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ENVIRONMENTAL AND ECONOMIC EFFECTS OF SUBSIDENCE

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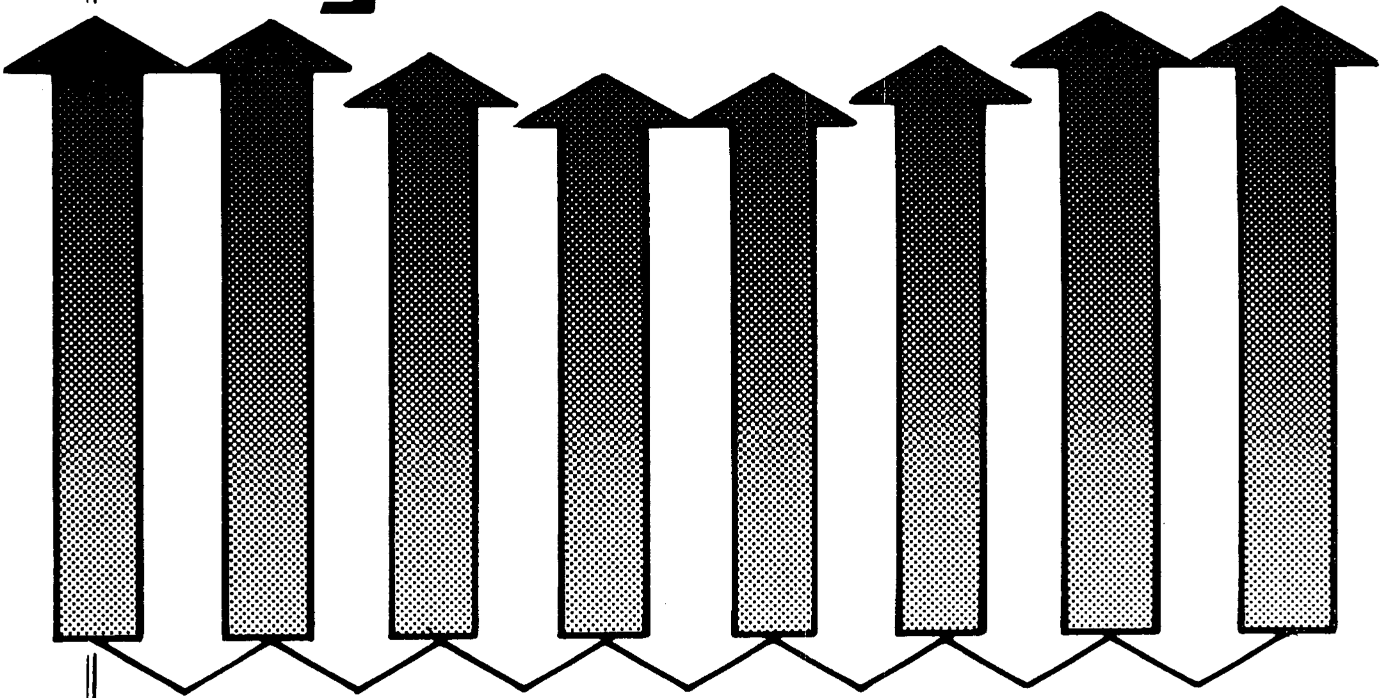
Environmental and Economic Effects of Subsidence

V.F. Viets, C.K. Vaughan, and R.C. Harding

EDAW • ESA—A Joint Venture of
EDAW, Inc. and
Earth Sciences Associates
Palo Alto, California

May 1979

Geothermal Subsidence Research Management Program



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EDAW·ESA

May 1979

Lawrence Berkeley Laboratory
Geothermal Subsidence Research Program

Category 4, Project 1

ENVIRONMENTAL AND ECONOMIC EFFECTS OF SUBSIDENCE

FINAL REPORT

Submitted to:

Lawrence Berkeley Laboratory
Berkeley, California

By:

EDAW·ESA - a Joint Venture
of EDAW, Inc. and Earth Sciences Associates
Palo Alto, California

FOREWORD

This final report on the Environmental and Economic Effects of Subsidence concerns the collection of data on actual subsided areas. This research was a part of the ongoing Geothermal Subsidence Research Program being conducted by Lawrence Berkeley Laboratory (LBL) of the University of California, under the auspices of the Division of Geothermal Energy of the U.S. Department of Energy. Table i shows the various levels of the total Subsidence program and the role of this research category within it. This project is part of the program element "Characterization of Subsidence."

EDAW•ESA, the contractor for this study, performed the work under Purchase Order 300-3902 with approximately twelve man-months of effort. EDAW•ESA is a joint venture of EDAW, Inc., an environmental planning firm, and Earth Sciences Associates, a geotechnical consulting firm. The project manager of this study was Victor F. Viets. The principal environmental and economic investigator was Christopher K. Vaughan. Principal geotechnical investigator was Richard C. Harding.

At LBL, this project was administered under the direction of Terry Simkin and technical coordination of John E. Noble. H. A. Todd was Contract Administrator.

Table i Location of Category 4, Study 1 in the Overall Geothermal Subsidence Research Program.

The Three Levels of the Subsidence Research Program.

Elements	Research Category	Projects
A. Characterization of Subsidence	1. Case Histories of Subsiding Areas and Geothermal Subsidence Potential Maps	1. Land Deformation Case Histories 2. Geothermal Subsidence Potential Maps
	2. Field Measurement Programs	1. Criteria to Distinguish Between Potential Subsidence Caused by a Geothermal Project and Subsidence Due to Other Causes 2. Monitor Horizontal and Vertical Displacement
	3. Direct Monitoring Instrumentation	1. Assess the State of the Art 2. Develop Prototypes and Conduct Field Tests
	4. Environmental and Economic Effects	1. Data Collection 2. Investigate Effects
B. Physical Theory of Subsidence	5. Physical Processes of Subsidence	Same as Research Category
C. Properties of Materials	6. Indirect Techniques to Estimate Subsidence at Depth	1. Assess Indirect Techniques 2. Develop Prototypes
	7. Laboratory Testing	Same as Research Category
D. Simulation of Subsidence	8. Subsidence Models	Same as Research Category
E. Subsidence Control	9. Reservoir Operational Control Policy	1. Industry Evaluation 2. Guidelines and Procedures

ENVIRONMENTAL AND ECONOMIC EFFECTS OF SUBSIDENCE

FINAL REPORT

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I. INTRODUCTION AND FINDINGS

The development of geothermal energy sources may result in land deformation, commonly referred to as subsidence, as a result of removal or injection of fluids from or into geothermal reservoirs. This potential problem was recognized by the U.S. Department of Energy (previously the Energy Research and Development Administration) which established the Geothermal Subsidence Research Program to study the control or mitigation of subsidence caused by energy development.

One of the difficulties encountered in planning the geothermal research program was that the nature of the subsidence problem, in terms of the damage and economic loss potentials, had not been clearly defined. It was thought that while unexpected and uncontrolled subsidence might have serious social, economic, and environmental consequences, subsidence occurring under controlled conditions might be acceptable. Reports of economic losses from subsidence due to groundwater development and other causes not related to geothermal development ranged from nominal to over $100 million at one area. To clarify the issue, this study was planned and conducted to collect data on the actual damages and economic losses that have occurred in subsiding areas and to document some of the specific local responses to subsidence in those areas.

Early in the formulation of this study, it was recognized that budgetary and schedule constraints would limit the analysis to a manageable number of case studies rather than to an analysis of all known subsidence areas. A list of all known subsidence areas was compiled from the available literature, from the International Survey on land subsidence (ISOLS) of the International Association of Hydrologic Sciences, and from interviews with key researchers familiar with many of the subsidence areas. This list of more than 70 areas was then screened to select those subsidence areas which seemed to have the best potential for providing reliable data. The screening process is described in Appendix A. Nine areas were selected for detailed case studies to collect all available data on the environmental and economic effects of the subsidence. Available information from the subsidence areas not selected as case studies was tabulated on Summary Sheets for each area and is included in Appendix B.

The nine case study areas are:

- Arizona
- San Joaquin Valley, California
- Baldwin Hills, California
- Santa Clara Valley, California

- Wilmington, California
- Las Vegas Valley, Nevada
- Houston-Galveston area, Texas
- Mexico City, Mexico
- Wairakei, New Zealand

The selection of these nine areas for case studies was an attempt to strike a balance between the number of areas studied and the detail of data collection at each area. Selected information from other areas was also collected and used in the preparation of this report. It should be pointed out that the nine areas studied represent relatively extreme cases of subsidence. All four locations in the world with more than 5 meters of vertical subsidence due to geofluid withdrawal were selected for study. Similarly, the other five areas are among those with the greatest amount of reported subsidence.

Information was collected by a combination of methods. The overall approach was to contact persons in three groups: (1) scientists and engineers studying the technical aspects of subsidence; (2) economists and others studying the environmental and economic effects of subsidence; and (3) public administrators and industry managers who might have primary data on the costs of subsidence.

Data collection methods used included: (1) literature review; (2) telephone interviews with researchers and officials; (3) personal interviews with key experts; (4) mail-out questionnaire (to Japan and other foreign countries); and (5) site visits to Houston-Galveston, Santa Clara Valley, and San Joaquin Valley. Members of the study team had previously conducted research in the Las Vegas Valley, Arizona, Wilmington and Baldwin Hills areas.

During the collection of data and preparation of the case studies, certain concepts were developed and used to distinguish primary subsidence phenomenon and their direct effects from the secondary aggravation of other hazards and their indirect effects. Figure I-1 illustrates these concepts which are important for developing an understanding of subsidence effects.

It should be noted that the data acquisition methods used for this project were limited to secondary data sources (i.e., from others who had previously studied the subject). No attempt was made to collect primary data by field work, by examining public works records, or by other labor-intensive methods. Considering overall project objectives, this use of secondary data sources was consistent with the level of effort budgeted and the number of case studies examined.

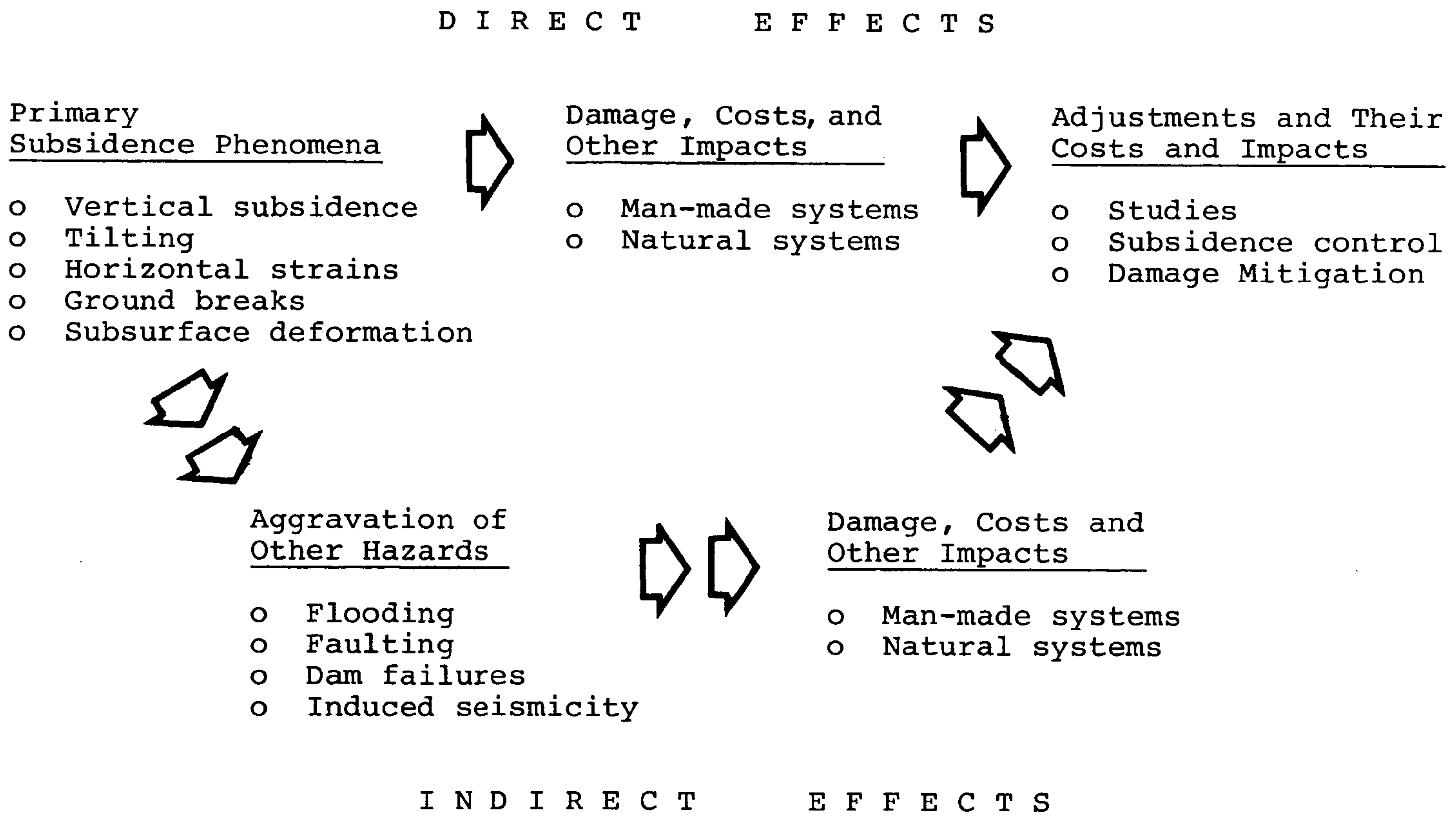


Figure I-1. Concepts Used in Examining Subsidence Effects.

General Findings

Data collected from the nine case studies illustrates a number of important aspects of subsidence:

- Environmental and economic effects directly from primary subsidence phenomena can vary from neglible to severe depending on the nature of the land uses present and the severity of the subsidence phenomena. Table I-1 illustrates this point and summarizes the data collection results. It should be pointed out that the case studies were selected partly because they offer examples of damage. This may give an initial impression that subsidence always causes significant damages and economic losses, but it must be remembered that many of the more than 60 subsidence areas not studied in detail reported little or no damage.

- Indirect effects of subsidence through aggravation of other hazards already present in the area are frequently more severe than the direct effects. Increased flooding from land subsidence was the most common indirect effect observed but aggravation of surface faulting and dam failures were also identified.

- Subsidence effects, both direct and indirect, are highly site-specific. Each case study area seems to have its own unique set of subsidence-related problems. Because of this site specific nature of the problems, it is generally not possible to use the results of one case study to predict the consequences of subsidence in another area. Additional analysis of the data may reveal similarities among the case studies or generic relationships for common types of land use.

- Subsidence phenomena such as tilting, horizontal strain, and fissuring of the ground surface appear to be more responsible for damage than the simple vertical subsidence of the ground. More analysis of the subsidence areas, however, is necessary to confirm this finding. Rates of surface deformations, such as the rate of horizontal strain accumulation, and the related amounts of natural adjustments to these deformations, such as stress relief mechanisms between structures and the surrounding soil, may also be important but no data or analysis is available for the case studies.

- The quantity and quality of data collected for all case studies were disappointing. There were several reasons for this:

Table I-1. Summary of Case Study Results

Subsidence Area	Maximum Subsidence	Subsidence Area	Examples of Direct Effects	Examples of Indirect Effects
Arizona	7.5-10 feet	625 sq. mi.	Ground fissuring effects on fields and highways/Well damages/Annual costs = $210,000	Dam failure from fissuring
Baldwin Hills	10 feet	2 sq. mi.	Minor sidewalk cracks/oil well damages	Dam failure from faulting aggravation (5 deaths, $15,500,000 damages)
Houston-Galveston, Texas	8.5 feet	4700 sq. mi.	Well damages	Structure damages from faulting. Inundation of seashore areas ($225,000,000 damages)
Las Vegas Valley, Nevada	5 feet	195 sq. mi.	Well damages = $400,000 Reservoir, pipeline, homes, roads, railroad damage from fissures = $200,000.	
Mexico City, Mexico	29 feet	88 sq. mi.	Damage to structures, utilities, streets = $1 billion; mostly due to foundation conditions.	
San Joaquin Valley, California	29 feet	5200 sq. mi.	Canal, well and irrigation system damages = $25,000,000 est.	
Santa Clara Valley, California	8 feet	254 sq. mi.	Well, sewer and bridge damage = $12,000,000 plus $200,000 annual cost for sewage plumbing.	Aggravated flood hazard = $9,000,000 for dikes.
Wairakei, New Zealand	16 feet	1 sq. mi.	Pipeline damage.	
Wilmington, California	29 feet	20 sq. mi.	Pavement, railroad, pipeline, building, bridge, and well damages = $100,000,000 including flood prevention work, plus $150,000 annual cost.	Aggravated flood hazard.

-- No comprehensive studies of the effects of subsidence were found for any of the subsidence areas.

-- Most cost data is based on estimates rather than actual records of expenditures and in most cases the assumptions used in making the estimates are not known. In addition, the timing of expenditures has not been documented so adjustments for construction cost indices are not possible.

-- Little or no information on the geographical distribution of damages within the subsidence bowls was found for any of the case studies. Similarly, there is little basis for determining what proportion of the features present were damaged. This is a major limitation to use of the data for prediction of damages in areas where subsidence may occur as a result of geothermal development.

-- In more than half of the case studies (i.e., Mexico City, Wilmington, San Joaquin Valley, Santa Clara Valley, and Baldwin Hills), the effects occurred many years ago and in many cases, successful mitigation measures were implemented long ago. The result is that any unpublished information is no longer available and few, if any, researchers are actively studying in the areas.

-- Operators of reservoirs have not been motivated to study subsidence effects except in cases where their own facilities have been damaged. Virtually all reservoir development, at least for the case studies, preceded present federal and state requirements for environmental impact studies.

-- There may be a general lack of public awareness of subsidence phenomena except in areas where other hazards, such as flooding, are aggravated.

-- Subsidence is widespread and there is a gradual onset of effects with each type of damage having a different threshold of occurrence. This is further complicated by the fact that there is not a unique set of effects that occur solely because of subsidence. Virtually all subsidence effects can occur as a result of other causes not related to subsidence (e.g., cracking of structures may result from earthquakes, foundation settlements, surface faulting, expansive soil, or poor construction).

- While there is a serious lack of reliable data on actual subsidence effects in the areas studied, it does appear that it is possible to quantitatively predict many types of subsidence effects using conventional engineering techniques to supplement the limited subsidence data. The National Coal Board of England has developed a Subsidence Engineers' Handbook which is useful for making predictions and for designing to avoid subsidence damages. The Handbook must be used with caution since it is designed for use with subsidence from underground coal mines and not for subsidence from geofluid withdrawal but the damage causing mechanisms at the ground surface (e.g., tilting and horizontal strains) are similar in many cases so the results are of considerable value. The Handbook discusses the relationships of ground movement to surface damage, the characteristics of surface damages, and structural precautions for minimizing damage to new and existing structures and pipelines. Additional guidance can be obtained from the Civil Engineering disciplines, particularly those related to soil and foundations engineering, and from a recent publication (1977) entitled Ground Subsidence by the Institution of Civil Engineers, London.

Implications for Program Objectives

Considering the overall objectives of the Geothermal Subsidence Research Program, these general findings have a number of implications:

- Subsidence effects, either direct or indirect, are clearly of potential major economic, public safety and environmental importance. Continuation of the Geothermal Subsidence Research Program is essential in order to identify and avoid or mitigate adverse effects from future geothermal development.

- Presently available data on the known effects of subsidence, including the data from this study, are adequate for developing a checklist of potential effects from future development. However, there is considerable doubt about the adequacy of the available data for use in developing quantitative models for predicting generic or site specific effects of subsidence on various types of land uses.

- Considering the apparent importance of tilting, horizontal strains, ground fissuring and rate of strain accumulation in determining the effects of subsidence, other projects in the Geothermal Subsidence Research

Program (e.g., field monitoring, subsidence models, and subsidence potential mapping) should be reviewed to insure that they will have the ability to deal with these phenomena as well as with vertical and horizontal surface movements.

- Additional information on the actual environmental and economic effects in existing subsidence areas could be developed, if needed, at least in the areas where subsidence is continuing. This information, however, would require more costly efforts than those applied to Category 4, Project 1. The efforts might include: extensive field surveys and mapping of the subsidence bowls and the existing land uses and other environmental conditions present in and near the subsiding areas; field reconnaissance and interviews to determine the location and nature of damges that have occurred; and overlay analysis of the subsidence, environmental, and damage data maps to determine cause-effect relationships for specific types of facilities.

- Regardless of which approach is used for subsequent studies of subsidence damage and economic effects, it is important that the social as well as the economic aspects of the problem be addressed. Specific study topics might include:

  - Effectiveness of institutional means, such as land use controls for avoiding adverse effects.

  - Methods for translating the results of the Geothermal Subsidence Research Program into public policies for controlling reservoir development. This would include definition of possible roles and responsibilities of reservoir developers, local governments and state and federal regulatory agencies.

  - Methods for presentation of subsidence-related issues to local areas, where development may occur, in ways that will solicit local cooperative participation in problem solving.

  - Inequities in the distribution of adverse impacts and costs from subsidence versus the distribution of benefits and profits from reservoir development.

II. SUMMARY OF SUBSIDENCE PHENOMENA, DAMAGE MECHANISMS, AND ADJUSTMENTS

A. Subsidence Phenomena and Damage Mechanisms

Removal of geofluids such as water, gas or oil or mining of solids from below the ground surface can result in the formation of a "subsidence bowl" where the ground surface has settled in response to the subsurface removal. Figure II-1 shows an idealized profile across a subsidence bowl. Actual subsidence bowl profiles depend on local geology and the depth and areal extent of the fluid removal but, in general, conform to the profile shown. As a subsidence bowl develops, a number of different types of ground surface movements, herein called subsidence phenomena, occur. First, vertical settlement of the ground surface occurs. The size of the area in which settlement occurs depends on nature and depth of the subsurface materials being removed. As the subsidence deepens, tilting of the ground surface occurs. All areas within the subsidence bowl usually tilt toward the center of the bowl. All points on the ground surface within the subsidence bowl also are displaced horizontally toward the center of the bowl. Curvature of the bowl introduces horizontal strains in the ground surface. In the outer part of the bowl, the surface is in tension and in the middle of the bowl, the surface is in compresssion. At the points of inflection in the subsidence bowl profile where the slope is a maximum, the horizontal strains are zero. If the tensional strains in the outer portion of the bowl become large enough, tension cracks or fissures in the ground surface may result. Cracking may also occur within the bowl at locations, such as existing faults, where the vertical subsidence is concentrated due to some subsurface discontinuities. The damage causing potential of these subsidence phenomena vary considerably, as discussed in the following sections, depending on the nature and magnitude of the phenomena and on the types of natural features, structures, or land uses present in the area.

It must be kept in mind that this discussion of subsidence phenomena is an oversimplification of the problem. In actual situations, the phenomena occur simultaneously and change with time as the subsidence bowl develops. There is often a problem with clearly isolating the mechanism causing damage, not only because of the complexity of the subsidence-related processes, but also because there are other physical conditions and processes that may also be contributing to the damage. Several subsidence mechanisms may be at work at the same time. In addition to subsidence due to fluid withdrawal (the focus of this study because of its implica-

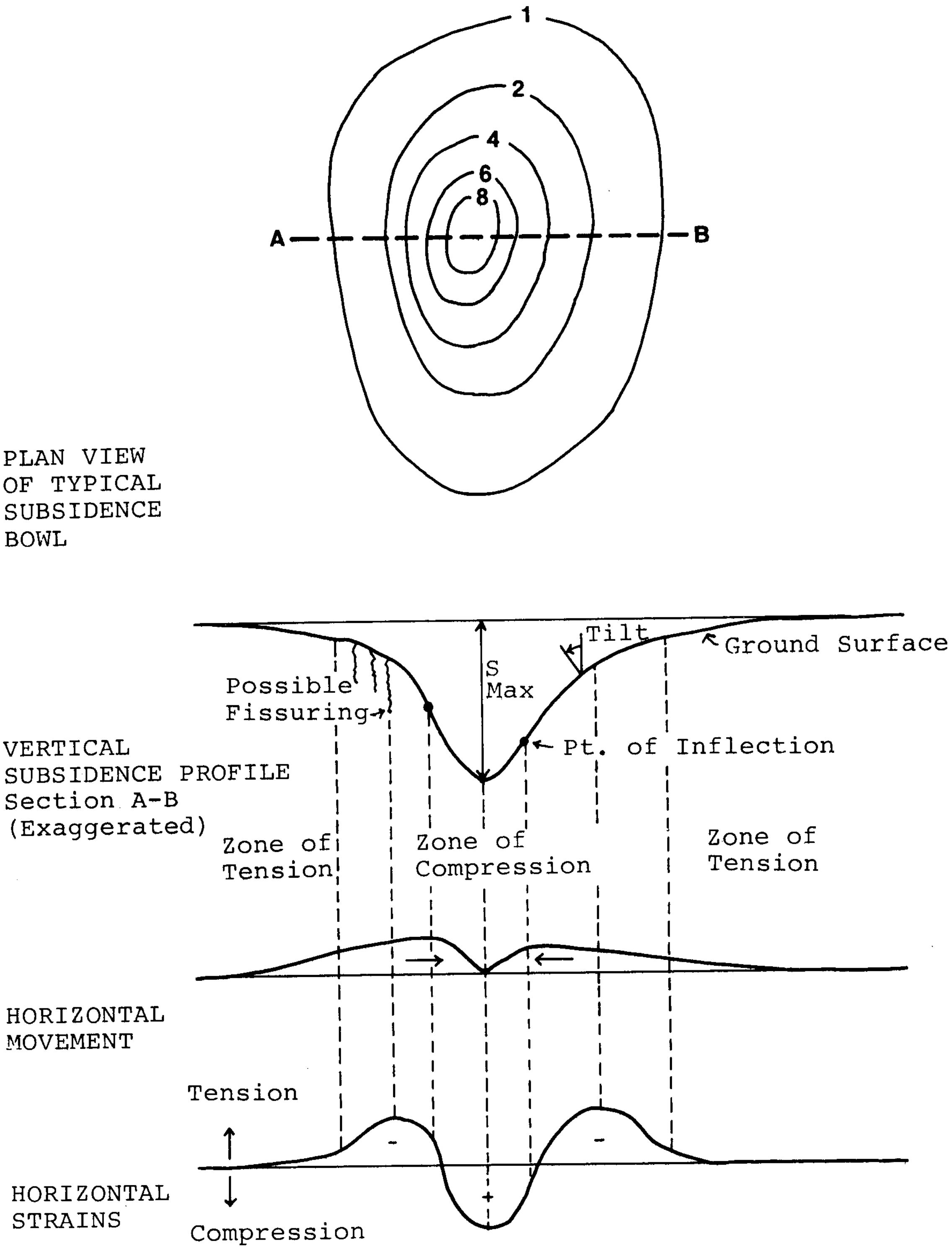


FIGURE II-1: RELATIONSHIP OF TYPICAL SUBSIDENCE PHENOMENA tions for withdrawal of geothermal fluids), subsidence may also be occurring at the same location due to compression of clay soils and physical loading by engineering structures (as in Mexico City), oxidation of deep organic soils (as in New Orleans), hydrocompaction of near-surface materials (as in the San Joaquin Valley), or from tectonic deformation. Damage from subsidence can be also disguised and difficult to recognize because it is often not dramatic, takes place over a prolonged period, and may be easily mistaken for normal deterioration or poor construction techniques and materials.

(1) Ground Surface Vertical Settlement

Total or maximum vertical settlement is the most frequently used parameter to describe subsidence. Settlement is measured vertically from the original ground surface to the deformed surface. Values of maximum settlement for the case studies are tabulated in Table II-1.

Table II-1. Vertical Subsidence Values for Case Study Areas

Case Study Subsidence Area	Maximum Subsidence	Subsidence Area	Geofluid Withdrawn
Arizona	7.5-10 feet	625 sq. mi.	Groundwater
Baldwin Hills	10 feet	2 sq. mi.	Oil & Gas
Houston-Galveston	8.5 feet	4700 sq. mi.	Groundwater/Oil/Gas
Las Vegas Valley	5 feet	195 sq. mi.	Groundwater
Mexico City	29 feet	88 sq. mi.	Groundwater
San Joaquin Valley	29 feet	5200 sq. mi.	Groundwater/Oil/Gas
Santa Clara Valley	8 feet	254 sq. mi.	Groundwater
Wairakei	16 feet	24 sq. mi.	Geothermal Fluids
Wilmington	29 feet	20 sq. mi.	Oil & Gas

Mexico City, San Joaquin Valley, and Wilmington with about 29 feet of subsidence have the maximum reported subsidence from fluid withdrawal of any locations worldwide. Numerous subsidence areas, however, reported less than three feet of total vertical subsidence. These case study areas, therefore, represent most of the areas of greatest subsidence.

Damage Causing Potential - Vertical Settlements

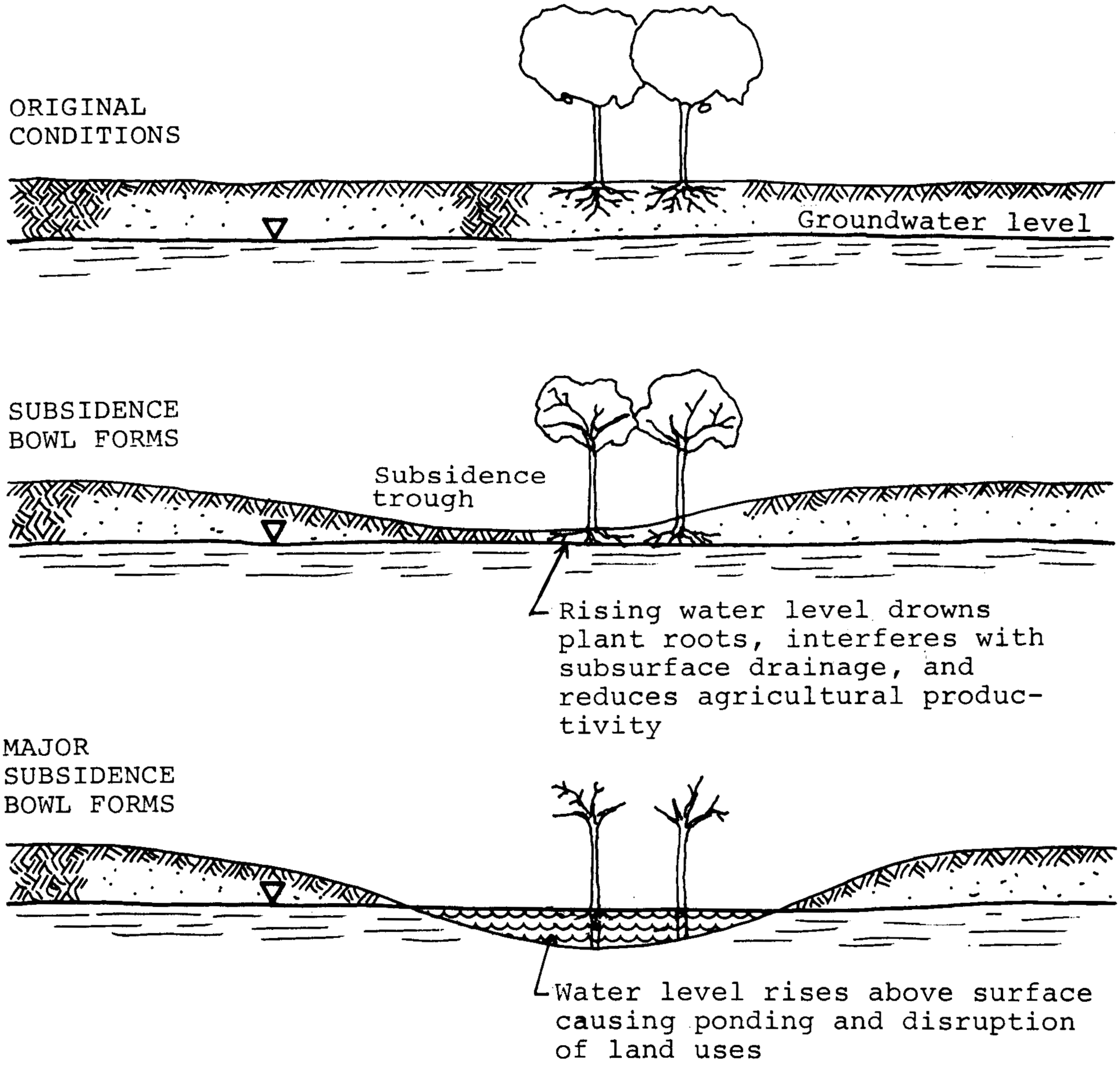
Uniform vertical settlements alone are not usually responsible for damage. Structures are generally not subject to damage from the vertical component of subsidence since a structure resting on the land surface subjected to uniform vertical settlement would maintain its locational relationship to the sinking surface.

However, when vertical settlements occur adjacent to a water body such as a river, lake, or the ocean, the increased risk of flooding in the subsidence bowl can be a serious problem. Permanent inundation of some lands and increased exposure to flooding have resulted from subsidence in Houston-Galveston; Long Beach; Santa Clara Valley; Venice, Italy; Lake Maracaibo, Venezuela; and in several Japanese coastal cities. In these areas the problems of land settlement in relationship to the water bodies far exceed in severity the problems related to other subsidence phenomena. Defense against permanent inundation and hazard of recurrent floods has required major capital investments to construct dikes, levees, pumping stations, and other facilities. Damages from vertical settlements in the case study areas are summarized in Table II-2.

In addition to increasing flooding potential, vertical settlement can cause difficulties with hydraulic systems such as canals, sewers, and streams which depend on gravity flow and can cause changes in the groundwater levels relative to the ground surface. Changes in hydraulic systems are discussed in the following section which deals with tilting. In shallow groundwater areas, subsidence of the surface can result in apparent rising groundwater levels which disrupt plant growth, interfere with subsurface drainage, and eventually cause surface ponding and disruptions in land use as illustrated in Figure II-2. These groundwater effects were not reported in the nine case study areas, but have been encountered in other subsidence areas. In some cases, permanent drains and wells with pumping stations may be necessary to avoid adverse effects. In shallow groundwater areas where water tables are perched on subsurface horizontal beds which restrict downward movement of water, a decline in groundwater levels may result if subsidence-induced fissures rupture the water-retarding beds.

Table II-2. Damage From Ground Surface Vertical Settlements Reported in Case Studies

Case Study Area	Reported Damage	Reported Dollar Value of Damage
Houston-Galveston	- Permanent inundation of shoreline areas and structures.	$250,000,000
	- Increased risk of flooding during hurricanes - possible flooding of escape roads.	N/A
	- Alteration of natural vegetation from saltwater intrusion (suspected).	N/A
	- Submergence of river mouths to create bays.	N/A
San Joaquin Valley	- Increased flood hazard (suspected).	N/A
	- Reduction of canal freeboard requiring extra construction.	$10,000,000.
Santa Clara Valley	- Required construction of levees to avoid inundation of 17 square miles.	$ 9,000,000.
	- Increased flood hazard behind levees.	N/A
	- Bridge raising required.	$100,000.
	- Pumping station required at sewage treatment plant.	$ 9,000,000. plus $ 200,000. per year for operation
Wilmington	- Required construction of dikes and land filling to avoid permanent inundation	
	- Required raising of wharves and structures for continued operation.	$100,000,000. including repair to structures
	- Increased flood hazard in diked areas.	N/A



ORIGINAL CONDITIONS

SUBSIDENCE BOWL FORMS

Rising water level drowns plant roots, interferes with subsurface drainage, and reduces agricultural productivity

MAJOR SUBSIDENCE BOWL FORMS

Water level rises above surface causing ponding and disruption of land uses

FIGURE II-2 EFFECTS OF SUBSIDENCE IN SHALLOW GROUNDWATER AREAS

(2) Ground Surface Tilt and Differential Settlement

Tilting of the ground surface toward the center of the subsidence bowl occurs in most parts of the bowl except at the edge of the bowl and in the center where the surface remains in its original orientation. In cases where fluids are withdrawn at a relatively uniform rate over a wide area, as in the San Joaquin Valley, the degree of tilt may be relatively minor or negligible. In other areas with considerable subsidence over a small area, the tilt may be considerable. Values of maximum and average tilt for the case studies are tabulated in Table II-3. These values were calculated from the subsidence profiles in the case study descriptions. The points of maximum tilt are at the points of inflection in the subsidence profiles. Tilting must be considered in two ways when evaluating damage causing potentials; rigid-body tilting and differential settlement, depending on the type of structures involved.

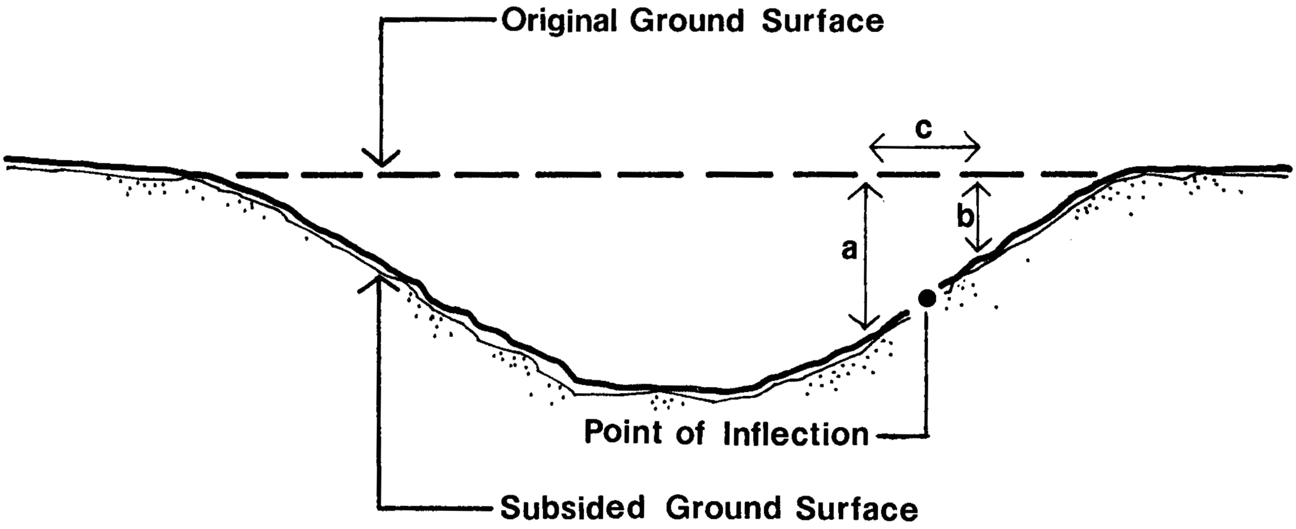
Damage Causing Potential-Rigid-Body Tilting

Tilting of the ground surface may adversely effect tall structures such as tall buildings, silos, smokestacks, and communication towers. The term tilting, as used in this context, refers to uniform or rigid-body tilting without bending deformations within the structure. Adverse effects from rigid-body tilting may include disruption of sensitive machinery, misalignment of elevators in tall buildings, and misalignment of microwave communication beams. Tilts as small as 0.0002 have been reported to affect sensitive machinery but tilts in the range of 0.003-0.005 may be generally acceptable for tall buildings. Reported damages from tilting in the case study areas are tabulated in Table II-4.

Tilting over considerable horizontal distances can change surface drainage patterns in relatively flat land and can cause changes in river hydrology through alteration of stream gradients which in turn alter natural erosion-sedimentation processes and flood carrying capacities. Formation of marshes and ponds may result from disruption of natural surface drainage. Tilting which increases stream gradients will tend to encourage erosion and increase flood carrying capacities while tilting which decreases stream gradients will have the opposite effects. Similarly, tilting can increase or decrease capacities of man-made hydraulic structures such as canals, agricultural drains and sewage collection systems and may require releveling of agricultural fields where flood irrigation is used. Tilting may also reduce the effective height of flood control levees and canal banks requiring costly reconstruction. Because of the

Table II-3. Tilt and Differential Settlement Values* For Case Study Areas

Case Study Subsidence Area	Maximum Tilt and Differential Settlement: Point of Inflection	Maximum Tilt and Differential Settlement: Average For 1/2 Bowl
Baldwin Hills	0.01	0.007
Houston-Galveston	0.001	0.0003
Las Vegas Valley	0.0007	0.0003
San Joaquin Valley:		
a. West of Mendota	-	0.0007
b. Tulare - Wasco	0.0007	-
c. Arvin - Maricopa	0.0003	-
Santa Clara Valley	0.001	0.0006
Wairakei	0.02	0.01
Wilmington	0.006	0.004



$$* \text{Tilt} = \frac{a-b}{c}$$

Table II-4. Damage From Ground Surface Tilt Reported in Case Studies

Case Study Area	Reported Damages	Reported Dollar Value of Damage
Arizona	- Land releveling for ditch irrigation.	$130,000 per year
Houston-Galveston	- Disruption of water and sewer systems.	N/A
	- Change in surface drainage patterns.	N/A
Mexico City	- Disruption of sewer system - requiring pumping stations and eventual replacement.	Major Cost
	- Excessive tilt in some buildings; releveling required.	N/A
San Joaquin Valley	- Disruption of natural and agricultural drainage.	N/A
Santa Clara Valley	- Reduction in stream gradients with increased sedimentation and decreased flood carrying capacity.	N/A
	- Changes in sewer gradients requiring reconstruction or replacement.	N/A

variability in design factors, it is impossible to accurately generalize as to the amount of slope change that is critical to hydraulic facilities. Canals with slopes of as little as 0.00004 (2.5 inches per mile) have been constructed so even very small amounts of tilting over appreciable distances can have significant effects.

Damage Causing Potential - Differential Settlement

Differential vertical settlement is the most common and one of the most potentially damaging of the subsidence phenomena. Normally, the differential settlement is represented in terms of the change in elevation between two points by the ratio of Δ/L, where Δ is the amount of differential settlement occurring over a distance L. This is the same definition as tilting but, as used here, differential settlement of a building refers to the amount of "angular distortion" or non-rigid-body tilt that the building experiences. In an idealized subsidence bowl, the greatest angular distortion also occurs at the point of inflection of the subsidence bowl's profile. Rigid structures, particularly those which occupy a relatively small surface area will experience mostly rigid-body tilting and little or no differential settlement. More flexible structures, particularly those which occupy a relatively large area will experience mostly angular distortion or differential settlement and little rigid-body tilting. Damages reported in the case studies are tabulated in Table II-5.

The results of a literature review to establish the range of angular distortion required to cause various levels of damage to different types of structures is shown on Table II-6.

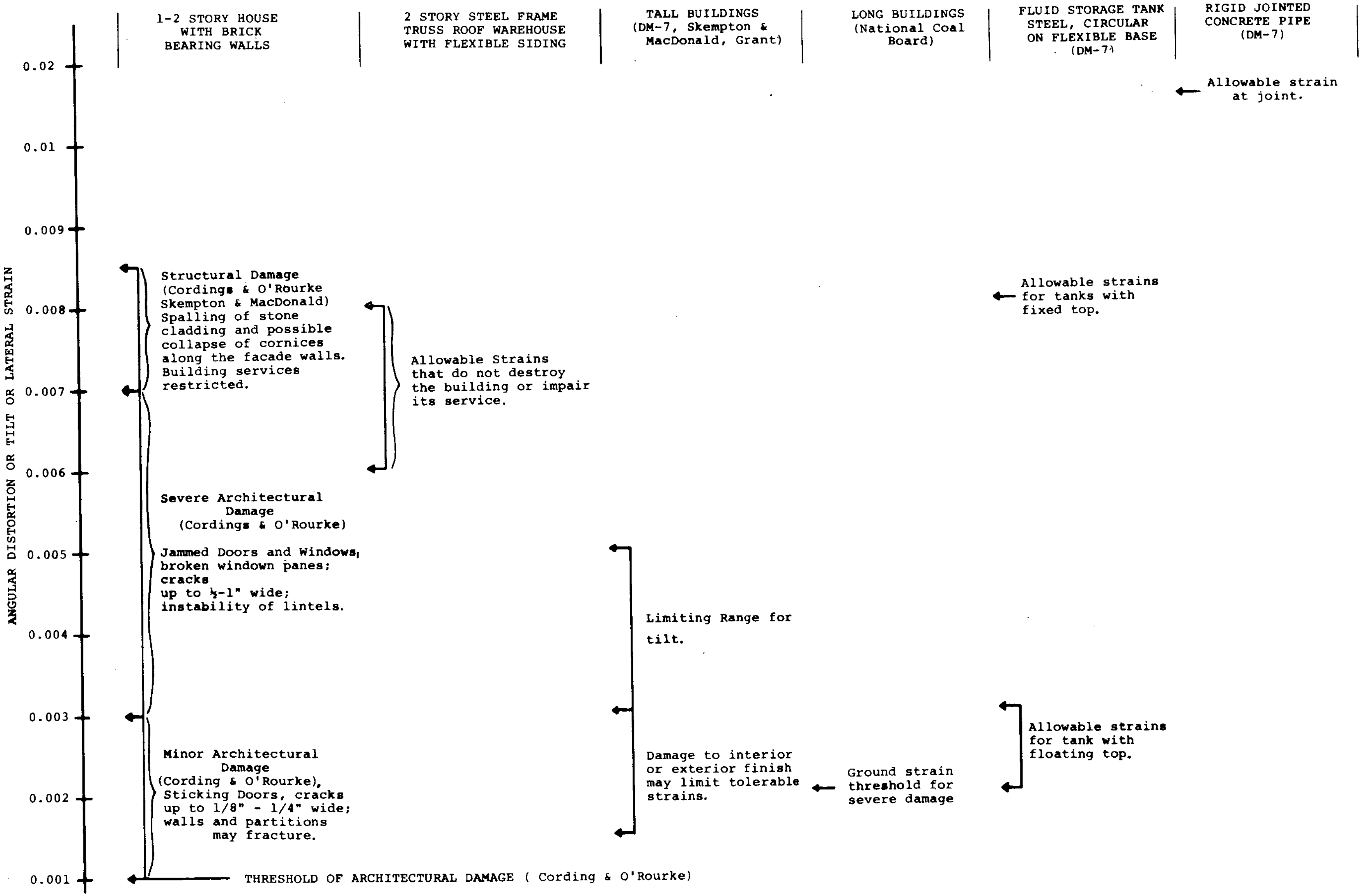
(3) Ground Surface Horizontal Displacement and Strain

When a subsidence bowl develops, not only do points on the ground surface move vertically downward, but they also move laterally toward the center of the bowl. Both tensile and compressive strains are produced in the ground surface, as shown on Figure II-1. It has been observed that there is usually no horizontal movement at the point of maximum subsidence in the center of the bowl. The point of maximum horizontal movement occurs at the point of inflection, the steepest slope of the vertical subsidence profile. Theoretically, horizontal strain at this point is zero. Compressive strains develop over the central area, and tensile strains develop in the outer portion of the subsidence bowl. Values of maximum horizontal strain computed from the subsidence profiles for the case study areas are tabulated in Table II-7.

Table II-5. Damage from Differential Settlement Reported in Case Studies

Case Study Area	Reported Damages
Baldwin Hills	Cracking of streets & highways.
Houston-Galveston	Roads & highways cracked (may be from fissuring)
Mexico City	Major damage to buildings, sewers, water systems, streets, sidewalks, tracks from near-surface & localized differential settlements.

Table II-6. The Effect of Subsidence Related Ground Surface Strains on Engineering Structures



Damage Causing Potential - Horizontal Displacement and Strain

It has been observed that horizontal strains induced in structures are sometimes less than the ground strains. In assessing the damage-causing potential of horizontal strains, it is therefore important to distinguish between ground strain and the strain transmitted to the structure. Damage from horizontal strains reported in the case studies are tabulated in Table II-8.

The results of a literature review to establish the levels of horizontal strain that may cause damage are shown on Table II-6. The total amount of strain that will accumulate in a structure depends not only on the level of strain in the underlying ground surface and the portion that is transferred to the building, but also depends on the length of the building. For instance, a short 20-foot building may be able to absorb 0.2 feet of movement from a compressional strain of 0.001 by distributing it over the structure. But for a 200-foot long structure subjected to the same strain level, the 0.2 foot shortening might concentrate at some weak point, causing severe damage. For this reason, some investigators feel that the total change in length of a structure is a better indication of damage potential than the level of horizontal strain.

Long, fairly rigid structures such as warehouses, bridges, pipelines, concrete highways, airport runways, and concrete curbs and sidewalks are most sensitive to damage from horizontal strain because they accummulate strains over long distances. Service pipe connections to long buildings are particularly susceptible to damage. Long structures with flexibility, such as asphalt pavements, or with numerous joints which can absorb strain, such as jointed concrete or clay pipe, are less sensitive to damage. Strains of about 0.0005 can cause slight structural damage while strains of 0.003 to 0.006 can cause severe structural damage. In terms of total change in structure length, changes of up to 0.2 feet may cause only slight damage while length changes of 0.4 feet and more may cause severe damage.

(4) Ground Surface Fissuring

Cracking or fissuring of the ground surface occasionally occurs in the zones of tension within the outer portions of subsidence bowls.

