE BORED WHICH HELPED IN THE EARLY DEVELOPMENT OF PIXLEY. THIS CIRCULAR CEMENT WATERING TROUGH SERVES AS A REMINDER TO US OF THESE WELLS WHICH SUPPLIED PIXLEY RESIDENTS AND TRAVELERS WITH A REFRESHING SOURCE OF WATER.

MEN BORED FOR WATER IN TULARE COUNTY AND FOUND UNDERGROUND STRATA WHICH UNDER ENOUGH PRESSURE FORCED THE WATER UPWARD WITHOUT PUMPING.

AN ARTESIAN BELT, TWENTY-FIVE MILES LONG AND FIFTEEN MILES WIDE WAS DEVELOPED ALONG THE AXIS OF THE VALLEY. THE BELT INCLUDED WHAT ARE NOW THE TOWNS OF HANFORD, GRANGEVILLE, ARMONA, LEMOORE, GOSHEN, TULARE, TIPTON, PIXLEY, AND EARLIMART. BY 1885 THERE WERE OVER 250 ARTESIAN WELLS IN TULARE COUNTY ALL OF WHICH HELPED DEVELOP THE SEMI-ARID WEST SIDE FOR AGRICULTURE.

BY THE FIRST DECADE OF THE TWENTIETH CENTURY MOST ARTESIAN WATER STOPPED FLOWING. SEVERAL EXPLANATIONS FOR THIS HAVE BEEN EXPLORED OVER THE YEARS.

ERECTED BY THE
TULARE COUNTY HISTORICAL SOCIETY
AND
PIXLEY WOMEN'S CLUB
MARCH 12, 1989

Figure 6: A memorial to the artesian belt that once occupied the San Joaquin Valley. It disappeared due to groundwater overdraft

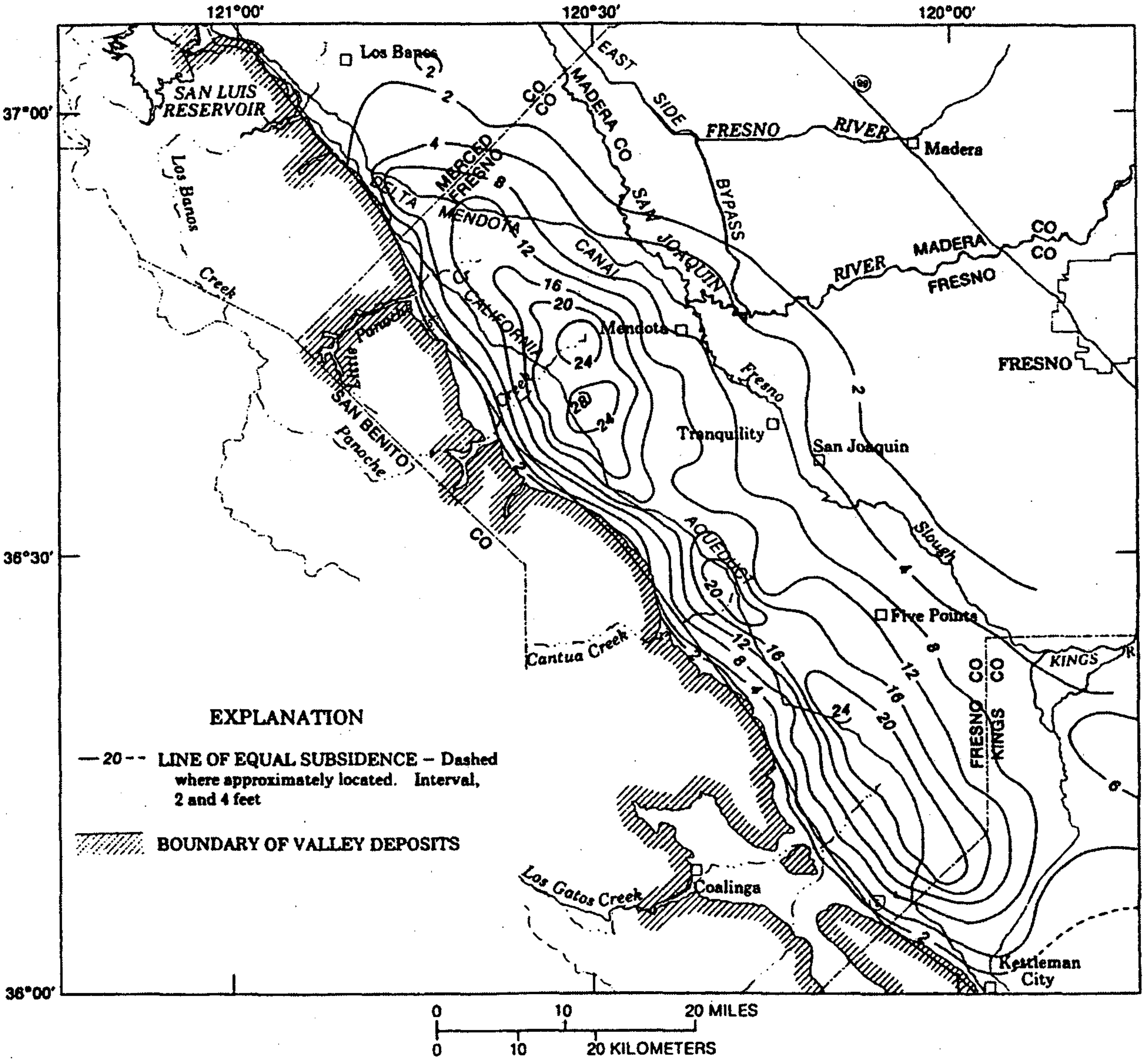

Figure 7: Land subsidence on the western side of the San Joaquin Valley , 1926-72 (From Belitz, 1990)

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