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Economics Effects of Land Subsidence Due to Excessive Groundwater Withdrawal in the Texas Gulf Coast Are

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SUMMARY AND CONCLUSIONS

Land surface subsidence continues to be a destructive force in the Texas Gulf Coast area. The sinking of the surface has been linked by engineers to the withdrawal of groundwater. Subsidence causes damages and property value losses as saltwater encroachment is increased, property is permanently inundated, and temporary flooding is intensified.

This study provides estimates of private and public costs attributable to land subsidence in a 945 square mile area that has subsided one foot or more since 1943. Estimates are divided into three sub-areas within this total area to provide insight into the incidence of subsidence-related costs. The sub-areas considered in this study were sub-area I, an 83 square mile area between Houston and Baytown containing square mile sample blocks adjacent to the upper Galveston bay and/or Buffalo Bayou and the Houston Ship Channel; sub-area II, the 25 square mile area surrounding Clear Lake and adjacent land fronting on Galveston bay; and sub-area III, the remaining area within the total 945 square mile area that had experienced subsidence of approximately two feet or more since 1943.

Personal interviews, using questionnaires designed for reporting of damages and property value losses by a random sample of owners of residential, commercial and industrial property, comprised the data base for estimating total private costs attributable to subsidence. Public costs (federal, state, county and municipal) were obtained from personal interviews with public officials. In total, over 1100 interviews were conducted

in the study area. Data from these interviews were expanded to total cost estimates for the subsiding area.

Physical effects of surface subsidence were found to be largely dependent upon location of the property. Most damages and losses in property value occur in those areas in close proximity to Galveston bay and/or major waterways. Temporary flooding, permanent inundation, bulkheading and landfilling were the major subsidence-related causes of cost and/or losses in property value. Structural damages, largely from subsidence aggravated surface faults, were also significant. These comprised a higher proportion of damges in areas remote from the waterfront than in low lying areas subject to frequent flooding or permanent inundation.

Estimated annual costs and property value losses totaled over $31.7 million per year for the study area as a whole. These were primarily costs to residential, commercial and industrial property owners, but included over $.5 million per year in public costs for damage abatement or repair to public facilities.

Estimated costs by sub-areas revealed a higher incidence and intensity of damage and property value loss in waterfront (I and II) than in non-waterfront areas (III). Estimated costs in sub-areas I, II and III were $8.79 million, $5 million and $17.4 million, respectively. Sub-area I, which made up about 8.8 percent of the total study area, experienced 27.7 percent of total subsidence-related costs. Sub-area II experienced 15.8 percent of total costs while occupying only 3 percent of the total study area. And, although sub-area III had almost 55 percent of the total costs, it includes over 88 percent of the total area. Hence, subsidence damages and losses in property value are concentrated heavily in areas in close proximity to the immediate coastline of Galveston bay, Buffalo Bayou, Clear Lake and Taylor Lake. Other sections throughout the study area experienced damages and property losses but less frequently and less intensively.

A comparative analysis of the total costs of groundwater pumping with alternative surface water importation was developed to examine the economic feasibility of importing surface water to displace groundwater as a means of avoiding annual subsidence costs. A break-even analysis revealed that for the five year period 1969-73, the importation of surface water to meet all the area's water needs (up to 198.16 billion gallons per year) would have been economically justified from the standpoint of reducing total area water costs.

ECONOMIC EFFECTS OF LAND SUBSIDENCE DUE TO EXCESSIVE GROUNDWATER WITHDRAWAL IN THE TEXAS GULF COAST AREA

Lonnie L. Jones and James Larson*

INTRODUCTION

Land surface subsidence continues to be a destructive force in the Texas Gulf Coast area. This phenomenon, generally agreed to result from compaction of subsurface soil strata, and consequent lowering of surface elevations, is a continuous hazard to land and real property. Surface subsidence of as much as nine feet has occurred at some sites. Engineering studies have linked land subsidence to the extensive withdrawal of groundwater [Gabrysch].

Problems are created for property owners and municipalities, particularly those located on the immediate coastline. As land subsides, tides encroach further each year. Frequent inundation renders many formerly dry areas useless for residential and commercial purposes. Often, homes and other property must be abandoned. Municipalities, counties and the state must continuously raise elevations of roads and ferry landings, repair damages and construct dikes and drainage facilities. Individual property owners incur expenses for bulkheading, landfill and other remedial actions against permanent and/or temporary inundation.

In addition to the continuous, day-to-day problems created or aggravated by land subsidence, the potential hazard of hurricane damages of unprecedented magnitude is made worse by the lowering of surface elevations.

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Each increment to subsidence means an increase in the land area that would be affected by a hurricane of given force. For example, a storm of comparable force to Hurricane Carla would inundate highly developed property today that was not subject to inundation in 1961. Comparisons of past and estimated future inundation are presented in recent studies by Brown, et. al.