Table II-7. Maximum Horizontal Strain Values For Case Study Areas

Case Study Subsidence Area	Maximum Horizontal Strain
Baldwin Hills	0.001
Houston-Galveston	0.0002
Las Vegas Valley	0.0003
San Joaquin Valley:	
a. West of Mendota	0.00007
b. Tulare - Wasco	0.0001
c. Arvin - Maricopa	0.00006
Santa Clara Valley	0.001
Wairakei	0.001
Wilmington	0.0007 (0.002 measured by others; 0.0014 computed by others)

Table II-8. Damage from Horizontal Strains Reported in Case Studies

Case Study Area	Reported Damage	Reported Dollar Value of Damages
Houston-Galveston	- Pipelines damaged (may be from fissuring)	N/A
Wairakei	- Steam lines and concrete drainage channel damaged.	250,000 plus 10,000 per year
Wilmington	- Damage to long buildings, pipelines, railroads, and highways.	Major Cost
	- Damage to movable bridge due to misalignment.	N/A

Depending on the local conditions, these fissures can exceed one kilometer in length but more commonly have lengths of the order of a few hundred meters. Fissures as deep as 10 meters and with widths much less than two centimeters are commonly observed. Fissures in arid zones are often considerably enlarged by erosion, and in fact, this may be the principal hazard associated with them.

In addition to the formation of fissures, fluid withdrawal in several cases has been documented as the cause of reactivation of mo vement on pre-existing faults. When this occurs, it can cause severe differential settlements over short distances.

Cracks and fissures have been reported at Arizona, Houston-Galveston, Las Vegas, San Joaquin Valley, Mexico City and Wilmington. Differential surface or subsurface movements along pre-existing faults have been reported in Houston-Galveston, Baldwin Hills, and Wilmington.

Damage-Causing Potential - Fissuring

Fissuring disrupts surface and subsurface water flow and drainage and can damage facilities located on the fissure erosion, loss of agricultural productivity and damage to irrigation systems and drains have been reported as a result of fissuring in agricultural areas. Cracking of highways and structures have also been reported from both new fissures and from differential movement along pre-existing faults within subsidence bowls. The most serious damage that may be attributed to ground surface cracking was at Baldwin Hills where differential movement along a pre-existing fault resulted in the failure of a dam and reservoir with major loss of life and property. Clearly, this catastrophic event was unique to the Baldwin Hills subsidence bowl but it serves as a reminder of the potential consequences of unanticipated or uncontrolled subsidence phenomena. Fissuring from subsidence has been suggested as the cause of failure of an embankment of Picacho Reservoir in Arizona. In that case, the desert soils have a very low resistance to piping so water retaining structures can be easily undermined and eroded if fissuring occurs to initiate piping.

Damages from fissuring reported in the case studies are tabulated in Table II-9.

(5) Subsurface Deformation

Both vertical and horizontal deformations of the subsurface materials occur between the zone of fluid withdrawal and

Table II-9. Damage from Fissuring Reported in the Case Studies

Case Study Area	Damage Mechanisms	Reported Damages	Reported Dollar Value of Damages
Arizona	Fissuring	- Highway & railroad damage requiring increased maintenance.	Minor Cost
		- Disrupt ditch irrigation requiring fissure repair.	$130,000 per year
		- Erosion adjacent to fissures.	N/A
		- Picacho Reservoir embankment failure.	$100,000.
		- Affects routing of new aqueducts.	N/A
Baldwin Hills	Differential movement on pre-existing faults	- Dam failure; 227 homes damaged; 5 deaths, even with some forewarning.	$13,000,000 for insurance claims $ 2,500,000. for dam
Houston-Galveston	Differential movement on pre-existing faults	- Damage to 220 structures on faults.	up to $17,000,000.
		- Cracks in roads and sewer systems.	N/A
Las Vegas Valley	Fissuring	- Damage to a few homes.	Minor Cost
		- Damage to streets & sidewalks.	$2,000. per year
		- Damage to pipelines.	Minor Cost
		- Damage to two reservoirs requiring abandonment or replacement.	$100,000.
		- Damage to railroad grade.	N/A
San Joaquin Valley	Minor fissuring around wells	- None reported.	N/A

the ground surface. Vertical subsurface deformations occur within the zones of fluid withdrawal due to vertical compaction of the geologic formations and within the overlying materials as they subside because of the loss of support. Horizontal movements and strains develop below the surface just as they do at the surface. These vertical and horizontal deformations may be relatively uniform or concentrated along geologic discontinuities and pre-existing faults.

Damage-Causing Potential - Subsurface Deformation

The vertical compression and horizontal and vertical shearing of strata at depth can result in serious damage to wells which pass through the zone of deformation. Vertical subsurface deformation can cause wells and well casings to be compressed and rupture or, if there is not much friction between the well casing and the rock material, subsurface deformation can cause wells to protrude from the ground as the ground surface sinks away from the well head. This mechanism is associated principally with groundwater production and has caused damage to wells and well casings in Arizona, the Houston-Galveston region, Las Vegas Valley, Mexico City and in the San Joaquin and Santa Clara Valleys to name some of the most significant experiences. Damages from subsurface deformation reported in the case studies are tabulated in Table II-10.

Some damaged wells have been abandoned, others have been repaired at depth, still others that have protruded from the ground have been cut off and the pump replaced at the new ground surface level. New wells in known subsidence areas may be installed with a sleeved casing to compensate for vertical compression along the axis of the casing.

The only notable report of damage from horizontal displacement at depth comes from the Wilmington Oil Field at Long Beach where numerous oil wells were sheared off at depth due to horizontal strains and their relief along pre-existing fault planes.

B. Adjustments to Subsidence

With an interest in the full range of possible adjustments to subsidence and the eventual definition of an optimal set of adjustments to subsidence due to geothermal resource development, an effort was made to categorize adjustments that are reported or inferred to have been made in areas experiencing subsidence. The classes of adjustments are as defined by Burton, et. al. (1968) and commonly used by natural hazards investigators (see also Natural Hazards, White, G. F., ed. 1974). Examples of the types of adjustments

Table II-10. Damage from Subsurface Deformations Reported in the Case Studies

Case Study Area	Reported Damage	Reported Dollar Value of Damage
Arizona	- Water wells damaged	$57,000 per year
Houston-Galveston	- Water wells damaged by compression & protrusion above surface	N/A
Las Vegas Valley	- Protrusion, deformation and breakage of about 100 water wells	$400,000 to date
San Joaquin Valley	- Water well damage	N/A
Santa Clara Valley	- Water well damage to about 2,000 wells	$4,000,000 est.
Wilmington	- Oil well casing damage from protrusion and subsurface shearing plus well raising for flood prevention	$20,000,000

to subsidence are listed in Table II-11. Some of the examples listed are from British practices and have not been reported in the case studies. For additional adjustments to reduce or prevent damage, refer to Ground Subsidence, 1977; Institution of Civil Engineers, London.

The adjustments practiced in the nine case study subsidence areas are shown in Table II-12. Subsidence from fluid withdrawal is a 20th century phenomenon, and has occurred in large volumes of groundwater or oil and gas. As a result, subsidence in these areas has been seen as a technological problem. Most of the adjustments identified are characteristic of the industrial or post-industrial techno-social stages. Adjustments characteristic of the industrial techno-social stage are made by government agencies, are capital intensive engineering projects and tend to be inflexible. Responses characteristic of the post-industrial techno-social stage tend to be heavily based on scientific study and emphasize the development that may include capital intensive engineering solutions but also may include the development of institutions and laws to govern man's manipulation of the environment.

For most of the case study areas there has been considerable scientific study of the subsidence and related problem and adjustments have included changes in institutional systems and laws as well as capital-intensive technological solutions. A typical pattern of comprehensive approach to the subsidence problem is for regulation or taxation of groundwater pumping to be implemented at the same time that alternative water resources are offered. This "carrot and stick" solution has been implemented in Houston-Galveston, Mexico City, the Santa Clara Valley, Wilmington, Venice and numerous coastal cities in Japan.

Some of the adjustments identified in the case studies may not be applicable to management of geothermal resource developments. For example, in several cases of subsidence due to groundwater withdrawal, the decision was made to develop alternative water supplies and to curtail groundwater withdrawals. Such a step would be undesirable from the point of view of the reservoir operator.

Other adjustments, however, are suited to geothermal development and are in practice or under consideration. Specifically, the reinjection of geothermal fluid by injection wells, a process developed and used in oil and gas fields, is an adjustment readily transferrable to geothermal production. Much like the experience with the Wilmington Oil Field, reinjection of fluid will not only aid in controling subsidence, but may also improve production from the field.

Table II-11. Classification and Examples of Adjustments to Subsidence

Class of Adjustment	Adjustment
Study the Problem	- Relevelling studies - Scientific studies - Economic studies
Bear the Loss	- Law suits - Abandonment
Repair Damage	- Repair buildings, roads, railroads - Land filling - Relevel agricultural fields - Repair port facility
Remedial Measures to Prevent Damage	- Install sleeved joints in wells - Construct dikes and levees - Construct seawall - Install pumping stations - Install flexible coupling on piping and aqueducts
Countermeasures to Affect the Cause	- Limit fluid withdrawal - Reinject fluid - Develop alternative resources
Develop Institutional Framework	- Adopt land use controls - Form regulatory framework to control pumping

Table II-12. Adjustments to Subsidence in the Case Study Areas

	CASE STUDY SUBSIDENCE AREAS								
Adjustments to Subsidence	Arizona	Baldwin Hills	Houston-Galveston	Las Vegas	Mexico City	San Joaquin Valley	Santa Clara Valley	Wairakei	Wilmington
Adjust to Losses	X	X	X	X	X	X	X	X	X
Remedial Measures to Prevent or Reduce Damage	X	X	X		X		X		X
Countermeasures to Affect Cause of Subsidence		X	X	X	X	X	X		X
Develop Alternative Resources			X	X	X	X	X		
Study the Problem		X	X	X	X	X	X	X	X
Institutional Changes			X		X		X		X

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III. CASE STUDIES

A. ARIZONA

(1) Introduction

Subsidence has been identified in several desert basins of central and southern Arizona, as shown in Figure III-A-1. Because of the arid climate of these basins, surface water supplies are small, and groundwater development for irrigated agriculture began on a relatively large scale in the early 1940's. By the mid-1960's, 1,000,000 acre-feet of water had been "mined" from the alluvium, causing water level declines of up to 360 feet. Thus far, environmental impacts due to subsidence have been relatively small, largely because of the remote and undeveloped character of the regions where it is occurring. Costs of subsidence-related problems have also been small relative to the economic benefit derived from the use of groundwater.

(2) Description of Primary Subsidence Phenomena

The best known and documented case of subsidence in Arizona is the Eloy-Picacho area, in the central part of the state. From 1948 to 1967, maximum subsidence was 7.5 feet near Eloy, all of which was attributable to groundwater withdrawals. Water level declines have increased the stress on compressible clays in the valley areas, and this in turn has caused the ground to subside.

The most common subsidence feature in Arizona is ground fissuring. These features develop as small cracks, but through erosion, grow into large fissures several feet deep and wide, and up to several miles long. One fissure near Eloy reportedly had a total length of 14 miles. As shown diagrammatically in Figure III-A-2, fissures commonly originate as tension cracks near the edge of a subsidence bowl. In Arizona, however, (as shown in Figure III-A-3) fissuring is not always continued to the edge of the basin, but occurs within the basin as well. Schumann and Poland (1970) offer the following description:

> "The fissures roughly parallel the surface contours and transect natural drainage patterns. Upon application of irrigation water or following high-intensity rainstorms, the fissures intercept overland flow and act as drains. The water moves downward into the fissures causing them to increase rapidly in width -- as much as several feet in

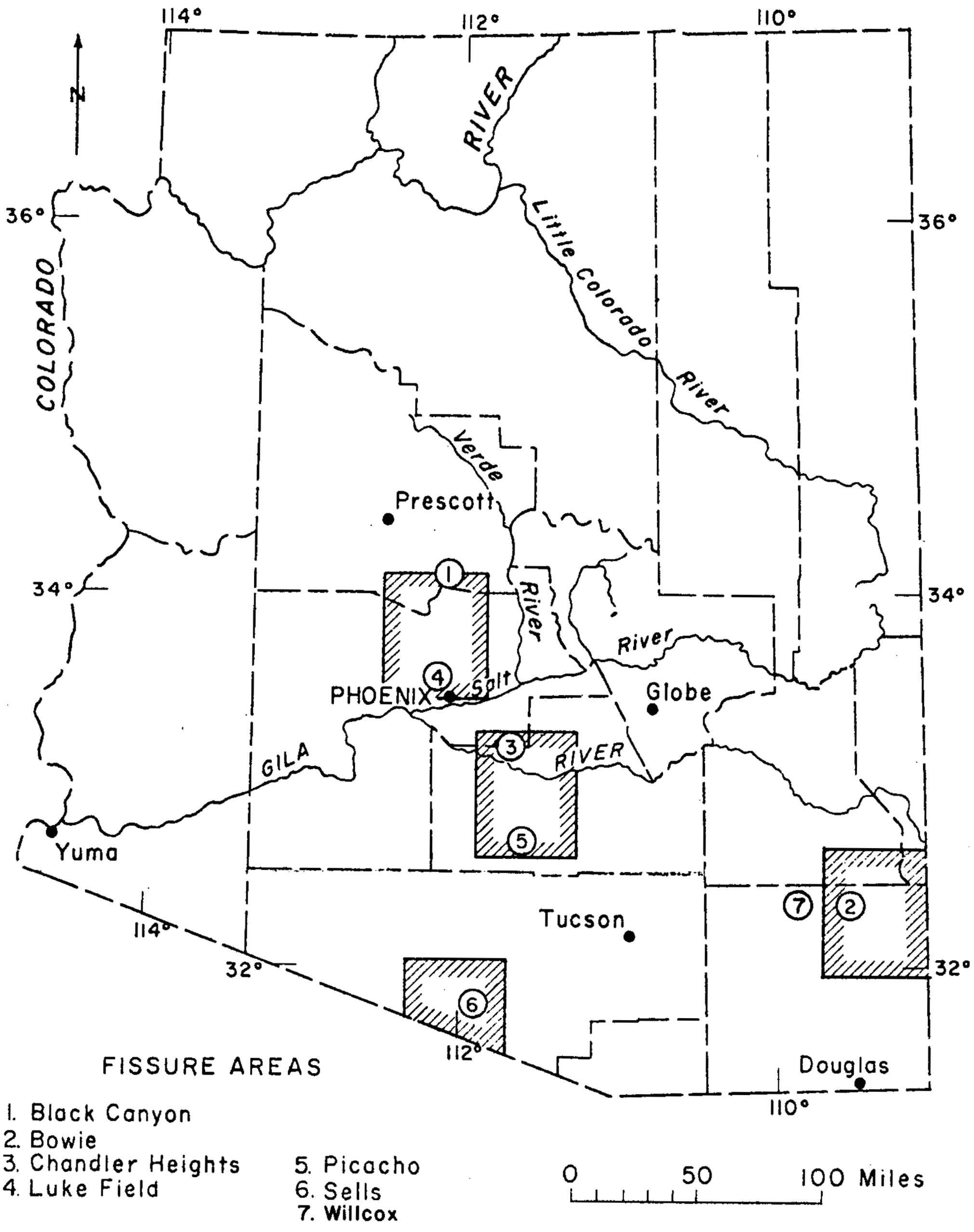
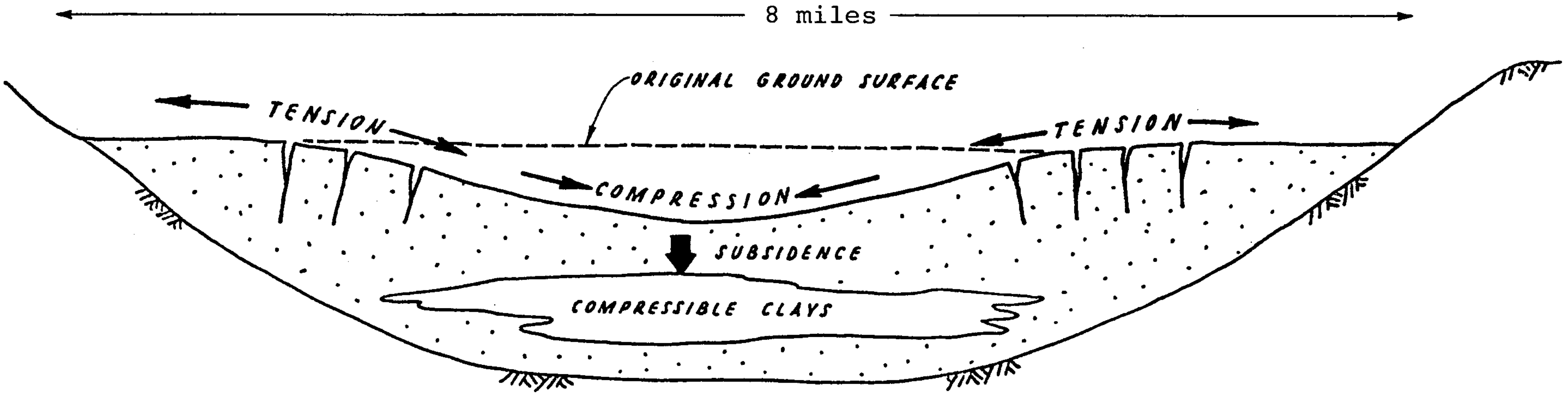


Figure III-A-1. Location of Subsidence Areas in Arizona (Modified from Robinson and Peterson, 1962)



(Maximum Subsidence ≃ 5 feet)

Figure III-A-2. Features of a typical subsidence area. (Willcox, Arizona).

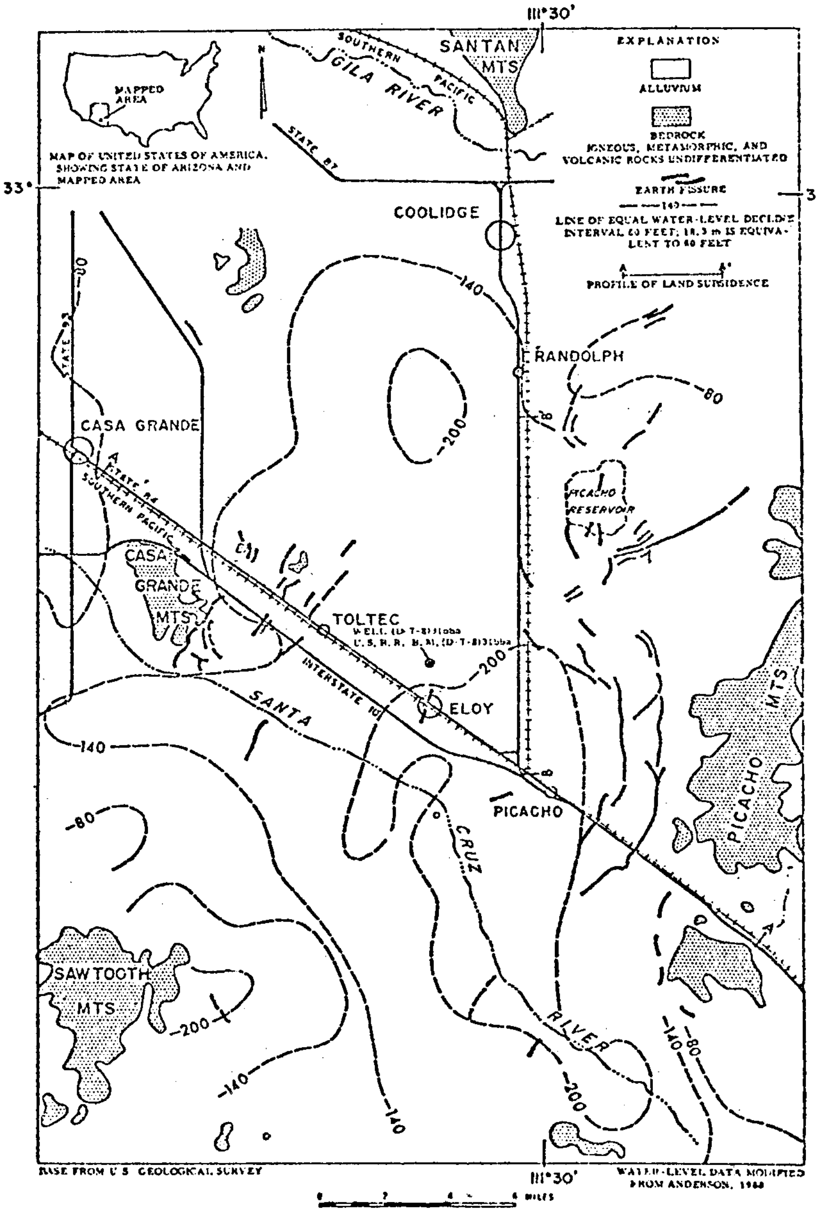


Figure III-A-3. Location of Earth Fissures, 1969, and Water-level declines, 1923-64 in Western Pinal Country (from Schumann and Poland, 1970).

> places. The fissures widen partly by slumping but mainly by erosion of the sides. Gullying often occurs on the upstream side of the fissure. The fissures tend to connect and to form fissure systems that are as much as 8 miles (12.8 km) long".
>
> The trends of many of the fissures roughly conform with linear zones of steep gravity gradients. Most of the steep gravity gradients are adjacent to the mountain masses and may reflect buried fault scarps along the periphery of the subsiding basin. If this is true, the buried fault scarps probably are sites of maximum tensile stress. Thus, the most likely sites for new fissures would be along these zones."

Principal investigators who have been studying subsidence phenomena in central Arizona include Thomas L. Holze of the U.S. Geological Survey, Menlo Park, California; Carl C. Winikka of the Arizona Resources Information System, Phoenix, Arizona; Robert L. Laney of the U.S. Geological Survey, Phoenix, Arizona; Charles McCauley of the Tucson Gas and Electric Company; and Richard L. Meehan of Earth Sciences Associates, Palo Alto, California.

(3) Effects of Primary Subsidence Phenomena

A dish-shaped reduction in ground elevation, several miles in diameter and up to 10 feet maximum depth is a typical natural feature. Cracking and fissuring occur on the periphery of the subsidence bowl, and in some cases lead to erosion and minor changes in surface drainage.

Changes in lowland ground elevation might be expected to cause changes in surface hydrology, and perhaps increase the risk of flooding in some areas. Whether because the surface drainage adjusts itself rapidly to the changed condition, or because subsidence has not been of great magnitude, or because of the relatively remote character of the subsided areas, this potentially adverse impact does not seem to have occurred in Arizona.

Several impacts on man-made features have been noted. Damage to wells, including damage to casings and pumps, occurs mainly as a result of stresses from the subsiding ground acting on the well casing. Protrusion of well casings from the ground is a tell-tale sign of subsidence. Charles McCauley of the Tucson Gas and Electric Company estimates the annual cost of well repair in Pinal County (site of the most severe subsidence) at $57,250 per year.

There are no reports of significant damage to houses, commercial or industrial structures, or appurtenant services such as pipelines. However, fissure development could have a serious impact in urbanized areas, and could pose a significant cost or feasibility barrier to subdivision development. So far, the absence of these problems is related to the absence of urbanization in subsiding areas.

Earth fissures crossing road and railroad rights-of-way (e.g., Highway I-10, State Highway 87) have caused continuing maintenance problems, although the cost of the few reported cases of damage has not been great. Given the potentially sudden development of fissures, however, it seems possible that their development beneath high-speed traffic lanes could pose a hazard to traffic. There are no documented cases of bridge damage.

Both the development of fissures and changes in grade due to subsidence reportedly have caused some impacts on agricultural operations, requiring extra land leveling and crack repair, and affecting ditch irrigation efficiency or feasibility. Mr. McCauley estimates these annual costs in Pinal County at $130,000, but points out that these costs are relatively small in comparison to the benefits obtained from water use.

Although there are no reports of damage to major water conveyance or storage facilities such as canals, aqueducts, flood control dams, or reservoirs, the failure of an embankment at the Picacho Reservoir in 1961 was attributed to subsidence. Earth dams and dikes, or earth-lined reservoirs or water conveyance facilities, are extremely sensitive to tensile strains which occur on the edges of subsidence areas and cause ground cracking and fissuring. This is especially true in Arizona, where many local desert soils have a very low resistance to piping, a form of hazardous erosion. The safety of existing earth water conveyance or retaining structures on the edge of subsidence bowls should always be carefully reviewed, and the feasibility of building new earth dams or canals across areas which have been or might be subject to subsidence should be evaluated with this potential hazard in mind. The failure of earth dams as a result of tensile cracking and consequent piping is apt to be sudden and may be catastrophic where downstream areas are populated. In the case of flood control reservoirs which are infrequently filled, cracking could occur without obvious premonitory signs, and the existence of the hazard discovered only after sudden failure of the dam.

Cost data are not available for the reportedly subsidence-induced failure of Picacho Reservoir or of the reported rerouting of the aqueduct. It is probable that the cost is not large in comparison to the benefits obtained from groundwater overdraft. In general, costs associated with subsidence-induced hazards to water conveyance and storage facilities could be of several types, including:

- The cost of lost opportunity; such as having to avoid siting facilities in certain areas because of the hazard;
- Extra engineering and construction costs required to build or modify the structure in order to partially or fully negate the hazard;
- Risk costs associated with unavoidable extra hazards, which cannot be eliminated by design -- essentially the insurance cost associated with the special risks accompanying subsidence induced ground movements.

(4) Aggravation of Other Hazards

None are known.

(5) Effects of Aggravated Hazards

None are known.

(6) Adjustments to Subsidence

Several adjustments have been employed to mitigate or avoid problems. Others have been considered and rejected, and further measures may have to be employed as subsidence continues.

Investigations of the problem are underway by the Arizona State Highway Department, the Department of Water Resources, the United States Geological Survey and the University of Arizona. These investigations are aimed at identification and monitoring of areas of subsidence and cracking, and development of mitigation measures.

Maintenance and repair of various facilities affected by subsidence, including wells, irrigation systems, roads, etc., is the principal form of response. Costs of these adjustments in 1975 are estimated at some $207,000 in Pinal County (Eloy-Picacho area). These costs were incurred as the result of the withdrawal of about 1,000,000 acre-feet of groundwater, and accordingly amount to about 21 cents per acre-foot of water.

Because the current costs in Pinal County are relatively small in comparison to the value of groundwater obtained, there is little incentive to control groundwater use, which is the usual method of controlling subsidence.

(7) Summary of Effects

Available data on the economic effects of subsidence in Arizona are summarized below.

Damages	Remedies	Costs
Cracking and disruption of roads and railroads	Repair	Relatively minor
Damage to wells and well casings	Repair or Replace	$57,250 per year in Pinal Co.
Failure of Picacho Reservoir	Abandonment, aqueduct re-routing	Not available
Tilting of fields and irrigation ditches	Relevelling fields and regrading ditches	$130,000 per year in Pinal Co.

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(9) Persons Contacted

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B. BALDWIN HILLS, CALIFORNIA

(1) Introduction

Land surface subsidence in the Baldwin Hills area of California has occurred as a result of oil and gas withdrawal from the Inglewood Oil Field, discovered in 1924. The Baldwin Hills, site of the Inglewood Oil Field, form part of an interrupted chain of low hills that rise in contrast to the surrounding flat terrain of the Los Angeles Basin (Figure III-B-1). The primary anticlinal fold structure in the hills has been much modified by faulting, especially by strike-slip and dip-slip displacements along the Newport-Inglewood fault which bisects them. Other subsidiary and apparently related faults are also present in the area.

The Inglewood Oil Field occupies a roughly oval area that extends diagonally across the trend of the hills along the axis of the faulted Inglewood anticline. By 1964, oil extraction had caused approximately 10 feet of subsidence at the field. No significant damage was reported from the direct effects of subsidence, but numerous ground breaks occurred. These breaks have resulted either from strains induced by the ground subsidence or by the fluid injection which has been conducted to increase recovery from the oil field. One of the ground breaks passes through the Baldwin Hills Reservoir site and was responsible for failure of the dam on December 14, 1963. About 250 million gallons of water emptied within hours and inundated a square mile of residences with mud and debris, damaging or destroying 277 homes and causing five deaths. This case study illustrates the extreme consequences that can result from uncontrolled subsidence-related phenomena in the presence of a dam and reservoir.

(2) Description of Primary Subsidence Phenomena

The Inglewood Oil Field developed rapidly after its discovery in 1924. In 1954, Standard Oil initiated a pilot "water-flood" program of secondary recovery and began full scale operations in 1957. Although "earth crack" ground rupturing may not have been definitely observed in the area before 1957, the existence of a more widespread and larger scale form of ground surface movement was recognized by the Los Angeles Department of Water and Power as early as 1943. In any case, the Department opened the reservoir in 1951. In 1957, surface cracking and faulting at a nearby local street intersection were noted. Six years later, the dam failure occurred.

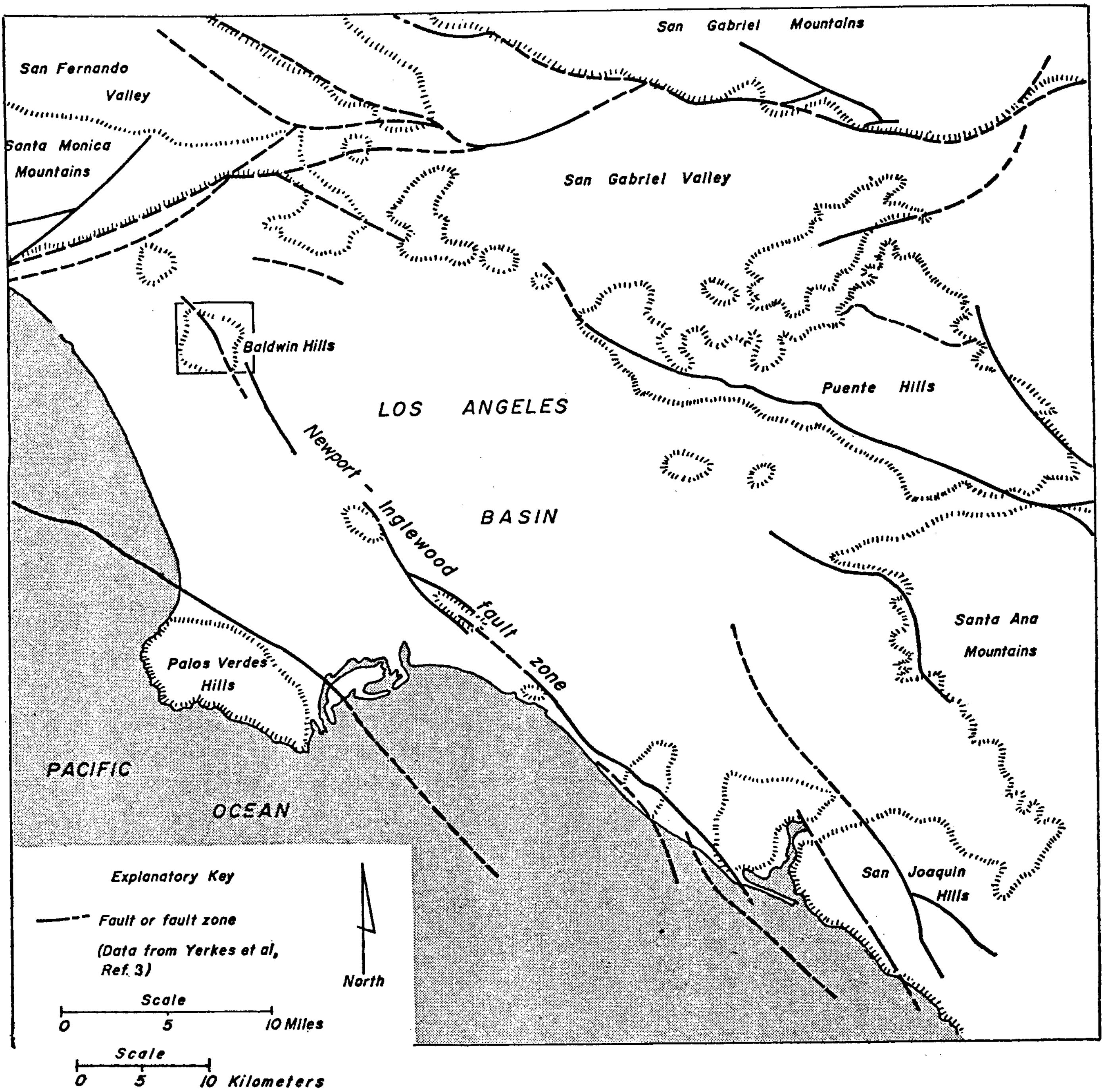

Figure III-B-1. Baldwin Hills - Inglewood Area Location Map (From Hamilton and Meehan, 1971)

Although some observers differ slightly in their interpretation of the pattern, magnitude and history of the deformation, the principal features of the recent ground subsidence and surface rupture have been clearly established (Figure III-B-2). The origin of deformations has been divided into two distinct categories:

- Activities associated with operation of the Inglewood Oil Field, including response of reservoir and overburden materials to lowering of fluid pressure, fluid withdrawal, reinjection and related phenomena;
- Deformation largely or wholly of tectonic origin.

Hamilton and Meehan (1971) conclude that the ground breaks were genetically related to high pressure injection of fluid into the previously faulted and subsidence-stressed subsurface.

(3) Effects of Primary Subsidence Phenomena

While there is evidence of surface cracking and faulting, there have been no reports of significant damage other than to the dam and reservoir (exclusive of flood damage). Winston Tyler, of the City of Los Angeles Attorney's Office, feels that cracking in streets or sidewalks due to ground breakage was probably repaired as part of the normal street maintenance of the city. In any case, the extent or cost of any such damage cannot now be determined, principally because it occurred 15 to 20 years ago. Any data that was available has been made inaccessible by the controversy and litigation procedures that followed the failure of the dam.

(4) Aggravation of Other Hazards

The Baldwin Hills Dam and reservoir were located on a hilltop above a populated area, and are now unused. The surface cracking in the subsidence bowl clearly increased the risk of dam failure and the hazard to downstream residents and property.

(5) Effects of Aggravated Hazards

In order to determine the cost of damages incurred as a result of the Baldwin Hills failure, the lawyers most involved in the ensuing litigation were interviewed. These were R. C. Ericson of Chevron who represented the oil companies; Winston Tyler, who represented the insurance carriers and is now with the City of Los Angeles Attorney's Office; and Stephen Powers, who represented the Department of Water and Power. Hamilton and Meehan's 1971 paper in Science also contained some damage cost estimates.

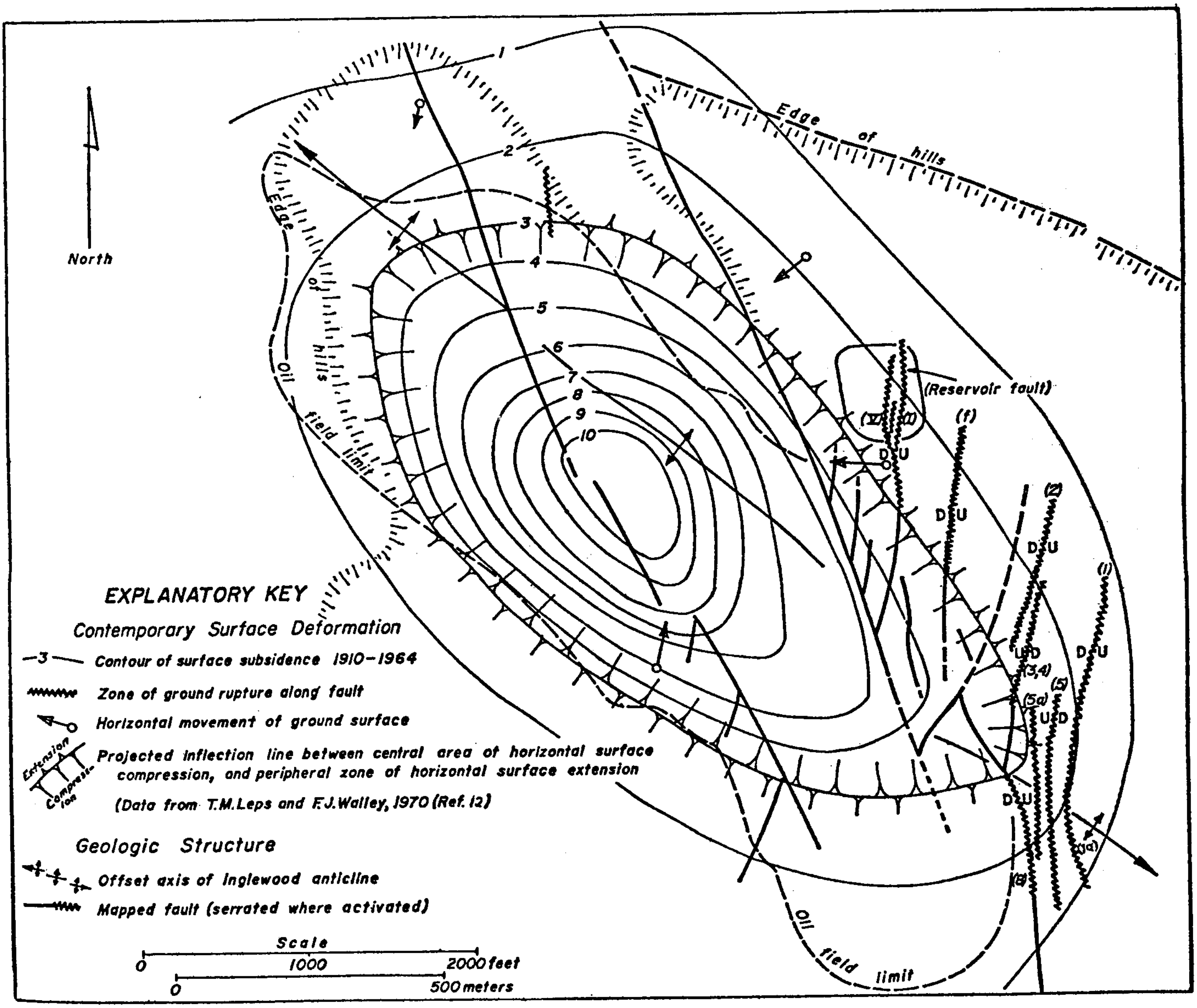

Figure III-B-2. Contemporary surface deformation, Baldwin Hills - Inglewood area.
(From Hamilton and Meehan, 1971)

Mr. Ericson stated from memory that total damage costs as a result of the dam failure were $25 million, but that the insurance companies paid out about $14 million. The Department of Water and Power of the City of Los Angeles, he said, sued the oil companies for $10.5 million, but settled for "15 cents on the dollar." This amount included $750,000 for loss of the reservoir.

Hamilton and Meehan (1971) quoted property damage losses of $12 million plus the loss of the reservoir and five deaths. They also mentioned an out-of-court settlement of $3.9 million by the oil companies to the city and its insurers. Winston Tyler estimated $14 million damage.

Steve Powers of the Department of Water and Power stated that total damages were $13,018,000 which was paid to about 3,700 claimants. These included suits involving the five dead, damages to homes and businesses, plus some claims for overtime police and fire protection during the crisis.

(6) Adjustments to Subsidence

No significant adjustments to the subsidence were reported other than the abandonment of the reservoir. The first recognized earth crack occurred in 1957. Eight more faults were activated from 1957 to 1963 during the secondary recovery observations. Monthly strain gage readings were taken across a crack in a concrete inspection gallery beneath the reservoir and across the fault, so displacement due to subsidence was well monitored up to the time of the reservoir failure in 1963. Similar monitoring procedures would have been followed in most well-supervised dam sites regardless of subsidence effects, so the incremental costs are probably not applicable, even if they could be obtained.

The Inglewood Oil Field is still in operation, but the damaged reservoir stands empty today and the site will probably never be reused.

(7) Summary of Effects

The summary of effects is as follows:

Damage	Remedies	Costs
Street Cracks (not well documented)	Repair	Unknown, but probably minor
Baldwin Hills Reservoir	Abandonment	Valued at $2.5 million, insurance paid $0.75 million
Flood From Reservoir Failure; Five Deaths	Damages paid to 3,700 claimants	$13+ million

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Steve Powers, Attorney, Los Angeles Department of Water and Power, Los Angeles, California: telephone interview.

C. HOUSTON-GALVESTON REGION, TEXAS

(1) Introduction

Land subsidence due to the withdrawal of groundwater has become a serious environmental problem in the Houston-Galveston Region. The area affected includes all of Harris and Galveston Counties and parts of Brazoria, Fort Bend, Waller, Montgomery, Liberty, and Chambers Counties. The Houston-Galveston area is situated on the nearly flat Texas coastal plain bordering the Gulf of Mexico. The shoreline is characterized by interconnecting natural waterways, bays, lagoons and estuaries, including Galveston and Trinity Bays which extend more than 25 miles inland.

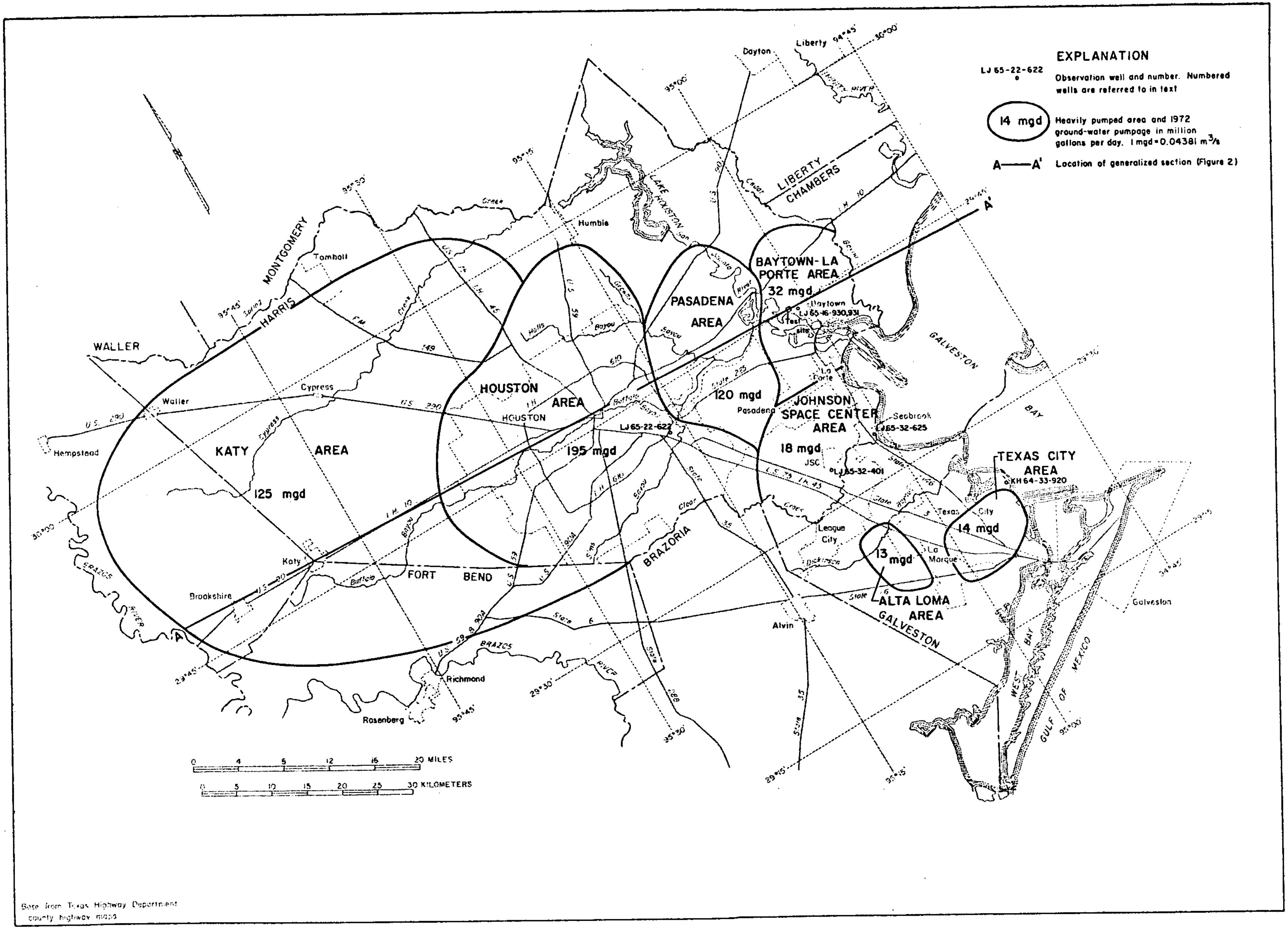
Land uses in the area include agriculture, recreation, metropolitan commerce, residential, and heavy industry. The area bordering the west shore of Galveston Bay has one of the highest concentrations of heavy industry in the world. The principal environmental impacts of ground surface subsidence have resulted from the inundation of large areas of shoreline bordering Galveston Bay and the increase in areas subject to hurricane tidal flooding.

(2) Description of Primary Subsidence Phenomena

Pressure decline in artesian aquifers due to the withdrawal of groundwater is the principal cause of ground surface subsidence in the Houston-Galveston area (Figure III-C-1). All groundwater is pumped from the Chicot and Evangeline aquifers as shown in the generalized cross section, Figure III-C-2. As of 1973, about 4,700 square miles had subsided 0.5 foot or more (Figures III-C-3, III-C-4, III-C-5). The greatest subsidence has occurred at Pasadena, an industrial area east of Houston, where the ground surface has subsided as much as 8.5 feet between 1906 and 1973. Smaller, localized subsidence bowls have developed around well fields within the larger bowl.

Two localized subsidence bowls are related to the withdrawal of oil, gas and brines from deep hydrocarbon reservoirs. As much as 3.2 feet of subsidence occurred at the Goose Creek Oil Field between 1906 and 1943. At the Chocolate Bayou oil field in Brazoria County, 1.5 feet of subsidence has occurred, probably due to a combination of groundwater withdrawal and extraction of hydrocarbons.

The most obvious consequences of land subsidence in coastal areas are the actual loss of land area due to inundation and the increase in area subject to flooding during tropical storms. Permanent innundation and flood damage has tended



Base from Texas Highway Department county highway maps

Figure III-C-1. Locations of Principal Areas of Ground-Water Withdrawals and Average Rate of Pumping in 1972. (From Gabrysch and Bonnet, 1975)

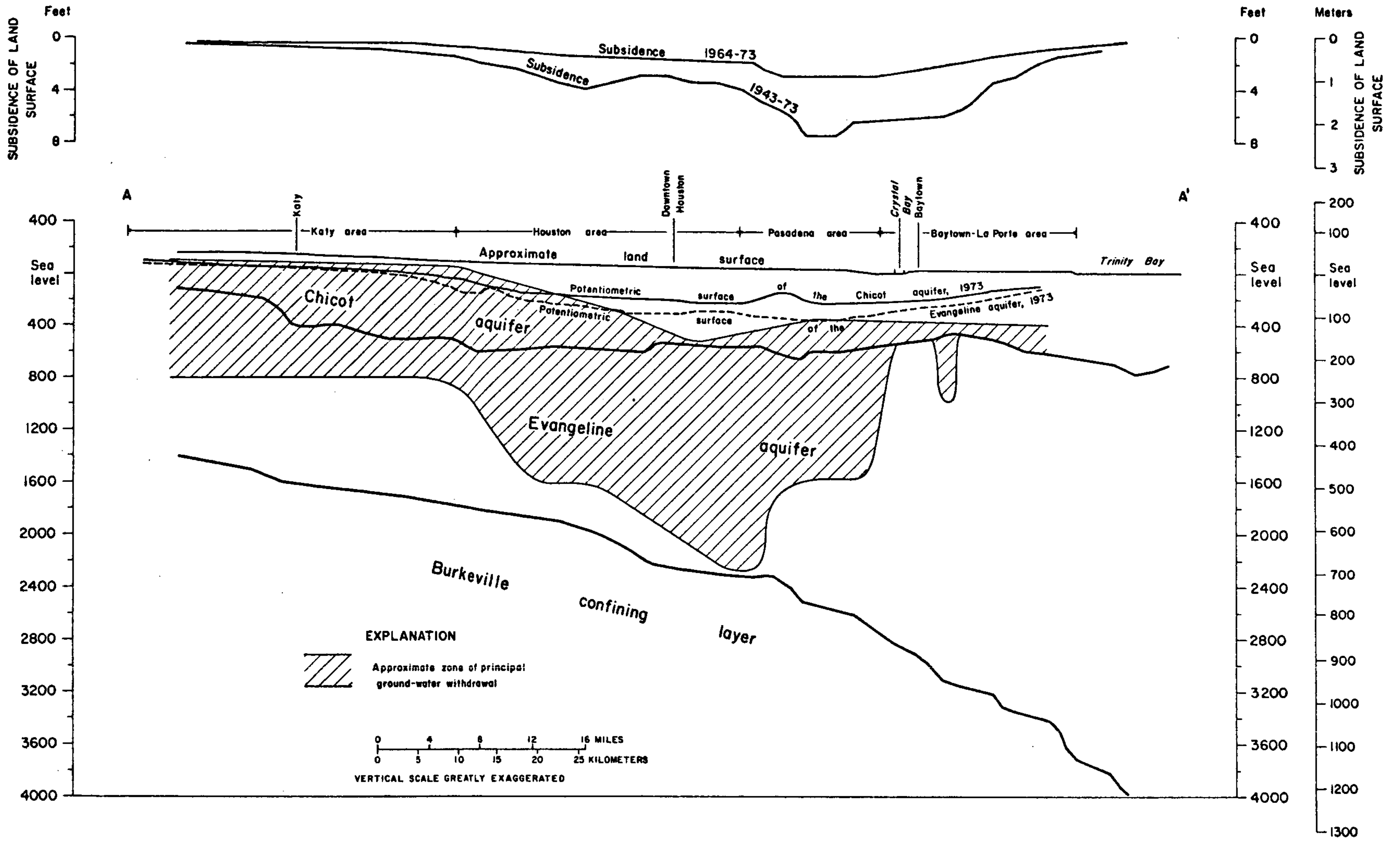


Figure III-C-2. Generalized Hydrologic Section in the Houston-Galveston Region. (From Gabrysch and Bonnet, 1975)

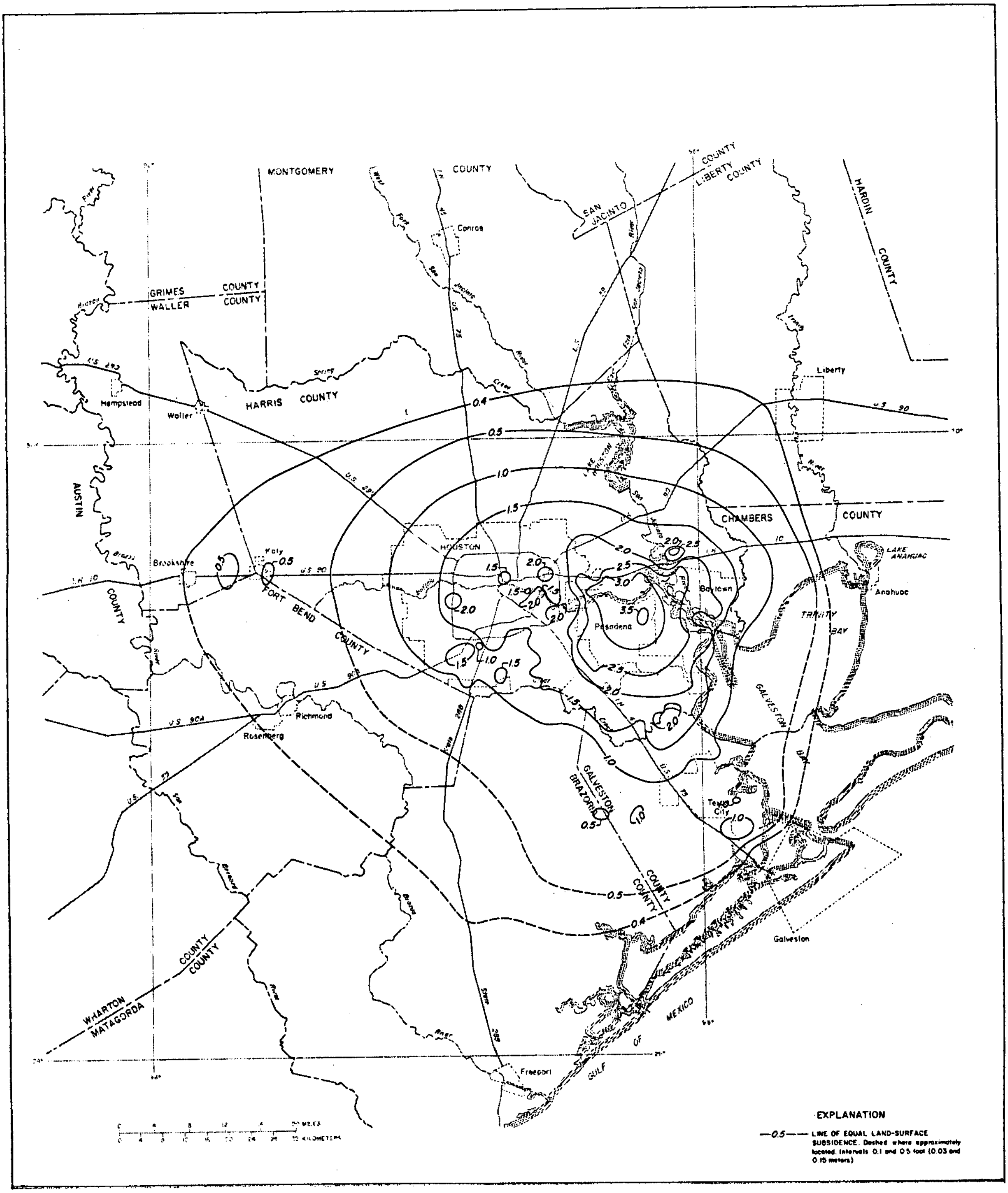


Figure III-C-3. Subsidence of the Land Surface, 1964-1973. (From Gabrysch and Bonnet, 1975)

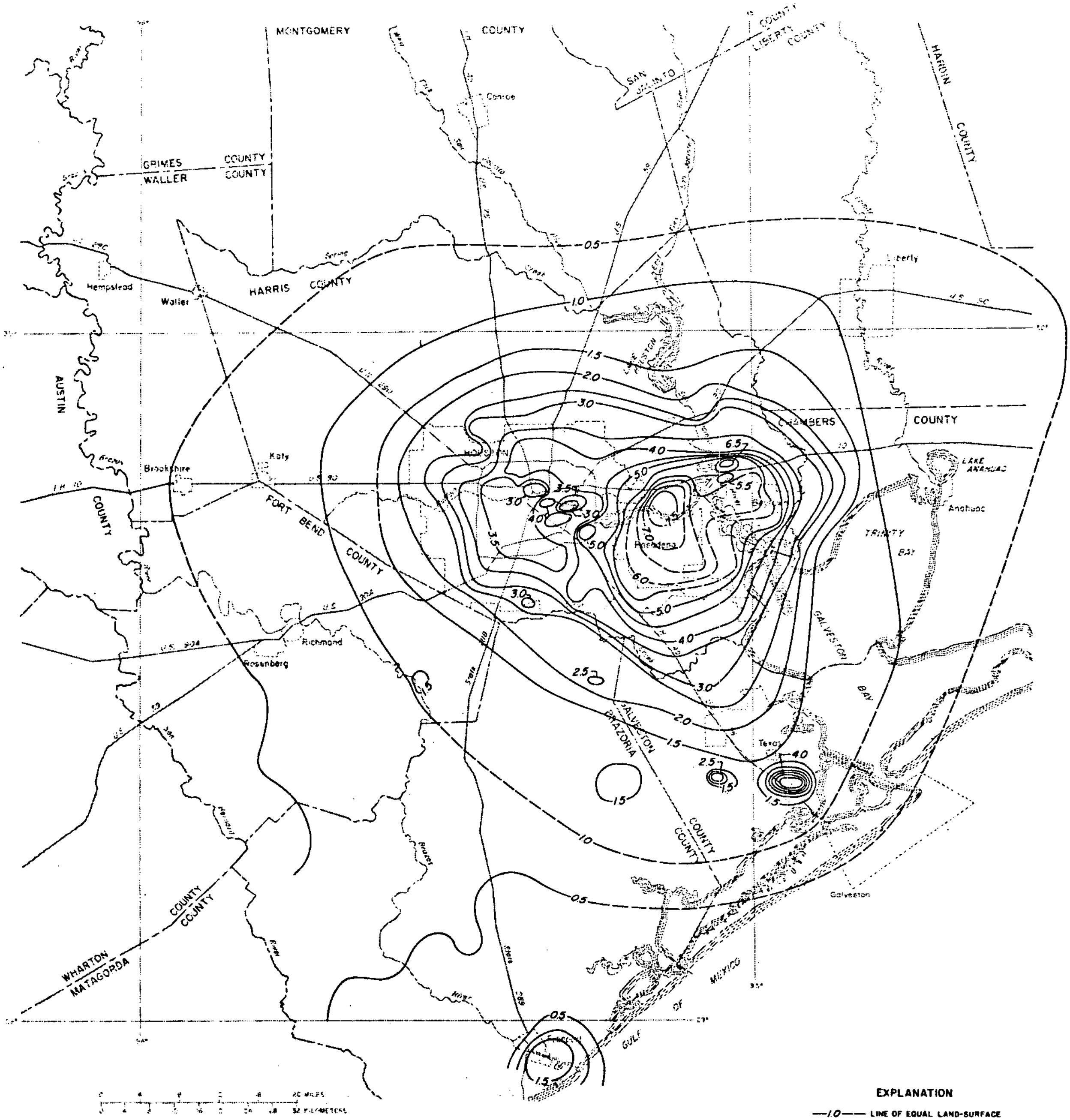


Figure III-C-4. Subsidence of the Land Surface, 1943-1973. (From Gabrysch and Bonnet, 1975)

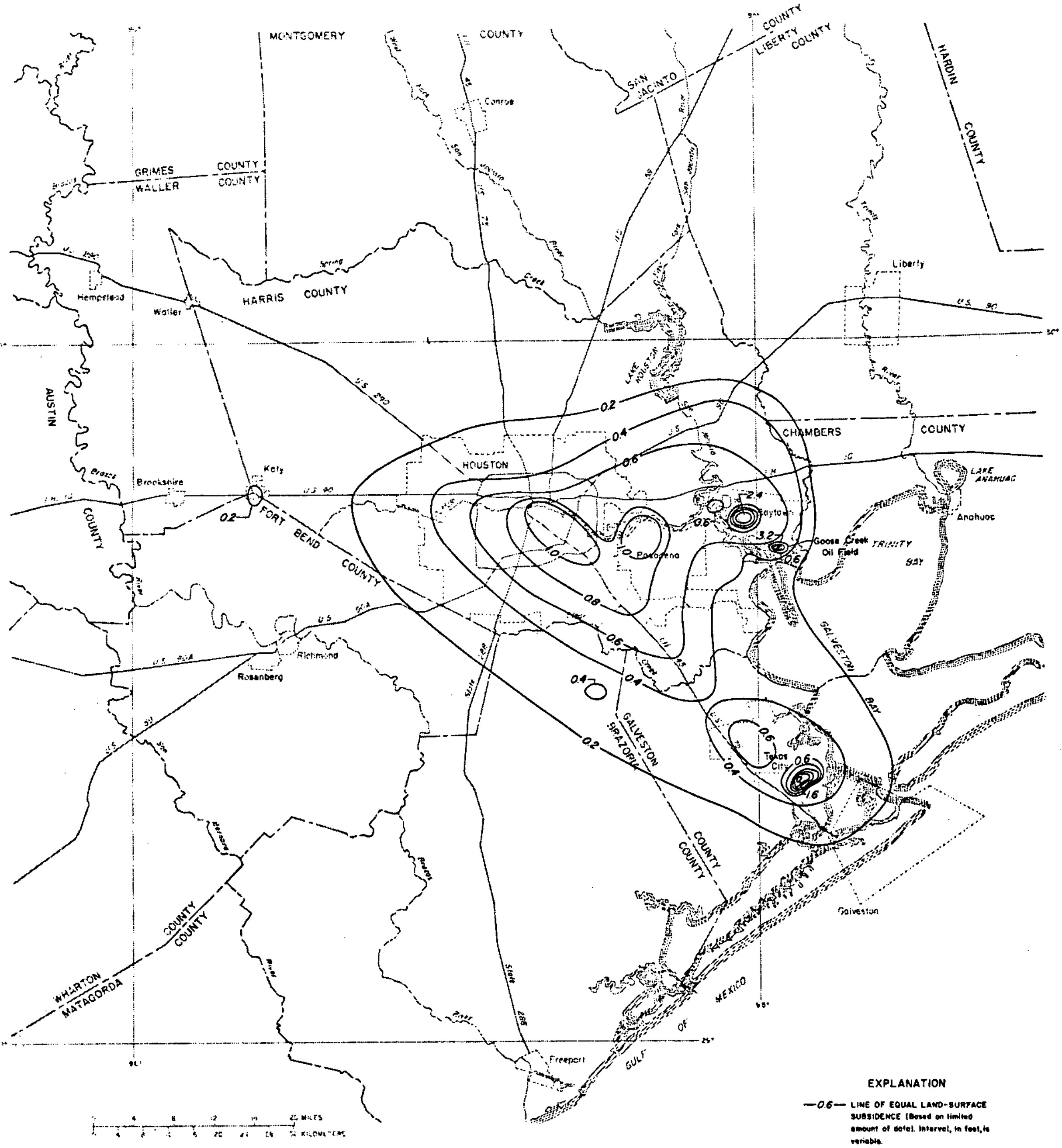


Figure III-C-5. Approximate Subsidence of the Land Surface, 1906-1943 (From Gabryscht and Bonnet, 1975) to overshadow other damages, but structures also have been damaged by ground cracking and wells have been damaged by subsurface compaction. Tilting of the ground has caused problems in such gravity transport systems as water and sewage systems.

(3) Effects of Primary Subsidence Phenomena

Changes to natural features in the Houston-Galveston region include changes in land slope, stream gradients and stream drainage patterns, with a resultant worsening of drainage problems. At their lower reaches, former river channels such as the San Jacinto River are now baylands.

The most dramatic and costly environmental effect of subsidence in the Houston-Galveston Region, however, is the change in land surface elevation with respect to sea level. An increasing amount of land is becoming inundated by salt water, and the area subject to flooding by tidal surge during tropical storms and hurricanes has increased dramatically. This submergence of land has further resulted in the alteration of natural vegetation where salt water has intruded.

Roads and highways in both Harris and Galveston Counties have been cracked and tilted as a result of subsidence. Estimates by both counties of the cost of road repairs due to subsidence appear in Table III-C-1. Damage to railroads has been reported, but no specific examples or cost estimates were obtained in this study. No reports of significant damage to aqueduct and irrigation channels were found, but damages to sewage systems have been severe. The extent of damage to small structures, houses or commercial buildings by tilting appears to be slight in comparison to the damage caused by flooding and inundation and by aggravated surface faulting. Except near the waterfront, subsidence is not generally recognized because of its regional nature. The changes in altitudes are not usually abrupt, and subsidence has not caused widespread structural damage. No reports of damage or losses to dams and reservoirs due to subsidence in the region have been found.

There have been few if any reported effects on agricultural fields in the region, even though rice farmers west of Houston and Galveston produce two crops a year using groundwater from the Chicot and Evangeline aquifers. However, wells and well casings have been damaged by the compression of water bearing strata below the surface and by the protrusion of wellheads above ground. No estimates of the cost of damage to wells and well casings were found. Pipelines also have been damaged by earth movement in the area, but it is not clear whether this is a result of differential subsidence or simply the movement of expansive clay soils, also a problem in the region.

Table III-C-1

Examples of Economic Effects (from Harris-Galveston Coastal Subsidence District)

SAN JACINTO BATTLEGROUND STATE PARK	
130 Acres Inundated	
Total Damages and Losses	$ 4.5 Million
TEXAS HIGHWAY DEPARTMENT	
Each Foot of Subsidence Will Add $680,000 to the Cost of an 8-Lane Structure to be Built at Beltway 8 and the Ship Channel.	
Over $3 Million Spent on Highway Reconstruction in 5 Years.	
GALVESTON COUNTY	
Road Repairs	$ 250,000
Park Reconstruction	$ 200,000
Tax Base Erosion	$35-$40 Million
Tax Revenue Loss	$ 125,000 Per Year
HARRIS COUNTY	
Road Repairs	$ 1,254,000
Park Reconstruction	$ 469,000
Tax Base Erosion	$Several Million
CITY OF BAYTOWN	
Drainage Improvements	$ 77,000
Planned Drainage Improvements	$ 1,000,000
Perimeter Road (Brownwood Subdivision)	$ 450,000
Surface WAter Treatment and Distribution	$13,600,000
HOUSTON LIGHTING AND POWER BERTRON PLANT	
Hurricane Protection Facilities Required Due to Underestimating Rate of Subsidence	$ 9,000,000
CITY OF TEXAS CITY	
Levees and Pumps	$ 5 Million
Surface Water Facilities	$ 8 Million
EXXON REFINERY	
Repair to Facilities	$50 Million
Estimated Repairs	$60 Million
Surface Water:	
Facilities	$ 6 Million
Operational Costs	$1/2 Million/Year

SHELL OIL	
Repair to Facilities	$40 Million
U.S. GOVERNMENT	
Brownwood Subdivision Relocation, Baytown Pending Appropriation	$12.7 Million
Local Cost	$ 3.2 Million
THE GULF COAST WASTE DISPOSAL AUTHORITY	
Reports 19 Sewage Treatment Plants Affected by Subsidence; 8 Have Experienced Tidal Inundation Since 1972	
GALVESTON COUNTY W.C. & I.D. NO. 12 (KEMAH)	
Planned Sewage Treatment Plant Relocation and Sewage Collection System Reconstruction	$ 3.5 Million

(4) Aggravation of Other Hazards

Hazards aggravated by land subsidence in the Houston-Galveston area include flooding and surface faulting. The most prominent effects of subsidence are related to the change in coastal elevation with respect to sea level. Subsidence has permanently inundated some shoreline areas, increased the risk of periodic flooding in other areas, and will cause flooding of escape routes from Galveston Island during the next hurricane.

The Harris-Galveston Coastal Subsidence District's bimonthly newsletter Subsidence Update, September, 1977, supports its headline "SUBSIDENCE INCREASES DAMAGE POTENTIAL" with the following:

> ...if storm tides with the same surge height as those generated by Hurricane Carla in 1961 had struck the Galveston Bay in 1974, an additional 70 square miles of subsiding land, much of it highly developed, would be flooded by hurricane-surge waters.
>
> ...if Carla returned today, she would directly affect at least 50,000 more people and cover Interstate 45 in several places not affected in 1961; thus cutting off escape routes that were usable in 1961.
>
> A massive hurricane will cross Galveston Island, sooner or later. When it does, the Johnson Space Center (elevation 15-25 feet), the Texas City Refinery Complex (elevation 5-15 feet), many of the industries along the upper Ship Channel (elevation 10-35 feet), and more than 1,000 square miles of land will be under water.
>
> The loss of property from Carla was $350 million; from a major hurricane striking directly at the Galveston Bay area, the cost would be in the billions of dollars.

The public safety implications of subsidence in the Houston-Galveston area are ponderous. Subsidence has seriously increased the potential for loss of lines during a hurricane. Due to subsidence Interstate 45 will be flooded during the next hurricane, effectively cutting off evacuation by automobile and trapping the hapless residents of Galveston with no means of escape. The possibility for catastrophic loss of lives, unusual in recent American history, is very real.

Ground rupture as a result of faulting is a major geologic hazard in the Houston-Galveston area, where more than 95 miles of lineaments and fault traces have been mapped. Active faults can cause damage to structures, city streets, interstate highways, railroad tracks, and airport runways. The differential movement across the reflection pool at the San Jacinto Monument is a rather spectacular result of localized subsidence along one of these faults.

Faults in the Texas Coastal Zone are products of natural geologic phenomena and have been explained as resulting from the deposition and differential compaction of thousands of feet of sediments, the upward movement of salt masses to form salt domes, the gulfward creep of the coastal land mass, and the bending of the landmass due to regional tectonics. There are clear indications, however, that whatever the origin of these faults, in some cases subsidence from fluid withdrawal has increased fault activity. The faults divide the earth's crust into discrete blocks and, in some cases, act as barriers between aquifers in one block and those in an adjoining block. If the pressure decline from fluid withdrawal is greater in one block than the other, differential compaction occurs across the blocks resulting in vertical movements on the intervening fault. There has been no seismic activity associated with the active faults in the Texas Coastal Region.

(5) Effects of Aggravated Hazards

Inundation has damaged homes, ferry terminals, shipping docks, parks, roadways, railroads and sewage systems, but data on the cost of subsidence is fragmentary and the subject of debate. Cost information has been gathered for various purposes by the U.S. Army Corps of Engineers (1975), by economists at Texas A&M University (Warren, Jones et. al., 1974, and Jones and Larson, 1975), and by the Harris-Galveston Coastal Subsidence District (1977). According to Frank A. Marshall of McClelland Engineers, Inc., no one has done a comprehensive study of costs. He pointed out that a proper cost analysis should also include an account of the benefits of subsidence. For example, subsidence has made it unnecessary to dredge the Houston Ship Channel for several years.

The work of John D. Warren, Lonnie Jones, James Larson and others at Texas A&M University was the first systematic effort to estimate costs of subsidence. Their investigations, however, concentrated on limited study areas rather than attempting to estimate all costs due to subsidence throughout the region.

In a 1974 study, Warren, Jones, et. al., selected a 300 square mile portion of the Greater Houston-Galveston area. They estimated the costs of subsidence-related damages in the area as $60.67 million in private damages, $48.76 million in private property losses, and $4 million in public property losses. A six-foot tide in 1973, which may be expected to occur once every five years, was found responsible for $53 million of this $113.43 million total. Balancing the benefits of groundwater use against these costs, they concluded that:

> If the historic losses estimated in the study were included in the cost of groundwater use, the purchase of all of the areas' recent water needs (up to 132 billion gallons a year) from surface water sources would have been justified.

A subsequent study by Jones and Larson focused on a 945 square mile area that has subsided one foot or more since 1943. Estimated annual costs in damage and property loss exceeded $31.7 million, primarily costs to residential, commercial and industrial property but including over $.5 million in public costs for damage abatement or repair to facilities. The study revealed higher incidence, intensity, and costs for waterfront areas. Twelve percent of the study area was waterfront land and accounted for 45% of the costs of subsidence-related damages (Areas I and II, Figure III-C-6). Jones and Larson also did a comparative analysis of the costs of groundwater pumping as opposed to importing surface water to meet area needs. They concluded that the importation of surface water would have been economically justified from the standpoint of reducing costs; thus concurring with the results of the earlier study (see Figure III-C-6).

In 1977, the Harris-Galveston Coastal Subsidence District testified before the House and Senate Natural Resources Committee of the 65th Texas Legislature and presented a list of economic effects for areas within the district (Table III-C-1).

The U.S. Army Corps of Engineers (1975) has reported that houses have been subjected both to permanent and periodic flooding, most notably in a coastal area which borders Burnett, Crystal and Scott Bays at Baytown, Texas (Figures III-C-7 and III-C-8, "study area" and "selected plan"). As a remedy, the Corps of Engineers has proposed "...to acquire and remove 448 dwellings; evacuate and relocate about 1,550 residents and deed to the city of Baytown the 750 acres of acquired land for use by the City as a nature area or as deemed appropriate for lands vulnerable to recurrent tidal, hurricane, or rain runoff flooding."

An article in the Houston Post (January 23, 1977) discusses a secondary socioeconomic problem due to coastal subsidence in residential areas: the loss of homeowners insurance for the residents who still live in the Brownwood Subdivision in Baywood. Residents of the subdivision find themselves

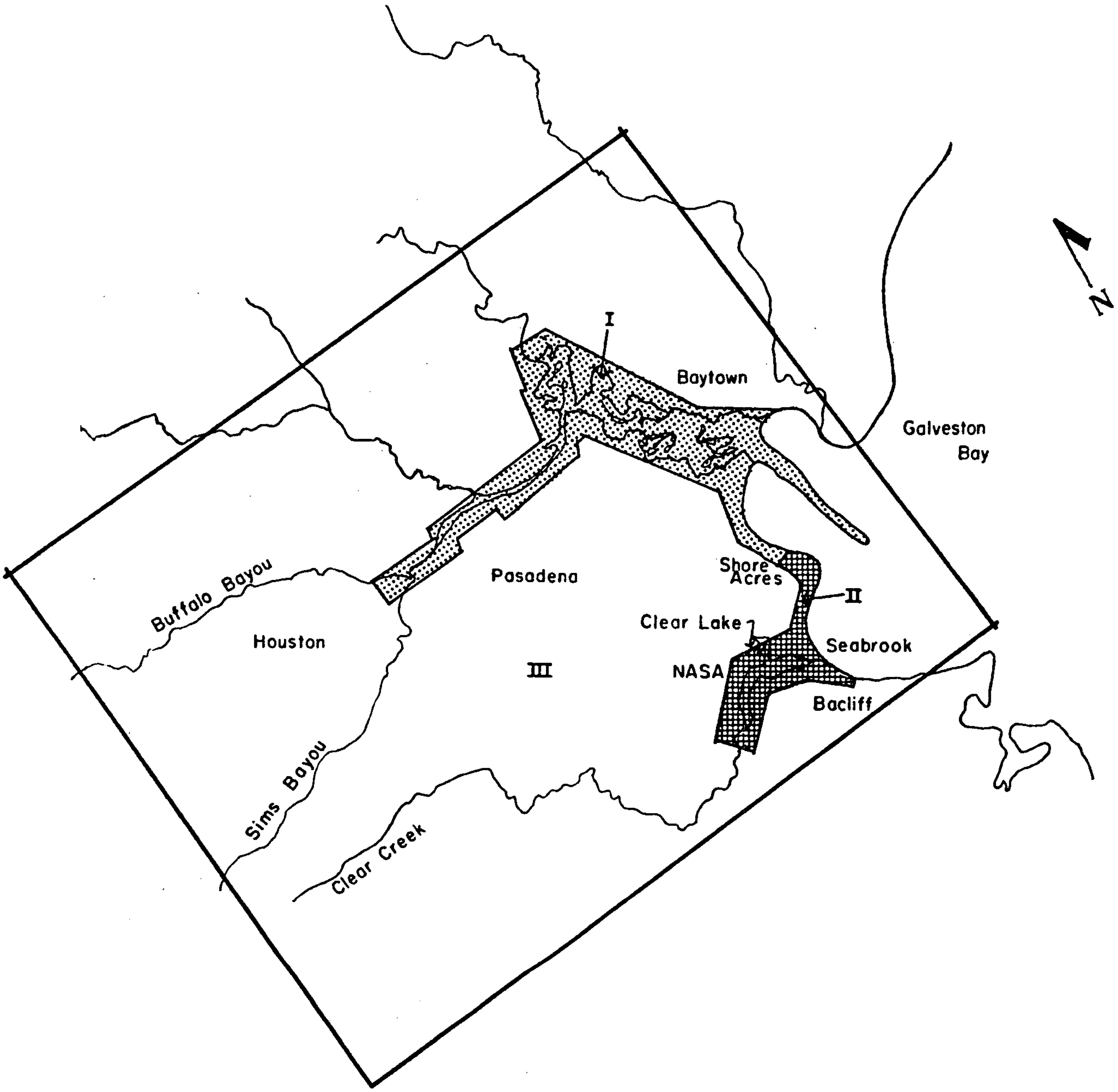


Figure III-C-6. Approximate location of the study area and sub-areas I, II and III. (From Jones and Larson, 1975)

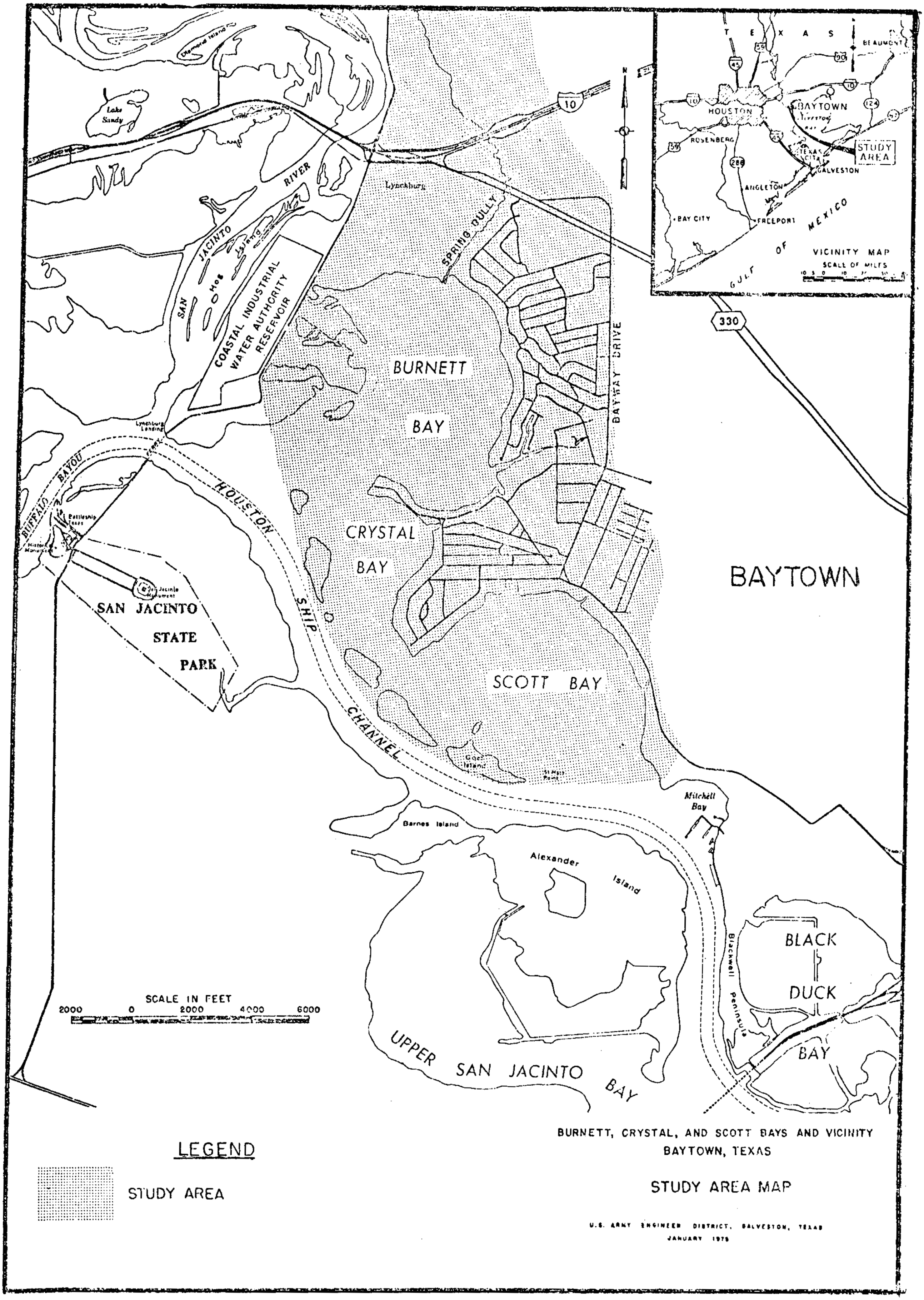


Figure III-C-7. Study Area. (From U.S. Army Corps of Engineers, 1975)

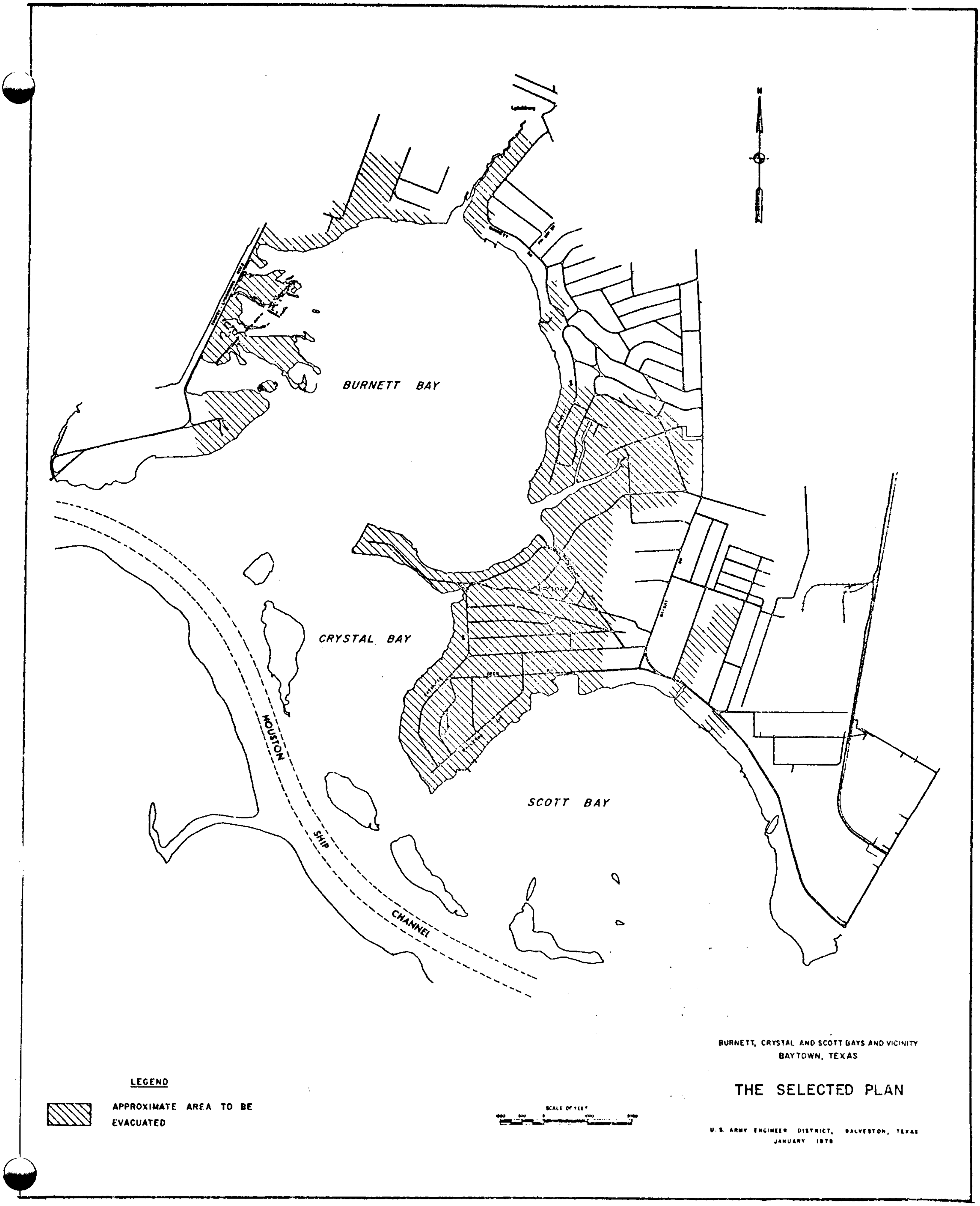


Figure III-C-8. The Selected Plan (From U.S. Army Corps of Engineers, 1975) unable to get homeowners insurance which protects against fire, windstorm, hail, theft, and other risks as insurance companies will no longer write homeowners policies on homes highly susceptible to inundation.

Surface faulting, another environmental hazard aggravated by subsidence, has reportedly caused extensive damage in the Houston-Galveston area. However, no information has been found to indicate what portion of the damage is due to faulting aggravated by subsidence as compared to that due to naturally occurring faulting. The data collected by Jones and Larson (1975) from property owners in the area suggest that structural damages in areas away from the waterfront "...caused an estimated $17 million in costs to residential and commercial property owners", and that "these damages are manifested primarily as cracking, shifting and separation in residential and commercial structures and attachments such as sewer and water lines."

Kreitler and McKalips (report in preparation) report that a total of 345 homes in the Houston area are located on active fault traces. Of these, 141 (41%) have experienced major damage (defined as cracks in concrete foundation slabs or cracks in house walls), and 70 (20%) have experienced minor damage such as tilting ridgelines of roofs or separation of driveways from house slabs. Their data are summarized in Table III-C-2 for various categories of property values. Assuming minor damage amounts to 25% of the estimated property value of each home and major damage amounts to 50%, the total property damage from surface faulting in the area would amount to roughly three to four million dollars.

(6) Adjustments to Subsidence

A full range of adjustments to subsidence problems has been practiced in the Houston-Galveston area by individual homeowners, homeowners groups, industries, insurance companies, and government bodies at the local, state and federal levels. Table III-C-3 is a summary of adjustments to subsidence and flooding practiced in the area.

In their feasibility study for flood damage reduction to residences at Baytown, the Corps of Engineers evaluated several alternative solutions to the flooding problem. These included construction of flood walls, flood proofing existing structures, imposition of zoning regulations, improved flood forecasting and temporary or permanent evacuation with relocation assistance.

The recommended plan proposes evacuation of all residents from the projected 50-year flood plain, assistance in their relocation at project expense and removal of the structures from the flood plain. The vacated lands would be deeded to

Table III-C-2

Home Damage by Active Faults In The Houston Area (data from Kreitler and McKalips)

Number of Homes Destroyed
By Category of Estimated Property Value

Damage Level (Refer to Text)	Less Than $25,000	$25,000-$50,000	More Than $50,000
No Visible Damage	81	37	16
Minor Damage	39	23	8
Major Damage	68	58	15

Table III-C-3

Summary of Adjustments to Subsidence in the Houston-Galveston Area

Class of Adjustment	Adjustment	Action
Study the problem	Scientific Studies	U.S. Army Corps of Engineers USGS McClelland Engineers, Universities
	Releveling Studies	USGS, 1964-1973 New study proposed for 1978
	Economic Studies	Texas A&M (Warren, Jones, et. al.)
Bear-the-loss	Law Suits	Class action suit against Exxon Exxon won,then lost in Appellate court Individuals have suffered losses
Repair damage	Road Repair	Public Works Departments, Harris and Galveston Counties
	Park Repair	Harris County, land filling of park
	Port Facility Repair	Petrochemical Companies
Remedial measures to prevent damage to prevent damage	Construct and maintain dikes Levees	U.S. Army Corps of Engineers Petrochemical Companies City of Baytown constructed perimeter road
	Seawall Construction	U.S. Army Corps of Engineers at Galveston and Texas City
	Abandonment	Permanent abandonment of 450 homes in Baytown proposed by Army Corps of Engineers
Countermeasures to affect the cause	Limit groundwater pumping	Harris-Galveston Coastal Subsidence District controls groundwater withdrawal
	Develop alternative resource	Coastal Industrial Water Authority and City of Houston are both developing surface water supplies
Develop institutional framework	Adopt land use controls	Baytown has adopted land use controls as a requisite for Federal Flood Insurance coverage
	Form Regulatory framework to curtail groundwater pumping	Harris-Galveston Coastal Subsidence District formed by Texas Legislature in 1975

the City of Baytown for management as nature areas or for other passive uses consistent with the high potential for recurrent flooding. The annual costs for this plan (based on December, 1974 prices) were estimated as $1,261,000. Measurable benefits to be derived from the plan include the reduction of the costs for insurance, utility service, temporary evacuation and relief; the elimination of abandonment losses; the value of the land for open space; and the prevention of flood damages. Two alternative methods of comparison were used and produced benefits to cost ratios of 2.3 to one and 1.3 to one. The overall cost of the proposed plan was estimated to be $12.7 million to the Corps of Engineers and $3.2 million to the City of Baytown. These estimates were criticized by the staff of the Texas Water Rights Commission as being "extremely low." The Commission also suggested that further consideration be given to the precedent that would be set by the public acquisition of residential properties and the evacuation and relocation of residents.

Damage repair has been practiced at all levels, from private homeowners in lowland areas subjected to recurrent floods, to port facilities of heavy industries and local public works departments responsible for ferry terminals, road and park maintenance. Costs of damage repair have been listed by the Harris-Galveston Coastal Subsidence District and have been studied by Warren, Jones et. al. (1974), and Jones and Larson (1975).

In an effort to prevent damage to low lying homes near Crystal, Burnett, and Scott Bays, the City of Baytown constructed a raised dike with a "perimeter" road on top; and the residents of the area paid for the installation of pumps to prevent inundation. The City's share of the costs was $500,000. The dike and pump system gives the homes some measure of protection against the daily tidal inundation and moderate tidal surges, but it is likely to provide little protection against storms and hurricanes.

The Harris-Galveston Coastal Subsidence District is a new institution created to deal with subsidence. It was formed by the Texas Legislature in 1975 to provide for the regulation of the withdrawal of groundwater within the district boundaries in order to halt subsidence. It is believed that the proper control of groundwater will assist in the abatement of land subsidence: that if groundwater withdrawal can be controlled at a level below 490 million gallons per day, water levels will stabilize and only residual subsidence will remain. The district now controls the pumping of groundwater by a permit system as provided in House Bill 552. Owners of wells with casing of more than five inches in diameter or who own more than one well must secure a permit from the district. Permit fees were levied in 1976 at 1.2 cents per thousand gallons pumped. In 1977, the fee was reduced to 0.69 cent per thousand gallons pumped.

Efforts are also being made to develop alternative surface water supplies and thus to lower the demand for groundwater. The Coastal Industrial Water Authority (CIWA) has a project to bring Trinity River water to Houston Ship Channel industries and other users that now pump large volumes of groundwater. The City of Houston also plans to divert Lake Livingston water into the Lake Houston surface water supply. Galveston began using surface water late in 1973, and several communities in Harris and Galveston Counties are studying the possibility of obtaining surface as opposed to groundwater resources in order to substantially decrease subsidence in the more critical areas.

(7) Summary of Effects

Damages	Remedies	Cost
San Jacinto Battleground State Park Inundated		$4.5 million
Damage to State Highway	Reconstruction	$3.0 million in five years
Cracking and Flood Damage to County Highways	Repair and Reconstruction	$1.5 million
Flood Damage to County Parks	Landfill and Reconstruction	$669,000
Erosion of Tax Base	None Mentioned	$40 million
Tax Revenue Lost	None Mentioned	$125,000/year
Inundation and Flooding of Brownwood Subdivision, Baytown	Drainage Improvements	$1,077,000
" " "	Construct Perimeter Road/Levee	$450,000
" " "	Abandonment and Relocation	$15.9 million
" " "	Construct Surface Water Treatment & Distribution System (as alternative to groundwater)	$13.6 million

Inundation & Flooding of City of Texas City	Construct Levees; Install Pumps	$5 million
" " "	Construct Surface Water Facilities	$8 million
Hurricane Flood Hazard to Power Plant	Construct Hurricane Protection Facilities	$4 million
Subsidence of Inundation at EXXON Refinery	Repairs, Flood Protection	$110 million
" " "	Develop Surface Water Facilities	$6 million $.5 million/year
Subsidence and Inundation at Shell Refinery	Repairs, Flood Protection	$40 million
Changed Gradients, Inundation of Sewage Collection System & Treatment Plants	Redesign & Reconstruct Collection Facilities, Install Pumps. Relocate Sewage Treatment Plant	$3.5 million

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D. LAS VEGAS VALLEY, NEVADA

(1) Introduction

The Las Vegas Valley is a fault-bounded structural depression in the basin and range province, which is filled with 4000 feet or more of sediments derived from the surrounding mountains. Approximately 500 square kilometers in the central part of the Valley has subsided up to 1.5 meters, primarily as a result of the withdrawal of large quantities of groundwater. The region consists of arid desert with sparse natural vegetation. Land uses in the valley include agriculture, recreation, commercial, residential and open space with open space predominating. The closest major water body is Lake Mead, located several miles to the east.

(2) Description of Primary Subsidence Phenomena

Levelling and survey data have been available for the area since 1935, when stations were established to record the effects of the filling of Lake Mead. Since that time, the U.S. Bureau of Reclamation, National Geodetic Survey (formerly U.S. Coast and Geodetic Survey), U.S. Geological Survey and the Nevada Highway Department have established additional stations and conducted periodic relevelling surveys. The Desert Research Institute in Reno, Nevada has been investigating subsidence in the Las Vegas Valley for over 14 years. Principal investigators have included A. L. Mindling, John A. Blume and Associates, and Ralph Patt. Contributions through other agencies have been made by Jim Harrill and C. T. Malmberg.

Subsidence was first documented in the area in 1948 by Maxey and Jameson. It has since been determined that three forms of ground surface warping are affecting the area:

- A regional tilting to the south, believed to be of tectonic origin and considered to have been in progress prior to the filling of Lake Mead, although changes in the rate and direction of tilting may have been triggered by the added stress of reservoir filling;
- A broad shallow downwarping, centered on Lake Mead, probably related to the elastic strain response of the underlying rocks to the weight of water in Lake Mead;
- A steep localized depression in Las Vegas Valley related to groundwater withdrawals.

Although all three types of surface warping are presently active in the Valley, groundwater withdrawal has caused 90% of the total elevation change.

Land subsidence from fluid withdrawal results from the compaction of fine-grained sediments due to the increase in effective stress caused by lowering of the artesian head within the groundwater system. Comparison of leveling data from 1935 to 1963, as illustrated in Figures III-D-1 to III-D-6, graphically illustrates the history of subsidence in this area. The maximum cumulative elevation change was 1.2 meters in 1963, with 1.5 meters reported in 1974.

It is interesting to note that the area of maximum subsidence does not coincide with, but lies two to three miles to the east of the major cone of groundwater depression. This is most likely due to an increase in both compressibility and aggregate thickness of fine grained sediments from west to east. Because the valley fill sediments vary laterally from east to west in their compressibility, it has been proposed that the prominent, north trending fault scarps crossing the valley (Figure III-D-7) are related to differential compaction which has been occurring throughout the recent geologic past. The present pumping activities have served to accelerate and localize the rate of compaction.

Associated effects which have occurred as a result of subsidence include tilting, ground surface ruptures and subsurface deformation. Tilting of the ground surface has occurred on a regional scale as well as along the margins of the subsidence bowl. Ground surface ruptures in the form of cracks and fissures have occurred in Las Vegas Valley as a result of tensile stresses associated with differential subsidence. These fissures begin as small cracks less than an inch wide, but may be widened to several feet across as the result of erosion. Much of the fissuring is in the vicinity of the compaction fault scarps which apparently serve as boundaries along which stress adjustments are made. Fissures and cracks also occur immediately adjacent to some wells where subsidence is intensely localized. To date, there has been no reported seismicity that is known to be related to the subsidence phenomena.

A subsidence effect of considerable economic impact is subsurface deformation. In the Las Vegas Valley, this effect is manifested by the compaction of sedimentary layers at depth and has caused protrusion, deformation, and breakage of well casings, often requiring redrilling or abandonment of wells.

(3) Effects of Primary Subsidence Phenomena

Subsidence has caused damage to many wells, several pipelines, a few houses, numerous roads, two reservoirs and a railroad.

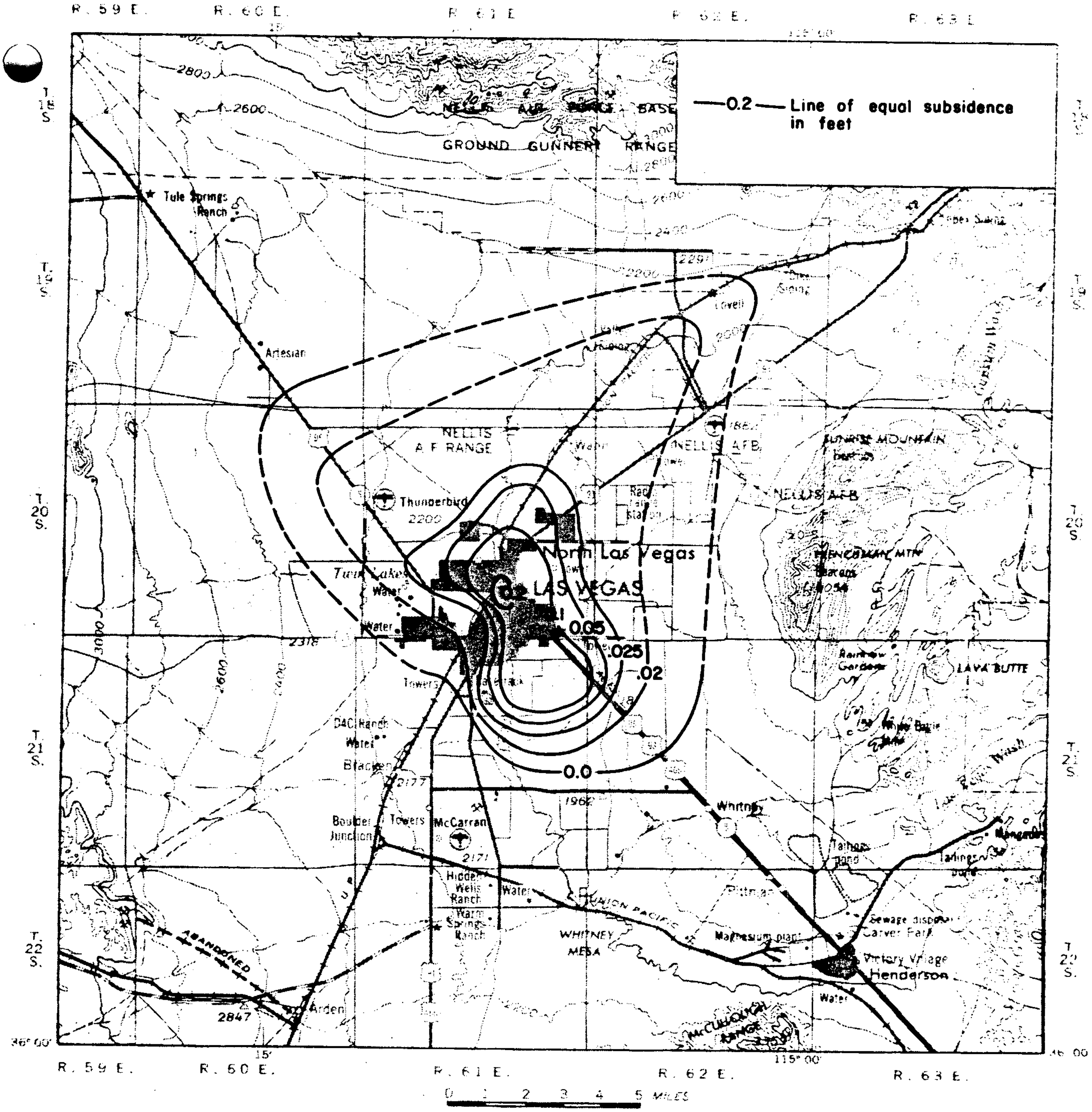

Figure III-D-1. Land Subsidence in Las Vegas Valley Between 1935 and 1941 Due to Artesian Head Decline. (From Mindling, 1971)

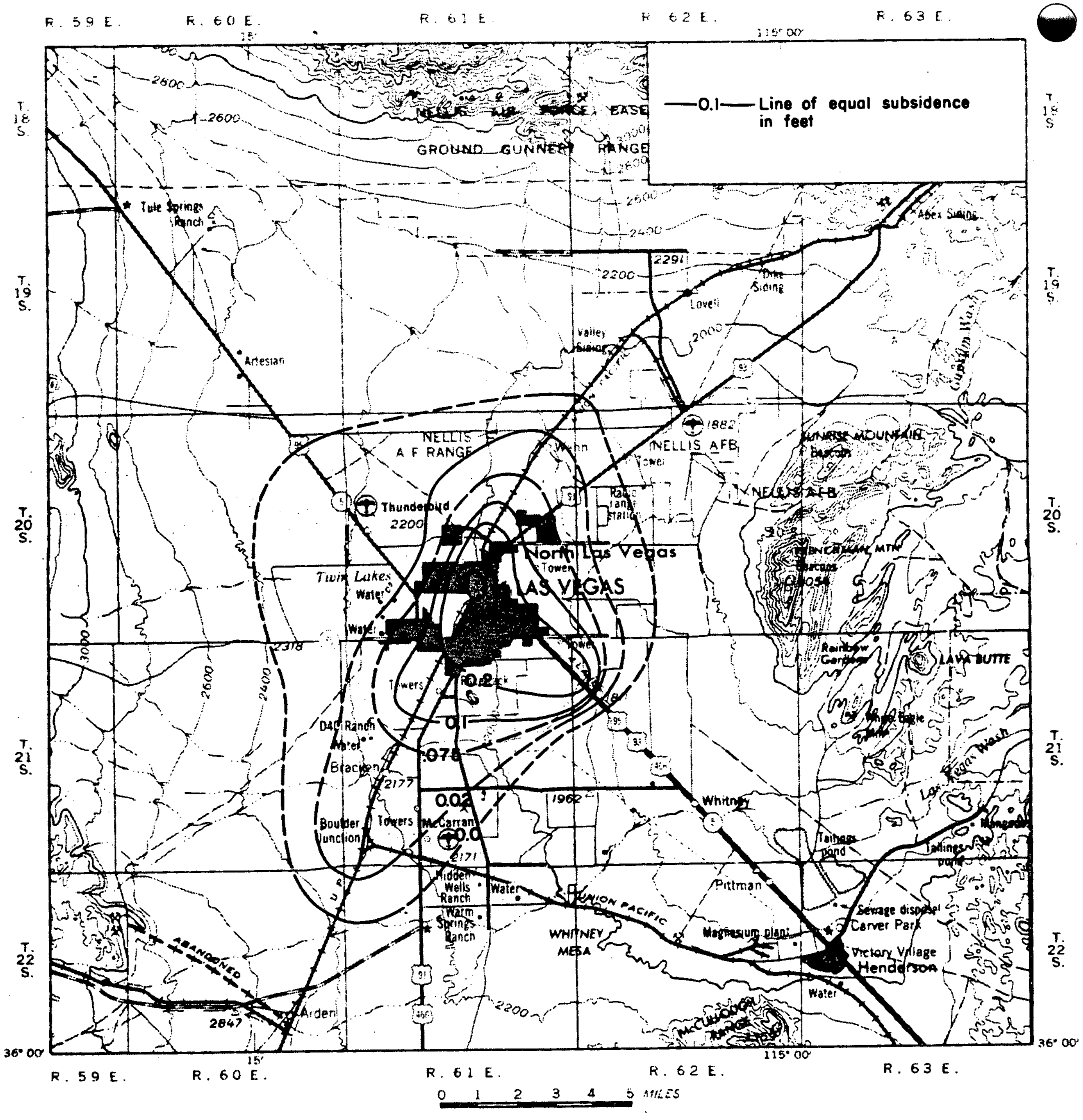

Figure III-D-2. Land Subsidence in Las Vegas Valley Between 1941 and 1950 Due to Artesian Head Decline. (From Mindling, 1971)

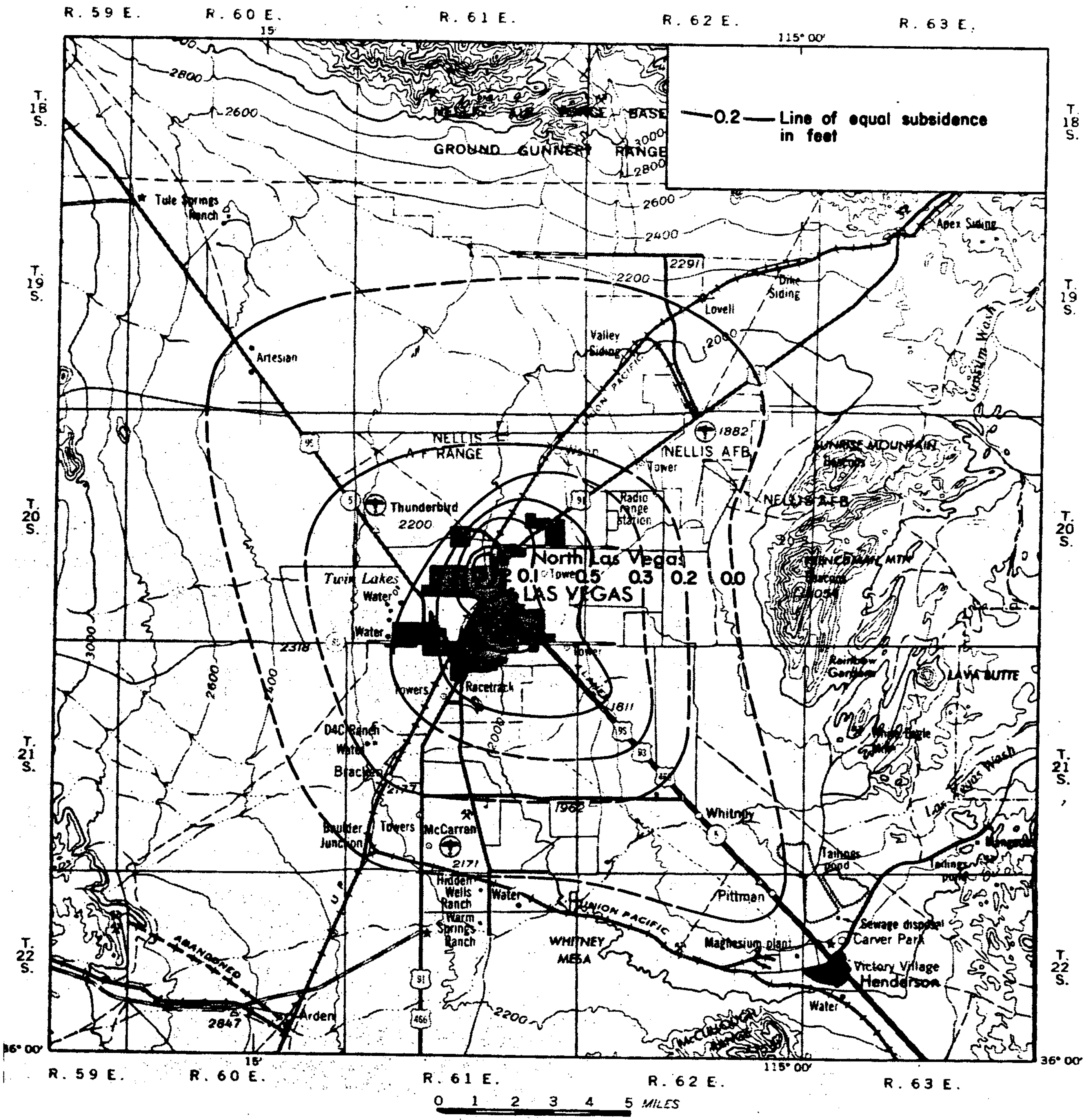

Figure III-D-3. Land Subsidence in Las Vegas Between 1950 and 1963 Due to Artesian Head Decline. (From Mindling, 1971)

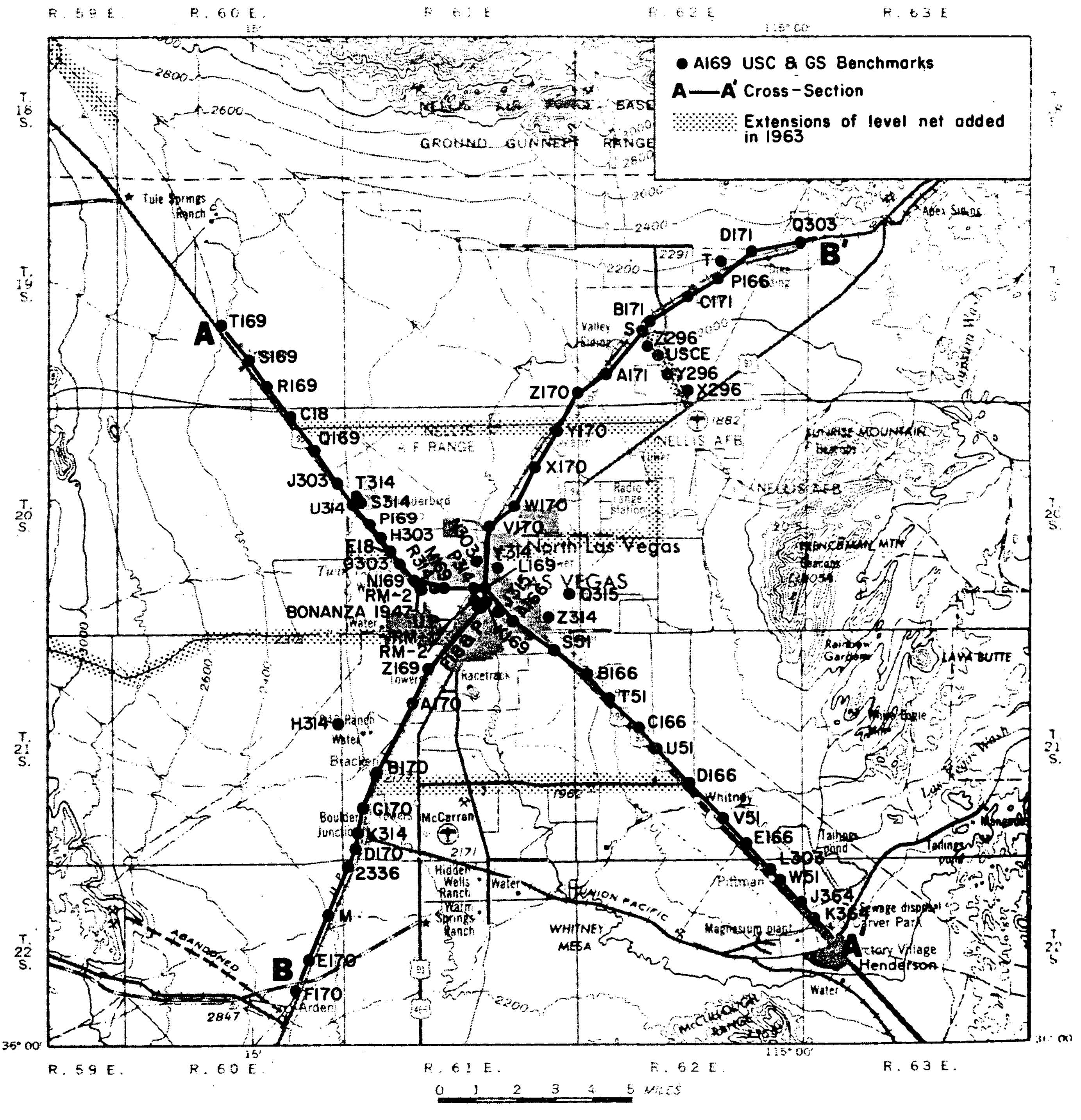

Figure III-D-4. A portion of the Hoover Dam Level Net in Las Vegas Valley. (From Mindling, 1971)

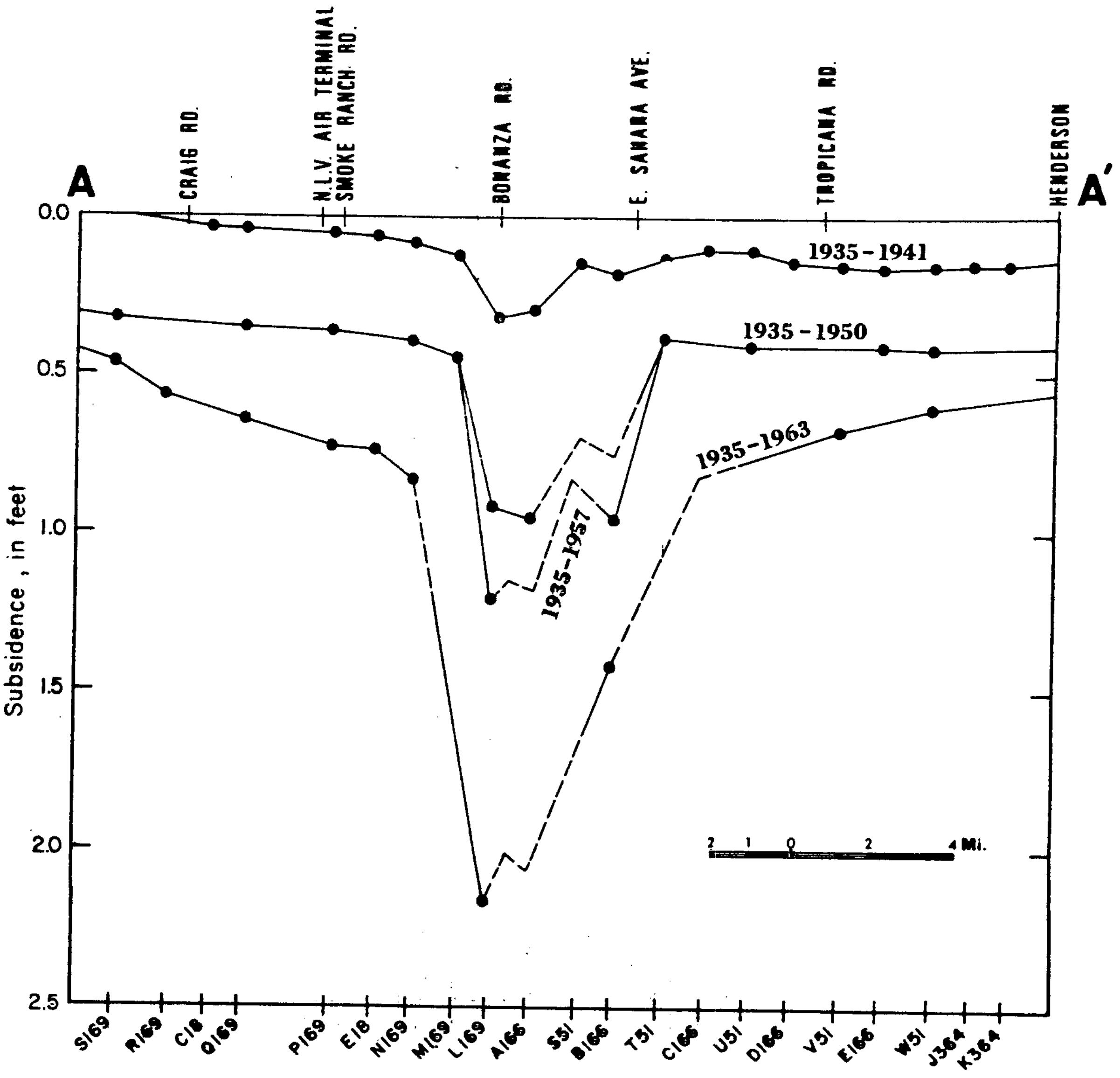

Figure III-D-5. Northwest-Southeast Cross Section of Total Land Subsidence in Las Vegas Valley. (From Mindling, 1971)

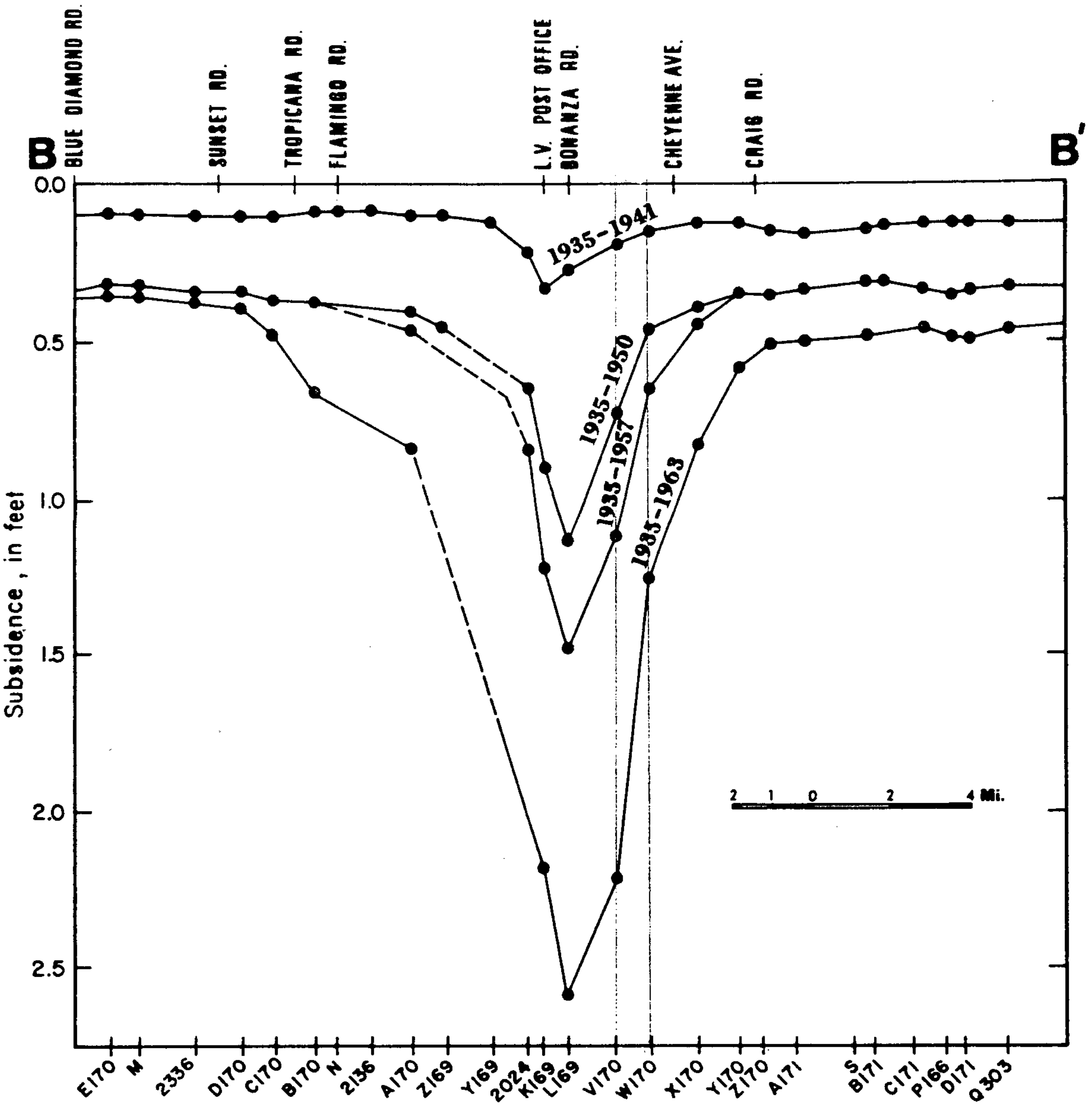

Figure III-D-6. Northeast-Southwest Cross Section of Total Land Subsidence in Las Vegas Valley. (From Mindling, 1971)

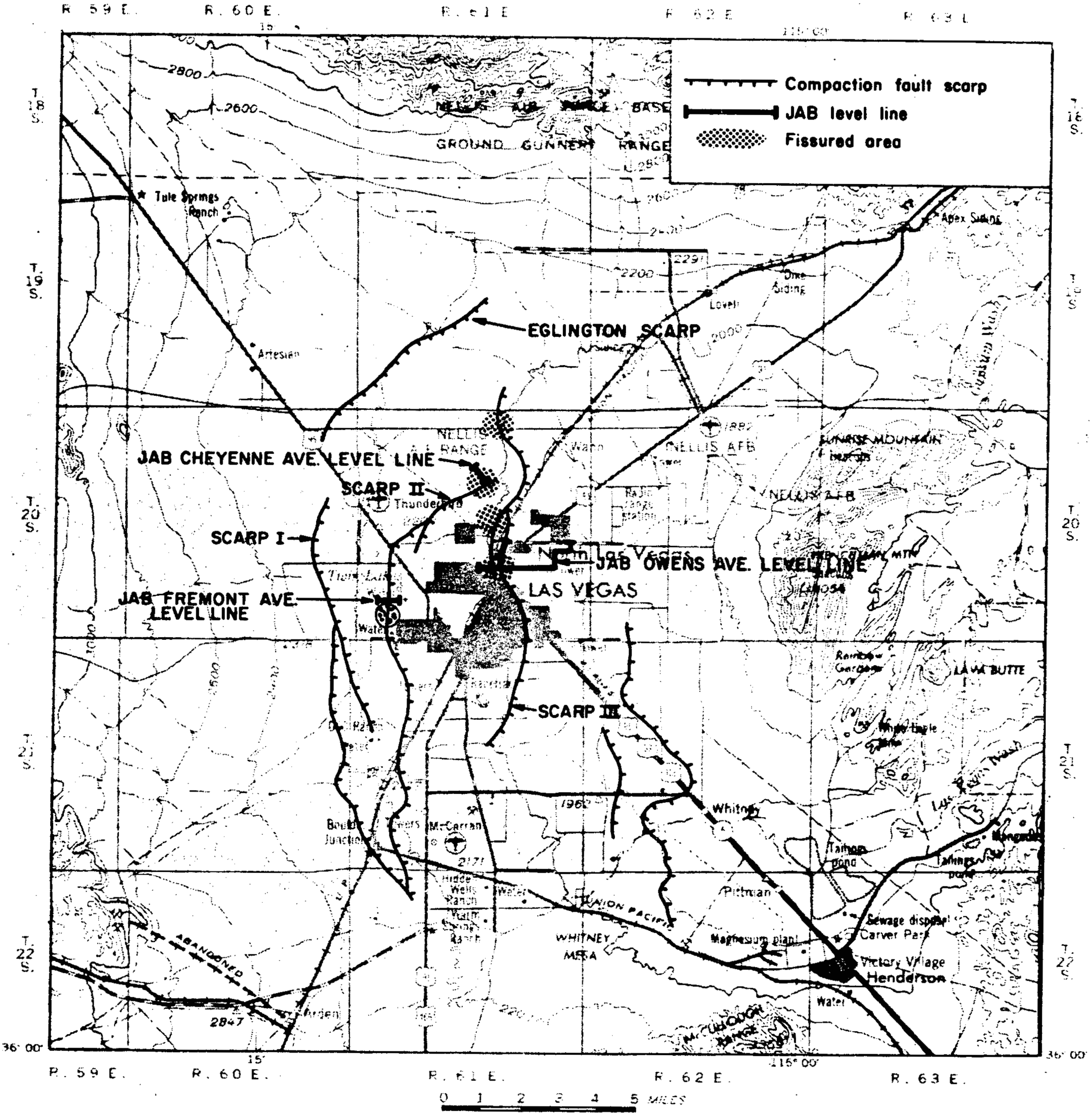

Figure III-D-7. John A. Blume Level Lines, Compaction Fault Scarps, and Areas of Fissuring. (From Mindling, 1971)

Subsurface deformation and ground cracking are the main contributors to significant damage in the area.

Local well drillers have estimated that approximately 100 wells have been adversely affected by subsidence resulting in a repair/replacement cost in the vicinity of $400,000. Pipeline repairs related to subsidence effects have cost the City of Las Vegas approximately $1,500. Although damage from fissuring has been documented for a few homes, no cost estimates were projected, due to extenuating circumstances involving the cases. At least one home which was severely damaged by fissuring is reported to have been abandoned: it was located within a road right-of-way and was slated to be torn down anyway. The city engineering and road departments of Las Vegas and North Las Vegas spend approximately 2% of their annual budget, or about $19,000 a year, repairing road damage resulting from subsidence, including fissuring and cracking of roads, sidewalks, and curbs.

Two reservoirs were adversely affected by fissuring to the point of abandonment. One was abandoned for reasons not related to subsidence, and the replacement cost of the other was $100,000. One portion of a railroad grade was repaired after a fissure went through it, but the cost of repair is not known. The total estimated cost of damages described above clearly exceeds $500,000 to date.

(4) Aggravation of Other Hazards

Subsidence has been known to aggravate existing hazards such as flooding in other areas. In the Las Vegas area, periodic flash flooding is a hazard, but subsidence is not known to have significantly affected the pattern of flood prone areas or the frequency and depth of flooding. Conceivably fissuring could affect some of the reservoirs in the area, causing piping (erosion) or possibly failure of the embankment. However, there are no large dams in the valley which would present a significant flooding hazard.

(5) Effects of Aggravated Hazards

None known.

(6) Adjustments to Subsidence

Adjustments to subsidence-related damage have included abandonment of some wells and relocation of others, in an effort to disperse the area of withdrawal so localized cones of depression can be relieved. Numerous scientific studies have been undertaken to evaluate the cause, extent, and potential impact of the subsidence and related effects. Relevelling studies are conducted periodically by the National Geodetic Survey, the U.S. Geological Survey, the Nevada Highway Department, and the Cities of Las Vegas and North Las Vegas. Las Vegas and North Las Vegas have spent over $80,000 to date on these relevelling studies, but the cost to the other agencies is not known. Further adjustments by the cities has included road and pipeline repair as discussed above. In addition, an alternative, supplementary water source has also been developed by importing Colorado River water for domestic use. The governor of Nevada has recently appointed the Nevada Bureau of Mines to study the subsidence problem in the Las Vegas Valley.

(7) Summary of Effects

Damages	Remedies	Costs
Well casings deformed or broken (100 wells)	Repair or replacement	$400,000
Reservoir damaged by fissuring	Replacement	$100,000
Pipelines	Repair	$ 1,500
Home damage by fissures	Repair or abandonment	Not Available
Roads, sidewalks and curbs cracked by fissures	Repair	$ 19,000 per year
Railroad damaged by fissures	Repair	Not Available
Subsidence control	Relevelling	$ 80,000

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R. O. Patt, Research Associate, Desert Research Institute, University of Nevada, Reno, Nevada: telephone interview, March 10, 1978.

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Kerry Rowe, Engineering Designer for the City of North Las Vegas, California: telephone interview, March 10, 1978.

A. F. Effinger, Owner, Effinger Drilling, Las Vegas, Nevada: telephone interview, March 10, 1978.

M. E. McKinney, Owner, McKinney & Sons (well drillers), Las Vegas, Nevada: telephone interview, March 10, 1978.

E. MEXICO CITY, MEXICO

(1) Introduction

An area of 225 square kilometers in and around Mexico City, Mexico has experienced considerable subsidence due to the withdrawal of groundwater from aquifers beneath the city to provide municipal and industrial water supplies. The maximum subsidence of almost nine meters and the considerable amount of differential subsidence has caused much damage and many engineering problems within the city. As a result, Mexico City is known worldwide as one of the classic examples of subsidence.

Mexico City is located in the Valley of Mexico at the south end of the Mexican Plateau. Surrounding mountains have made the valley a closed basin with internal drainage to intermittent lakes in the lowest areas. Mexico City is partly located on what was formerly the bottom of a large lake. The city's location on the young lake sediments has resulted in many foundation problems for buildings, including excessive settlement of new structures and settlement damage to adjacent buildings and utilities during construction of new buildings. These foundation problems are not directly related to subsidence caused by fluid withdrawal, but their effects on structures are similar. Because poor foundation conditions occur in areas which are also subsiding, it is difficult to separate the effects of the two problems.

(2) Description of Primary Subsidence Phenomena

The closed basin of the Valley of Mexico has been partially filled by materials eroded from the surrounding mountains and by ash deposited from eruptions of nearby volcanoes during the last few million years. These materials, primarily gravels, sands, silty clays and ash, have been deposited in a series of layers to a depth of several hundred meters. From a depth of about 10 meters to 35 meters, these materials are mostly fine grained lacustrine deposits of Late Pleistocene age, when much of the valley was under water. Groundwater has been pumped from the more permeable sand and gravel aquifers from a depth of about 35 meters to depths of up to 500 meters. The fluid removal has caused a lowering of the deep groundwater table and the consolidation of the more compressible portions of the aquifer. Surface subsidence has occurred over an area of 225 square kilometers, with maximum subsidence reported to be about 8.5 meters to date. Eighty to eighty-five percent of this subsidence is the result of consolidation of sediments at depths of less than 50 meters. This shallow consolidation depth and the non-uniform withdrawal of groundwater over the area has resulted in highly irregular subsidence contours. These irregular contours at Mexico City do not resemble the relatively smooth subsidence bowl contours found where geofluids are withdrawn from much greater depths.

Subsidence from fluid withdrawal was first discovered in 1925, although it probably dates back to about 1860 when the first deep well was drilled. Subsidence from normal consolidation of the basin sediments is also occurring, but at a much slower rate than that caused by water withdrawal. The maximum rate of surface subisidence due to groundwater extraction reached 45 cm/year in 1951 in the central part of Mexico City. In the early 1950s, a new aqueduct was constructed to import water for the supply of Mexico City. Since that time, over-pumping of groundwater has ceased and the water table has stabilized. The rate of subsidence decreased accordingly, but some settlements of the ground surface continue to occur, at a rate which is decreasing with time.

Some ground surface cracking has also resulted from the removal of groundwater. These cracks occurred in areas where the near-surface water table was lowered enough to cause the drying of near-surface clay deposits. Large shrinkage cracks resulted. In some cases, these shrinkage cracks opened as much as a meter at the surface and extended to depths of over 15 meters. The cracks were mostly in undeveloped areas and caused little damage.

(3) Effects of Primary Subsidence Phenomena

Mexico City has experienced extensive damage from subsidence and related phenomena. The most severe damage from subsidence has occurred in the local subsidence bowls around major wells. The abrupt depressions around these wells have destroyed buildings, broken sewers and water supply lines, disturbed streets, sidewalks, and train tracks and in general have been responsible for most of the more obvious and spectacular damage in the city.

More widespread damage has occurred to the sewage systems. Breaks have been reported where differential subsidence occurred, and the surface subsidence has decreased slopes in some of the sewers to the point where pumps have been necessary to move sewage water to higher levels in the system. Leaks from cracks in the sewage systems pose major health problems since groundwater is used for domestic supplies. Approximately 60 kilometers of new sewer main has been constructed at a lower elevation.

Breaks in the water supply system have also been reported. Broken water mains have been difficult to detect and much water has been lost.

Pile foundations of buildings have also been subject to damage. Friction forces from consolidating materials along the piles have caused piles to sink further into the ground and in some cases have caused differential settlements. Grouting under the piles to improve their bearing capacity enough to overcome the friction forces has been necessary in some cases. In other cases, buildings on shallow foundations have been damaged because they were located adjacent to buildings on piles. During shallow subsidence, the pile structures did not subside and emerged slowly from the ground surface, while the adjacent building sank with the ground surface. The resultant differential movement between the two buildings has caused the building on shallow foundations to tilt away. Timber sheet piles have been driven into the ground between buildings in this situation to form a slip surface and minimize damage. These relative movements between buildings or between buildings and the adjacent ground have damaged utilities entering the buildings, unless flexible connections have been provided.

Since most of the subsidence occurred from the consolidation of near-surface materials at depths less than 50 meters, the well casings which extended to depths greater than 50 meters did not subside appreciably. The result was that the ground subsided around many of the deeper well casings, leaving them protruding several meters above the ground surface.

(4) Aggravation of Other Hazards

In addition to subsidence phenomena associated with fluid withdrawal, Mexico City is adversely affected by unfavorable foundation conditions. These conditions are not aggravated by the subsidence, but settlement damage arising from them is difficult to separate from that due to subsidence. The clay deposits underlying much of the city are so weak that new buildings experience large total and differential settlement unless the buildings receive careful attention to foundation investigation and design. Heavy buildings on raft foundations have experienced settlements of 1.0 to 1.5 meters within a few years when their weight exceeded the critical compressive strength of the clays. Long buildings have suffered considerable differential settlement; and in some storage buildings, relevelling of floors has been required, because handling of merchandise became too difficult.

Buildings on pile foundations have not suffered appreciable settlement, but differential movements between them and adjacent buildings not on piles have damaged the adjacent buildings. These foundation problems have plagued residents of the city since the Aztecs first noticed settlements of their city in 1325. Large buildings from the Seventeenth and Eighteenth Centuries have settled so much that their first floors are now nearly buried below the street level.

(5) Effects of Aggravated Hazards

In spite of the large amount of damage that has occurred in Mexico City, no reliable estimates of economic losses have been made. It has been estimated that the cost of the new sewer system -- roughly 10 billion pesos ($500 million±) -- represents about 50 percent of the total cost of subsidence damage in Mexico City. Although foundation problems have been extensive in the city, they have not been attributed to subsidence. The total cost of damage to structures is probably on the order of several hundred million dollars.

(6) Adjustment to Subsidence

The residents have learned to live with these problems and have developed building designs and construction techniques to minimize adverse effects. Advances in the understanding of soil mechanics and foundation design in the last 30 years have also helped reduce damage. Nevertheless, many structures and public works in the city which have experienced foundation settlement damage are within the same areas that are also subsiding from fluid withdrawal. This overlap makes it almost impossible to isolate the damage caused by subsidence alone.

Importation of water supplies into the city and prohibition of new wells have succeeded in stopping most of the subsidence.

It is interesting to note that Mexico City has used subsidence phenomena for beneficial uses. A new surface water reservoir has been created outside of town by pumping groundwater to induce a subsidence bowl which was then filled with the pumped water.

(7) Summary of Effects

Principal effects of subsidence in Mexico City are tabulated below:

Damage	Remedies	Cost
Large shrinkage cracks	None to date, as cracks are mainly in undeveloped areas	-
Breaks and disruption of sewer system	Build 60 km of new sewer line	Approximately 10 billion pesos (Estimated $500 million at 20p/$ exchange)
Damage to structures, utilities streets, sidewalks and railroad tracks	For new buildings: use improved fdn design, flexible utility connections. For existing structures: repair where possible such as grouting under piles, use of sheet piles, between buildings, releveling floors, etc.	Total probably on the order of several hundred million dollars
Deep wells protrude above ground.	Not known.	Not available.

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F. SAN JOAQUIN VALLEY, CALIFORNIA

(1) Introduction

The San Joaquin Valley is a broad alluviated trough making up two-thirds of the Central Valley of California. It is about 90 kilometers wide, bordered by the Sierra Nevada on the east and the Coast Ranges on the west. The United States Geological Survey has done extensive work documenting and describing the extent and causes of land subsidence in the San Joaquin Valley of California.

Surface streams from the mountain runoff provide most of the irrigation needs in the northeast part of the valley. South of Kings River and throughout the west of the valley, however, natural runoff is inadequate or negligible. Before major canals were built, the valley's western and southern areas were irrigated by thousands of large and deep irrigation wells.

According to Lofgren (1976) three man-induced processes are causing land subsidence in the San Joaquin Valley: the compaction of aquifer systems caused by the intensive pumping of groundwater; the compaction of moisture-deficient deposits when water is first applied (hydrocompaction); and the extraction of fluids in several oil fields. Figure III-F-1 indicates areas affected by compaction. In the north end of the Valley, farming practices in the delta area of the Sacramento and San Joaquin Rivers have also resulted in subsidence of the land surface. In addition to man-made changes, the slow uplift of the southern and western mountains and very slow settlement of the Valley -- tectonic adjustments -- affect ground surface levels.

Approximately half of the area of the Valley has been affected by subsidence, and maximum subsidence exceeds 2.8 meters (29 feet). Changes have occurred so slowly and uniformly over a broad area that the effects of subsidence have gone unnoticed by most residents. In local areas, however, abrupt effects are in evidence.

(2) Description of Primary Subsidence Phenomena

The extraction of deep groundwater has been the principal cause of subsidence in the San Joaquin Valley. The practice of using groundwater for irrigation began during World War I and surged in popularity during and after World War II. By 1950, more than one quarter of all groundwater pumped for irrigation in the country was used in the San Joaquin Valley. Groundwater overdraft has prevailed in the area since the 1930's, and the decline in water levels has been recognized for a long time. Subsidence has been the cause of increasing concern for some thirty years, raising the height of pumping lifts, causing well casing failures and creating various other problems.

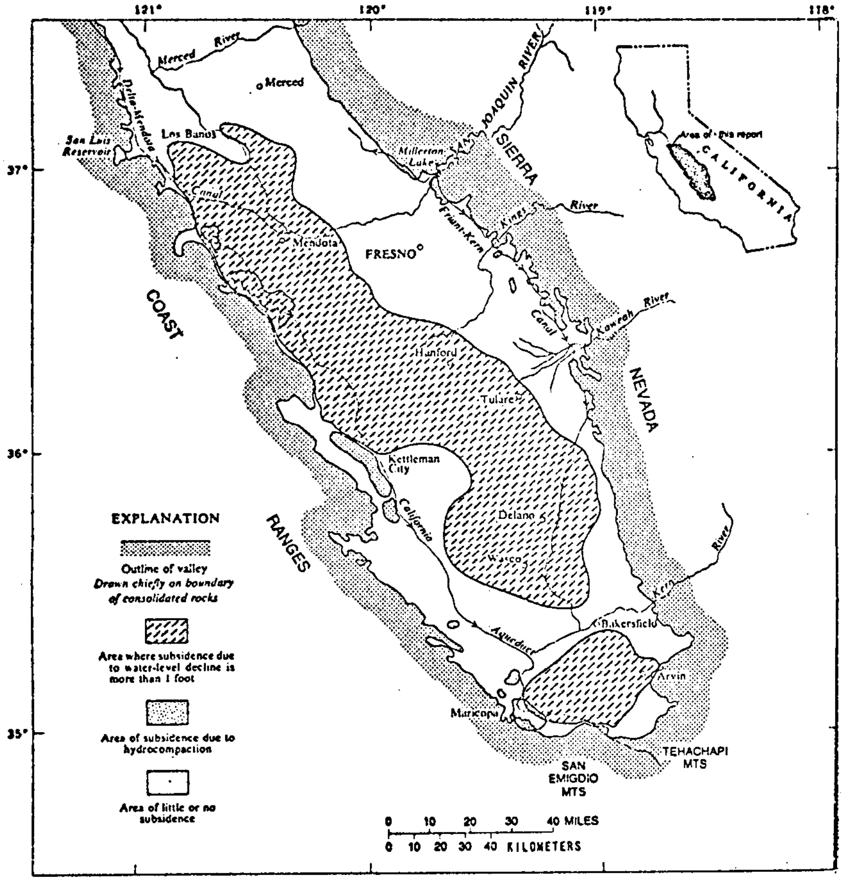

Figure III-F-1. Pertinent Geographic Features of Central and Southern San Joaquin Valley and Areas Affected by Subsidence (From Lofgren, 1976).

Groundwater pumping increased with the drought of 1976-77 and is likely to remain above the predrought rate, even though the drought ended in early 1978. Farmers, fearing a recurrence of water shortages, are likely to keep those wells that were put into operation during the drought at some minimum level of pumpage in order to be prepared. The effect of this on groundwater levels or subsidence is not now known.

Lofgren (1976) described the subsidence as follows:

> ...there are three centers of major subsidence: (1) a long narrow trough west of Fresno, referred to as the Los Banos-Kettleman City area, with a maximum subsidence of over 8.8 m (29 feet); (2) a central subsidence bowl between Tulare and Wasco with more than 3.6 m (12 feet) of settlement; and (3) a southern depression south of Bakersfield, commonly referred to as the Arvin-Maricopa area with maximum subsidence of about 2.7 m (9 feet).
>
> Subsidence due to groundwater pumping began in the middle 1920s, but the cumulative volume of subsidence remained small until after World War II. By 1970... roughly 11.1 x 103 km (4300 square miles) of farm land had subsided more than 1 foot.

Figures III-F-2 through III-F-5 illustrate the overall subsidence phenomena.

At the U.S. Geological Survey in Sacramento, California, B. E. Lofgren and J. F. Poland have been the principal investigators of the subsidence phenomena since 1955. Both have published several articles and appeared at a number of symposia to discuss their findings. Nikolas P. Prokopovich, a geologist with the U.S. Bureau of Reclamation, has also done extensive work on subsidence in the San Joaquin Valley. The Bureau has planned and constructed several canal projects in the valley that have been affected by subsidence or have had to be designed with subsidence in mind. Mr. Prokopovich has published several articles on the problem since 1968; and he and the Bureau have been attempting since the 1960s to predict ultimate land subsidence, so that new canals could be designed with allowances for eventual subsidence effects.

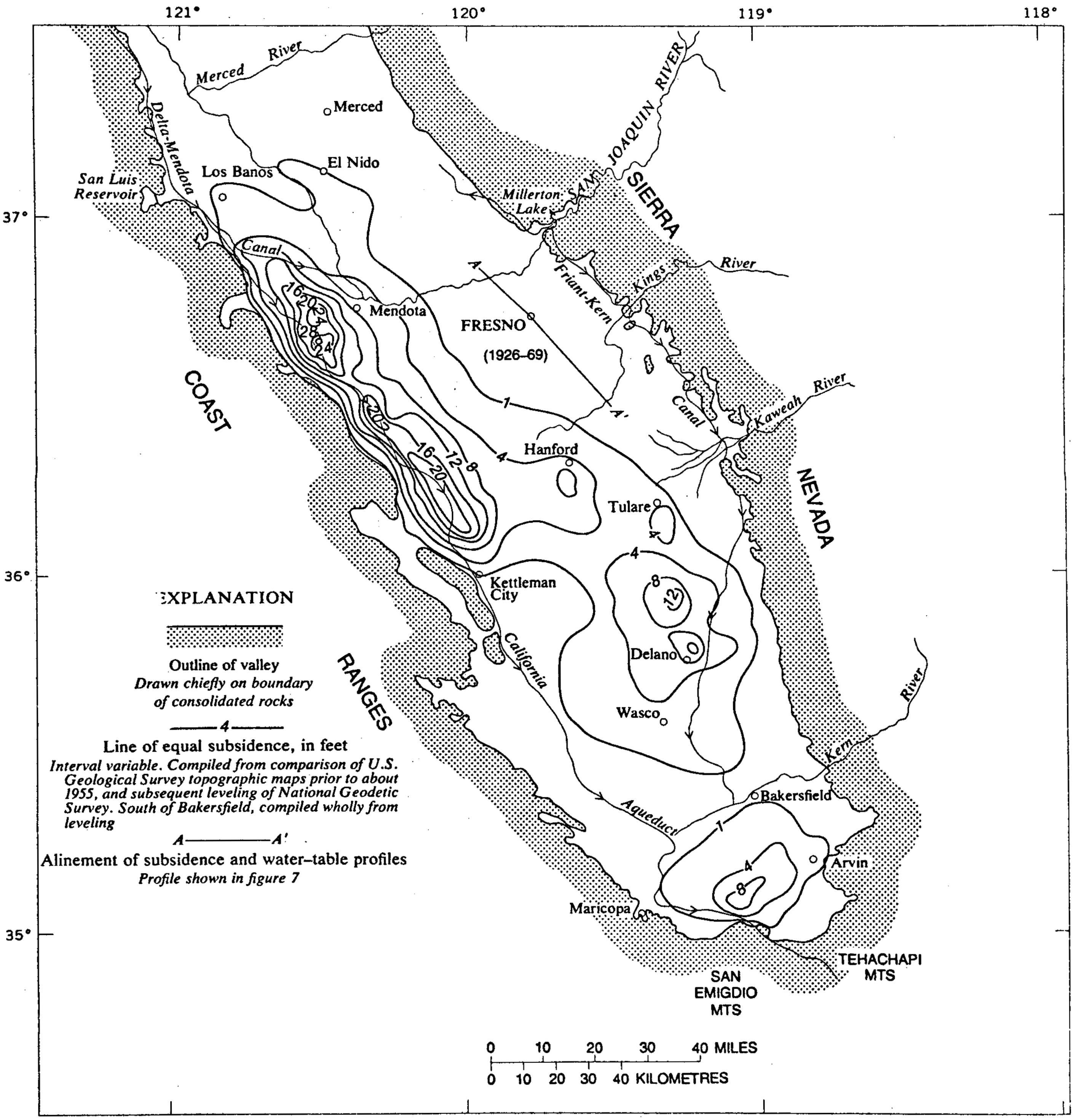

Figure III-F-2. Land Subsidence in the San Joaquin Valley, 1926 - 1970 (from Poland, Lofgren, et. al., 1975)

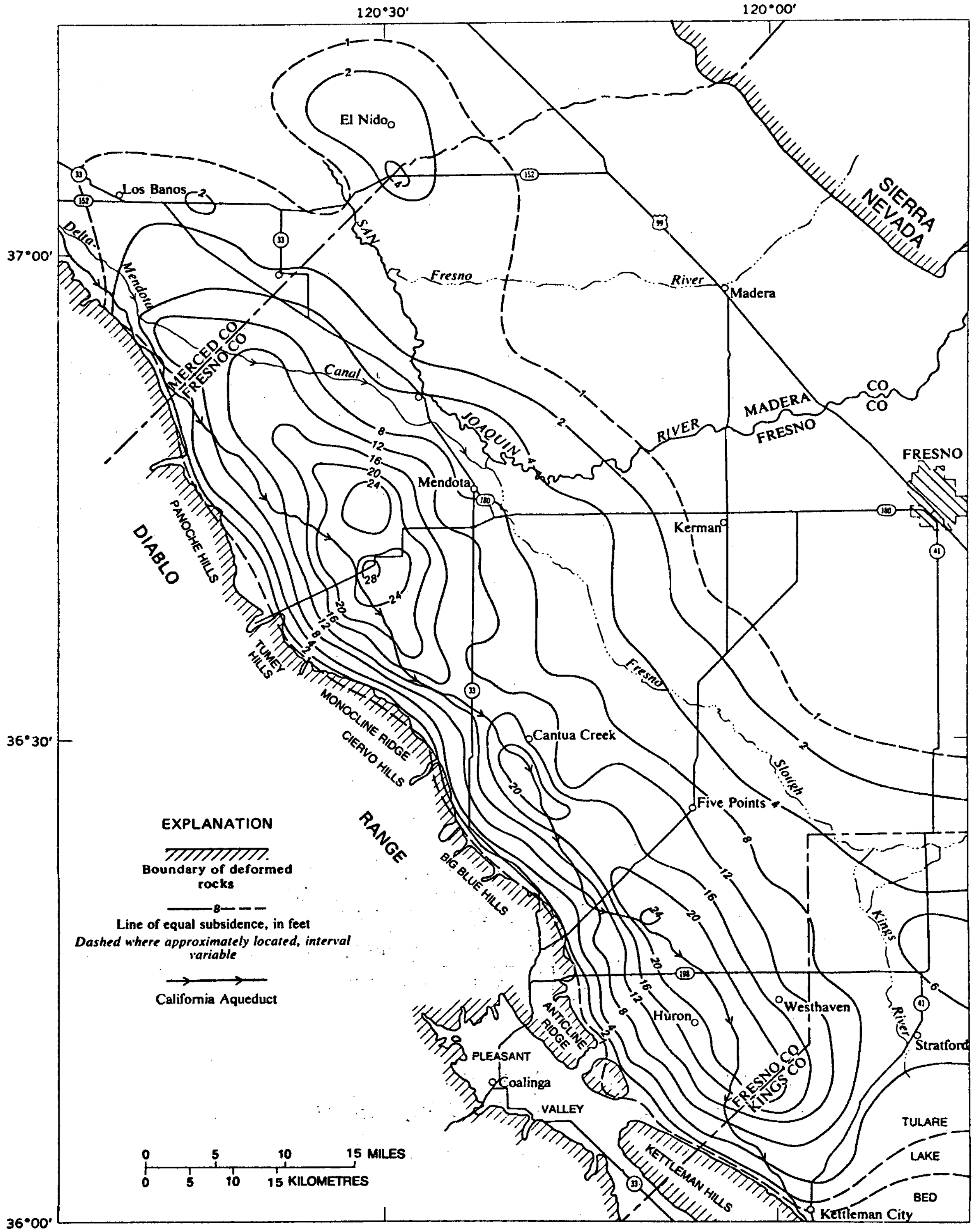

Figure III-F-3. Detail of Land Subsidence, 1926 - 1972, Los Banos-Kettleman City Area (from Poland, Lofgren, et. al., 1975).

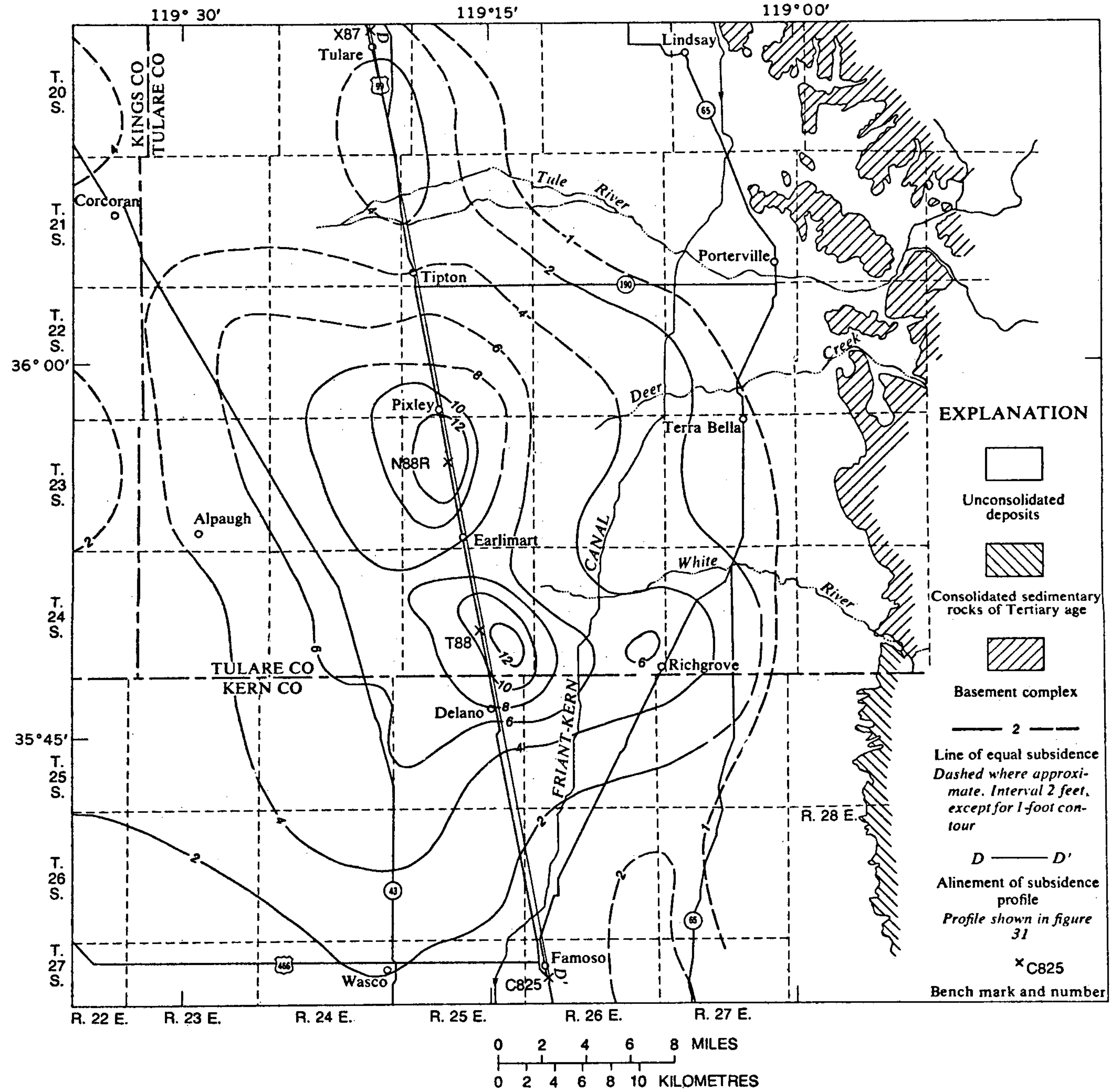

Figure III-F-4. Detail of Land Subsidence, 1926 - 1970, Tulare-Wasco Area (from Poland, Lofgren et. al., 1975)

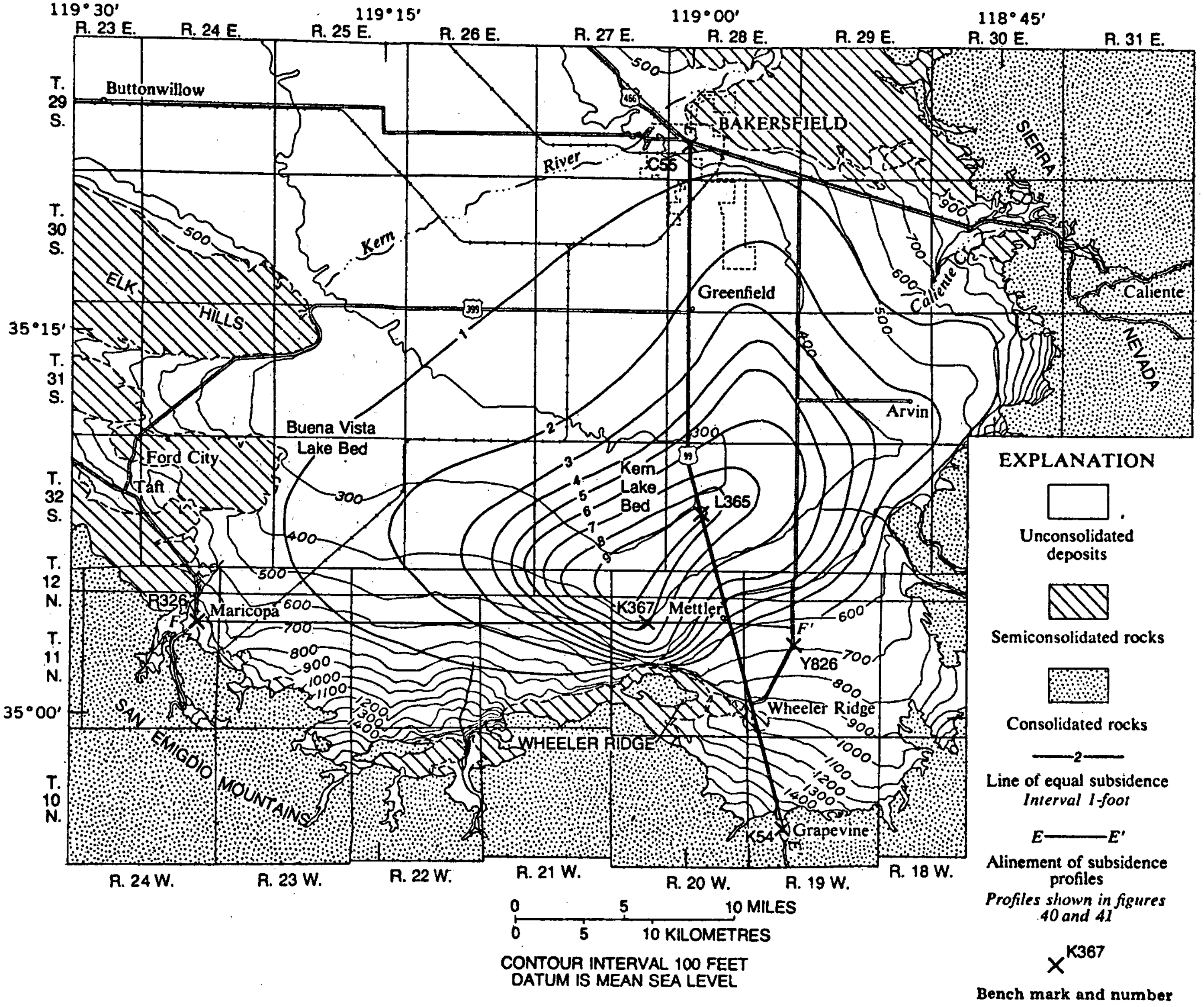

Figure III-F-5. Detail of Lane Subsidence 1926 - 1970, Arvin-Maricopa Area (from Poland, Lofgren, et. al., 1975)

(3) Effects of Primary Subsidence Phenomena

Deep subsidence has caused permanent changes in aquifers, as well as alterations to natural and man-made drainage. No physical deterioration of man-made structures other than wells and canals has been noted. No subsidence related problems have been reported by local sewer and water districts. Ground surface cracking has only been found in two places, and that appears to be associated more with the local drawdown of water than with the regional subsidence phenomenon itself. Obvious surface effects have been noted in the valley due to hydrocompaction, but have not been reported as a result of deep fluid withdrawal. Except for the damage to wells, the effects of subsidence caused by compaction at depth are generally more subtle because the changes in elevation are spread over a much larger surface area.

As large areas of the valley floor have subsided, the gradient of streams from the mountains has become steeper. This allows the water passing through the generally dry streambeds to move faster. However, since the natural flow of most streams entering the valley has been altered by dams in the mountains, it is difficult to quantify the degree to which erosion may have been increased by subsidence. Surface flow on the valley floor northward towards the natural outlet to San Francisco Bay has been slowed because gradients have been decreased in subsidence areas.

Flash floods were a common occurrence until flood control dams were constructed in the mountains. Now they occur only when storage reservoirs get full and flood waters must be released. The steeper gradients in the streams generally allow more water to be carried, decreasing the potential for flooding along streambeds leading into the valley. However, many of the streambeds enter the floor of the valley in curvilinear courses with many oxbow bends. Where the course bends back towards the mountains, the gradient decreases. Due to subsidence, this increases the probability that a rush of water from the mountains may have to leave the banks of the streambed, causing a flood. Studies have not been conducted to find the extent of this damage, so it has not been confirmed as the cause of any flooding in the valley.

The permanent change in the aquifers should also be considered in an assessment of damage. Although there is a simple volumetric way to measure that damage, assessment of the benefits and detriments is more difficult. Lofgren estimates that in the area roughly from Kettleman City in the south to Los Banos in the north, 1.1 million acre-feet was water permanently squeezed from the deep subsurface clays in three years. Once squeezed out, the water-bearing capacity is permanently lost.

The principal measurable damage to man-made systems in the valley has been to wells, canals and to the aquifers. The effect on canals is best documented by Prokopovich and Hebert (1968). They cite an area along the last 30-40 miles of the Delta-Mendota Canal as a good example of the effects of subsidence phenomena. Subsidence was not taken into consideration during construction of the canal, with the result that bridges, concrete lining, pipe crossings and other structures eventually became partially or completely submerged. On the western side of the San Joaquin Valley, the San Luis Canal was designed and constructed with features which anticipate subsidence effects. Minor subsidence has also been noted in the vicinity of other canals, including the Friant-Kern, the Tehama-Colusa, the Folsom-South, and near the proposed Peripheral Canal. Additional freeboard was designed into the canal planning in order to anticipate subsidence effects. In general, this was adequate to compensate for construction and post construction subsidence.

Collector drains, which catch water after irrigation, are located on the valley floor and run northward. Subsidence has lowered the gradients in these, reducing their capacity and making them more costly to design and build. Subsidence along the routes of other canals in the central valley is caused by two other phenomena not related to deep water withdrawal: hydrocompaction of near surface soils with the introduction of irrigation; and oxidation of deltaic peat in the delta areas of Sacramento.

Researchers for the U.S. Geological Survey estimate that damage to wells caused by subsidence has been the greatest dollar cost of subsidence. However, it is difficult to estimate the number or cost of wells affected. It seems clear that the expected life span of wells was reduced as a consequence of subsidence. During the 1930s and 40s, the expected life span of a well was ten to fifteen years, and when subsidence began to cause damage, many wells were already old. New wells were often drilled in areas where the chances of finding an ample water supply were not as good. Subsidence was just one additional factor making the investment in a well risky. The Bank of America in Fresno lends money for wells on a five-year note; however, both a farmer and a well industry executive in the area estimate that the average well life is still at least ten years.

On one farm of 120,000 acres, there were about 240 wells. The farm manager estimates that probably 25% of those wells were damaged by deep subsidence. A typical depth is about 2,000 feet. Although, the construction cost of these wells was about $10/foot when pumping and subsidence were at their peaks, cost of replacement in 1978 would be about $60/foot. The same farm manager noted that over the years, when subsidence was causing serious problems with the wells, the quality of water in the wells was improving. Boron, a major problem for San Joaquin Valley irrigation was at a level of about two parts per million in the 1940s, but by 1978 it had gone down to about .5 parts per million (Wolf, personal communication). A new form of casing that has sleeve joints so that it can accept some vertical movement is now in general use. It costs about $1,000 extra per well.

No study has been made of the complete dollar cost of subsidence in the San Joaquin Valley. Poland and Lofgren (1976) estimated the total cost to be $25,000,000. Their estimate came primarily from discussions with the Bureau of Reclamation and the Department of Water Resources of the State of California. They view the cost of well damage and repair as the major item that is difficult to estimate.

The Bureau of Reclamation has made some estimates of cost of damages and preventative measures to the Delta Mendota and San Luis Canals. Twenty-six miles of the Bureau of Reclamation's Delta-Mendota Canal have required rehabilitation following damage due to deep subsidence from 1969 to 1978, and the Bureau has had to raise the concrete canal lining and some bridges at a cost of $5 million.

(4) Aggravation of Other Hazards

As noted earlier, flooding may be accentuated by subsidence along curvilinear streambeds with oxbow bends that turn back towards the mountains. However, this hazard has not been specifically documented. No flood has been attributed to it.

(5) Effects of Aggravated Hazards

None are known.

(6) Adjustments to Subsidence

Efforts to mitigate the subsidence problem have included:

- Countermeasures to Affect the Cause. The canal and aqueduct system in the San Joaquin Valley has provided an alternative to groundwater pumping by importing surface water to areas of serious overdraft. These waters were not brought in just to stop subsidence, but as a cheaper source of irrigation water. In any case, the effect has been to reduce pumping and subsidence, and to reverse the decline of artesian pressure. Today, much of the overdrawn area is returning to a stable water budget.

- Research. U.S. Geological Survey and the Bureau of Reclamation have been studying the causes and effects of subsidence in the area since the 1950s. This work has helped them and others understand the problem.
- Repair. Freeboard has been added to canals where needed. Wells have been replaced or repaired.
- Planning. The Bureau of Reclamation pioneered efforts to predict subsidence and included subsidence considerations in its design of its most recent canals in the valley.

Making use of the experience gained from subsidence problems elsewhere, the Bureau of Reclamation specially designed certain reaches of the San Luis Canal where subsidence was likely to occur. The cost of these preventive measures was $4.5 million over the cost of construction if no special measures had been taken (Prokopovich, personal communication, 1978).

Beyond the direct cost of subsidence, there is a cost involved in monitoring and studying it. The network of benchmarks that has been used to monitor the progress of subsidence in the valley has been surveyed 12 times. The 1967 survey alone cost $35,000. Overall, between $100,000 and $200,000 has been spent on these surveys. Added to that is the cost of supporting the scientists who have been studying the problem on a full or part-time basis. While there is a great deal of cooperation and collaboration among Federal, State and local agencies regarding subsidence, there is no adopted comprehensive plan of response.

(7) Summary of Effects

Available data on subsidence damage and direct associated costs for the San Joaquin Valley are summarized below:

Damages	Remedies	Costs
Decreased storage in aquifers	Increased reliance on surface supplies	Difficult to assess
Partial or complete submergence of canals, and associated bridges and pipe crossings	Construct additional freeboard; plan for subsidence in new construction	$4.5 million for San Luis Canal

Damage to wells and well casings	Repair, replacement; increased reliance on surface supplies	Major cost, but no estimates given*
Damage to wells and well casings	Use of sleeve joints on new wells	$1000 per well
Disruption of collector drains, and irrigation ditches	Repair drains; relevel fields	Unknown

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* Poland and Lofgren (1976) estimated total costs to be about $25,000,000.

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G. SANTA CLARA VALLEY, CALIFORNIA

(1) Introduction

The Santa Clara Valley, an alluvial plain at the south end of San Francisco Bay exhibits the direct effects of subsidence caused by overdraft of water from a deep confined aquifer. It also exhibits an indirect increase in the flood related hazards due to being a bayshore area.

The Valley is bounded on the southwest by the Santa Cruz Mountains and on the northeast by the Diablo range. It is a structural trough, with bedrock forming the floor and sides. Fresh water is available from wells that draw on alluvial and bay deposits and underlying deposits of the Santa Clara formation. Deposits have a combined thickness of from 1,000 feet to possibly as much as 2,000 feet, and water wells range from 200 to 1,000 feet in depth. Artesian conditions prevail beneath most of the valley area (Poland and Davis, 1969).

There are several cities in the valley subsidence area, San Jose being the largest, and Alviso the closest to San Francisco Bay. Historically, Alviso was separated from open bay waters by about four miles of low marshland. These low lands, which formed the shore for most of the south end of the bay, had been converted to salt production ponds long before subsidence began.

(2) Description of Primary Subsidence Phenomena

Subsidence in the valley was caused by steadily increasing withdrawal of deep groundwater, primarily for irrigation. According to Roll (1964), little water was pumped before 1900 and only for domestic use. By 1936, irrigation was widespread and most of the valley was being irrigated from groundwater sources.

Land subsidence was first noticed in 1932. A network of benchmarks was established in the valley in 1934; and regular surveys have been conducted by the National Geologic Survey, most recently in 1967. Subsidence ranged from 0.3 to 1.2 meters under San Francisco Bay to 2.4 meters in San Jose during the 33-year period (Poland, 1976).

In 1929, a water conservation district was formed. Dams were constructed on major streams to hold flood waters that had previously flowed into the Bay. These would be slowly released during the dry seasons to percolate into the underground basins. Eight dams were constructed by 1952, with a total storage capacity of 156,900 acre-feet. The Santa Clara Valley Water Conservation District has also built 48 miles of canals, 14 miles of pipelines, and 500 acres of percolation ponds.

Nevertheless, the area was not able to meet its water requirements without continued overpumping of the groundwater basin. Imported water was first delivered to the area by the State of California's South Bay aqueduct in 1965 (Roll, 1967).

The water level recovery has been dramatic. Poland (1976) reported that:

> By 1975, the spring high water level at index well 7R1...was 32 m (104 feet) above that of 1967, and about equal to the level in this well in 1925. This major recovery of artesian head was due to several factors, including increased imports of water, favorable local water supply, decreased pumpage and increased recharge. The most important factor was the increase in imports.

Two major agencies have been investigating causes and solutions to the subsidence problem. The subsidence study team of the U.S. Geological Survey in Sacramento, California has been primarily responsible for monitoring the progress of subsidence and identifying the causes. J. F. Poland of that team has been the principal investigator. The Santa Clara Valley Water Conservation District has been responsible for the water conservation and importation measures that have caused the subsidence to virtually cease. Also, Santa Clara County has hired a staff geologist to assist the county with groundwater and subsidence problems.

The broad expanse of subsidence in the valley has been well-documented by the U.S. Geological Survey. Figure III-G-1 shows the extent of subsidence measured in feet. The subsidence bowl has a volume of 500,000 acre-feet, which represents the amount of water that was squeezed out of deep clays.

(3) Effects of Primary Subsidence Phenomena

There appears to be no direct structural damage to buildings or other structures because the subsidence is essentially uniform over the small area occupied by most structures. Linear construction such as roads, railroads, pipelines and canals have enough flexibility to bend with the very gradual changes in gradients. However, it is believed that deep subsidence may be a contributing factor to damage to buildings

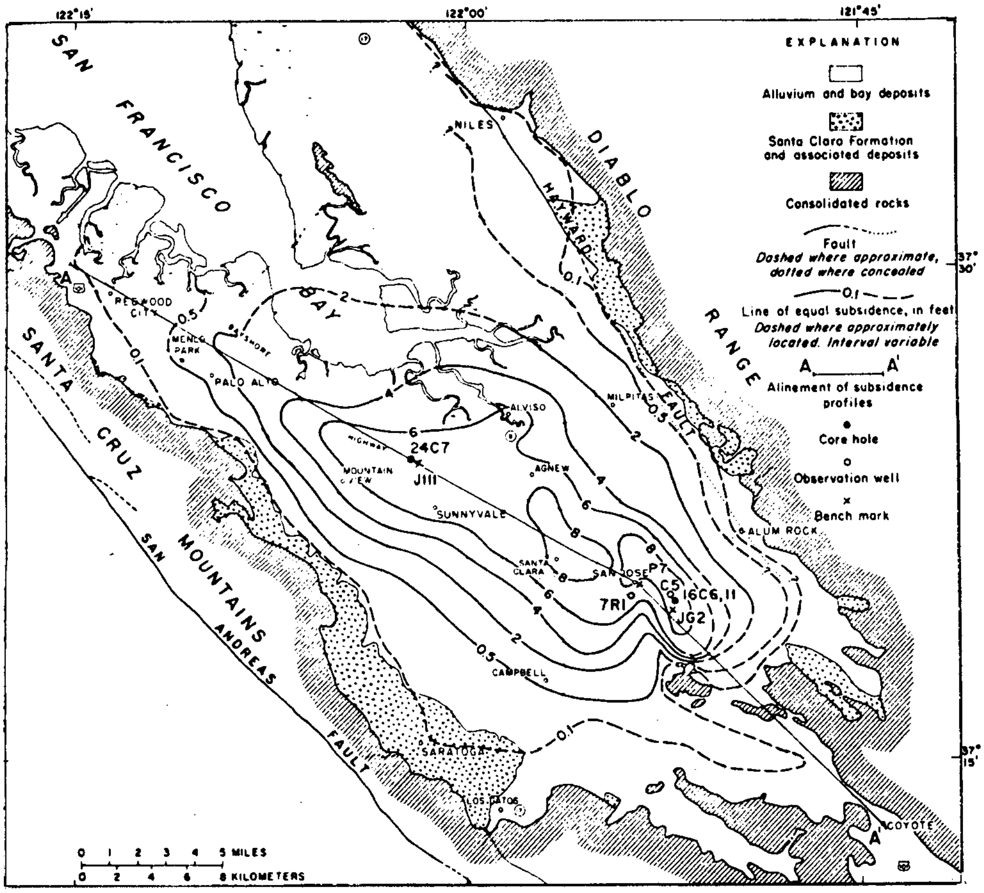

Figure III-G-1. Land Subsidence from 1937 to 1967, Santa Clara Valley, California; from leveling of National Geodetic Survey in 1934 and 1967 (from Poland, 1976).

in a ten square block area of Santa Clara. Surface settlement due to construction over an old swamp appears to be the primary cause (Berkland, personal communication).

The Santa Clara Valley area has experienced damage to wells, flood drainage systems, the aquifer, and to sewer systems.

The Santa Clara Valley Water Conservation District has had to deal with some difficult flood control problems caused by subsidence as described by Roll (1967). Two major streams, the Guadalupe River and Coyote Creek, and several smaller streams have slowed due to a flattening of the gradient. A serious reduction in carrying capacity has ensued, which has resulted in some cases in a six-foot deep deposit of erosion material in a channel that was originally 8-10 feet deep. When this happens, the flow of water in the channel becomes impeded and flooding occurs in the surrounding areas.

Extensive damage to well casings has also been caused by the subsidence. Some work has been done in the Santa Clara Valley to document the extent of the damage. Poland (1976) estimated that several hundred wells were damaged. Roll (1967) assessed the damage for the Santa Clara Valley Water Conservation District.

Damage to wells occurs as a telescoping action which causes buckling of the casings. Well casings have also been known to protrude at a rate which has required cutting every few years in order to keep the pumps on the floor of the pump house. There are approximately 5,000 wells in the valley, with as estimated one-half of these located in subsidence areas. Water companies estimate the total number of wells damaged as being around 2,000. The cost of repairs is estimated by local agencies and companies at $2,000 per well, of well repair for the Valley comes to some $5 million or more.

Roll (1967) reported that subsidence had caused significant problems with sewer systems in the valley, due to a loss in carrying capacity. Storm and sanitary sewers have had to be replaced with larger lines or new lines added, because of the change in grade from land subsidence. There are no exact records of the costs involved, but it has been estimated that they run into many millions of dollars. Two local public works officials were not able to document this problem, but noted that many lines run <u>with</u> the subsidence so that capacity increases. A definite problem was reported at the combined Santa Clara-San Jose Sewage Treatment Plant. The plant requires three pumping stations to move effluent through the plant and into the bay. At least one of those would not be needed were it not for subsidence. Construction of that additional pump station cost $8,000,000 to $9,000,000 in 1970 and its operation consumes $200,000 worth of electricity annually.

(4) Aggravation of Other Hazards

The increased flood hazard caused by subsidence is probably the greatest danger and probably the costliest damage caused by subsidence. As previously noted, the channel capacities are decreased by reduced gradients and increased siltation, with the result that channels overflow more quickly and cause flooding.

(5) Effects of Aggravated Hazards

Poland (1976) estimates that about $9 million of public expenditures through 1974 for flood control levees along the streams are attributable to subsidence. Most of this has been work done by the Santa Clara Valley Water Conservation District. No disastrous floods have occurred that can be attributed to subsidence. However, there are 17 square miles of land that would be inundated by the bay were it not for the levees. The Leslie Salt Company has about fifty miles of levees in the south bay to protect its salt marsh evaporation ponds which now occupy most of the old lowland and marshes around that end of the Bay (about 45,000 acres). Originally these levees which are located adjacent to the Bay, were about 2.5 to 3 feet high. One company engineer estimates that about 15 miles of the levees have had to be raised several feet to protect against overtopping by the Bay waters. Another 30 miles of levees may have been affected to some extent. The company has made no estimate of the dollar costs of protecting against the increased flood hazard to its ponds (Wilkins, and Walton, personal communication). The Southern Pacific Railroad participated in a $100,000 bridge raising project with the Water Conservation District in order to move some of its tracks near Alviso out of intermittent flood waters.

(6) Adjustments to Subsidence

Efforts to mitigate subsidence problems have included research to determine the cause of subsidence, measures to halt the subsidence and repair of damage.

The U.S. Geological Survey, and the Santa Clara Valley Water Conservation District have been studying the causes and effects of subsidence since the 1930s. Most of the actual research has been undertaken by the Survey. This work has assisted the District and the State to design appropriate measures to combat the problem.

As noted earlier, the Santa Clara Valley Water Conservation District constructed dams and ponds along streams to capture flood water and release it slowly to increase the amount of water percolating back into the aquifer. These 156,900 acre-feet of storage capacity, 48 miles of canals, 14 miles of pipelines and 500 acres of percolation ponds slowed subsidence by decreasing the ratio between amount of water pumped and amount of water recharged into the aquifer. The total investment in conservation facilities by 1964 was in excess of $13 million.

The District also imported water to reduce the need for pumping. In 1940, San Francisco began selling surface water from the Sierra Nevada. Water imported from the Central Valley through the South Bay aqueduct first became available in 1965, and total imports to Santa Clara County increased five-fold in the ten-year period from 1964-65 to 1974-75, from 30,000 to 148,300 acre-feet per year (Poland, 1976).

To further reduce pumping, Santa Clara placed a tax on groundwater in 1964 imposing a strong disincentive to pump groundwater. According to Poland (1976):

> In 1970-71, for example, the groundwater tax was levied at $8 per acre-foot for groundwater extracted for agricultural purposes and at $29 per acre-foot for groundwater extracted for other uses. For water delivered on the surface in lieu of extraction the cost was $10.50 per acre-foot for water used for agriculture and $31.50 per acre-foot for water used for other purposes. The economic advantage of using surface water where available is obvious.

These combined strategies worked very well. Yearly pumpage of groundwater decreased from 185,000 acre-feet in 1960-65 to 150,000 acre-feet in 1970. Poland judges that the increase in imported water was the most important of the measures that have virtually eliminated subsidence in the Santa Clara Valley.

The Water Conservation District and the Leslie Salt Company continually repaired and raised their levees to compensate for the increasing relative height of the Bay and the decreasing carrying capacity of stream channels. The Southern Pacific Railroad has had to raise some tracks and a bridge to keep the tracks out of the water. Hundreds of wells have been replaced or repaired.

(7) Summary of Effects

Subsidence effects in the Santa Clara Valley include:

Damage	Remedies	Costs
Several hundred to 2,000 well casings	Repair	$2,000 average per well, $4,000,000 total
Settlement of sewage treatment plant	Pump sewage through plant and into discharge pipes	$8,000,000 for pump station, $200,000 per year for pumping energy
Increased flood hazard from sinking below bay level	Dike construction	$9,000,000 through 1974
	Raise railroad bridge	$100,000

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H. WAIRAKEI, NEW ZEALAND

(1) Introduction

Ground subsidence in water-dominated geothermal fields has been clearly demonstrated following almost 20 years of exploitation of the Wairakei Field in New Zealand. The Wairakei Geothermal Power Plant is 10 kilometers north of Lake Taupo in the central volcanic district of the North Island (Figure III-H-1). Although the terrain of the region is generally rugged, in the vicinity of the field it is flat to gently rolling. The Wairakei Power Station lies on the Waikato River about 7 kilometers east of the main production area. At the wellhead, the steam to water ratio is about 1 to 4 by weight. After processing, the dried stream is transferred to the power station via several pipelines. Land uses in the area include two main transportation routes, a workman's residential "village", small farming, some forestry, and recreation.

(2) Description of Primary Subsidence Phenomena

Subsidence at the Wairakei Field was first measured in 1956. Since that time, the network of benchmarks has been extended, and periodic releveling surveys of these points has indicated that the area affected by subsidence exceeds 1.3 square kilometers lying predominantly outside and to the east of the well field (Figure III-H-2). Total subsidence is believed to be on the order of 5 meters with the rate of movement being approximately 40 centimeters per year at the point of maximum deflection. Principal investigators who have been studying subsidence at the field include J. W. Hatton, R. C. Axtmann, W. B. Stilwell, R. C. Bowen, and S. K. Garg.

Exploitation of the Wairakei Geothermal Field is considered to be the major cause of ground subsidence in this area, although the reason for the subsidence is not completely understood. Contributing factors are thought to be a loss of aquifer pressure relating to mass output, a substantial decrease in vapor pressure beneath the cap rock, and deferred strain or consolidation of the rock within the reservoir (Hatton, 1970). The associated physical effect resulting from the subsidence has been the formation of a subsidence bowl with localized areas of extension and compression.

(3) Effects of Primary Subsidence Phenomena

Subsidence has damaged production facilities and the main highway. Although the area of maximum subsidence occurs outside the production field, the steam transmission pipes and the main hot water drain at Wairakei have been affected

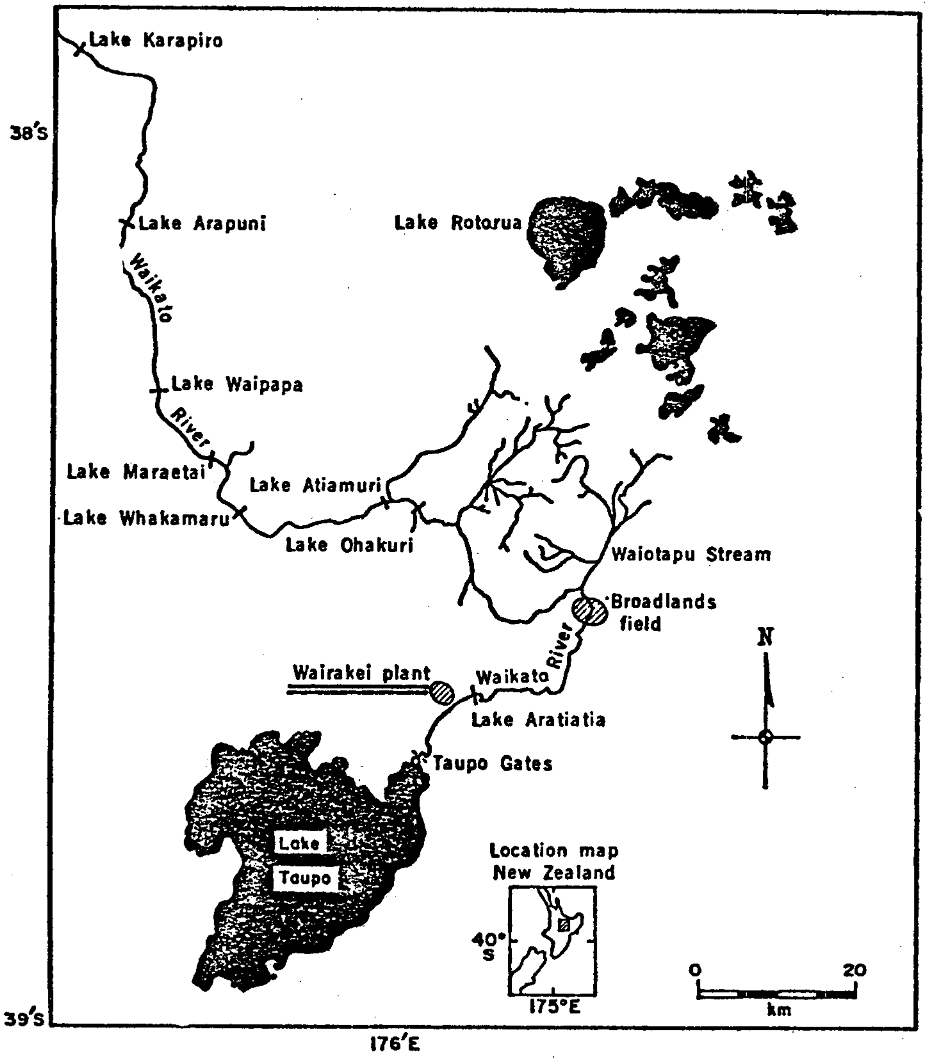

Figure III-H-1. Index Map, Wairakei Subsidence Area, New Zealand. (From Axtmann, 1975)

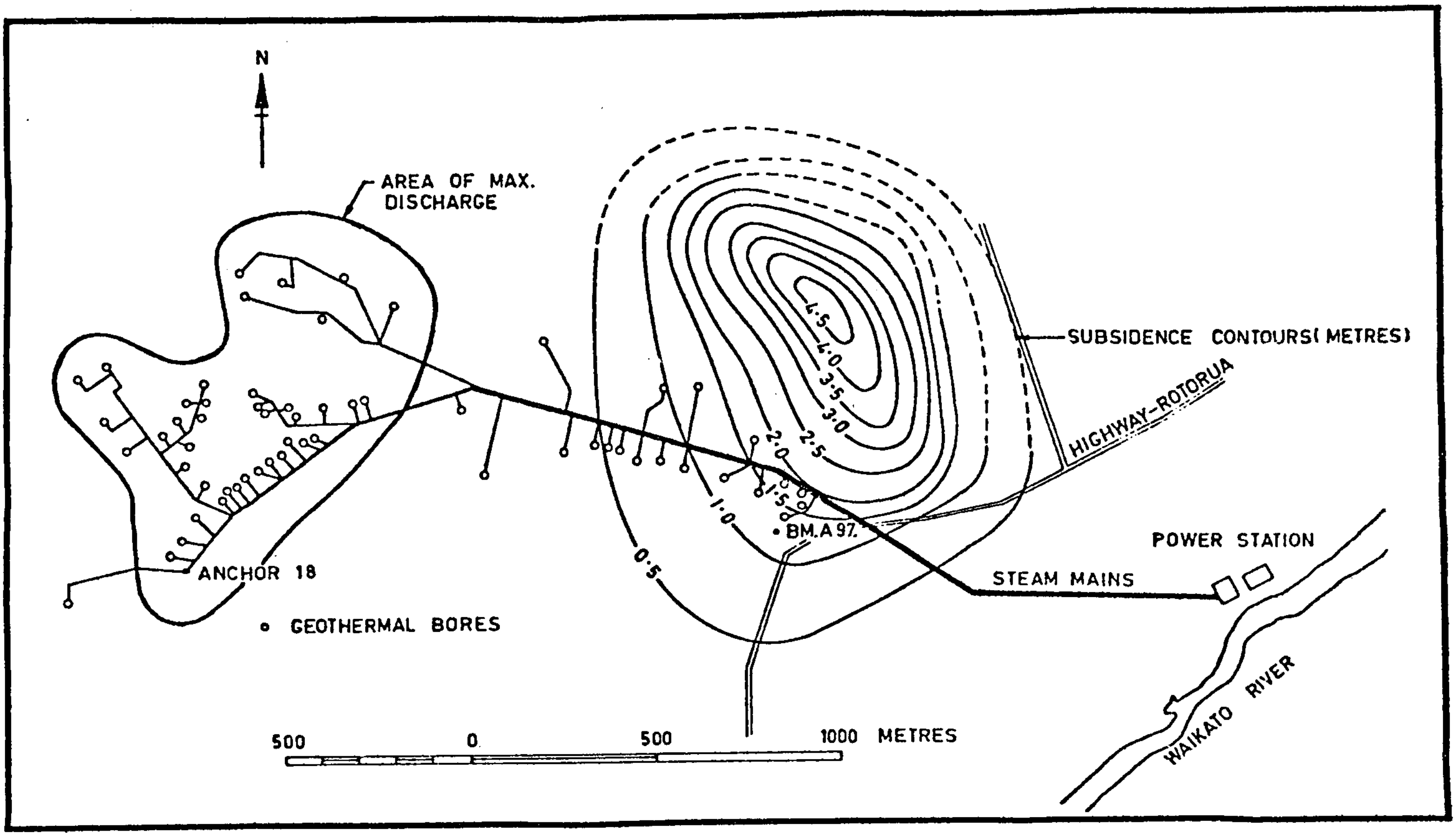

Figure III-H-2. Total Subsidence at Wairakei, 1964-1974 (from Stillwell, et. al., 1975).

NOTE: Subsidence Prior to 1964 is Estimated to be .5 Meter by the ground movement, and modifications have been necessary to accommodate the surface strain. Subsidence along the steam mains has resulted in both compressive and tensile strains, requiring modifications to the steam mains at eight yearly intervals. The pipes are dismantled at joints and sections are added or subtracted as necessary. In some instances, sliding joints have also been installed. Some of the steam mains are no longer at grade and in some cases slope opposite to original grade. As a result, condensate now drains back toward the wells. This could conceivably increase corrosion effects in the long run.

The concrete drainage channel, constructed to carry the hot wastewater from the bores to the river was also cracked by horizontal ground strain, which in turn caused a washout of pumiceous soils.

(4) Aggravation of Other Hazards

No other hazards which might be aggravated by subsidence are known in this area.

(5) Effects of Aggravated Hazards

None are known.

(6) Adjustments to Subsidence

One adjustment to the subsidence has been to study and define it. Since 1952, the checking and expansion of a precise level network has been accomplished through surveying, releveling, and the installation of additional benchmarks. Since 1966, the network has been releveled every three to four years, while local checks on the area of subsidence were made every six months until 1968 and annually through 1972. The costs of these surveys is not known.

Continuing damage to steam mains has been repaired routinely on an annual basis for eight years. Costs range from $2,000 to $10,000 per year, but average closer to $10,000.

Damage to the concrete wastewater channel has been repaired by the installation of a flexible joint. Eroded slopes have been stabilized. Costs of repairs are estimated at $250,000 of which half was to repair the washout in erodible pumiceous soils.

Axtmann (1975) reports that a program of reinjection of the hot wastewater is being studied as a possible means of mitigating subsidence, but the feasibility of reinjection and its possible effects on the performance of the reservoir have not yet been documented.

A pilot program for reinjection to control subsidence has been started at the Broadlands Geothermal Field according to recent information from W. B. Stillwell and B. W. Denton at the New Zealand Ministry of Works and Development.

(7) Summary of Effects

Damage	Remedies	Cost
Disruption of steam transmission pipelines	Repair, remove or add sections as necessary	$2,000 to $10,000 per year
Cracking of drinage channel	Replacement with telescopic joint; repair washout of erodible pumiceous soils	$250,000
Main Road has subsided 2m.	None as yet	None reported

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I. WILMINGTON, CALIFORNIA

(1) Introduction

The Wilmington Oil Field is located near the southwestern margin of the Los Angeles basin, in and near the City of Long Beach (Figure III-I-1). It is generally agreed that the withdrawal of fluids and gas from the field resulted in the reduction of subsurface pressures in the oil reservoirs causing compaction in the oil zones and subsequent subsidence. The subsidence area once measured 50 square kilometers, and the center of the elliptical, bowl-shaped area has subsided as much as 9 meters (29 feet) since 1926 (Figure III-I-2). Damage and economic impacts in the area have been extensive due to large amount of subsidence, the problems of flooding, and the highly developed industrial land uses.

(2) Description of Primary Subsidence Phenomena

Appreciable subsidence did not occur until after the oil field development in 1938. During the early war years, the Navy was building a dry dock which entailed a considerable dewatering operation, and subsidence at this time was thought to be caused by the dry dock construction. Major subsidence of up to 122 centimeters (4 feet) by July 1945 showed no decline, however, even after dry dock construction stopped. As reported by the City of Long Beach in The Subsidence Story (no date):

> Some of the earliest studies related the subsiding area to the oil field outline. The consensus of authorities was that the withdrawal of fluids from the oil zones and the consequent loss of underground pressure support enabled the weight of the earth above the oil zones to exert a large downward force and compact the oil formations. The surface then sank in response to the underground compaction.

By 1952, the area reached its maximum subsidence rate of 71 centimeters (28 inches) per year at the center of the bowl. The vertical subsidence was accompanied by horizontal movements amounting to as much as three meters (10 feet) in the area. These horizontal movements were responsible for extensive damage to surface structures, pipelines, and oil well casings.

After 1952, subsidence slowly diminished. Mitigation measures (water injection) began to be effective about 1960, and most of the area had stabilized or was even regaining elevation six years later. The rebounded area now covers ten square

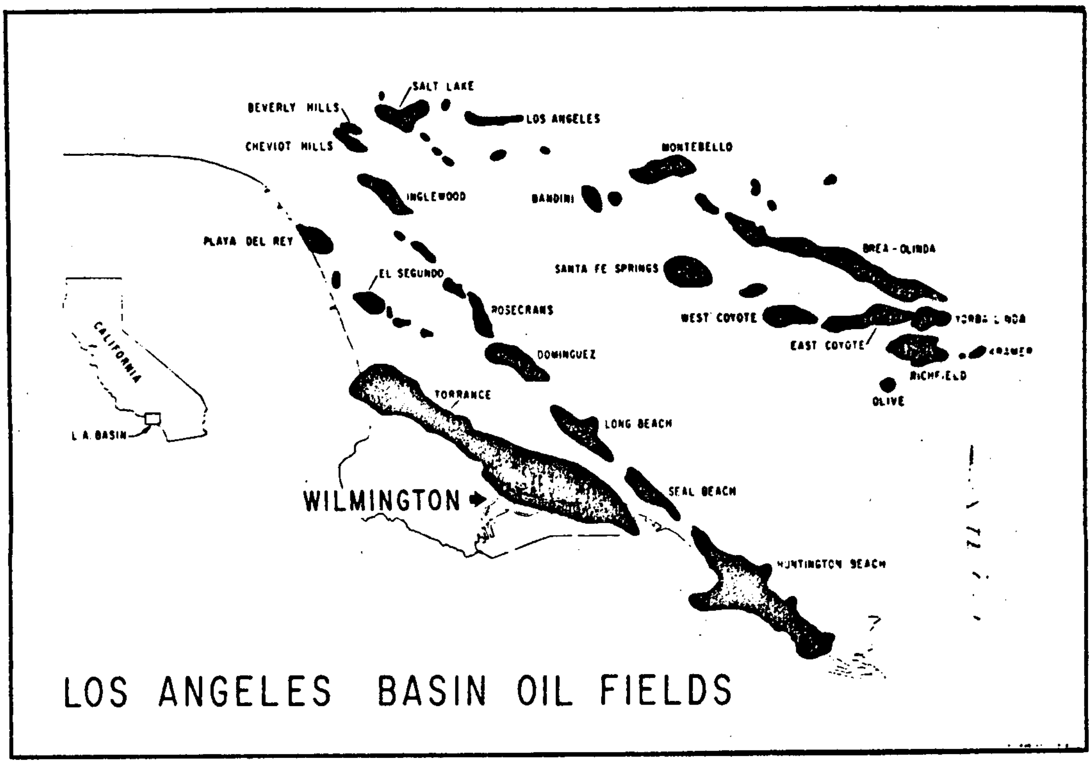

Figure III-I-1. Los Angeles Basin Oil Fields (from Mayuga, 1970)

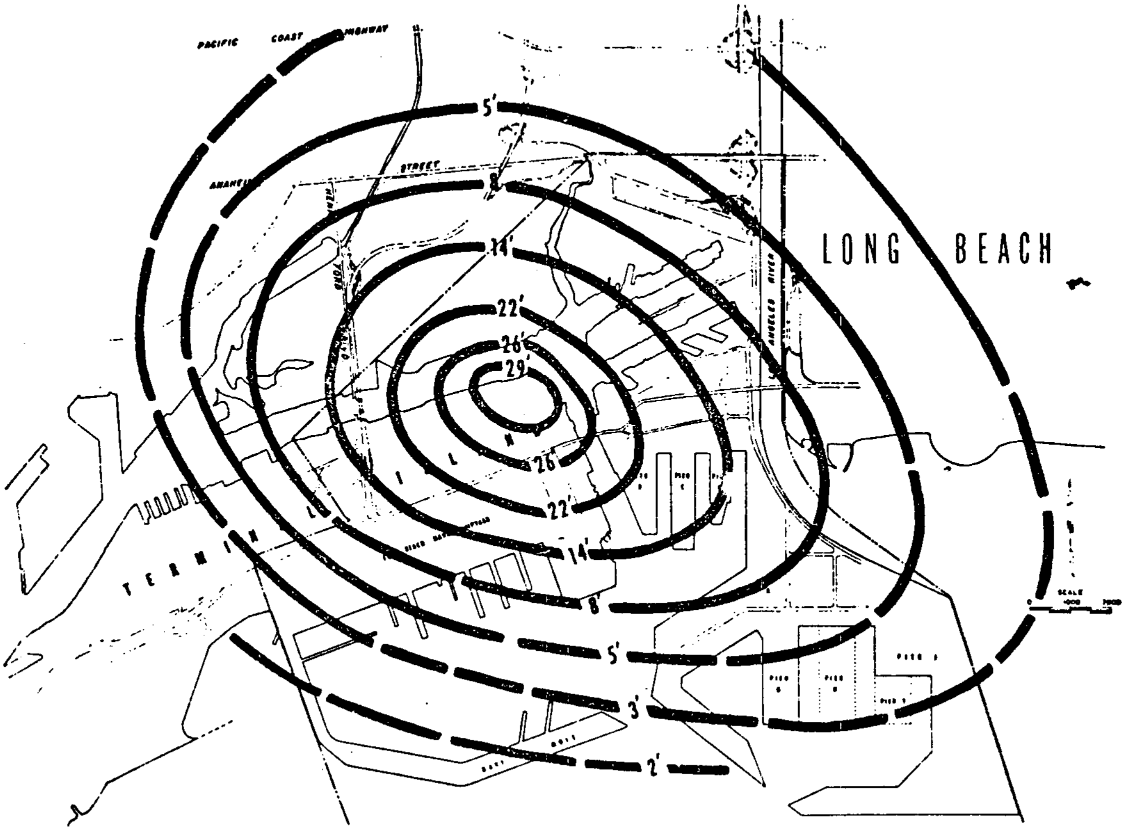

Figure III-I-2. Total Subsidence 1926 - 1967, Wilington Field. Contour Value in Feet, Internal Variable (from Mayuga, 1970).

miles, and one point in the harbor area has actually risen more than one foot. Figure III-I-3 shows the area of rebound.

(3) Effects of Primary Subsidence Phenomena

Horizontal movements and subsurface shearing associated with the subsidence caused extensive damage to oil wells and other structures. Mayuga and Allen (1969) described damage to pavement, railroad tracks, buried pipelines, buildings, bridges and roadways, which ranged from moderate to extensive. The Commodore Heim Bridge and its elevated approach roadways, about 1,220 meters, underwent approximately 2.3 meters of shortening due to horizontal movements. Concrete columns were sheared off, support towers tilted, and the bridge was rendered inoperable. Stresses were relieved somewhat by several sudden earthquakes (five between November, 1949 and April, 1961) which generated horizontal movement between 450 and 600 meters below the land surface. Slow "creeping" movement was also noted during periods of earthquakes.

Widespread damage to oil wells was evidenced by the protrusion of tubing and casing at well heads, constriction of casing diameters, corkscrewing of pulled pipe and failure of liner hangers. Subsidence in and around the Wilmington Oil Field caused an estimated $20 million damage to the oil facilities, specifically to wells and well casings. This includes the cost of raising many wellheads to avoid flooding or disruptions by the land filling operations.

Costs of repair or replacement of other damaged facilities have never been accurately determined. Mayuga and Allen (1969) estimated that over $100 million had been spent for surface remedial work due to subsidence, but this number includes the costs associated with the flood prevention measures related to other hazards as well as the direct effects discussed here.

The City of Long Beach spends about $150,000 a year to monitor subsidence in the area. About $100,000 of this is spent on surveys. The remaining $50,000 covers labor plus equipment such as recorders and tide gages. The Long Beach Harbor Department spends another $100,000 annually on surveys of the field for its own purposes.

Southern California Edison Company has reported that from January, 1941 to December, 1976, $4.9 million were expended for maintenance related to subsidence at the Long Beach Generating Station.

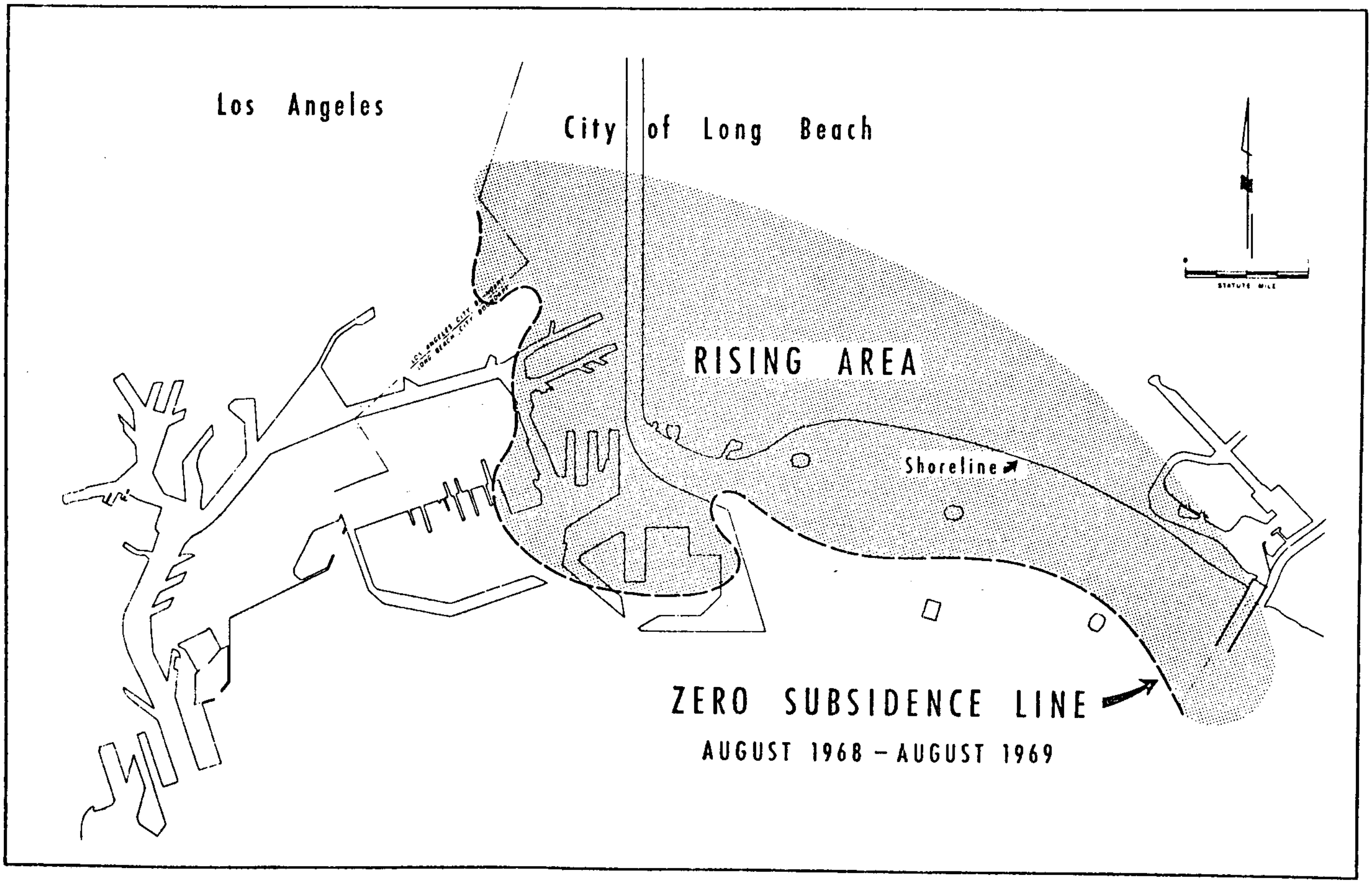

Figure III-I-3. Rebound as a result of Injection Well Operations (from City of Long Beach, Department of Oil Properties, No Date)

(4) Aggravation of Other Hazards

Flooding from the ocean was the most serious consequence of the subsidence at Wilmington. Most of the harbor area was initially at elevations of only a few meters. Over 1,300 hectares of land subsided below sea level, requiring construction of dikes and filling of land. Wharves and other structures had to be raised to higher elevations or replaced.

(5) Effects of Aggravated Hazards

Flood prevention measures combined with the repair of damaged structures as described in Section 3 resulted in costs amounting to more than $100 million dollars.

There has apparently been no direct correlation of specific earthquake damages caused by the oil withdrawal and subsequent subsidence.

(6) Adjustments

An extensive reservoir repressurization program was undertaken to halt subsidence. Due to the tremendous geological complexity of the oil reservoir structure, coupled with the diverse ownerships, large scale water injection to halt subsidence was feasible only as a cooperative effort or by forming a pool in which all interests would share. The sharing of oil in this manner is called "unitization." It is an involved process, which required special laws and legal agreements in the State of California. If water had been injected without unitization, individual wells would have been flooded out as the water pushed oil to other wells, and many lawsuits would have resulted.

Fluid reinjection has been costly, but it is a cost which cannot be entirely attributed to subsidence control; for although reinjection controls subsidence, it also "doubles production" (over primary recovery rates). The reinjection procedures would, therefore, take place without subsidence. The costs involve an economic benefit as well as an adjustment for subsidence. About 75% of the oil production in 1969 was attributable to the reinjection program.

While damage was extensive at Wilmington, most parties who were damaged were themselves involved in the oil operation and received benefits from the oil production. Reportedly, no lawsuits have been adjudicated to establish liability. The U.S. Navy filed a suit for damages to their shipyard, but settled for an out-of-court financial compromise.

(7) Summary of Effects

Subsidence effects in the Wilmington, California area include the following:

Damages	Remedies	Costs
Buckling of asphalt paving	Repair	a
Buckling of Railroad Tracks	Repair	a
Buckling of Pipelines	Repair	a
Large Buildings - Wall Shear Failures & Column Cracking	Repair Possible Abandonment	a
Transit Shed-Buckling of Side Trusses, Wall Compression Failure	Repaired, Raised and Landfilled	a
Lift Bridge Damage-Column Shearing, Tower Movement, Approach Road Damage	Repair	a
Oil Well Casings - Several Hundred Sheared or Severely Damaged; Earthquakes Also Responsible	Abandoned, Replaced and Raised	$20 Million
Naval Shipyard	Landfill & Dike Partial Abandonment	Unknown
Southern California Edison Long Beach Generating Station	Survey, earth fill, install pumps, raise dikes, engineering studies	$4.94 Million
General Flooding	Landfill, Raising Structures & Bulkheads, Rebuilding Access, Dikes	a
General Subsidence	Construction of Water Injection Plants, supply & distribution systems by City	$17.3 Million but investment is recovered through sale of injection water

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a) Part of the $100 million estimate by Mayuga and Allen.

(8) References

City of Long Beach, no date, *The Subsidence Story*, Department of Oil Properties, Long Beach, California.

Mayuga, M. N. and D. R. Allen, 1970, "Subsidence in the Wilmington Oil Field, Long Beach, California, USA", *Land Subsidence*, Proceedings of the Tokyo Symposium, 1969, IASH/AIHS-UNESCO, Volume 1, p. 66-79.

Mayuga, M. N., 1970, "Geology and Development of California's Giant - Wilmington Oil Field", *Geology of Giant Petroleum Fields*; American Association Petroleum Geology, Mem. 14, p. 158-184.

(9) Persons Contacted

D. R. Allen, Subsidence Engineer, City of Long Beach, Department of Oil Properties: telephone interview, February 9, 1978.

Herb Robb, Western Oil and Gas Association, Los Angeles: telephone interview, February 14, 1978.

Dallas J. Downs, Senior Civil Engineer, Southern California Edison, Rosemead, California: telephone interview, March 27, 1978.

Earl R. Sample, Southern California Edison Company, Rosemead, California: correspondence April, 1978.

Thomas M. Leps, Consulting Engineer: Interview, Palo Alto, California.

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APPENDIX A

EDAW·ESA

December 15, 1977

Lawrence Berkeley Laboratory
Geothermal Subsidence Research Program

Category 4, Project 1
ENVIRONMENTAL AND ECONOMIC EFFECTS OF SUBSIDENCE

Interim Summary Report

Task 1. Identify Subsidence Areas
Task 2. Develop Methods for Acquiring Information

Submitted to:

Lawrence Berkeley Laboratory
Berkeley, California

By:

EDAW·ESA - A Joint Venture
of EDAW, Inc. and Earth Sciences Associates
Palo Alto, California

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TASK 1. IDENTIFY SUBSIDENCE AREAS

TASK 2. DEVELOP METHODS FOR OBTAINING DATA

List of Figures and Tables

INTRODUCTION

The collection of data on the environmental and economic effects of subsidence is Research Category 4, Project 1, of Lawrence Berkeley Laboratory's Geothermal Subsidence Research Program.

This interim summary report documents the work performed to date on Tasks 1 and 2 of this project. The respective purposes of Tasks 1 and 2 are to identify subsidence areas and develop methods for acquiring data on environmental and economic effects of subsidence.

This report evaluates the work completed on Tasks 1 and 2 and recommends steps for the timely and effective completion of Task 3 - "Data Collection".

TASK 1. IDENTIFY AREAS WITH SUBSIDENCE DUE TO FLUID WITHDRAWAL

Purpose - The purposes of Task 1 are to identify areas experiencing subsidence due to fluid withdrawal (water, oil, gas and geothermal), to determine which of these areas have experienced environmental and economic effects, which of these areas have been studied in terms of the environmental and economic efforts and where good additional information on the effects of subsidence is likely to be found. Those areas with the most likelihood of yielding useful data were selected in Task 1 to narrow the focus of the data collection effort in Task 3. Recommendations growing out of Task 1 will provide guidance to ensure the greatest effectiveness from Task 3 - Data Collection.

Selection Process - The process used to identify and select subsidence areas is a screening process shown in Figure 1. The steps of the screening process are described in the following discussion.

STEP 1: COMPILE INFORMATION TO IDENTIFY SUBSIDENCE AREAS

Initially, information was gathered from three sources:

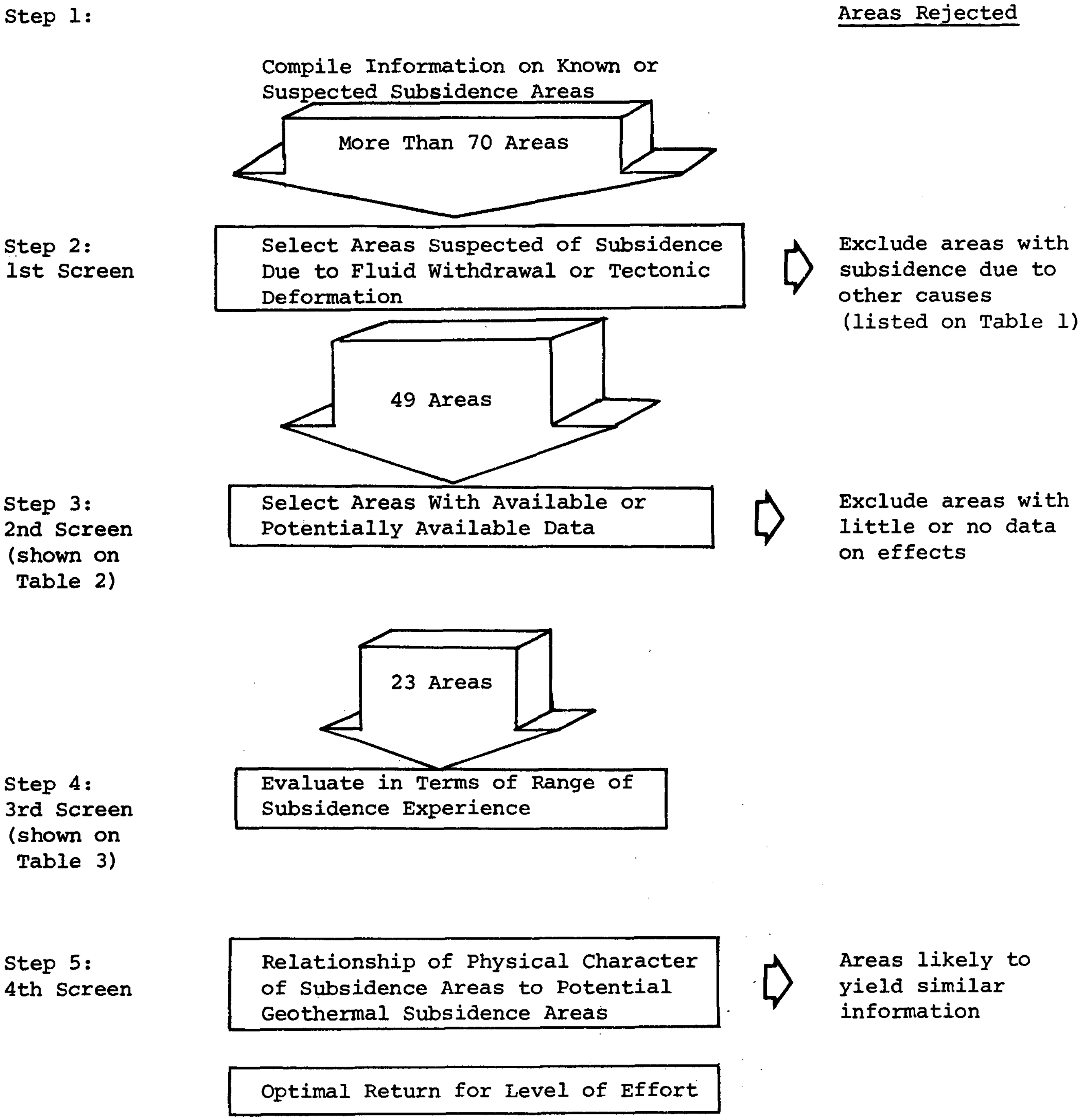
- Review of the International Survey on Land Subsidence (ISOLS), an International Association of Hydrological Sciences publication in preparation,
- Intensive review of the literature, and
- Telephone conversations and interviews with members of the scientific community.

From the review of responses to the ISOLS questionnaire, the literature review, and interviews, all areas where subsidence has been reported or suspected were identified.

This initial data gathering effort could be considered the first part of Task 3 - Data Collection. A description of the methods used in the initial data collection appears later in this report in the discussion Task 2 - Develop Methods to Acquire Information.

Figure 1.

SUBSIDENCE AREA SELECTION PROCESS



STEP 2: IDENTIFY AREAS WITH SUBSIDENCE DUE TO FLUID WITHDRAWAL OR TECTONIC DEFORMATION

Areas with subsidence due to causes other than fluid withdrawal or tectonic deformation were eliminated from the list of subsidence areas under consideration.

While subsidence has occurred from other causes, subsidence due to fluid withdrawal or tectonic deformation are most similar to subsidence that may be expected from geothermal resource development.

Other causes of subsidence reported in ISOLS are:

Hydrocompaction
Loading by Engineering Structures
Karst Collapse
Salt Solution
Mining (coal, iron, salt)
Dewatering of Organic Soils
Liquifaction

Subsidence areas excluded by the first screen are listed in Table 1.

The areas with suspected subsidence due to fluid withdrawal or tectonic deformation which passed through the first screen are listed on Table 2. The locations of these subsidence areas are shown in Figure 2.

Geothermal Areas - Some areas where geothermal powerplants are in production or testing phases are also listed because it was suspected that subsidence might have occurred at these areas. Our review of the subsidence literature has revealed no information on subsidence for these geothermal fields:

Geysers, California
Imperial Valley, California
Larderello, Italy
Monte Amiata, Italy
Cerro Prieto, Mexico

While it is generally thought that there is potential for subsidence at some of these fields, notably Imperial Valley and Cerro Prieto, we found no reports of actual subsidence and more importantly, no reports of damage from subsidence for these geothermal fields.

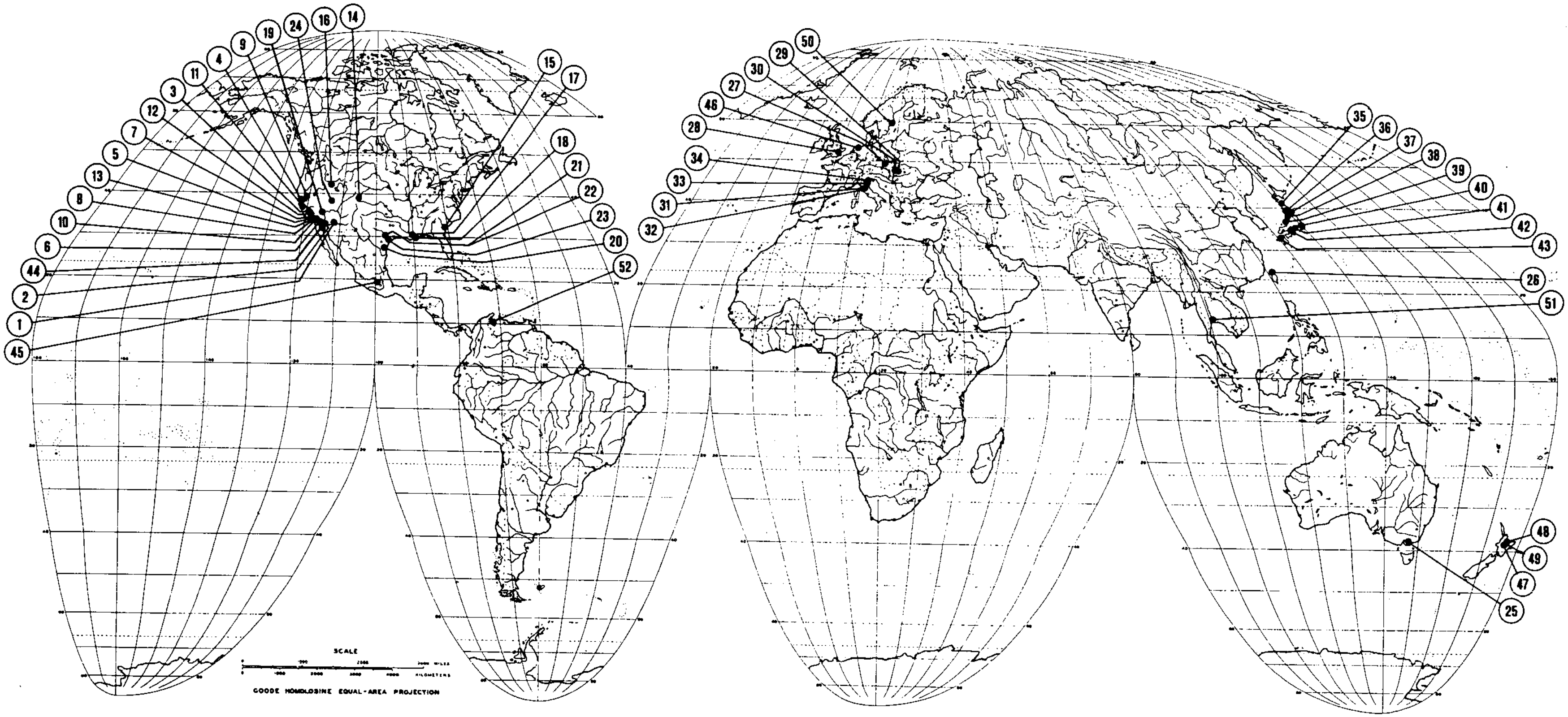
Table 1. Areas With Subsidence From Causes Other Than Fluid Withdrawal or Tectonic Deformation (Excluded by Step 2)

Subsidence Area	Cause of Subsidence
United States	
Alabama, numerous sites	karst collapse
Illinois, 5 sites	loading by structures and coal mining
Iowa, Sioux City - Council Bluffs	hydrocompaction
Kansas, Salina - Wichita	salt solution
Maryland, site unknown	mining
Minnesota, Rochester	karst collapse
Missouri, numerous sites	karst collapse
New Jersey, Newark	iron mining
Ohio, several sites	various causes
Foreign	
Australia, Launceston	salt solution
Australia, Newcastle	coal mining
Australia, Perth	loading by engineering structures
Australia, Wollongong	loading by engineering structures & coal mining
Belgium, Liege	coal mining
Colombia, Bogota	salt mining
England, Cheshire Basin	salt solution
Hungary, Tuzla	salt mining
Netherlands, Amsterdam	loading by engineering structures & dewatering organic soils
Turkey, Zonguldak	mining

Table 2
Environmental and Economic Effects Data Evaluation

Site I.D. No. (see figure 2)		CAUSE OF SUBSIDENCE						EVALUATION OF EXISTING INFORMATION			POTENTIAL FOR OBTAINING MORE INFORMATION			CANDIDATE AREAS FOR FURTHER INFORMATION COLLECTION
		FLUID WITHDRAWAL					TECTONIC DEFORMATION							
		Water	Oil	Gas	Brine	Geothermal		Good	Fair	Poor	Good	Fair	Poor	
	SUBSIDENCE AREAS (UNITED STATES)													
①	Arizona, Phoenix (Eloy-Picacho)	●					●	●			●			●
②	Arizona, Gadsen						●			●			●	
③	California, Fresno-Bakersfield (San Joaquin Valley)	●	●	●			●		●		●			●
④	California, Geysers					●				●			●	
⑤	California, Huntington Beach	●	●	●					●			●		
⑥	California, Imperial Valley					●				●			●	
⑦	California, Inglewood (Baldwin Hills)		●	●					●		●			●
⑧	California, Palmdale	●								●		●		
⑨	California, Sacramento Valley	●							●		●			●
⑩	California, San Jacinto	●					●		●		●			●
⑪	California, San Jose (Santa Clara Valley)	●						●			●			●
⑫	California, Beverly Hills (East)		●	●						●		●		
⑬	California, Long Beach (Wilmington Field)		●	●				●			●			●
⑭	Colorado, Denver	●								●		●		
⑮	Georgia, Savannah	●								●			●	
⑯	Idaho, Malta (Raft River Valley)	●					●		●				●	
⑰	Louisiana, Baton Rouge	●								●		●		
⑱	Louisiana, New Orleans	●						●			●			●
⑲	Nevada, Las Vegas Valley	●							●		●			●
⑳	Texas, Corpus Christi (Saxet Oil Field)		●	●					●			●		
㉑	Texas, Houston (Chocolate Bayou)		●	●					●		●			
㉒	Texas, Houston (Goose Creek)		●	●					●		●			
㉓	Texas, Houston - Galveston	●	●	●				●			●			●
㉔	Utah, Milford	●								●			●	
	SUBSIDENCE AREAS (FOREIGN)													
㉕	Australia, Yallourn-Morwell	●							●			●		
㉖	China (Taiwan), Taipei	●							●			●		
㉗	Czechoslovakia, Komárno						●			●			●	
㉘	England, London	●								●			●	
㉙	Hungary, Debrecén	●								●			●	
㉚	Hungary, Visontia	●							●			●		
㉛	Italy, Larderello					●				●			●	
㉜	Italy, Monte Amiata Field					●				●			●	
㉝	Italy, Po Delta			●	●				●			●		●
㉞	Italy, Venice	●							●			●		●
㉟	Japan, Aomori Plain	●							●			●		●
㊱	Japan, Sendai Plain	●							●			●		●
㊲	Japan, Haranomachi	●							●			●		●
㊳	Japan, Niigata Fields	●		●	●				●			●		●
㊴	Japan, Nanao Basin	●							●			●		●
㊵	Japan, Tokyo	●		●					●			●		●
㊶	Japan, Nobi Plain (Nagoya City)	●		●					●			●		●
㊷	Japan, Osaka	●							●			●		●
㊸	Japan, Saga Plain	●							●			●		●
㊹	Mexico, Cerro Prieto					●				●			●	
㊺	Mexico, Mexico City	●							●			●		●
㊻	Netherlands, Groningen Field	●		●						●			●	
㊼	New Zealand, Wairakei					●			●			●		●
㊽	New Zealand, Kawerau					●				●			●	
㊾	New Zealand, Broadlands					●				●			●	
㊿	Sweden, Stockholm	●								●			●	
(51)	Thailand, Bangkok	●								●			●	
(52)	Venezuela, Bolivar Coast (L. Maricaibo)		●	●					●			●		

Figure 2
Subsidence Areas



Source: International Association of Hydrologic Sciences
International Survey on Land Subsidence
Publication in Preparation, 1977

Legend:

⑧	Site I.D. No. (see table 2)
▨	Area of Subsidence Caused by Fluid Withdrawal or Tectonic Deformation

For the areas listed on Table 2, the data obtained from the International Survey on Land Subsidence and the review of the literature will be summarized on individual subsidence area data summary sheets and will be part of the final project report. An example of the data summary sheet is Attachment 1 to this Interim Summary Report.

STEP 3: EVALUATE AND SELECT AREAS BASED ON AVAILABLE AND POTENTIALLY AVAILABLE INFORMATION

Available Information - Available information collected from the literature review and review of ISOLS was evaluated and given good, fair, or poor ratings based on the following criteria:

Rating Scale	Criteria
Good:	- A study has been done on economic effects; or - A well known history of subsidence and the costs of damages have been estimated in publications or by respondents to ISOLS.
Fair:	- Physical aspects of subsidence have been studied; and - Damages and economic impacts are mentioned; but - No study of economic effects.
Poor:	- Subsidence studied, but no mention of damages or costs; or - Damages and costs are reported as none.

Potential For More Information - The potential for obtaining more information was evaluated as good, fair, or poor, based on the following criteria:

Rating Scale	Criteria
Good:	- Good contacts with economists. - Some aspect of costs already studied.

- A variety of adjustments to damage have been identified.
- In U.S.A. only.

Fair:

- Good contacts with engineer, geologist or hydrologist.
- Apparent public awareness of problems.
- Public agencies have probably budgeted for damage repair, remedial work or countermeasures.
- In U.S.A. or foreign.

Poor:

- Poor contacts.
- Language problems.
- Little or no damage.
- Little apparent awareness of the problem.
- In U.S.A. or foreign.

The available information and the potential to obtain further information were evaluated jointly and 23 areas were identified as worthy of further efforts to collect data. Areas worthy of further data collection efforts are:

United States

Arizona, Phoenix (central Arizona including Eloy-Picacho)
California, Fresno-Bakersfield (San Joaquin Valley)
California, Inglewood (Baldwin Hills)
California, Sacramento Valley
California, San Jacinto
California, San Jose (Santa Clara Valley)
California, Long Beach (Wilmington Oil Field)
Louisiana, New Orleans
Nevada, Las Vegas Valley
Texas, Houston-Galveston (including Goose Creek & Chocolate Bayou)

Foreign

Italy, Po Delta
Italy, Venice
Japan, (9 areas)
Mexico, Mexico City
New Zealand, Wairakei

Table 3
Characteristics of Selected Subsidence Areas

Site I.D. No. (see figure 2)		VERTICAL SUBSIDENCE							PRIMARY SUBSIDENCE EFFECTS									LAND USE TYPES													ESTIMATE OF DAMAGE					TYPES OF ADJUSTMENTS			
		MAXIMUM VERTICAL SUBSIDENCE			AREAL EXTENT																																		
		Over 4 Meters	1 to 4 Meters	Less than 1 Meter	Over 1000 Km^2	100 - 1000 Km^2	10 - 100 Km^2	Less than 10 Km^2	Tilting, Differential Subsidence	Subsidence Bowl	Fissuring (Extensional Effects)	Ground Rupture (Compressional Effects)	Induced Faulting	Induced Seismicity	Subsurface Deformation	Inundation	Increased Risk of Flood/Storm Surge	Urban Centers	Industrial	Deep Water Port	Dense Residential	Dispersed Residential	Agriculture	Irrigated Agriculture	Grazing	Timber Production	Protected Natural Areas	Mineral Production	Groundwater, Oil and Gas Production	Surface Water Reservoirs	Severe	Moderate	Slight	None	Unknown	Adjust to Losses	Remedial Measures to Prevent Damage	Countermeasures to Affect the Cause	Institutional Changes
①	Arizona, Phoenix (Eloy-Picacho)		●		●				●	●	●										●	●		●	●			●	●	●		●				●	●		
③	California, Fresno-Bakersfield (San Joaquin Valley)	●			●				●	●					●	●								●					●	●	●					●	●	●	
⑦	California, Inglewood (Baldwin Hills)			●						●		●	●					●	●		●								●	●					●	●		●	
⑨	California, Sacramento Valley			●		●				●					●								●	●					●			●				●			
⑩	California, San Jacinto Valley		●				●		●	●		●	●						●					●								●				●			
⑪	California, San Jose (Santa Clara Valley)		●			●				●						●		●	●		●										●					●	●	●	
⑬	California, Long Beach (Wilmington Field)	●					●			●		●	●			●	●		●	●									●		●					●	●	●	
⑱	Louisiana, New Orleans			●			●		●	●								●	●	●	●								●				●			●			
⑲	Nevada, Las Vegas Valley		●			●				●					●			●			●								●	●		●				●			
㉓	Texas, Houston-Galveston ㉑㉒		●		●				●	●			●		●	●	●	●	●	●	●							●	●		●					●	●	●	●
㉝	Italy, Po Delta									●							●					●	●						●			●				●		●	
㉞	Italy, Venice			●		●											●	●	●		●								●			●				●		●	
	Japan, several cities ㉟ through ㊸	●	●	●	●	●	●	●								●	●	●	●	●	●		●						●		●	●				●	●	●	●
㊺	Mexico, Mexico City	●							●	●								●	●		●											●				●		●	
㊼	New Zealand, Wairakei	●						●		●									●							●						●				●	●		

Sources:

1. International Association of Hydrological Sciences, International Survey on Land Subsidence (ISOLS). Publication in preparation.
2. Poland and Davis, 1969 (Po Delta, Italy).
3. Lee, K., 1977; (Inglewood, California).

STEP 4: EVALUATE SELECTED AREAS IN TERMS OF RANGES OF SUBSIDENCE EXPERIENCE AND APPLICABILITY TO POTENTIAL GEOTHERMAL AREAS

Table 3 shows the extent to which the 23 selected areas represent a variety of experiences with subsidence, especially range of vertical subsidence, types of subsidence effects, types of land uses, level of damages and types of adjustments to subsidence. The characteristics shown on Table 3 are explained below.

Vertical Subsidence

Maximum vertical subsidence and areal extent are values obtained principally from the responses to ISOLS.

Primary Subsidence Effects

Several physical effects have been reported where subsidence has occurred.

Tilting or differential subsidence.
Development of a subsidence bowl.
Fissuring (tensional, extensional effects).
Ground rupture (compressional effects).
Subsurface deformation (well extrusion).
Induced faulting.
Induced seismicity.
Inundation.
Increased risk of flood, storm surge.

All of these effects are possible if subsidence should occur at prospective geothermal areas. Identification of these effects as occurring at specific subsidence areas is based upon complete information gained principally from the responses to ISOLS and our review of the literature. Some of the effects are reported to have occurred while others are inferred to have occurred.

Land Use Types

Potential geothermal resources, both hydrothermal and geopressured, are located in and among a variety of land uses. For modeling and predictive purposes, it is important to learn what effects subsidence has on human use systems in a variety of land use settings.

The environmental impact assessments for the Hydrothermal and Geopressure Subprograms of ERDA's Geothermal Development

Program were reviewed and the following land uses and features were found in one or more of the potential geothermal resource areas:

- Urban Centers
- Industrial
- Deep Water Port
- Dense Residential
- Dispersed Residential
- Agriculture
- Irrigated Agriculture
- Grazing
- Timber Production
- Protected Natural Areas
- Mineral Production
- Groundwater, Oil and Gas Production
- Surface Water Reservoirs

Land uses reported or inferred to exist in the listed subsidence areas are checked in the matrix to indicate the range of land uses represented in the subsidence areas. Choice of subsidence areas for further study based in part on land uses will permit the study of subsidence effects on land uses in potential geothermal resource areas.

Estimate of Damage

An estimate of the severity of damage due to subsidence was requested in the International Survey on Land Subsidence (ISOLS). The estimates of damage shown on the table are generally indicative of the level of damage, but are not comparable from area to area as the estimates are those made by individual respondents to the questionnaire and no common scale of damage was used.

Types of Adjustments

With an interest in the full range of possible adjustments to subsidence and the eventual definition of an optimal set of adjustments to subsidence due to geothermal resource development, an effort was made to categorize adjustments that are reported or inferred to have been made in areas experiencing subsidence. The classes of adjustments are as defined by Burton, Kates and White (1968) "The Human Ecology of Extreme Geophysical Events" and commonly used by natural hazards investigators (see also Natural Hazards, White, G. F., ed. 1974). Examples of the types of adjustments to subsidence are:

Adjustment Class		Examples
Adjust to Losses:	-	Repair damage to buildings, roads, railroads, etc.
	-	Abandon property.
Remedial Measures to Prevent Damage:	-	Raise levees.
	-	Build sea wall.
	-	Flexible coupling on piping, aqueducts.
Countermeasures to Affect The Cause:	-	Stop/restrict pumping.
	-	Find alternate source of resource.
	-	Reinject fluid.
Institutional Changes:	-	Develop subsidence district.
	-	Develop structure to control groundwater pumping.

STEP 5: ADDITIONAL CRITERIA FOR SELECTION OF SUBSIDENCE AREAS

- o Applicability of physical character of subsidence areas to potential subsidence from geothermal development.
- o Allocating work effort to obtain maximum yield of information for the number of sites in timely and cost effective manner.

Specific recommendations for the conduct of the remainder of the project follow Task 2 summary.

TASK 2. DEVELOP METHODS FOR OBTAINING DATA

The following methods for obtaining data on the environmental and economic effects of subsidence have been used to date in this project:

- Review of Responses to the International Survey on Land Subsidence (ISOLS)
- Literature Review
- Contacts With Active Researchers

The effectiveness of each of these approaches is discussed here.

Literature Review

An intensive literature review was made with the aid of Allan Conrad, and Gloria Smith Haire of Lawrence Berkeley Laboratory's Technical Information Group, which operates the Western Regional Information Service Center. Using the facilities at LBL, computerized literature searches were designed and made of data bases accessed on the RECON System at Oak Ridge National Laboratories:

- Selected Water Resources Abstracts (WRA).
- Energy Information Data Base (EDB).
- Environmental Services Index (ESI).
- Engineering Index (EIX).

Updated additions to the present citations contained in the RECON Data Bases will be provided to EDAW·ESA for the duration of the project. It is recommended that the update service be maintained throughout the Geothermal Subsidence Research Program.

Other computerized literature data bases that were scanned for references to environmental and economic effects of subsidence were:

- GEOREF;
- Smithsonian Scientific Information Exchange, Inc. (SSIE), both files in SDC's ORBIT data base; and

- The National Geothermal Information Resource (GRID) at Lawrence Berkeley Laboratory

Bibliographies reviewed for pertinent publications included:

- Systems Control, Inc. (1976), The Analysis of Subsidence Associated With Geothermal Development, Data Bank; and
- Keith, S. J. (1977), The Impact of Groundwater Development in Arid Lands, University of Arizona; Office of Arid Lands Studies, Tucson, Arizona.

The literature review was performed mostly by reading abstracts and resulted in the identification of a few journal articles, dissertations and monographs which investigate and report on the economic effects of subsidence in central Arizona, the Houston-Galveston and New Orleans areas of the Texas and Louisiana Gulf Coast. Copies of these publications have been ordered, and the authors of the Texas and Louisiana studies have been contacted by telephone.

With the completion of our literature review, we are reasonably certain that no other studies of the economic effects of subsidence have reached the published literature.

Review of Responses to ISOLS

The EDAW•ESA team was fortunate to obtain permission from A. Ivan Johnson to photocopy and use the responses to the International Survey on Land Subsidence prior to publication in a volume by the International Association of Hydrological Sciences. The information available from ISOLS was the principal source of information used to identify and select subsidence areas (Task 1 of this project).

The data requested in ISOLS cover many subsidence parameters. The data on economic effects provided by the respondents tend to be sketchy and incomplete for many areas. Despite these limitations, the information permitted the initial screening and selection of subsidence areas for further data gathering performed as Task 1, and provided names of investigators to contact.

Contacts With Scientific Community

In the planning of this project, this method was believed to be the most effective means of obtaining information on subsidence effects once a rapid review of the literature was performed. Contacts with various members of the scientific community have been made from the outset of the project. Some of the persons contacted to date are listed in Table 4.

Table 4. Partial List of Persons Contacted

Name	Title/Institution	Means of Contact	Topics Discussed
Dr. Gilbert F. White	Director/Institute of Behavioral Sciences, University of Colorado, Boulder	Telephone	Study design, referrals to investigators
A. Ivan Johnson	U.S.G.S. National Center, Reston, Virginia	Telephone	Permission to use ISOLS, referrals to investigators
Joseph Poland Dr. Donald C. Helm	U.S.G.S. Office of Subsidence Research, Sacramento, California	Meeting & telephone	Review of ISOLS responses, referrals to investigators
Dr. Lonnie Jones	Department of Agricultural Economics, Texas A&M University, College Station, Texas	Telephone	Study design, referrals to investigators
Dr. Daniel W. Earle, Jr.	Professor/Department of Landscape Architecture, Louisiana State University Baton Rouge, Louisiana	Telephone	Review of dissertation findings, referrals to other investigators

A structured form, Data Acquisition Form #1 was developed and has been used to ensure the effective acquisition and recordation of information and referrals to other investigators. This form is Attachment 2 to this interim summary report.

Development of Survey Questionnaires

Some effort has been expended to design questionnaires that could be used on site in a subsidence area to gather primary data from active investigators, public agencies and private industry managers working with subsidence problems. This form is Attachment 3 to this interim summary report.

TASK 3 - DATA COLLECTION

Recommendations for the Completion of Task 3 - In actuality, Task 3 - "Data Collection" began at the inception of Category 4, Project 1, and has been performed concurrently with Tasks 1 and 2. As of now, the data collection effort will be emphasized for much of the remainder of the project. EDAW•ESA recommends that for the subsidence areas selected in Task 1 the project team seeks additional detailed information on the effects of subsidence as may exist. For these areas within the United States, the team should direct its efforts to making telephone and personal contact with active investigators, public agencies and officials, and private industry managers to gather information on subsidence effects and referrals to other potential sources of information.

For those areas outside the United States, EDAW•ESA recommends that it undertake a program of written correspondence to select scientists and officials in Italy, Japan, Mexico and New Zealand.

Other Recommendations for Discussion

- Compile master mailing list of all investigators and establish regular informative mailings.
- Send notice of interest in effects data with mail-back response cards to all investigators.
- Contract with literature review services through LBL library.
- Retain local investigators to compile primary data under our direction.

ATTACHMENT 1

Subsidence Area:
Country:
District or Province:
Nearest City:

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal:
Other:

Subsidence Characteristics:

Area of subsidence in km^2:
Maximum amount of subsidence in meters:
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )
Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies ( )
Relevelling studies ( )
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )
Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

Source(s):

Subsidence Area:
Country:
District or Province:
Nearest City:

Publications:

Investigators:

ATTACHMENT 2

7s-119
CKV
October 5, 1977

SUBSIDENCE EFFECTS
DATA ACQUISITION FORM #1

Telephone Questionnaire

Subsidence area:

Geofluid withdrawn:

---

1. Person contacted

Name: Title:

Address: Institution:

City: State: Zip: Country:

Telephone: Date: Time:

Referred by:

Responded to A. I. Johnson's Questionnaire: Yes ( ) No ( )

---

2. Do you know of any environmental or economic effects of subsidence on the surface environment or on human use systems? List.

---

3. Do you know of any scientific studies that have been made of subsidence related problems: (Check focus of study)

Subsidence characteristics	( )	Biological/ecological effects	( )
Surface physical effects	( )	Effects on human use systems	( )
Surface hydrology	( )	Economic costs of subsidence	( )

---

4. List known publications: (Request bibliography by mail)
(Author, year, title, publisher, journal)

---

5. Do you know if any investigators have been studying the environmental and economic effects of subsidence?

Name: Title: Institution:

Address: City: State:

Telephone:

Principal research interest:

---

6. What government bodies have been dealing with subsidence problems?

Agency: Address:

Contact person: City: State: Zone:

Telephone number:

Principal interest/responsibility in subisdence problems:

---

7. Any suggestions? Comments.

ATTACHMENT 3

EDAW·ESA
8/4/77

ENVIRONMENTAL & ECONOMIC EFFECTS OF SUBSIDENCE

Telephone Questionnaire

1. Respondent

Name: Title:

Address:

City: State: Zone: Country:

Telephone:

Date:

2. Responded to A. I. Johnson's questionnaire: Yes ( ) No ( )

3. Location of Subsidence

Country: Nearest City:

District or Province:

Latitude: Longitude:

Elevation in metres:

Area Experiencing Subsidence in km^2:

Area Experiencing Damage in km^2:

Described by response to A. I. Johnson's questionnaire:

Yes ( ) No ( )

4. Environmental Setting

( ) Coastal ( ) Inland ( ) Other unique circumstances (explain)

5. Does subsidence make the area more susceptible to other natural hazards such as floods, tidal surges, hurricanes?

( ) Yes ( ) No

If so, identify hazards:

6a. What types of damage have occurred to natural features? (WRITE IN 'M' IF MENTIONED BY RESPONDENT; THEN PROBE FOR OTHERS)

	6b. Estimate of Severity		
Types of Damage (6a)	Low	Moderate	High
( ) Surface drainage features			
( ) Aquifers			
( ) Marshlands			
( ) Estuaries			
( ) Others (specify)			

6b. How would you estimate the severity of damage to these natural features? (CHECK APPROPRIATE SPACES IN TABLE ABOVE)

7. Cultural Setting

7a. What are the land uses in the subsiding area? (WRITE IN 'M' IF MENTIONED BY RESPONDENT, THEN PROBE FOR OTHERS.)

	7b. Estimate percentage of land use type in subsiding area.
( ) Agricultural	%
( ) Residential	%
( ) Commercial	%
( ) Industrial	%
( ) Other (specify)	%
	%
	%

7b. How would you estimate the percentage of land use in the subsiding area by type? (RECORD UNDER 7b. ABOVE)

8. Is a land use map of the subsiding area available?

( ) Yes ( ) No

Source (Author, Year, Publication): ______________________

____

9. Population in province, county, etc.: ______________________

Population in area of subsidence: ______________________

10. Per capita income (year): ______________________

11. Assessed valuation of area (year): ______________________

____

12. What is your estimate of the level of public awareness of the subsidence problem?

( ) Low ( ) Moderate ( ) High

Effects on Private Property

What types of damage have occurred to private property?
How would you estimate the severity of damage of private property?
(WRITE IN 'M' IF MENTIONED BY RESPONDENT; THEN PROBE FOR OTHERS.
INDICATE RESPONDENT'S ESTIMATE OF SEVERITY IN RIGHT-HAND COLUMN)

		Estimate of Severity	
	Low	Moderate	High
13. Residential			
( ) Structural damage to house			
( ) Inundation			
( ) Increased flooding			
( ) Driveway, sidewalk cracked			
( ) House tilted			
( ) Other (specify)			
14. Industrial			
( ) Damage to structures			
( ) Damage to resource			
( ) Other (specify)			

Commercial and Agricultural
property damage questions
on following page..........

	Estimate of Severity		
	Low	Moderate	High
15. Commercial			
( ) Damaged structures			
( ) Loss of business			
( ) Damaged inventories			
( ) Other (specify)			

16. Agricultural			
( ) Ground fissures			
( ) Inundation			
( ) Damage to irrigation system			
( ) Other (specify)			

Private Adjustments to Subsidence

17. What adjustments have been undertaken by people in this area to protect against damage from subsidence?

What portion of the affected property owners have adopted these measures?

(WRITE IN 'M' IF ADJUSTMENT IS MENTIONED BY RESPONDENT; INDICATE DEGREE OF ADOPTION OF ADJUSTMENT IN RIGHT-HAND COLUMN)

Adjustment	Adoption of Adjustment			
	Practiced by:			
	None	A Few	Some	Most
( ) Dikes				
( ) Bulkheading				
( ) Flood protection				
( ) Abandonment				
( ) Insurance				
( ) Nothing				
( ) Lawsuits				
( ) Other (specify)				

Effects on Public Agencies

18. What kind of government structure is there in the subsidence area?

19a. What government organizations in the area have responsibilities and interest in subsidence problems?

Agency	Contact Person(s)	Telephone	Responsibilities/Interests

19b. Have any of these agencies publications relating to subsidence problems? If so, what are they?

Publication Title/Author/Agency	Year

20. What types of damages have occurred to Public Property as a result of subsidence? How would you estimate the severity of these effects? (WRITE IN 'M' IF MENTIONED BY RESPONDENT; INDICATE ESTIMATED DEGREE OF SEVERITY IN RIGHT-HAND COLUMN)

	Estimate of Severity			
	Low	Moderate	High	Estimate Losses
( ) Roadways				
( ) Buildings				
( ) Sewerage systems				
( ) Water pipes				
( ) Surface aqueducts				
( ) Other (specify)				

Adjustments to Subsidence by Public Agencies

21. What have public agencies in the area done to protect against damage from subsidence?

What is the level of adoption of the adjustments? Their cost?

(WRITE IN 'M' IF THE ADJUSTMENT IS MENTIONED BY RESPONDENT; THEN PROBE FOR OTHERS. INDICATE LEVEL OF ADOPTION IN THE RIGHT-HAND COLUMNS. IDENTIFY AGENCY ADOPTING ADJUSTMENT BY INITIALS IN THE TABLE.)

	Adoption of Adjustment				
Adjustment Adopted	None	Low	Moderate	High	Estimate Cost
( ) Dike/levee construction					
( ) Roadway rebuilding					
( ) Repair of sewer, water lines					
( ) Sea wall construction					
( ) Adopt land use restrictions					
( ) Implement countermeasures to reduce subsidence					
( ) Change to Alternative Resource					
( ) Relief efforts					
( ) Others (specify)					

Other Researchers, Articles, Reports Available

22. Are there other investigators studying environmental and economic effects of subsidence in this area?

				Publications	
Investigator	Title	Telephone	Research Interest	Title	Year

APPENDIX B

Subsidence Area Data Summaries

SUBSIDENCE AREA DATA SUMMARIES

In Task 1 of this project, some 52 areas listed on Table B-1 were reviewed in order to identify and select those with the greatest potential for yielding information on the environmental and economic effects of land subsidence due to fluid withdrawal. The information has been compiled as a data summary for each area. No data summaries were prepared for some geothermal areas where subsidence has not yet proven to be a problem. These areas are identified by an asterisk on Table B-1.

Table B-1.

List of Subsidence Area Data Summaries

UNITED STATES

Identification Number	State, Area or Nearest City	Page
1	Arizona, 4 areas near Phoenix	B- 4
2	Arizona, Gadsen	B- 6
3	California, San Joaquin Valley	B- 7
4	*California, Geysers	
5	California, Huntington Beach	B- 9
6	*California, Imperial Valley	
7	California, Baldwin Hills Oil Field	B-10
8	California, Palmdale	B-12
9	California, Sacramento Valley	B-14
10	California, San Jacinto Valley	B-16
11	California, Santa Clara Valley	B-18
12	California, Beverly Hills (East) Oil Field	B-20
13	California, Wilmington Oil Field, Long Beach	B-21
14	Colorado, Denver	B-23
15	Georgia, Savannah	B-25
16	Idaho, Raft River Valley	B-26
17	Louisiana, Baton Rouge	B-28
18	Louisiana, New Orleans	B-29
19	Nevada, Las Vegas Valley	B-31
20	Texas, Saxet Oil Field, Corpus Christi	B-33
21	Texas, Chocolate Bayou Oil Field, Houston	B-35
22	**Texas, Goose Creek Oil Field	
23	Texas, Houston-Galveston	B-38
24	Utah, Milford	B-40

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* No data summary prepared. Geothermal field with no subsidence reported.

Table B-1.

List of Subsidence Area Data Summaries

FOREIGN

Identification Number	Country, Area or Nearest City	Page
25	Australia, Yallourn-Morwell	B-41
26	China (Taiwan), Taipei	B-43
27	Czechoslovakia, Komarno	B-45
28	England, London	B-46
29	Hungary, Debrecen	B-48
30	Hungary, Visonta	B-49
31	*Italy, Larderello	
32	*Italy, Monte Amiata Field	
33	Italy, Po Delta	B-51
34	Italy, Venice	B-53
35	Japan, Aomori Plain	B-55
36	Japan, Sendai Plain	B-57
37	Japan, Haranomachi	B-59
38	Japan, Niigata Fields	B-60
39	Japan, Nanao Basin	B-62
40	Japan, Tokyo	B-64
41	Japan, Nobi Plain	B-66
42	Japan, Osaka	B-68
43	Japan, Saga Plain	B-70
44	*Mexico, Cerro Prieto	
45	Mexico, Mexico City	B-72
46	Netherlands, Groningen Field	B-74
47	New Zealand, Wairakei	B-76
48	New Zealand, Kawerau	B-78
49	New Zealand, Broadlands	B-79
50	Sweden, Stockholm, Gothenberg	B-80
51	Thailand, Bangkok	B-81
52	Venezuela, Bolivar Coast (L. Maricaibo)	B-83

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* No data summary prepared, Geothermal Field with no subsidence reported.

Subsidence Area:	4 Areas in Central Arizona
Country:	USA
District or Province:	Arizona
Nearest City:	Phoenix
Identification No.	1

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Groundwater.

Other: Tectonic Deformation.

Subsidence Characteristics:

Area of subsidence in km^2: ± 1600 km^2

Maximum amount of subsidence in meters: 2.3 m

Average amount of subsidence in meters: 0.7 m

Maximum subsidence rate in cm/yr.: 17.1 cm/yr Year: 1952-1964

Geologic Setting:

Alluvial basin in Western Pinal County, Upper 15-180 m of alluvial deposits is silty sand and gravel, underlain by a silt and clay layer as much as 610 m thick.

Land Uses:

Agriculture	( )	Industrial	( )
Irrigated agriculture	(x)	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Ground cracks ,fissures, piping, erosion of cracks.

Economic Effects:

Damage has been: Severe ( ) Moderate (x) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	(x)	Roads	(x)
Pipelines	( )	Railroads	(x)
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	(x)
Irrigation channels	(x)	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

None given.

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	(X)
Relevelling studies	(x)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	(x)		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Reballast railroad ,irrigation system repair,relevel fields, relocate aqueduct.

Cost Estimate of Adjustments:

$187,000 per year.

Source(s):

1. Response to International Survey on Land Subsidence by Robert L. Laney, Hydrologist, USGS, Suite 1880, Valley Center, Phoenix, Arizona 85073 - January 23, 1976.
2. Schuman, H. H., and Poland, J. F., 1969 (see List of Publications).

Subsidence Area: 4 Areas in Central Arizona
Country: United States
District or Province: Arizona
Nearest City: Phoenix

Publications:

Bouwer, H., 1975, Subsidence of the Land Surface and Formation of Earth Cracks Due to Groundwater Withdrawal, Water Conservation Lab., Phoenix, Arizona, Geological Society of America/ New York 1975 Annual Meetings

Clyma, W., Young, R. A., 1968, Environmental Effects of Irrigation in the Central Valley of Arizona. American Society of Civil Engineers, National Meeting on Environmental Engineering, Chattanooga, Tennessee, May 13-17, Preprint. 28 p. SWRA W70-07053.

Earth Sciences Associates, 1971, Investigation of Earth Fissure Phenomena in the Vicinity of Willcox Arizona. Unpublished report for Southwest Properties, Inc. 4219 Indian School Road, Phoenix, AZ, 85018, Earth Sciences Associates, 701 Welch Road, Palo Alto, CA 94304

Heindl, L. A., and Feth, J. H., 1955, Piping and earth cracks-- a discussion: Am. Geophys. Union Trans., V. 36, No. 2, p. 342-345

Keith, Susan Jo, 1977, The Impact of Groundwater Development in Arid Lands: A Literature Review and Annotated Bibliography, Tucson, Arizona: University of Arizona, Office of Arid Lands Studies.

Leonard, R. J., 1929, An earth fissure in southern Arizona: Jour. Geology v. 37, no. 8 p. 765-774.

McCauley, C. A., 1973, Management of Subsiding Lands: An Economic Evaluation. Arizona University, Tucson, Department of Hydrology and Water Resources, Available from the National Technical, Information Service, Springfield, VA 22161 as PB-240 305, $4.75 in paper copy/$2.25 in microfiche. Phd. dissertation

McCauley C.A. and R. Gum, 1975, Land Subsidence: An Economic Analysis, Water Resources Bulletin Vol II, No. 1., pp. 148-154

McCauley C.A. and Gum, R.L., 1972, Subsidence Damage in Southern Arizona, Arizona University, Tucson, Dept. of Hydrology and Water Resources, in: Hydrology and Water Resources in Arizona and the Southwest, Vol 2, Proceedings of the 1972 Meetings of the Arizona Section, American Water Resources Assn., and the Hydrology Section, Arizona Academy of Science May 5-6, 1972, Prescott, Arizona, p. 87-94

Pashley, E. F., Jr., 1961, Subsidence cracks in alluvium near Casa Grande, Arizona: Arizona Geol. Soc. Digest, V. 4, p. 95-101.

Poland, J. F., 1973, Subsidence in United States due to ground-water overdraft--a review: Am. Soc. Civil Engineers, Proc. Irrigation and Drainage Div. Specialty Conf., Fort Collins p. 11-38.

Poland, J. F., and Davis, G. H., 1969, Land Subsidence due to withdrawal of fluids, in Reviews in engineering geology, volume 2: Geol. Soc. America, p. 187-269.

Sauck, W. A., 1975, "Geophysical Studies near subsidence fissures in Central Arizona: American Geophysical Union, Transactions V. 56, no. 12, p. 984-985.

Schumann, H. H., 1974, Land subsidence and earth fissures in alluvial deposits in the Phoenix area, Arizona: U. S. Geol. Survey Misc. Inv. Ser. Map I-845-H, I sheet.

Schumann, H. H., and Poland, J. F., 1970, Land subsidence, earth fissures, and groundwater withdrawal in south-central Arizona, U. S. A. in Land Subsidence: Tokyo, Internat. Assoc. Sci. Hydrology, Pub. 88, v. 1, p. 295-302.

Winikka, C. C. and P. D. Wold, 1977, "Land Subsidence in Central Arizona" in proceedings of Second Symposium on Land Subsidence December 10-17, 1976 Anaheim, CA. International Association of Hydrological Sciences Publication no. 121. p. 95-103

Subsidence Area: Gadsen
Country: United States
District or Province: Arizona
Nearest City: Gadsden
Identification Number: 2

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal:
Other: Tectonic Deformation and Liquifaction from the Imperial Fault Earthquake, May 18, 1940

Subsidence Characteristics:

Area of subsidence in km^2: Unknown
Maximum amount of subsidence in meters: .3 m
Average amount of subsidence in meters: .3m
Maximum subsidence rate in cm/yr.: Sudden Change Year: May 19, 1940

Geologic Setting:

Land Uses:

Agriculture	( )	Industrial	( )
Irrigated agriculture	(X)	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Alteration of River System

Economic Effects: As a Result of Liquifaction

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	(X)
Pipelines	( )	Railroads	(X)
Houses	( )	Sewers	( )
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	(X)	Floodwalls	
		Airports	

Irrigated Fields Tilted

Cost Estimate of Damage:

No estimate available.

Adjustments to Subsidence:

Scientific studies	( )	Abandonment	( )
Relevelling studies	( )	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	(X)	Law suits	( )
Develop institutional framework	( )		

Some Fields Relevelled

Cost Estimate of Adjustments:

No estimate available.

Source(s): Response to International Survey on Land Subsidence, Wayne Moffitt, Project Geologist, Bureau of Reclamation, Yuma, Arizona, USA. 1-23-76.
Publication: U.S. Bureau of Reclamation, Yuma Project, 1940, Annual Report.

Subsidence Area: San Joaquin Valley
Country: United States
District or Province: California
Nearest City: Fresno and Bakersfield
Identification Number: 3

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Groundwater, also oil and gas
Other: Teconic Deformation , Hydrocompaction , Oxidation of Organic Soils

Subsidence Characteristics:

Area of subsidence in km^2: 13,500 km^2
Maximum amount of subsidence in meters: 9 m
Average amount of subsidence in meters: 1.5 m
Maximum subsidence rate in cm/yr.: 52 **Year:** 1956-1957

Geologic Setting: Extensive alluviated structural valley. Alluvial & Lacustrine deposits contain groundwater to depths of 100 to 1200 m.

Land Uses:

Agriculture	( )	Industrial	( )
Irrigated agriculture	(X)	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Altered gradients to major canals, drains & streams. Subsurface deformation. Ground surface cracking in only 2 places.

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	(X)	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	(x)
Buildings	( )	Drains	(x)
Pile foundations	( )	Dams	( )
Irrigation channels	(X)	Levees	( )
Aqueducts	(X)		

Cost Estimate of Damage:

$20 - 30 Million

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource (water)	(X)
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	Water well repair and replacement	

Cost Estimate of Adjustments:

$25 Million

Ditches Redirected to maintain grade

New canals designed to compensate for subsidence.
New wells have sleeve joints.

Source(s):

Response to International Survey on Land Subsidence, Feb. 24, 1976 Ben E. Lofgren, reseach Geologist. U. S. Geological Survey, Room W-2528 Federal Bldg., 2800 Cottageway, Sacramento, CA. 95825 (916)484-4258

Subsidence Area: San Joaquin Valley
Country: United States
District or Province: California
Nearest City: Fresno & Bakersfield

Publications:

California Department of Water Resources , 1964 , Design and Construction Studies of Shallow Land Subsidence for the California Aqueduct in the San Joaquin Valley. Interim Report (Sacramento) 130 p. illus.

Lofgren, B. E., 1977, "Hydrogeologic Effects of Subsidence, San Joaquin Valley, California" in Proceedings of the Second Symposium on Land Subsidence Dec. 10-17, 1976 Ahaheim, CA. International Association of Hydrological Scienes, Publication No. 121.

Lofgren, B. E. ,1975,Land Subsidence Due to Ground-Water Withdrawal, Arvin-Mariopa Area, California. U. S. Geological Survey, Professional Paper 437-D. 55 p.

Lofgren, B. E.,Klausing, R. L.,1969,Land Subsidence Due to Ground-Water Withdrawal, Tulare-Wasco Area, California. U. S. Geological Survey, Professional Paper 437-B. 101 p.

Lucas, C. and L. James, 1977 , "Land Subsidence and the California State Water Project" in Porceedings of the Second International Symposium on Land Subsidence, Dec. 10-17, 1976, Anaheim, CA. International Association of Hydrological Sciences. Publication No. 121

Poland, J. F. et al.,1975,Land Subsidence in the San Joaquin Valley, California, as of 1972. U. S. Geological Survey, Professional Paper 437-H. 78 p.

Singer, R. , 1977 , "Legal Implications of Land Subsidence in the San Joaquin Valley" in Proceedings of the Second International Symposium on Land Subsidence Dec. 10-17, 1976 Anaheim, CA. International Association of Hydrological Sciences,Publication No. 121

Investigators:

- o Ben E. Lofgren, U. S. Geological Survey, Sacramento, California.
- o Clifford Lucas & Lawrence James. California Department of Water Resources, Sacramento, California.

Subsidence Area: Huntington Beach
Country: United States
District or Province: California
Nearest City: Huntington Beach
Identification Number: 5

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water, Oil and Gas
Other: Dewatering and Oxidation of Holocene Peat and Organic Sediments

Subsidence Characteristics:

Area of subsidence in km^2: Unknown Localized
Maximum amount of subsidence in meters: 6 m
Average amount of subsidence in meters: 3-4.3 m
Maximum subsidence rate in cm/yr.: Year:
Average subsidence rate: 5.8 - 8.1 cm/yr.

Geologic Setting:

Peat deposits

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other (X)

Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Lagoons, fishing lakes, driving ranges, gold courses, playing fields, parks & recreation areas, parking lots, mobile home parks, drive-in movies

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (X)

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

NONE GIVEN

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection (X)
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )
Construct Hydraulic Salinity Barrier

Cost Estimate of Adjustments:

NONE GIVEN

Source(s): Fairchild, J. B. and Karl H. Wiebe, 1977, "Subsidence of Organic Soils and Salinity Barrier Design in Coastal Orange County," in Land Subsidence, Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, December 1976 Ann Arbor, Michigan, International Association of Hydrological Sciences, pp. 334-356

Subsidence Area: Baldwin Hills Oil Field
Country: United States
District or Province: California
Nearest City: Inglewood & Los Angeles
Identification Number: 7

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Oil, Gas
Other: Tectonic Deformation

Subsidence Characteristics:

Area of subsidence in km^2:
Maximum amount of subsidence in meters: 2.7 m vertical 0.7 m horizontal movement
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )
Industrial ( )
Business & residential (X)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Subsidence bowl, ground rupture, faulting

Economic Effects:

Damage has been: Severe (x) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Roads (X)
Railroads ( )
Sewers ( )
Drains ( )
Dams (X)
Levees ( )

Baldwin Hills Dam failed December 14, 1963
Valued at $2.5 million. Insurance paid $.75 million

Cost Estimate of Damage:

$15 Million property damage from Baldwin Hills Dam failure. Insurance paid over $13 million to 3700 claimants.

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair (x)
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )
Abandonment (X)
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits (X)

Cost Estimate of Adjustments:

Source(s): Lee, Kenneth L. 1977, "Calculated Horizontal Movements at Baldwin Hills, California," in Land Subsidence, Proceedings of Second Symposium on Land Subsidence, December 10-17, 1976 Anaheim, California. International Association of Hydrological Sciences. Publication No. 121. pp. 299-308

Subsidence Area: Baldwin Hills Oil Field
Country: United States
District or Province: California
Nearest City: Inglewood & Los Angeles

Publications:

Castle, R. O.,Yerkes, R. F.,1976, Recent Surface Movements in the Baldwin Hills, Los Angeles County, California, U. S. Geol. Surv., Prof. Pap./882/1-132

California Department of Water Resources, 1964, Investigation of Failure Baldwin Hills Reservoir, California DWR 64 p.

Lee, Kenneth L.,1977,"Calculated and Observed Subsidence and Horizontal Movements at Baldwin Hill, California" in proceedings of Second Symposium on Land Subsidence, December 10-17, 1976 Anaheim, California. International Association of Hydrological Sciences, Publication No. 181.

Richards, C. A.,1973, Engineering Geology Aspects of Petroleum in the Urban Environment Oil Drilling and Seepage, Los Angeles, California. Assoc. Eng. Geol., Los Angeles, in Geology, Seismicity, and Environmental Impact, p. 391-400, Illus. (incl. sketch map)

Investigators:

(see authors above)

None known to be studying economic effects

Subsidence Area: Palmdale
Country: United States
District or Province: California
Nearest City: Palmdale

Identification Number: 8

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Hydrocompaction of Local Importance in Lancaster and Little Rock

Subsidence Characteristics:

Area of subsidence in km^2: 1200 km^2
Maximum amount of subsidence in meters: 1.04 m
Average amount of subsidence in meters: .6 m
Maximum subsidence rate in cm/yr.: 9 cm/year Year: 1973

Geologic Setting:

After Bloyd 1967. Unconsolidated alluvium and fine grained sediments of an old playa lake.

Land Uses:

Agriculture	( )	Industrial	( )
Irrigated agriculture	(X)	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (X)

Damage Has Been To:

Wells & well casings	(X)	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

Damage to wells in excess of $100,000.
Damage to drainage in excess of $10,000.

Adjustments to Subsidence:

Scientific studies	(x)	Abandonment	( )
Relevelling studies	(x)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	None known	

Cost Estimate of Adjustments:

No adjustments known.

Source(s) Response to International Survey on Land Subsidence, by Richard J. Mitchell, Assistant Division Engineer Survey Division, Los Angeles County Engineer, 108 West Second Street, Room 430, Los Angeles, California, 90012. January 26, 1976.

Subsidence Area:	Palmdale
Country:	United States
District or Province:	California
Nearest City:	Palmdale

Publications:

J. F. McMillan, 1973, Land Subsidence - Antelope Valley Area of Los Angeles County, 11 pages and 2 diagrams.

Lewis, R. E. and Miller, R. E., 1968, Geologic and Hydrologic Maps of Southern Part of Antelope Valley, California; supplement to U.S.D.A. Soil Survey Report of the Antelope Valley Area, U.S.G.S. Water Resources Division, 13 pages, 8 figures.

Groundwater References:

Woodruff, G. A., McCoy, W. J. and Sheldon, W. B., 1970, Soil Survey, Antelope Valley, California: U.S.D.Agric., p. 177.

Bloyd, Jr., R. M., 1967, Water Resources of the Antelope Valley - East Kern Water Agency Area, California, U.S.G.S. open-file report, 73 pages.

Chandler, T. S., 1972, Water Resources Inventory, Spring 1966 to Spring 1971, Antelope Valley - East Kern Water Agency Area, California, U.S.G.S. open-file report, 14 pages.

Investigators:

Subsidence Area: Sacramento Valley
Country: United States
District or Province: California
Nearest City: Sacramento
Identification No. 9

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 500 km^2
Maximum amount of subsidence in meters: 0.7 m
Average amount of subsidence in meters: 0.3 m
Maximum subsidence rate in cm/yr.: 3 cm/yr Year: ?

Geologic Setting:

Relatively flat elongated alluviated structural valley; semi-consolidated Tertiary sedimentary rocks.

Land Uses:

Agriculture (x)
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate (x) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings (x)
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

$50,000

Adjustments to Subsidence:

Scientific studies (x)
Relevelling studies ( )
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )
Well repair and replacement

Cost Estimate of Adjustments:

Source(s):

Response to International Survey on Land Subsidence by Ben E. Lofgren, Research Geologist, U.S. Geological Survey, Room W-2528, Federal Building
2800 Cottage Way
Sacramento, California 95825

Subsidence Area: Sacramento Valley
Country: United States
District or Province: California
Nearest City: Sacramento

Publications:

Bryan, Kirk, 1923, Geology and groundwater resources of the Sacramento Valley, California: U.S. Geol. Survey Water-Supply Paper 495, 285 p.

Lofgren, B. E., and Ireland, R. L., 1973, Preliminary investigation of land subsidence in the Sacramento Valley, California: U.S. Geol. Survey open-file report, 32 p.

Olmsted, F. H., and Davis, G. H., 1961, Geologic features and groundwater storage capacity of the Sacramento Valley, California: U.S. Geol. Survey Water-Supply Paper 1497, 241 p.

Richardson, H. E., and Prokopovich, N. P., 1968, Land subsidence in the southwestern portion of the Sacramento Valley, California: Assoc. Eng. Geologists Natl. Mtg., Seattle, Washington, October 22-26, 1968, Program, p. 45-46.

Investigators:

Ben E. Lofgren (see sources).

Subsidence Area:	San Jacinto Valley
Country:	United States
District or Province:	California
Nearest City:	San Jacinto
Identification No.	10

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal:	Water
Other:	Tectonic Deformation

Subsidence Characteristics:

Area of subsidence in km^2:	10+ km^2	
Maximum amount of subsidence in meters:	1 m	
Average amount of subsidence in meters:	.4 m	
Maximum subsidence rate in cm/yr.:	3 cm/yr	Year: 1938-56 (average)

Geologic Setting:

Alluviated structural graben valley in active San Jacinto fault zone.

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	(X)	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Surface tilting.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	(X)	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Pipeline offset; surface reservoir tilted.

Cost Estimate of Damage:

$50,000

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	( )	Fluid reinjection	(X)
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	(X)	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Groundwater Recharge Experimentation

Cost Estimate of Adjustments:

"Slight"

Source(s):

Response to International Survey on Land Subsidence
Ben E. Lofgren, Research Geologist,
U.S. Geological Survey, Room W-2528, Federal Building, Sacramento, California 95825

Subsidence Area: San Jacinto Valley
Country: United States
District or Province: California
Nearest City: San Jacinto

Publications:

Fett, J. D., Hamilton, D. H., and Fleming, F. A., 1967, Continuing surface displacements along the Casa Loma and San Jacinto faults in San Jacinto Valley, Riverside County, California: Eng. Geol., V. 4, No. 1, p. 22-32.

Lofgren, B. E., 1976, Land subsidence and aquifer-system compaction in the San Jacinto Valley, Riverside County, California -- A progress report: U.S. Geol. Survey Journal of Research, V. 4, No. 1, February 1976, p. 9-18.

Lofgren, B. E., and Rubin, Meyer, 1975, Radiocarbon dates indicate rates of graben downfaulting, San Jacinto Valley, California: U.S. Geol. Survey Journal of Research, V. 3, No. 1, p. 45-46.

Proctor, R. J., 1962, Geologic features of a section across the Casa Loma fault, exposed in an aquecudt trench near San Jacinto, California: Geol. Soc. America Bull., V. 73, p. 1293-1296.

Proctor, R. J., 1974, New localities for fault creep in southern California -- Raymond and Casa Loma faults: Cordilleran Section, 70th Ann. Mtg., Geol. Soc. America, Las Vegas, Nevada, 1974, Abst. with Prog., p. 238.

Sharp, R. V., 1967, San Jacinto fault zone in the Peninsular Ranges of Southern California: Geol. Soc. America Bull., V. 78, No. 6, p. 705-730.

Sharp, R. V., 1972, Map showing recently active breaks along the San Jacinto fault zone between San Bernardino area and Borrego Valley, California: U.S. Geol. Survey Misc. Geologic Inv., Map I-675, Sheet 2 of 3.

Waring, G. A., 1919, Groundwater in the San Jacinto and Temecula basins, California: U.S. Geol. Survey Water Supply Paper 429, p. 113.

Woodford, A. O., Shelton, J. S., Doehring, D. O., and Morton, D. K., 1971, Pliocene-Pleistocene history of the Perris Block, Southern California: Geol. Soc. America Bull., V. 82, No. 12, p. 3421-3448.

Investigators:

Ben E. Lofgren (see sources).

Subsidence Area:	Santa Clara Valley
Country:	United States
District or Province:	California
Nearest City:	San Jose
Identification No.	11

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW-ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water

Other:

Subsidence Characteristics:

Area of subsidence in km^2: 650 km^2

Maximum amount of subsidence in meters: 4 m

Average amount of subsidence in meters: 1.4 m

Maximum subsidence rate in cm/yr.: 30 cm/yr Year: 1962

Geologic Setting: Alluvial fill, unconsolidated to semi-consolidated gravel, sand, silt, clay.

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects: Subsidence and warping of stream channels and change of gradients has caused reduced sediment transport and flooding.

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	(X)	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	(X)
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	(X)
Aqueducts	( )		

Cost Estimate of Damage:

Repair or replacement of wells about $5 million. Levee construction & stream channel repair $10 million. Maintenance and repair of salt pond dikes unknown.

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource (water)	(X)
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	(X)	Construct South Bay Aqueduct. Construct Retention Dams. Raise bridge. Tax on Groundwater	

Cost Estimate of Adjustments:

Sewage treatment plant $4 million, water conservation facilities $13 million

Source(s):

Response to International Survey on Land Subsidence
Joseph F. Poland, Research Geologist
U.S. Geological Survey, Room W-2528, Federal Building
2800 Cottage Way, Sacramento, California 95825

Subsidence Area: Santa Clara Valley
Country: United States
District or Province: California
Nearest City: San Jose

Publications:

California State Water Resources Board, 1955, Santa Clara Valley Investigation: Bull. no.7, 154 p.

California Department of Water Resources, 1967, Evaluation of ground-water resources, South Bay: Bull. No. 118-1, Appendix A, Geology, 153 p.

Hunt, G. W., 1940,Description and results of operation of the Santa Clara Valley Water Conservation Districts project: Am. Geophys. Union Trans., pt. 1, p. 13-22.

Poland, J. F., and Green, J. H., 1962, Subsidence in the Santa Clara Valley, California--A progress report: U. S. Geol. Survey Water-Supply Paper 1619-C, 16 p.

Poland, J. F., 1977 "Land Subsidence Stopped by Artesian-Head Recovery", Proceedings of Second Symposium on Land Subsidence. December 10-17 , 1976 Anaheim, California International Association of Hydrological Sciences. Publication No. 121

Poland, J. F., and Green, J. H., 1962, Subsidence in the Santa Clara Valley, California--A progress report: U. S. Geol. Survey Water-Supply Paper 1619-C, 16 p.

Roll, J. R., 1967, Effect of subsidence on well fields: Am. Water Works Assoc. Jour., v. 59, no.1, p. 80-88.

Investigators:

Joseph F. Poland (See Sources)

Contacts

Santa Clara Valley Water District

Subsidence Area:	Beverly Hills (East) Oilfield
Country:	United States
District or Province:	California
Nearest City:	Beverly Hills- Los Angeles
Identification Number:	12

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal:	Oil and Gas, Water
Other:	Tectonic Activity, Vibration, Subsurface Solution

Subsidence Characteristics:

Area of subsidence in km^2: Unknown. "Minor Bowl of Subsidence"

Maximum amount of subsidence in meters: .12 m (max. 1966-1975)

Average amount of subsidence in meters: Unknown

Maximum subsidence rate in cm/yr.: 1.8 cm/year Year: 1968-1969

Geologic Setting:

East-west trending elongate complexly folded and faulted anticline.

Land Uses:

Agriculture	( )	Industrial	( )
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Economic Effects: No damage mentioned by Erickson.

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (X) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

None mentioned.

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	(X)
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

No mention of costs by Erickson.

Source(s): Erickson, R. C., 1977, "Subsidence Control and Urban Oil Production - A Case History Beverly Hills (East) Oil Field, California", in Land Subsidence, Proceedings of The Second International Symposium on Land Subsidence, Anaheim, California, December 1976, Ann Arbor, Michigan: International Association of Hydrological Sciences, pp. 285-297.

Subsidence Area: Wilmington Oil Field
Country: United States
District or Province: California
Nearest City: Long Beach
Identification No. 13

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Oil and Gas
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 50 km^2
Maximum amount of subsidence in meters: 9m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 75 cm/yr Year: 1952

Geologic Setting:

Asymmetrical anticline broken by transverse normal faults, buried by 550 to 600 m of late Pliocene, Pleistocene and Recent Sediments.

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (x)
Business & residential ( )
Well fields ( )
Water-related shipping (x)
Mining ( )

Surface Environmental Effects:

Horizontal movements, up to 3m. Induced seismicity. Over 1300 hectares subsided below sea level.

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings (X)
Pipelines (X)
Houses ( )
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Bridges

Roads (x)
Railroads (X)
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Damage to oil facilities $20 million.

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair (X)
Road repair (X)
Pipeline repair ( )
Building repair (X)
Land Filling (X)
Develop institutional framework (X)

Abandonment ( )
Fluid reinjection (X)
Stop resource production ( )
Develop alt. resource ( )
Law suits (x)
Elevating wharves and other structures.

Cost Estimate of Adjustments:

Cost of remedial measures in excess of $100 million.

Source(s): Mayuga, M. N. and D. R. Allen, 1970, "Subsidence in the Wilmington Oil Field" in Land Subsidence: Proceedings of the Tokyo Symposium, Volume 1, International Association of Scientific Hydrology and UNESCO, September 1969, pp. 66-79.

Subsidence Area: Wilmington Oil Field
Country: United States
District or Province: California
Nearest City: Long Beach

Publications:

Allen, D. R., Chilingar, G. C., Sawabini, C. T., Mayuga, M. N., 1971, Study and Prevention of Subsidence. (Translated by) Dept. of Oil Properties, Long Beach, Calif., 1971, 21 p., Translated from Encyclopedia Della Scienza e Della Teonica Mondadcri, Annuario Della Est.

Allen, D. R., Mayuga, M. N., 1970, The Mechanics of Compaction and Rebound, in Proceedings of the Tokyo Symposium on Land Subsidence, Vol. 2, International Association of Scientific Hydrology and UNESCO, September 1969, Tokyo, p. 410-423.

Casile, R. U., Yerkes, R. F., Riley, F. S., 1970, A Linear Relationship Between Liquid Production and Oil Field Subsidence, in Proceedings of the Tokyo Symposium on Land Subsidence, Vol. 1, International Association of Scientific Hydrology and UNESCO, September 1969, p. 162.

Colazas, Z. C., 1971, Subsidence, Compaction of Sediments and Effects of Water Injection, Wilmington and Long Beach Offshore Oil Fields, Los Angeles County, Calif., M.S. Thesis, Univ. of Southern California, Los Angeles, Calif., 1971, 198 p.

Compton, R. L., 1961, The Right to the Subjacent Support of Oil and Gas, California Law Review, 49:354-367.

Gates, G. L., Caraway, W. H., Lechtenberg, H. J., 1977, Problems in Injection of Waters in Wilmington Oil Field, California.

Huey, W. F., 1964, Subsidence and Repressuring in Wilmington Oil Field, Summary of Operations 50(2), Calif., Div. of Oil and Gas, Sacramento, California, 1964, p. 5-25.

Mayuga, M. N., 1965, How Subsidence Affects the City of Long Beach in the State of California, The Resources Agency, Landslides and Subsidence, Geologic Hazards Conference, Los Angeles, California, p. 122-129.

Mayuga, M. N., Allen, D. R., 1970, Subsidence in the Wilmington Oil Field, Long Beach, California, in Proceedings of the Tokyo Symposium on Land Subsidence, Vol. 1, International Association of Scientific Hydrology and UNESCO, September 1969, pp. 66-79.

Pierce, R. L., 1970, Reducing Land Subsidence in the Wilmington Oil Field by Use of Saline Waters, Water Resources Res., V. 6 (5), p. 1505-1514.

Investigators:

Allen, D. R., Subsidence Engineer, City of Long Beach, Department of Oil Properties.

Subsidence Area: Denver
Country: United States
District or Province: Colorado
Nearest City: Denver
Identification Number: 14

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW-ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: Unknown
Maximum amount of subsidence in meters: .38 m to 1962
Average amount of subsidence in meters: Unknown
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

None reported.

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (X)

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies ( )
Relevelling studies ( )
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

Source(s): Poland, J. F. & Davis, 1969, Land Subsidence Due to Withdrawal of Fluids, in Reviews in Engineering Geology II, Geological Society of American, Boulder, Colorado.

Subsidence Area:	Denver
Country:	United States
District or Province:	Colorado
Nearest City:	Denver

Publications:

Poland & Davis, 1969.

Miller, W. L., 1974, "Geothermal Energy and the Environment", in proceedings of A Symposium on Geothermal Energy and Colorado, Denver, Colorado, United States, December 6, 1973. Pearl, R. H. (ed.) Bureau of Mines, Washington, D. C.; Colorado Geological Survey, Denver 1974.

Investigators:

Hansen, W. R., U. S. Geological Survey, Denver, Colorado, "Denver Urban Corridor Studies". Period of performance: July 1974 to June 1975. Note: Project aims to derive maximum possible geotechnical information from existing available data.

Subsidence Area: Savannah
Country: United States
District or Province: Georgia
Nearest City: Savannah
Identification Number: 15

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 330 km^2 exceeds 20 mm subsidence
Maximum amount of subsidence in meters: 150 mm
Average amount of subsidence in meters: 100 mm
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Land Uses:

Agriculture	( )	Industrial	( )
Irrigated agriculture	( )	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects: "... it should be noted that land subsidence at Savannah has not been sufficient to be recognized as a serious engineering problem..." (Davis, Counts & Holdahl, 1977).

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

Source(s): Davis, G. H., J. B. Small and H. B. Counts, 1963, "Land Subsidence Related to Decline of Artesian Pressure in the Ocala Limestone at Savannah, Georgia", Geological Society of America Engineering Geology Case History #4, p. 1-8.

Davis, G. H., H. B. Counts and S. R. Holdahl, 1977, "Further Examination of Subsidence at Savannah, Georgia in Land Subsidence, Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, December, 1976, Ann Arbor, Michigan: International Association of Hydrological Sciences, pp. 347-354.

Subsidence Area: Raft River Valley
Country: United States
District or Province: Idaho
Nearest City: Malta
Identification Number: 16

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Tectonic Deformation

Subsidence Characteristics:

Area of subsidence in km^2: 260 km
Maximum amount of subsidence in meters: 0.8 m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 4 cm/year Year: 1965

Geologic Setting:

Alluviated Structural Valley, Unconsolidated Sand and Gravel

Land Uses:

Agriculture	(X)	Industrial	( )
Irrigated agriculture	( )	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

None Known

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (X)

Damage Has Been To: None Known

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

None

Adjustments to Subsidence: None Known

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

None

Source(s): Response to International Survey on Land Subsidence, Lofgren, B.E., U. S. Geological Survey, Sacramento, California.

Subsidence Area: Raft River Valley
Country: United States
District or Province: Idaho
Nearest City: Malta

Publications:

Idaho National Engineering Laboratory, 1976, Geothermal Research and Development Project Report, Idaho Falls, United States: Idaho National Engineering Laboratory.

Lofgren, B. E., 1975, Land Subsidence and Tectonism, Raft River Valley, Idaho: U. S. Geological Survey open-file report 75-585, 20 pp.

Mundorff, M. J., and Sisco, H. G., 1963, Ground Water in the Raft River Basin, Idaho, with Special Reference to Irrigation Use, 1956-60: U. S. Geological Survey Water-Supply Paper 1619-CC, 23 pp.

Nace, R. L., and others, 1961, Water Resources of the Raft River Basin, Idaho-Utah: U. S. Geological Survey Water-Supply Paper 1587, 138 pp.

Spencer, S. G., 1975, Environmental Report - Deep Geothermal Test Wells in the Raft River Valley: Aerojet Nuclear Company, Idaho National Engineering Laboratory.

Walker, E. H., Dutcher, L. C., Decker, S. O., and Dyer, K. L., 1970, The Raft River Basin, Idaho-Utah as of 1966: A Reappraisal of the Water Resources and Effects of Ground-water Development: Idaho Department of Water Administration Water Information Bulletin No. 19, 95 pp.

Investigators:

Idaho National Engineering Laboratory.

Subsidence Area: Baton Rouge
Country: United States
District or Province: Louisiana
Nearest City: Baton Rouge
Identification Number: 17

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 500 km^2
Maximum amount of subsidence in meters: 0.3 m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Fluviatile and shallow marine sediments, miocene to holocene.

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (X) None Reported ( )

Damage Has Been To: None

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

None

Adjustments to Subsidence: None

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

None

Source(s): Davis, G. H. and Rollo, J. R., 1969, "Land Subsidence Related to Decline of Artesian Head at Baton Rouge, Lower Mississippi Valley, U.S.A.," in Land Subsidence: Proceedings of the Tokyo Symposium, Volume 1, International Association of Scientific Hydrology and UNESCO, September 1969, pp. 174-184.
Publications: Several others cited in Davis & Rollo; none on economics effects.

Subsidence Area: New Orleans
Country: United States
District or Province: Louisiana
Nearest City: New Orleans
Identification Number: 18

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: water
Other: dewatering organic soils, loading by structures

Subsidence Characteristics:

Area of subsidence in km^2: ± 150 km^2
Maximum amount of subsidence in meters: 0.8 m
Average amount of subsidence in meters: 0.4 m
Maximum subsidence rate in cm/yr.: ? Year:

Geologic Setting: Gulf Coast Recent and Pleistocene deposits

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (x)
Business & residential (x)
Well fields ( )
Water-related shipping (x)
Mining ( )

Surface Environmental Effects:

differential subsidence, increased risk of flooding

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight (X) None (X) None Reported ( )
(Earle, 1976) (Kazman, 1975)

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses (X)
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

No Cost estimate made

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies ( )
Dike const. & repair (X)
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling (x)
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )
Sandbag levees

Cost Estimate of Adjustments:

None available

Source(s): Response to International Survey on Land Subsidence R. G. Kazmann, Professor. Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana 70803 December 9, 1975

Subsidence Area: New Orleans
Country: United States
District or Province: Louisiana
Nearest City: New Orleans

Publications:

Earle, D. W., Jr. Land Subsidence problems and maintenance costs to homeowners in East New Orleans Louisiana, Doctoral, 1975, Louisiana State: Baton Rouge, Diss., Abstr. Int., Vol. 36, No. 7 p. 3287B-3288B, 1976

Environmental Assessment of Proposed Geothermal well testing in the Tigre Lagoon Oil Field, Vermilion Parish, Louisiana, Energy Research and Development Administration, Washington, D. C. (USA) Div. of Geothermal Energy/Coast, Baton Rouge, Louisiana,(USA). March 1976/Dep. NTIS $5.00

Kazmann, R. G., and Heath, M. M., "Land Subsidence Related to Groundwater Offtake in the New Orleans Area, "Gulf Coast Assoc. Geological Societies Trans., Vol. 18, p. 108-113, 1968.

Rollo, J. R., "Ground-Water Resources of the Greater New Orleans Area, Louisiana," Louisiana Geol. Survey, Water Resources Bull., No. 9, 1966.

Wagner, F. W., Durabb, E. J., 1976 The Sinking City. Environment, May 1976 VI8, N4, P32 (8)

Investigators:

Daniel W. Earle, Jr., Professor of Landscape Architecture, Louisiana State University.
Baton Rouge, Louisiana 70803

Subsidence Area: Las Vegas Valley
Country: United States
District or Province: Nevada
Nearest City: Las Vegas
Identification No. 19

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water

Other: Hydrostatic loading due to filling Lake Mead behind Hoover Dam. Tilting of Tectonic origin.

Subsidence Characteristics:

Area of subsidence in km^2:	291 km^2 (Dinger)	375 km^2 (Harrill)	500 km^2
Maximum amount of subsidence in meters:	1.68 m "	.6 "	
Average amount of subsidence in meters:	.84 m "	.1 "	
Maximum subsidence rate in cm/yr.:	Not Available Year:	5-6 cm/yr (1975)	

Geologic Setting:

Basin alluvial fill, late Cenozoic clay and silt.

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial ( )
Business & residential (x)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects: Tilting, ground surface rupture: cracks & fissures.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings (X)
Pipelines (X)
Houses (X)
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads (X)
Railroads (X)
Sewers ( )
Drains ( )
Dams (X)
Levees ( )
Reservoir Failure

Cost Estimate of Damage:

$1 million (Dinger)

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair (X)
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment (wells)(X)
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource (water) (X)
Law suits ( )

Cost Estimate of Adjustments:

$400,000 in well repair/replacement. $19,000/yr. for Road repairs.

Source(s): 2 Respondents to International Survey on Land Subsidence:

James S. Dinger, Research Fellow
Center for Water Resources Research,
Desert Research Institute, Univ. of Nevada
Reno, Nevada 89507

James R. Harrill, Hydrologist
U.S. Geological Survey, Room 227, Federal Building
Building 701, N. Plaza Street
Carson City, Nevada 89701

Subsidence Area: Las Vegas Valley
Country: United States
District or Province: Nevada
Nearest City: Las Vegas

Publications:

Blume, John A. and Associates, 1965, "Report on a Survey of Las Vegas Foundation Conditions", John A. Blume and Associates Research Division, NVO-99-05.

Converse, Davis and Associates, 1971, "Subsurface Investigations", Campbell Pumping Station, 4095 East Flamingo Road, Las Vegas, Nevada, Report to Las Vegas Valley Water District.

Dawson, Raymond, 1962, "An Evaluation of the Effect of Soil and Climatic Conditions on the Cut Section of Interstate Highway 15 in the Owens Avenue Area of Las Vegas, Nevada", Report to DeLeuw, Cather & Co., Consulting Engineers.

Domenico, P. A. and G. B. Maxey, 1964, "An Evaluation of the Cause and Effect of Land Subsidence in Las Vegas Valley with Special Reference to the Owens Avenue Area", Desert Research Institute, University of Nevada, unpublished report to the State Highway Department.

Domenico, P. A., D. A. Stephenson and G. B. Maxey, 1964, "Groundwater in Las Vegas Valley", Desert Research Institute, University of Nevada, Technical Report No. 7.

Domenico, P. A., M. D. Mifflin and A. L. Mindling, 1966, "Geologic Controls on Land Subsidence in Las Vegas Valley, Nevada", Proc. 4th Annual Engineering Geology and Soils Engineering Symposium, Moscow, Idaho, pp. 113-120.

Harrill, J. R., 1972, "Water Level Change Associated with Groundwater Development in Las Vegas Valley, Nevada, 1971-72", USGS Open File Report.

Longwell, C. R., E. H. Pampeyan, Ben Bowyer and R. J. Roberts, 1965, "Geology and Mineral Deposits of Clark County, Nevada", Bureau of Mines, Bulletin 62.

Malmberg, G. T., 1961, "A Summary of the Hydrology of the Las Vegas Groundwater Basin, Nevada, with Special Reference to the Available Supply", Nevada Department of Conservation and Natural Resources, Water Resources Bulletin No. 18.

Malmberg, G. T., 1963, Land Subsidence in Las Vegas Valley, Nevada, 1935-63: Nevada Department of Conservation and Natural Resources, Water Resources Information Series Report 5, 10 p.

Malmberg, G. T., 1965, Available water supply of the Las Vegas groundwater basin, Nevada: U.S. Geol. Survey Water Supply Paper 1780, 110 p.

Maxey, G. B. and C. H. Jameson, 1948, "Geology and Water Resources of Las Vegas, Pahrump and Indian Springs Valley, Clark and Nye Counties, Nevada", State of Nevada, Office of the State Engineer, Water Resources Bulletin No. 5.

Mindling, A. L., 1965, "An Investigation of the Relationship of the Physical Properties of Fine-Grained Sediments to Land Subsidence in Las Vegas Valley, Nevada", University of Nevada, Master's Thesis.

Mindling, A. L., 1971, "A Summary of Data Relating to Land Subsidence in Las Vegas Valley", University of Nevada, Desert Research Institute, Center for Water Resources Research.

Montgomery Engineers of Nevada, 1971, "Water Supply for the Future of Southern Nevada", Water for Nevada, Special Planning Report, Nevada Division of Water Resources.

Nevada Testing Laboratories, Ltd., 1965, "Soils Investigation, Proposed Flamingo Reservoir, Clark County, Nevada", Report to Montgomery Engineers of Nevada.

Price, C. E., Jr., 1966, "Surficial Geology of the Las Vegas Quadrangle, Nevada", Master's Thesis, University of Utah.

United States Bureau of Reclamation, 1963, "Report on Southern Nevada Water Supply Project, Nevada", Project Development Report.

Wilbur-Clark and Associates, 1971, "Las Vegas Valley Transportation Study", Report to Las Vegas Valley Transportation Policy Committee.

Investigators:

Contacts:
Dr. M. D. Miflin, Desert Research Institute, Las Vegas, Nevada (702) 736-2293
James R. Harrill (see sources)
Barbara Salmon, Center for Water Resources Research,
Desert Research Institute
University of Nevada
Reno, Nevada 89507

(702) 673-4750

Subsidence Area: Saxet Oil Field
Country: United States
District or Province: Texas
Nearest City: Corpus Christi

Identification Number: 20

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Oil and Gas
Other: Fault Movement

Subsidence Characteristics:

Area of subsidence in km^2: 92 km^2
Maximum amount of subsidence in meters: .925 m
Average amount of subsidence in meters: .496 m
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Gas producing from 610-1143 m Lagarto Shale with sand lenses, no producing aquifer-saline water.

Land Uses:

Agriculture	(X)	Industrial	( )
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Fault movement related to subsidence.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	(X)
Pipelines	( )	Railroads	(X)
Houses	( )	Sewers	( )
Buildings	(X)	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

No Estimates

Adjustments to Subsidence: No Countermeasures

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	(X)		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

No Estimates

Source(s): Response to International Survey on Land Subsidence by Charles W. Kreitter, Research Scientist, Bureau of Economic Geology, University of Texas, Austin, Texas 78712.

Subsidence Area:	Saxet Oil Field
Country:	United States
District or Province:	Texas
Nearest City:	Corpus Christi

Publications:

Kreitler, C. W. and Gustavson, T. C., "Geothermal Resources of the Texas Gulf Coast - Environmental Concerns Arising from the Production of Geothermal Waters", 2nd Geopressure, Geothermal Conference, February 23-24, 1976, CES, University of Texas at Austin, (in press)-

Yerkes, R. F. and Castle, R. O., "Surface Deformation Associated with Oil and Gas Field Operations in the United States," Land Subsidence, Publication No. 88, AIHS-UNESCO (no date of issue) I, 55.

Investigators:

Subsidence Area: Chocolate Bayou Oil Field
Country: United States
District or Province: Brazoria County, Texas
Nearest City: Houston
Identification No. 21

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Oil and gas; some water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 40.5 km^2
Maximum amount of subsidence in meters: .53 m
Average amount of subsidence in meters: .31 m
Maximum subsidence rate in cm/yr.: 3.7 cm/yr Year: 1959-1963

Geologic Setting:

Production from 2438-3962 in Frio Formation oil: normally pressured;
gas: geopressured

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing ( )
Other ( )
Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

None reported.

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (X)

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies ( )
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )
Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

Source(s):

Response to International Survey on Land Subsidence, Charles W. Kreitler, Research Scientist, Bureau of Economic Geology, University of Texas, University Station, Box X, Austin, Texas 78712

Subsidence Area:	Chocolate Bayou Oil Field
Country:	United States
District or Province:	Brazoria County, Texas
Nearest City:	Houston

Publications:

Kreitler, C. W., "Lineations and Faulting in Texas Coastal Zone", Report of Investigations No. 85, Bureau of Economic Geology, University of Texas at Austin, (in press).

Kreitler, C. W., and Gustavson, T. C., "Geothermal Resources of the Texas Gulf Coast -- Environmental Concerns Arising from the Production of Geothermal Waters", 2nd Geopressure, Geothermal Conference, February 23-24, 1976, CES, University of Texas at Austin (in press).

Investigators:

Subsidence Area: Houston - Galveston
Country: United States
District or Province: Texas
Nearest City: Houston & Galveston
Identification Number: 23
(including Goose Creek, I.D. No. 22)

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water, Oil and Gas
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 12,173 km^2
Maximum amount of subsidence in meters: 2.75 m^2
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting: Fluviatile and shallow marine, Late Cenozoic; Unconsolidated Holocene, Pleistocene and Pliocene sands and clays.

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	(X)
Other	( )	Mining	(X)

Surface Environmental Effects: Areas of extension & compression, ground rupture due to faulting. Coastal areas permanently inundated, aggravated flood hazard.

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	(x)	Roads	(X)
Pipelines	(X)	Railroads	(X)
Houses	(X)	Sewers	(X)
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	(X)
Aqueducts	( )		

Property inundated, and subject to flooding at high tide

Cost Estimate of Damage:

Estimates of total subsidence costs from $275 million to over $1 billion from 1943 to 1975

Adjustments to Subsidence:

Scientific studies	(x)	Abandonment	(X)
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	(X)
Road repair	(X)		
Pipeline repair	( )	Develop alt. resource	(X)
Building repair	( )		
Land Filling	(X)	Law suits	(X)
Develop institutional framework	(X)		

Cost Estimate of Adjustments:

Source(s):

Response to International Survey on Land Subsidence Robert K. Gabrysch, Hydrologist (Engineer) U. S. Geological Survey, 2320 La Branch Street, Houston, Texas 77004

Subsidence Area: Houston-Galveston
Country: United States
District or Province: Texas
Nearest City: Houston-Galveston

Publications:

Brown, L. F. Jr.et al. 1974, Natural Hazards of the Texas Coastal Zone, Texas Bureau of Economic Geology, University of Texas Austin

Carothers, H. P., and Lockwood, M. G., 1964, Discussion of "Land Subsidence Problems", Journal of the Surveying and Mapping Division, ASCE, No. SU 1, pp. 75-78.

Dawson, R. F., 1963. "Land Subsidence Problems", Journal of the Surveying and Mapping Division, ASCE, No. SU 2, pp. 1-12.

Gabrygch, R. K., 1969, Land-surface subsidence in the Houston-Galveston region, Texas: International symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 43-54.

Gabrysch, R. K., 1977 "Land-surface Subsidence in the Houston-Galveston Region, Texas" in proceedings of the Second Symposium on Land Subsidence, December 10-17, 1976 Anaheim, CA International Association of Hydrological Sciences,publication No. 121.

Gabrysch, R. K., and Bonnet, C. W., 1974, Land-surface subsidence in the area of Burnett, Scott, and Crystal Bays near Baytown, Texas: U.S. Geol. Survey Water Resources Inv. 21-74, 48 p.

1974a, Land-surface subsidence in the Houston-Galveston region, Texas: Texas Water Development Board Report 188, 19 p.

1975b, Land-surface subsidence at Seabrook, Texas, U.S. Geol. Survey Water Resources Inv. 75-413

1975c, Land-surface subsidence in the area of Moses Lake near Texas City, Texas, U.S. Geol. Survey Water Resources Inv. 75-424.

Gray, E. V., 1958. "The Geology, Ground Water, and Surface Subsidence of the Baytown-LaPorte Area, Harris County, Texas", unpublished thesis, Dept. of Geology, Texas A&M Univ., Bryan

Groat, Charles G., 1973, Holocene Faulting and Subsidence in the Texas Coastal Zone ABSTR., Geol, Soc. Am., ABSTR., Vol. 5, No. 7, p. 645

Gustavson, T.C./Kreiiler, C. W., 1976, Geothermal Resources of the Texas Gulf Coast: Environmental Concerns Arising from the production and disposal of Geothermal Waters, Geological Circular 76-71, Texas Univ., Autstin (U.S.A.), Bureau of Economic Geology, Univ. of Texas, Bureau of Economic Geology, Austin.

Herrin, E., Goforth. T., 1975, Environmental problems associated with power production from geopressured reservoirs with discussion, in proceedings: First Geopressured Geothermal Energy Conference, p. 311-320, University of Texas, at Austin, Austin,Texas, United States.

Jones, Lonnie L., James Larson, 1975, Economic Effects of Land Subsidence due to Excessive Ground-water Withdrawal in the Texas Gulf Coast Area, Texas Water Resources Institute, Texas A&M University Techinical Report #67

Jones, L. L., Warfen, J. P., Land Subsidence Costs in the Houston-Baytown Area of Texas, (Texas Agricultural and Mechanical University, College Station (USA). Dept. of Agriculturol Economics J. AM. Water Works Assoc., V. 68 (11), p. 597-599 (1976)

Jones, Lonnie L. 1977 "Economic Effects of Land Subsidence Due to Excessive Groundwater Withdrawal in the Texas Gulf Coast Area", in proceedings of Second Symposium on Land Subsidence December 10-17, 1976 Anaheim, CA. International Association of Hydrological Sciences. Publication No. 121.

Kreitler, C. W., 1977 "Fault Control of Land Subsidence, Houston-Galveston, Texas" in proceedings of the Second Symposium on Land Subsidence. December 10-17, 1976 Anaheim, CA. International Association of Hydrological Sciences. Publication No. 121.

Lockwood, Mason G., 1954. "Ground Subsides in Houston Area". Civil Engineering, Vol. 24, pp. 370-372.

McClelland Engineers, 1962, Study of probable subsidence, Manned Spacecraft Center, Clear Lake, Texas, in a study of land-surface subsidence conditions at the National Administrative Space Association site in the vicinity of Houston, Texas: Layne Texas Co., Inc.

McClelland Engineers, Inc., 1966, Land-surface subsidence and surface faulting, Appendix C in Comprehensive study of Houston's Municipal Water System, Phase 1, Basic Studies: Turner, Collie and Braden, Inc.

Subsidence Area: Houston-Galveston
Country: United States
District or Province: Texas
Nearest City: Houston-Galveston

Publications:

Morse, Everett D., 1964, Discussion of "Land Subsidence Problems", Journal of the Surveying and Mapping Division, ASCE, No. SU 1, pp. 73-75.

Pratt, W. E., and Johnson, D. W., 1926, Local subsidence of the Goose Creek Oil Field: The Journal of Geology, V. XXXIV, no. 7, pt. 1, p. 577-590.

Rose, N. A., 1949. "Subsidence in the Texas City Area:, text of oral presentation Annual Meeting, Society of Economic Geology.

Sheets, Martin M., and Weaver, Paul, 1962, "Faulting on Surface and Progressive Subsidence in the Texas Gulf Coast in Vicinity of Fluid Withdrawals through Wells", text of oral presentation, Annual Meeting of Geological Society of America and Associated Societies, Houston, Texas.

Spencer, Glenn W. "The Flight to keep Houston from Sinking", Civil Engineering ASCE Sept. 1977 pp. 69-71. Describes history of subsidence in Houston-Galveston area. Discusses consequences including abandonment of subdivision land fill to keep back tides, flood risk, rebuilt dock structures. Class action suit $25 million filed in 1973. Texas A&M Studies. (Warren & Jones) cites annual losses of $30 million/yr. ASCE chapter active in public information and legislature formed Harris Galveston Coastal, Subsidence District. New Surface Water Supplies available to industry.

Steelhammer, R. H., Garland, J. G., 1970 , Subsidence Resulting from the Removal of Groundwaters, South Texas Law Journal 12: 201-213 SWRA W71-07209

Warren, John P., L. L. Jones., W. L. Griffin, R. D. Lacewell, July 1974, Costs of Land Subsidence due to Groundwater Withdrawal. Texas Water Resources Institute, Texas A&M University. Technical Report #57.

Weaver,Paul, 1963. Discussion of "Land Subsidence Problems", Journal of the Surveying and Mapping Division, ASCE, No. SU 3, pp. 218-223.

Weaver, Paul, and Sheets, Martin M., 1962. "Active Faults, Subsidence and Foundation Problems in the Houston, Texas Area", Geology of the Gulf Coast and Central Texas, Houston Geological Society, pp. 254-265.

Winslow, A. G., and Doyel, W. W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: Econ. Geol. v. 49, no. 4, p. 413-422.

Winslow, A. G., and Wood, L. A., 1959, Relation of Land subsidence to ground-water withdrawals in the upper Gulf Coast Region, Texas: Mining Engin., Oct., p.1030-1034; Am. Inst. Mining, Metall., Petroleum Engin., Trans. v. 214.

Wolfskill, L. A., 1960, The consolidation characteristics of undisturbed soil samples of deep formations and their application to problems of regional subsidence: Master of Science Thesis, Texas A&M University, College Station, 70 p.

Yerkes, R. F.; Castle, R. O. (Dec. 1976) Seismicity and Faulting attributable to fluid extraction, (US Geol. Surv.Menlo Park, California), Eng. Geol. (Amsterdam); 10, no. 2-4, 151-167

Investigators: Dr. Lonnie Jones, Department of Agricultural Economics, Texas A&M University College Station, Texas

Subsidence Area: Milford
Country: United States
District or Province: Utah
Nearest City: Milford
Identification Number: 24

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: Unknown. Obtained reference only.
Maximum amount of subsidence in meters:
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Land Uses: Unknown. See Reference.

Agriculture	( )	Industrial	( )
Irrigated agriculture	( )	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Unknown. See Reference.

Economic Effects: Unknown.

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To: Unknown.

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

Unknown.

Adjustments to Subsidence: Unknown.

Scientific studies	( )	Abandonment	( )
Relevelling studies	( )	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

Unknown.

Source(s): Cordova, R. M. and Mower, R. W., Geological Survey, Salt Lake City, 1975, "Fracturing and Subsidence of the Land Surface Caused by the Withdrawal of Ground Water in the Milford Area, Utah," Geological Society of America Annual Meetings, Salt Lake City, Utah, October 20, 1975. New York: Geological Society of America.

Subsidence Area: Yallourn - Morwell
Country: Australia
District or Province: Victoria - Gippsland
Nearest City: Morwell
Identification Number: 25

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water. Dewatering associated with coal mining.
Other: Coal mining

Subsidence Characteristics:

Area of subsidence in km^2: 102 km^2
Maximum amount of subsidence in meters: 1.6 m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 3.8 cm/year Year: 1970

Geologic Setting:

Aquifers of sands and aquichioles of clay separate and underlie thick brown coal seams.

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	(X)

Surface Environmental Effects:

Minor change in stream gradients, large vertical and horizontal movements.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	(X)	Railroads	( )
Houses	( )	Sewers	(X)
Buildings	(X)	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		
Water Mains			

Cost Estimate of Damage:

"Very Small"

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	(X)		

Restrictions of Buiding Types within Zone of Critical Movement.

Cost Estimate of Adjustments:

None

Source(s): Response to International Survey on Land Subsidence by C. S. Gloe, Geologist-in-Charge, State Electricity Commission of Victoria, 15 Williams Street, Welbourne, Victoria. 3000.

Subsidence Area: Yallourn - Morwell
Country: Australia
District or Province: Victoria-Gippsland
Nearest City: Morwell

Publications:

Gloe, C. S., James, J. P. and McKenzie, R. J., 1973, "Earth Movements Resulting from Brown Coal Open Cut Mining", Latrobe Valley, Victoria Fourth Annual Symposium, Illawarra Branch, Australian Institute of Mining Met., 8, pp. 1-9.

Gloe, C. S., 1977, "Land Subsidence Related to Brown Coal Open Cut Operations Latrobe Valley, Victoria, Australia, in Land Subsidence, Proceedings of the Second Symposium on Land Subsidence, Anaheim, California, December 1976. Ann Arbor, Michigan: International Association of Hydrological Sciences, pp. 399-407.

Investigators:

Gloe, C. S. (See Sources)

Subsidence Area: Taipei
Country: Republic of China
District or Province: Taiwan
Nearest City: Taipei
Identification Number: 26

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Hydrocompaction

Subsidence Characteristics:

Area of subsidence in km^2: 235 km^2
Maximum amount of subsidence in meters: 1.9 m
Average amount of subsidence in meters: 1-1.7 m
Maximum subsidence rate in cm/yr.: 14 cm/year Year: 1975

Geologic Setting:

Alluvial, Late Cenozoic,Gravel, Sand and Clay. 35-50 m deep.

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )	Floodwalls	X
Paddy Fields Frequently Flooded			X

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework as of 1968, Strict Control of Groundwater Extraction.	(X)		

Cost Estimate of Adjustments:

Source(s): Response to International Survey on Land Subsidence by Tieh-Liang Hsu, Senior Geologist, Geological Survey of Taiwan, P. O. Box 1001, Taichung, Taiwan, 400 Republic of China, February 18, 1976.

Subsidence Area: Taipei
Country: Republic of China
District or Province: Taiwan
Nearest City: Taipei

Publications:

Hwang, Jui-Ming and Wu, Chiang-Min, 1969, "Land Subsidence Problems in Taipei Basin", in: Proceedings of the Tokyo Symposium on Land Subsidence, Vol, 1, International Association of Scientific Hydrology and UNESCO, September 1969, Tokyo, pp. 21-34.

Wu, Chian-Min, 1977, "Groundwater Depletion and Land Subsidence in Taipei Basin," in Land Subsidence, Proceedings of the Second Symposium on Land Subsidence, Anaheim, California, December 1976. Ann Arbor, Michigan: International Association of Hydrological Sciences, pp. 389-398.

Investigators:

Subsidence Area: Komárno
Country: Czechoslovakia
District or Province: West Slovakia
Nearest City: Komárno
Identification Number: 27

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal:
Other: Tectonic Deformation

Subsidence Characteristics:

Area of subsidence in km^2: 50-100 km^2
Maximum amount of subsidence in meters: .01 m
Average amount of subsidence in meters: .006 m
Maximum subsidence rate in cm/yr.: 0.2 to 0.3 Year: 1957-1963

Geologic Setting:

Quaternary Period: Silts and Sandy Gravels
Tertiary Period: Silts, Sands, Clays

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing ( )
Other ( )
Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

None Reported

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (X)

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Not Estimated

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )
Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

Not Estimated

Source(s): Response to International Survey on Land Subsidence by A. Dvořák, Ing.Dr.Csc., Stavební Geologic n.p., Gorkého nám. 7, 110 00 Praha 1, ČSSR, February 1976.

Subsidence Area: London
Country: England
District or Province:
Nearest City: London
Identification Number: 28

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 450 km^2
Maximum amount of subsidence in meters: .35 m
Average amount of subsidence in meters: .06 m
Maximum subsidence rate in cm/yr.: Not Known Year: ____ Average Subsidence Rate 0.5 cm/yr.

Geologic Setting:

Eocene	(London Clay	20-80 m (clay)
	(Lower London Tertiaries	10-20 m (sands, loams, clays)
U^r Cretaceous Chalk		180=250 m (limestone)

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (X)
Business & residential (X)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Economic Effects: Not Significant

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (x) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

Source(s): Response to International Survey on Land Subsidence by R. A. Downing, Central Water Planning Unit, Reading Bridge House, Reading RGI 8PS England, January 2, 1976.

Subsidence Area:	London
Country:	England
District or Province:	
Nearest City:	London

Publications:

Longfield, T. E., 1932. "The Subsidence of London", Ordnance Surfey Professional Paper, New Series, No. 14.

Wilson, G. and Grace, H., 1942. "The Settlement of London Due to Underdrainage of the London Clay", J. Instn. Civ. Engrs. 19, 100-27.

Water Resources Board, 1972. The Hydrogeology of the London Basin, Water Resources Board, Reading, 139 pp.

Investigators:

Subsidence Area: Debrecen
Country: Hungary
District or Province: Hajdu-Bihar
Nearest City: Debrecen
Identification Number: 29

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Hydrocompaction

Subsidence Characteristics:

Area of subsidence in km^2: 392 km^2
Maximum amount of subsidence in meters: .42 m
Average amount of subsidence in meters: .13 m
Maximum subsidence rate in cm/yr.: .36 cm/year Year: 1975

Geologic Setting:

Pleistocene Sands, Clay, Mud

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

None Known

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (X) None Reported ( )

Damage Has Been To: None Known

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

None Given

Adjustments to Subsidence: None

Scientific studies	(x)	Abandonment	( )
Relevelling studies	(x)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )		

Cost Estimate of Adjustments:

None Given

Source(s): Response to International Survey on Land Subsidence by Árpád Lorberer, Scientific Assistant, Research Institute for Water Resources Development, Vituki Rákóczi, at 41 Budapest, VIII H-1424 Hungary, December 18, 1975.

Publications: Several technical papers; none on economic effects.

Subsidence Area: Visonta by Gyöngyös
Country: Hungary
District or Province: Prov: Heves
Dist: Gyöngyös
Nearest City: Visonta by Gyöngyös
Identification Number: 30

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Hydrocompaction

Subsidence Characteristics:

Area of subsidence in km^2: 40 km
Maximum amount of subsidence in meters: .5065 m
Average amount of subsidence in meters: .2946 m
Maximum subsidence rate in cm/yr.: 10 cm/year Year: 1967-1968

Geologic Setting:

Quaternary Sands, Clays, Lignite; Micene Volcanic Rocks

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing ( )
Other ( )
Industrial (X)
Business & residential (X)
Well fields ( )
Water-related shipping ( )
Mining (X)
Coal Mining

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

No Estimates Given

Adjustments to Subsidence: None

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )
Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

No Estimates Given

Source(s): Response to International Survey on Land Subsidence by Árpád Lorbeper, Scientific Assistant, Research Institute for Water Resources Development, Vituki Rákóczi at 41 Budapest, VIII H-1428, Hungary, December 18, 1975.

Subsidence Area: Visonta by Gyöngyös
Country: Hungary
District or Province: Prov: Heves
Dist: Gyöngyös
Nearest City: Visonta by Gyöngyös

Publications:

Kesserü, Zsolt, 1970, "Land Subsidence Due to the Effects of Sinking the Groundwater Table, Conference of Mine- drainage Networks, Hungarian Academy of Sciences, Budapest, 1970, I.a/Vol. No. 3.

Kesserü, Zsolt, 1972, "Forecasting Potential Building Damages Due to the Effect of Sinking the Underground Water Table", II. International Conference of Mining Geodesy, Budapest, Vol. V.

Investigators:

Subsidence Area: Po Delta
Country: Italy
District or Province:
Nearest City:
Identification No. 33

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Gas, methane in saline groundwater.
Other:

Subsidence Characteristics:

Area of subsidence in km^2:
Maximum amount of subsidence in meters:
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 30 cm/yr Year: After 1950.

Geologic Setting:

Quaternary alluvium.

Land Uses: Not reported

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:
Flooding and damage has led to construction and repair of levees, reclamation of land.

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported (x) Not Estimated

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:
No estimate made.

Adjustments to Subsidence:

Scientific studies ( )
Relevelling studies ( )
Dike const. & repair (x)
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling (x)
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

May have terminated production

Cost Estimate of Adjustments:
No estimate made.

Source(s):
Poland, J. F., and G. H. Davis, 1969, "Land Subsidence Due to Withdrawal of Fluids", Reviews in Engineering Geology, Volume 2, D. L. Varnes and G. Kiersch, eds., Geological Society of America.

Subsidence Area: Po Delta
Country: Italy
District or Province:
Nearest City:

Publications:

Poland and Davis, 1969 (see sources).

Comments: Experience since the early 1960's is unknown at this time. In 1960, the Italians were contemplating terminating pumping for methane to halt subsidence, but they faced a trade-off between the cost of remedial measures and the value of gas produced.

Investigators:

Joseph F. Poland, U.S. Geological Survey, Room W-2528, Federal Building,
Professor Francisco Penta, University of Rome
2800 Cottage Way
Sacramento, California 95825

Contacts: *Al Freeze, University of British Columbia*
G. Gambolati

Subsidence Area: Venice
Country: Italy
District or Province: Veneto
Nearest City: Venice
Identification Number: 34

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 400 km^2
Maximum amount of subsidence in meters: .14 m
Average amount of subsidence in meters: .10 m
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Sand, Silt and Clay

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Increased flooding of Venice (Storm surge effects), even for small high water levels.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	(X)	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Historical Monuments

Cost Estimate of Damage:

No estimate given

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	(X)
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	(X)
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	Construct industrial aqueduct.	
		Sluice construction	

Cost Estimate of Adjustments:

200.000.000 = $

Source(s): Response to International Survey on Land Subsidence Laura Carbonin, Paolo Gatto & Guiseppe Mozzi, Researchers Lab. Studio Dinamica Grandi Masse - CNR, S. Polo 1364 Venezia, 30125 Italy

Subsidence Area: Venice
Country: Italy
District or Province: Veneto
Nearest City: Venice

Publications:

Carbognin, L., P. Gatto, G. Mozzi, G. Gambolati, G. Ricceri, 1977. New Trend in the Subsidence of Venice, in Proceedings of Second Symposium on Land Subsidence December 10-17 1976 Anaheim, CA. International Association of Hydrological Sciences Publication No. 121

Carbognin L., Gatto P. and Mozzi G., 1972, Situazione Idro geologica nel Sottosuolo di Venezia - Ricostruzione degli acquiferi soggetti a struttamento sulla base dei dati relativi ai pozzi artesiani. Tech. Rep. 32, Cons. Naz. delle Ric. Lab. per lo S. della D. della G. M., Venezia.

Gambolati G. and Freeze R. A., 1973, Mathematical Simulation of the Subsidence of Venice I. Theory: Water Resources Research, v. 9, n. 3, p. 721-733.

Gambolati G., Gatto P. and Freeze R. A., 1974, Mathematical Simulation of the Subsidence of Venice 2. Results: Water Resources Research, v. 10, n. 3 p. 563-577.

Gambolati G., Gatto P. and Freeze R. A., 1974, Predictive Simulation of the Subsidence of Venice: Science, v. 183, p. 849-851.

Ricceri G. and Butterfield R., 1974, An analysis of the compressibility data from a deep borehole in Venice: Geoltechnique v. 24, n. 2, p. 175-192.

Investigators:

Contacts: Al Freeze, University of British Columbia
G. Gambolati

Subsidence Area: Aomori Plain
Country: Japan
District or Province: Aomori Prefecture
Nearest City: Aomori City
Identification Number: 35

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 40 km^2
Maximum amount of subsidence in meters: .42 m (1958-1975)
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 8.2 cm/year Year: 1973

Geologic Setting:

Alluvium: Silt and Clay Layers ± 35 m
Diluvium: Gravel and Clay Layers ± 100 m
Neogens Tertiary: Sandstone and Siltstone ± 200 m

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Inundation at high tide, drainage problems, intrusion of salt water.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	(X)
Pipelines	( )	Railroads	( )
Houses	(X)	Sewers	( )
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )	Bridges	X

Cost Estimate of Damage:

Unknown in Detail.

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	(X)	Establish Permit System for Withdrawal of Groundwater.	

Cost Estimate of Adjustments: Improvement of Breakwaters and Piers.

$US 5.3 million (1969-1977).

Source(s): Response to International Survey on Land Subsidence by Water Quality Bureau, Environment Agency EA:3-1-1 and River Bureau, Ministry of Construction. MOC:2-1-3. Kasumigaseki, Chiyoda-ku, Tokyo 100, Japan.

Subsidence Area:	Aomori Plain
Country:	Japan
District or Province:	Aomori Prefecture
Nearest City:	Aomori City

Publications:

Environment and Health Department, Aomori Prefectural Government, March 1973, Report on Analysis of Water Balance in Aomori Region (in Japanese).

Sendai Industry Office, 1973, Investigation Report on Proper Usage of Ground Water Around Aomori City (in Japanese).

Investigators:

Subsidence Area: Sendai Plain
Country: Japan
District or Province: Miyagi
Nearest City: Sendai City
Identification Number: 36

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Dewatering Organic Soils

Subsidence Characteristics:

Area of subsidence in km^2: 30 km^2
Maximum amount of subsidence in meters: .5 m 1966-1975
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 20 cm/year Year: 1973

Geologic Setting:

Alluvium: Upper 5 m mainly peat, lower 30 m sand and clay layers
Diluvium: Mainly gravel layer, ± 30 m
Neogene Tertiary: Tuff and sandstaone, ± 100 m

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (X)
Business & residential (X)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Drainage Problems

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines (X)
Houses (X)
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads (X)
Railroads (X)
Sewers ( )
Drains (X)
Dams ( )
Levees ( )

Cost Estimate of Damage:

$US 3.77 million (1971-1974)

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework (X)

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource (X)
Law suits ( )
Regulation to Withdrawal of Groundwater

Cost Estimate of Adjustments:

Unknown

Source(s): Response to International Survey on Land Subsidence by Water Quality Bureau, Environment Agency and River Bureau, Ministry of Construction.

Subsidence Area:	Sendai Plain
Country:	Japan
District or Province:	Miyagi
Nearest City:	Sendai City

Publications:

Sendai Industry Office, 1975, Investigation Report on Proper Usage of Groundwater in Sendai and Natori (in Japanese).

Environment Countermeasure Council, Sendai City, October 1975, Report on Cause of Subsidence and its Countermeasure in East Region of Nigatake, Sendai City (in Japanese).

Investigators:

Subsidence Area: Haranomachi City
Country: Japan
District or Province: Fukushima Prefecture
Nearest City: Haranomachi
Identification Number: 37

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 25 km^2
Maximum amount of subsidence in meters: 2 m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 20 cm/year Year: 1972

Geologic Setting: Alluvium: Peat and clay layer, 30m± thick
Neogene Tertiary: Mudstone, sandstone

Land Uses:

Agriculture	(X)	Industrial	( )
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:
Change of paddy fields to ponds and swamps

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	(X)
Pipelines	(X)	Railroads	( )
Houses	( )	Sewers	( )
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	(X)	Levees	( )
Aqueducts	( )		
Floodwalls			

Cost Estimate of Damage:

$ US 230,000

Adjustments to Subsidence:

Scientific studies	( )	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	(X)
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	(X)	Ordinance regulating groundwater withdrawal	(X)
		Construction of Multi-purpose dams & Water supply systems	(X)

Cost Estimate of Adjustments:

None Given

Source(s):

Response to International Survey on Land Subsidence by Water Quality Bureau, Environment Agency and River Bureau, Ministry of Construction, Kasumigaseki, Chiyoda-ku, Tokyo. 30 January 1976

Subsidence Area:	Niigata Fields
Country:	Japan
District or Province:	Niigata Prefecture
Nearest City:	Niigata City
Identification Number:	38

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water, Gas

Other:

Subsidence Characteristics:

Area of subsidence in km^2: 430 km^2

Maximum amount of subsidence in meters: 2.6m (1955-1974)

Average amount of subsidence in meters:

Maximum subsidence rate in cm/yr.: %$ CM/Year Year: 1959-1960

Geologic Setting:
Alluvium: Sand and Gravel
Diluvium: Clay, silt, sandy gravel
Tertiary: Clay, silt, sandy gravel

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects: Ground subsidence of areas below high tide level (200 km^2)
Risk of inundation

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	(X)	Railroads	( )
Houses	(X)	Sewers	( )
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	(X)
Aqueducts	( )		

Cost Estimate of Damage:

Unknown in Detail

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	(X)
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	Pumping stations behind dikes	(X)

Cost Estimate of Adjustments:

$ US 12 Million (1957-1974)

Source(s):

Response to International Survey on Land Subsidence by the Water Quality Bureau, Environment Agency and River Basin Bureau, Ministry of Construction, Kasumigaseki, Chiyoda-ku, Tokyo. 30 January 1976

Subsidence Area:	Niigata Fields
Country:	Japan
District or Province:	Niigata Prefecture
Nearest City:	Niigata City

Publications:

Poland, J. F. and Davis, G. H., 1969, "Land Subsidence Due to Withdrawal of Fluids," reviews in Engineering Geology, Volume II, D. L. Varnes and G. Kiersch, eds., Geological Society of America, Boulder, Colorado.

Niigata Prefectural Government, 1961, Report on present status of subsidence in Niigata (in Japanese).

Investigation Committee of Subsidence in Niigata, 1958, 1962, 1963, Subsidence in Niigata No. 1, 2, 3 (in Japanese).

Industry Promotion Section, Niigata Prefecture, 1965, Subsidence in and around Niigata (in Japanese).

Shnano River Agricultural Water Usage Investigation Office, Hokuriku Agricultural Water Usage Investigation Office, Hokuriku Agricultural Administration Bureau, Ministry of Agriculture, 1971, Subsidence in the Niigata Plain (in Japanese).

Niigata Prefectural Government, 1971-1975, Subsidence in the Niigata Plain (in Japanese).

Geographical Survey Institute, Ministry of Construction, 1959-1975, Report on surveying and investigation of ground level changes in Niigata No. 1-27 (in Japanese).

Investigators:

Subsidence Area: Nanao Basin
Country: Japan
District or Province: Ishikawa Prefecture
Nearest City: Nanao City
Identification Number: 39

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 15 km^2
Maximum amount of subsidence in meters: .27 m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 8.3cm/year Year: 1970

Geologic Setting:
Alluvium: Mainly silt, clay layer 20m±
Diluvium: Alternation of sandy gravel and clay layer 60m±
Tertiary: Alternation of mudstone and sandstone 200m±

Land Uses:

Agriculture ( )
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (X)
Business & residential (X)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects: Risk of flood and storm surge, inundation of buildings and other structures.

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported ( ) Not Estimated (X)

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Unknown in Details

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair (X)
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework (X)

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )
Regulation of withdrawal of Groundwater (X)

Cost Estimate of Adjustments:

$ US 1.2 Million (1970-1974)

Source(s):

Response to International Survey on Land Subsidence by the Water Quality Bureau, Environment Agency and River Basin Bureau, Ministry of Construction Kasumigaseki, Chiyoda-ku, Tokyo. 30 January 1976

Subsidence Area:	Nanao Basin
Country:	Japan
District or Province:	Ishikawa Prefecture
Nearest City:	Nanao City

Publications:

Committee on Countermeasures of Subsidence around the Nanao Port, Ishikawa Prefecture, 1971-1974, Investigation Report on Subsidence around the Nanao Port (in Japanese).

Investigators:

Subsidence Area: Tokyo
Country: Japan
District or Province: Tokyo, Saitama, Chiba, Kanagawa Prefectures
Nearest City: Tokyo City
Identification Number: 40

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water, Gas
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 2420 km^2
Maximum amount of subsidence in meters: 4.6 m (1919-1974)
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 27 cm/year Year: 1973-1974

Geologic Setting:
Alluvrium: Clay, 40 m ±
Dilluvium: Alternation of Clay, sand, sandy gravel, 350 m±
Neogene Tertiary Alternation of Clay, silt and gravel layer, 2000 m±

Land Uses:

Agriculture	(x)	Industrial	(x)
Irrigated agriculture	( )	Business & residential	(x)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects: 150 km^2 have subsided below high tide

Economic Effects:

Damage has been: Severe (x) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	(x)	Railroads	(x)
Houses	(x)	Sewers	(x)
Buildings	(x)	Drains	(x)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	(x)
Aqueducts	( )		

Cost Estimate of Damage:

$ US 21 Million was expended in Koto, Edogwa, and Sumida wards of Tokyo between 1957 and 1970

Adjustments to Subsidence:

Scientific studies	(x)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	(x)
Road repair	( )		
Pipeline repair	(X)	Develop alt. resource	(X)
Building repair	(X)		
Land Filling	( )	Law suits	( )
Develop institutional framework	(X)	Pumping Stations	(X)
		Regulations of groundwater and natural gas withdrawal	(X)

Cost Estimate of Adjustments:

$ US 225 Million was expended in Koto, Edogama and Sumida wards in Tokyo between 1957 and 1970.

Source(s):

Response to International Survey on Land Subsidence by the Water Quality Bureau, Environment Agency and River Basin Bureau, Ministry of Construction, Kasumigaschi, Chiyoda-ku, Tokyo, 30 January 1976.

Subsidence Area: Tokyo
Country: Japan
District or Province:
Nearest City: Tokyo City

Publications:

Investigation Group of Subsidence in South Kanto, 1974, Bulletin on Subsidence in South Kanto R551 (in Japanese).

Civil Engineering Research Institute, Tokyo Metropolitan Government (TMG), 1950-1975, Bulletin on Subsidence (in Japanese).

Environment Department and Environment Research Institute, Chiba Prefectural Government, 1964-1975, Subsidence in Chiba Prefecture (in Japanese).

Miyamoto Takashi, 1975, "Estimates of Economic Losses Caused by Environmental Pollution," Annual Report of the Tokyo Metropolitan Research Institute for Environmental Protection, pp. 45-85 (in English).

Tokyo Metropolitan Government, 1977, Tokyo Fights Pollution. (in English)

Investigators:

Miyamoto Takashi

Subsidence Area: Nobi Plain
Country: Japan
District or Province: Aichi, Cifu, Mie Prefecture
Nearest City: Nagoya City
Identification Number: 41

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 800 km^2
Maximum amount of subsidence in meters: 1.5 m (1961-1974)
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 23 cm/year Year: 1972-1973

Geologic Setting:

Alluvium: Clay 40 m ±
Diluvium: Alternation of gravel, sand and clay 300 m ±

Land Uses:

Agriculture (x)
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (x)
Business & residential (x)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

480 km^2 has now subsided below high tide level.

Economic Effects:

Damage has been: Severe (x) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees (X)

Cost Estimate of Damage:

Unknown in detail

Adjustments to Subsidence:

Scientific studies (x)
Relevelling studies (x)
Dike const. & repair (X)
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework (X)

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource (X)
Law suits ( )
Pumping Facilities (X)
Control ground water pumping (X)

Cost Estimate of Adjustments:

$ US 8 Million (in Aichi Prefecture only).

Source(s):

Response to International Survey on Land Subsidence by the Water Quality Bureau, Environment Agency and River Basin Bureau, Ministry of Construction, Kasuniipasaki, Chiyoda-Ku, Tokyo. 30 January, 1976

Subsidence Area:	Nobi Plain
Country:	Japan
District or Province:	Aichi, Cifu, Mie
Nearest City:	Nagoya City

Publications:

Environment Department and Research Group of Subsidence, Aichi Prefectural Government, 1975, Report on Research and Investigation on the Actual Condition of Subsidence and its Countermeasure, p354 (in Japanese).

Geographical Survey Institute and Chubu Regional Construction Bureau, Ministry of Construction, 1973-1975, Investigation on the Correlation between Subsidence and Regional Structure No. 1-3. (in Japanese).

Geographical Survey Institute, Ministry of Construction, 1959-1975, Report on surveying and investigation of ground level changes in Tokai-Regional No. 1-3 (in Japanese).

Investigators:

Subsidence Area:	Osaka
Country:	Japan
District or Province:	Osaka and Hyogo Prefecture
Nearest City:	Osaka City
Identification Number:	42

Subsidence Area Data Summary

Geothermal Subsidence Research Prograr
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water

Other:

Subsidence Characteristics:

Area of subsidence in km^2: 570 km^2

Maximum amount of subsidence in meters: 2.8 m (1934-1974)

Average amount of subsidence in meters:

Maximum subsidence rate in cm/yr.: 20 cm/year Year: 1961

Geologic Setting:

Alluvium: Mainly, clay, sand layer, 35 m+
Diluvium: Alternation of clay, sand, sandy gravel layer, 400 m±

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

100 km^2 now below high tide

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	(X)
Pipelines	(X)	Railroads	(X)
Houses	( )	Sewers	( )
Buildings	(X)	Drains	(X)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

Unknown in detail

Adjustments to Subsidence:

Scientific studies	(x)	Abandonment	( )
Relevelling studies	(x)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	(X)
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	Pumping Stations	(X)
		Surface Water Supply works	(X)
		Regulation of ground water withdrawal	(X)

Cost Estimate of Adjustments:

$ US 200 Million
between 1955 and 1974

Source(s):

Response to International Survey on Land Subsidence by Water Quality Bureau, Environment Agency and River Bureau, Ministry of Construction.
30 January, 1976

Subsidence Area:	Osaka
Country:	Japan
District or Province:	Osaka and Hyogo
Nearest City:	Osaka City

Publications:

Committee of Comprehensive Countermeasure for Subsidence in Osaka, 1966-1974, Outline of subsidence in Osaka (in Japanese).

Environment and Health Bureau, Osaka City, 1968-1974, Bulletin on the results of the levelling (in Japanese).

Investigators:

Subsidence Area: Saga Plain
Country: Japan
District or Province: Saga Prefecture
Nearest City: Saga City
Identification Number: 43

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 400 km^2
Maximum amount of subsidence in meters: 1.2 m
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 29cm/year Year: Average 1967-1970

Geologic Setting:

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial (X)
Business & residential (X)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Drainage Problems, intrusion of salt waters

Economic Effects:

Damage has been: Severe (X) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )
Canals & River Systems (x)

Cost Estimate of Damage:

Unknown in Detail

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair (X)
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework (X)

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource (X)
Law suits ( )
Regulation to ground water withdrawal (X)

Cost Estimate of Adjustments:

$US 523 Million (1960-1979)

Source(s):

Response to International Survey on Land Subsidence by Water Quality Bureau, Environment Agency and River Bureau, Ministry of Construction.

Subsidence Area:	Saga Plain
Country:	Japan
District or Province:	Saga Prefecture
Nearest City:	Saga City

Publications:

Geology News, Sep. 1967, Geological condition in the Saga Plain and Subsidence in Saga City (in Japanese).

Agriculture and Public Works Department, Saga Prefectural Government, 1966, Subsidence in the Shiraishi Plain (in Japanese).

Geographical Survey Institute, Ministry of Construction, 1974-1975, Report on surveying and investigation of ground level changes in Saga (in Japanese).

Investigators:

Subsidence Area: Mexico City
Country: Mexico
District or Province: Distrito Federal
Nearest City:
Identification Number: 45

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water
Other: Loading by Engineering structures on compressible clays.

Subsidence Characteristics:

Area of subsidence in km^2: 225 km^2
Maximum amount of subsidence in meters: 8.5 m
Average amount of subsidence in meters: -
Maximum subsidence rate in cm/yr.: 45 cm/yr. **Year:** 1951

Geologic Setting: Lacustrine deposits; water withdrawn from sand and gravel at 60-300 m depth.

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

differential subsidence, ground rupture

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	(x)	Roads	(x)
Pipelines	(x)	Railroads	(x)
Houses	( )	Sewers	(X)
Buildings	(x)	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	(x)		

Cost Estimate of Damage:

Roughly estimated at greater than $100 million

Adjustments to Subsidence:

Scientific studies	(x)	Abandonment	( )
Relevelling studies	(x)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource (water)	(X)
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	(x)	Limitations to groundwater withdrawal	

Cost Estimate of Adjustments:

Source(s): Response to International Survey on Land Subsidence. Ing. German E. Figueroa Vega, Director de Control de Acuiferos. Balderas No. 55, Mexico, D. F. Postal Zone 1 Mexico. January 29, 1975

Subsidence Area: Mexico City
Country: Mexico
District or Province: Distrito Federal
Nearest City:

Publications:

Chase, Arthur P., 1972, Precast Segmented Tunnel Lining for the Mexico City Subway, Geologic Conditions, Environmental Factors, Construction Methods in Two Tacubaya Tunnels. North AM. Rapid Excavation Tunneling Conf., Proc., Vol. 1, p. 439-467. Illus. (Incl. Sketch Map),

Figueroa Vega, German E. 1977, "Subsidence of the City of Mexico: A Historical Review" in proceedings of Second Symposium on Land Subsidence December 10-17, 1976 Anaheim, California. International Association of Hydrological Sciences. Publication No. 121

Ortiz, T. S., 1967, Subsidence in Mexico City in Relation to Groundwater Overdraft. In Hydrology of Fractured Rocks, Proceedings of the Dubovnik Symposium, October 1965, Vol. 2. International Association of Scientific Hydrology, Publication 74:665-671

Powers, Patrick, 1972, Groundwater Control in Tunnel Construction Use of Predrainage in Free Air and Compressed Air Tunnels to Lower Construction Costs, Recent examples. North AM. Rapid Excavation Tunneling Conf., Pro., Vol. 1. p. 331-369. Illus.,

Investigators:

Ing. German E. Figueroa Vega

Subsidence Area: Groningen Field
Country: Netherlands
District or Province: Groningen
Nearest City: Groningen
Identification Number: 46

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
EDAW·ESA - December, 1977

Cause of Subsidence:

Fluid Withdrawal: Water, Gas
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 1000 km^2
Maximum amount of subsidence in meters: 0.05 m
Average amount of subsidence in meters: 0.03 m
Maximum subsidence rate in cm/yr.: .02 cm/yr. Year:

Geologic Setting:

Gas extraction from Permian Sandstone at 2700-2900 m depth over an area of 900 km^2

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing ( )
Other ( )

Industrial ( )
Business & residential (x)
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

None Known

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (x) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Damage has not yet occurred

Cost Estimate of Damage:

None

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

None

Source(s):

Response to International Survey on Land Subsidence by J. B. Schoobeek, mining engineer c/o Nederlandse Aardolie Maatschappij B. V. (NAM) Schepersmaat 2, Assen, the Netherlands 12/2/76

Subsidence Area:	Gromingen Field
Country:	Netherlands
District or Province:	Groningen
Nearest City:	Groningen

Publications:

Schoonbeek, J. B. 1976 "Land Subsidence as a result of natural gas extraction in the province of Groningen", preprint Spring Meeting SPE, Amsterdam (in preparation).

Kesteren, J. van, 1973, "The analysis of future surface subsidence resulting from gas production in the Groningen field". Verhandelingen Kon. Ned. Geol. Mijnbouwk. Gen. Volume 28, p. 11.

Investigators:

Subsidence Area:	Wairakei
Country:	New Zealand
District or Province:	South Aukland
Nearest City:	Taupo
Identification No.	47

Subsidence Area Data Summary

Geothermal Subsidence Research Program
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Cause of Subsidence:

Fluid Withdrawal:	Geothermal brine and steam.
Other:	

Subsidence Characteristics:

Area of subsidence in km^2:	1.3 km^2
Maximum amount of subsidence in meters:	6-7 m
Average amount of subsidence in meters:	
Maximum subsidence rate in cm/yr.:	45 cm/yr Year: 1964-74

Geologic Setting:

Extraction between 250 and 800 meters below ground level from fractures in a porous pumice breccia formation and in underlying ignimbrite.

Land Uses:

Agriculture	(X)	Industrial	( )
Irrigated agriculture	( )	Business & residential	( )
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	(X)	Mining	( )

Forestry

Surface Environmental Effects:

Subsidence Bowl.

Economic Effects:

Damage has been: Severe ( ) Moderate (x) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	(x)	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	(x)
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Comprehensive tensile strain to steam mains (pipelines).

Cost Estimate of Damage:

Not known.

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	(x)	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	Construct sliding joint in concrete lined canal.	

Cost Estimate of Adjustments:

Not known.

Source(s):

Respondent to International Survey on Land Subsidence
W. B. Stillwell, Geothermal Projects Engineer
c/o Ministry of Works and Development, Wairakei, P.B. Taupo, New Zealand
August, 2, 1975

Subsidence Area: Wairakei
Country: New Zealand
District or Province: S. Aukland
Nearest City: Taupo

Publications:

Bowen, R. G., 1973, Environmental Impact of Geothermal Development. "Hot water fields by contrast, could behave more like an unconsolidated petroleum reservoir and unless pressures are maintained by fluid return, there may be subsidence. Indeed this has occurred in Wairakei, New Zealand (Hatton, 1970), or where the water is not returned to the reservoir.

Garg, S. K./Pritchett, J. W./Rice, L. F./ Brownell, D. H, Jr., 1976, Study of the Geothermal Production and Subsidence History of the Wairakei Field.

Hatton, J. W., 1970, Ground Subsidence of a Geothermal Field During Exploitation, Ministry of Works, Waikalei, New Zealand, Geothermics Special Issue.

Hatton, J. W., 1970, Ground Subsidence of a Geothermal Field During Exploitation, in United Nations Symposium on Utilization of Geothermal Resources, Pisa Italy, Elmsford, N.Y., Maxwell Scientific International, Inc.

Pritchett, J. W./Garg, S. K./Brownell, D. H., Jr./Levine, H. B., 1975, Geohydrological Environmental Effects of Geothermal Power Production: Phase I, Final Report, National Science Foundation, Washington, D.C.

Pritchett, J. W./Garg, S. K./Brownell, D. H., Jr./Rice, L. E./Rice, M. H./Riney, T. D./ Hendrickson, R. R., 1976, Geohydrological Environmental Effects of Geothermal Power Production: Phase IIA - Final Report, National Science Foundation, Washington, D.C.

Stilwell, W. B., et. al., 1975, Ground Movement in New Zealand Geothermal Field (Abstract) in Second U.N. Symposium on the Development and Use of Geothermal Resources, Abstracts, San Francisco, California, Lawrence Berkeley Laboratory, California, No. IV-15, May, 1975.

Investigators:

Garg, Sabood (Engineer, numerical analysis)
Systems, Science and Softwave, Inc.
La Jolla, California

Subsidence Area: Kawerau
Country: New Zealand
District or Province:
Nearest City: Kawerau
Identification Number: 48

Subsidence Area Data Summary

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Cause of Subsidence:

Fluid Withdrawal: Geothermal
Other:

Subsidence Characteristics:

Area of subsidence in km^2: not known
Maximum amount of subsidence in meters: not known
Average amount of subsidence in meters:
Maximum subsidence rate in cm/yr.: 2.8 cm/year **Year:** 1970-1972

Geologic Setting: Extraction from fissures in Volcanic flow rocks and breccias 400-1100 meters below ground level.

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing ( )
Other ( )
Industrial (x)
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

1

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (x) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

None

Adjustments to Subsidence: None

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )
Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

None

Source(s): Response to International Survey on Land Subsidence by W. B. Stilwell, geothermal Projects Engineer, Ministry of Works and Development, Wairakei, Private Bag. Taupo, New Zealand. February 4, 1976

Publications: Stilwell, W. B., Hall W. K. Tawhai J., 1975 Ground Movement in New Zealand Geothermal Fields. Second United Nations Symposium on the Development and Use of Geothermal Resources.

Subsidence Area: Broadlands
Country: New Zealand
District or Province: South Auckland
Nearest City: Taupo
Identification Number: 49

Subsidence Area Data Summary

Geothermal Subsidence Research Program
Category 4, Project 1
Environmental and Economic Effects
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Cause of Subsidence:

Fluid Withdrawal: Geothermal Brine and Steam
Other:

Subsidence Characteristics:

Area of subsidence in km^2: 3.1 km^2 area quater than 25 mm
Maximum amount of subsidence in meters: .022 m (1969-1972)
Average amount of subsidence in meters: .07 m/year
Maximum subsidence rate in cm/yr.: not known Year:

Geologic Setting: Extraction from fracture zones in Volcanic flow rocks and porous Volcanic breccias between 430 and 1160 meters below ground level.

Land Uses:

Agriculture (X)
Irrigated agriculture ( )
Grazing (X)
Other (X)
Forestry (X)

Industrial ( )
Business & residential ( )
Well fields ( )
Water-related shipping ( )
Mining ( )

Surface Environmental Effects:

Ground surface subsidence

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (X) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings ( )
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )

Roads ( )
Railroads ( )
Sewers ( )
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies ( )
Relevelling studies ( )
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling ( )
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection ( )
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

Source(s): Response to International Survey on Land Subsidence by W. B. Stilwell, geothermal Projects Engineer, Ministry ow Works and Development, Wairakei, Private Bag. Taupo, New Zealand. February 4, 1976

Publication: Stilwell, W. B., Hall W. K., Tawhai J., 1975 Ground Movement in New Zealand Geothermal Fields. Second United Nations Symposium on the Development and Use of Geothermal Resources.

Subsidence Area: Stockholm, Gothenberg
Country: Sweden
District or Province:
Nearest City: Stockholm, Gothenberg
Identification Number: 50

Subsidence Area Data Summary

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Cause of Subsidence:

Fluid Withdrawal:
Other: Dewatering quaternary clays by leakage to deep lying utility tunnels, loading by engineering structures.

Subsidence Characteristics:

Area of subsidence in km^2: unknown
Maximum amount of subsidence in meters: more than 1.0 m
Average amount of subsidence in meters: less than .5 m
Maximum subsidence rate in cm/yr.: Year:

Geologic Setting:

Quaternary clays over glacially scoured crystalline bedrock.

Land Uses:

Agriculture	( )	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

Damage to structures, streets and sidewalks, utility lines.

Economic Effects:

Damage has been: Severe ( ) Moderate (X) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings ( )
Pipelines ( )
Houses ( )
Buildings (X)
Pile foundations ( )
Irrigation channels ( )
Aqueducts ( )
Water Lines (X)

Streets & Sidewalks (X)
Roads (X)
Railroads ( )
Sewers (X)
Drains ( )
Dams ( )
Levees ( )

Cost Estimate of Damage:

none made

Adjustments to Subsidence:

Scientific studies (X)
Relevelling studies (X)
Dike const. & repair ( )
Road repair ( )
Pipeline repair ( )
Building repair ( )
Land Filling (X)
Develop institutional framework ( )

Abandonment ( )
Fluid reinjection (X)
Stop resource production ( )
Develop alt. resource ( )
Law suits ( )

Cost Estimate of Adjustments:

none made

Source(s): Broms, B., L. Carlsson, A. Fredriksson 1977 "Land Subsidence in Sweden Due to Water-Leakage into deep-lying tunnels and its effects on pile supported structures" in Land Subsidence Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, December 1976, Publication #121, International Association of Hydrological Sciences. Washington D. C. IAHS. pp. 375-387

Subsidence Area:	Bankok
Country:	Thailand
District or Province:	
Nearest City:	Bankok
Identification Number:	51

Subsidence Area Data Summary

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Cause of Subsidence:

Fluid Withdrawal: Water

Other:

Note: No actual subsidence has been observed, but Theoretical computation indicates the possibility.

Subsidence Characteristics:

Area of subsidence in km^2:	-
Maximum amount of subsidence in meters:	-
Average amount of subsidence in meters:	-
Maximum subsidence rate in cm/yr.:	Year:

Geologic Setting:

Land Uses:

Agriculture	(X)	Industrial	(X)
Irrigated agriculture	( )	Business & residential	(X)
		Well fields	( )
Grazing	( )	Water-related shipping	( )
Other	( )	Mining	( )

Surface Environmental Effects:

None

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None (X) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies	(X)	Abandonment	( )
Relevelling studies	( )	Fluid reinjection	( )
Dike const. & repair	( )	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	(X)		

Cost Estimate of Adjustments:

The government plans to enact the Ground Water Act to control drilling and pumping of ground water.

Source(s):

Response to International Survey on Land Subsidence by Mr. Charoen Piacharoen, Chief hydrogeologist, Department of Mineral Resource, Ministry of Industry, Bankok, Thailand. April 21, 1976

Subsidence Area: Bangkok
Country: Thailand
District or Province:
Nearest City: Bangkok

Publications:

Brand, E. W. and Paveenchana, T., 1971, Deepwell pumping and subsidence in the Bangkok area: Proc. 4th Asian Regional Conference on Soil Mechanics and Foundation Engineer, Bangkok, Vol. 1 pp. 1-7.

Haley & Aldrich, Inc., 1970, Effect of deep well pumping on land subsidence in Bangkok: in Master Plan, Water Supply and Distribution, Metropolitan Bangkok, Thaoiland, Vol. 4: as prepared by Camp, Dresser & McKee Consulting Engineers.

Piancharoen, C., 1977, Ground Water and land subsidence in Bangkok, Thaoiland: in Land Subsidence, proceedings of the 2nd Symposium on Land Subsidence, Anaheim, California, December 1976. Publications #121 International Association of Hydrological sciences. Washington, D. C., IAHS. pp. 355-364

Sitthichaikasem, S., 1975, Bangkok subsidence, too late for tomorrow: Technical article in the Prachachart daily newspaper, Bangkok, 27 October 1975. (Text in Thai).

Investigators:

Subsidence Area:	Bolivar Coast, Lake Maricaibo
Country:	Venezuela
District or Province:	
Nearest City:	
Identification Number:	52

Subsidence Area Data Summary

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Cause of Subsidence:

Fluid Withdrawal:	Oil and Gas
Other:	

Subsidence Characteristics:

Area of subsidence in km^2:	452 km^2 (189 km^2 under lake; 263 km^2 along shore)
Maximum amount of subsidence in meters:	0.41 m
Average amount of subsidence in meters:	-
Maximum subsidence rate in cm/yr.:	_ Year:

Geologic Setting:

Soft clays over sand producing layers.

Land Uses:

Agriculture	( )	Industrial	( )	
Irrigated agriculture	( )	Business & residential	( )	
		Well fields	(X)	Oil fields
Grazing	( )	Water-related shipping	( )	
Other	( )	Mining	( )	

Surface Environmental Effects:

Economic Effects:

Damage has been: Severe ( ) Moderate ( ) Slight ( ) None ( ) None Reported ( )

Damage Has Been To:

Wells & well casings	( )	Roads	( )
Pipelines	( )	Railroads	( )
Houses	( )	Sewers	( )
Buildings	( )	Drains	( )
Pile foundations	( )	Dams	( )
Irrigation channels	( )	Levees	( )
Aqueducts	( )		

Cost Estimate of Damage:

Adjustments to Subsidence:

Scientific studies	( )	Abandonment	( )
Relevelling studies	(X)	Fluid reinjection	( )
Dike const. & repair	(X)	Stop resource production	( )
Road repair	( )		
Pipeline repair	( )	Develop alt. resource	( )
Building repair	( )		
Land Filling	( )	Law suits	( )
Develop institutional framework	( )	Drainage System	(X)

Cost Estimate of Adjustments:

$ 35 Million up to 1976 estimated $5 Million/yr. future spending

Source(s): O. Nunez and D. Escojido. 1977 "Subsidence in the Bolivar Coast" in Land Subsidence Proceedings of the Second International Symposium on Land Subsidence, Anaheim, CA. December, 1976, Publication Number 121, International Association of Hydrological Sciences, Washington, D. C., pp. 257-266.

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