These continuous and potential hazards have increased the concern of subsidence-area residents and led to a search for means of subsidence abatement. The evaluation of alternatives for protective or preventive action has been hampered by a lack of information on the total costs of subsidence to the subsiding area. An earlier study of the costs of subsidence by Warren, et. al., estimated public and private costs for a 300-square mile study area within the total area affected by subsidence. The present study builds upon that earlier work and extends the analysis to include the following objectives:

(1) To estimate private subsidence-related costs for other selected subsiding areas of the Texas Gulf Coast region,

(2) To estimate current and expected subsidence-related public expenditures within the subsidence study area, and

(3) To analyze and compare total costs of alternative water supplies (surface and ground) to meet needs of the subsidence study area.

STUDY AREA

The approximate subsiding area of the Texas Gulf Coast is depicted in Figure 1. It includes major portions of Harris, Brazoria and Galveston counties, and extends to Chambers County to the East. Certain other areas along the Gulf Coast have experienced subsidence of an isolated nature.

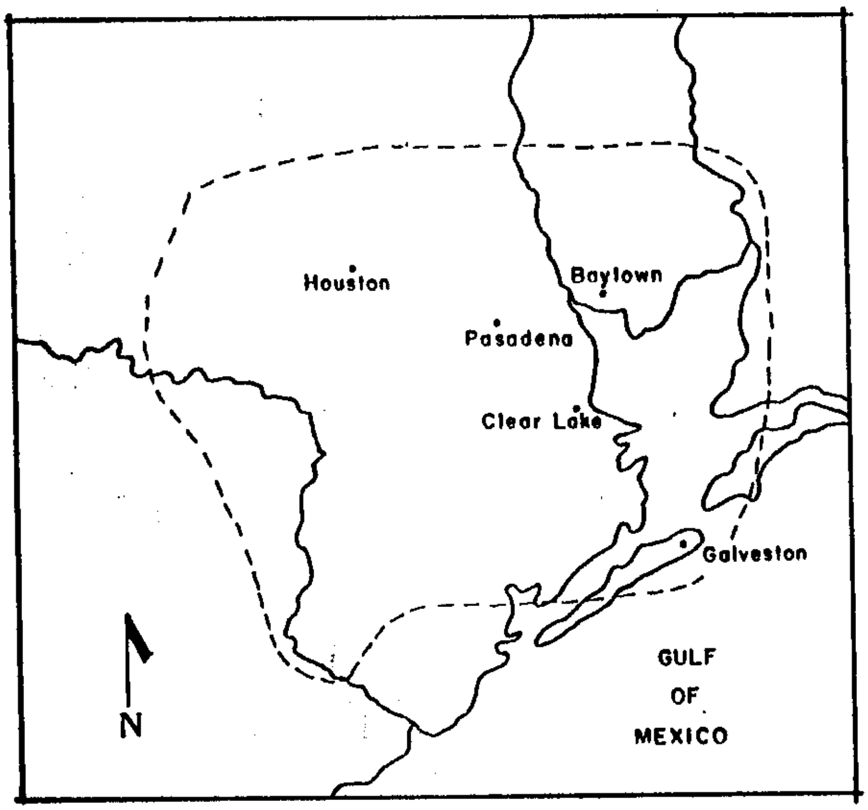

Figure 1. Approximate 3,000 square miles (within dashed line) affected by land surface subsidence in the Texas Gulf Coast area.

But, none have had the magnitude of sinking as the area depicted in Figure 1 [Brown].

For purposes of analysis presented in this report, a study area of 945 square miles was delineated [Figure 2]. Land within this study area had subsided approximately 2.0 feet or more within the period from 1943 to 1973. To identify the incidence of subsidence economic effects, this 945 square mile study area was further divided into three sub-areas and cost estimates were developed for each sub-area. Previous analyses show the intensity of subsidence-related damages to be quite high for property located adjacent to waterfronts and subject to frequent inundation and temporary flooding [Warren, et. al.]. Hence, two of the sub-areas are composed chiefly of waterfront property. Costs were estimated separately for the two waterfront sub-areas since they are geographically distinct and have experienced different development patterns. A brief description of each sub-area is presented as follows.

Sub-area I

This sub-area contains 83 one-square mile blocks along the immediate waterfront of Galveston bay and Buffalo Bayou and includes the major industrial areas of the Houston Ship Channel (Figure 2). It is highly developed. It is composed of residential, commercial and industrial properties. Extending from east to west, sub-area I includes much of the city of Baytown, with commercial, residential and industrial developments, and some of the eastern portion of the city of Houston. Houston's central business district is not included in sub-area I, although much of its commercial and industrial area is included. Most of this sub-area

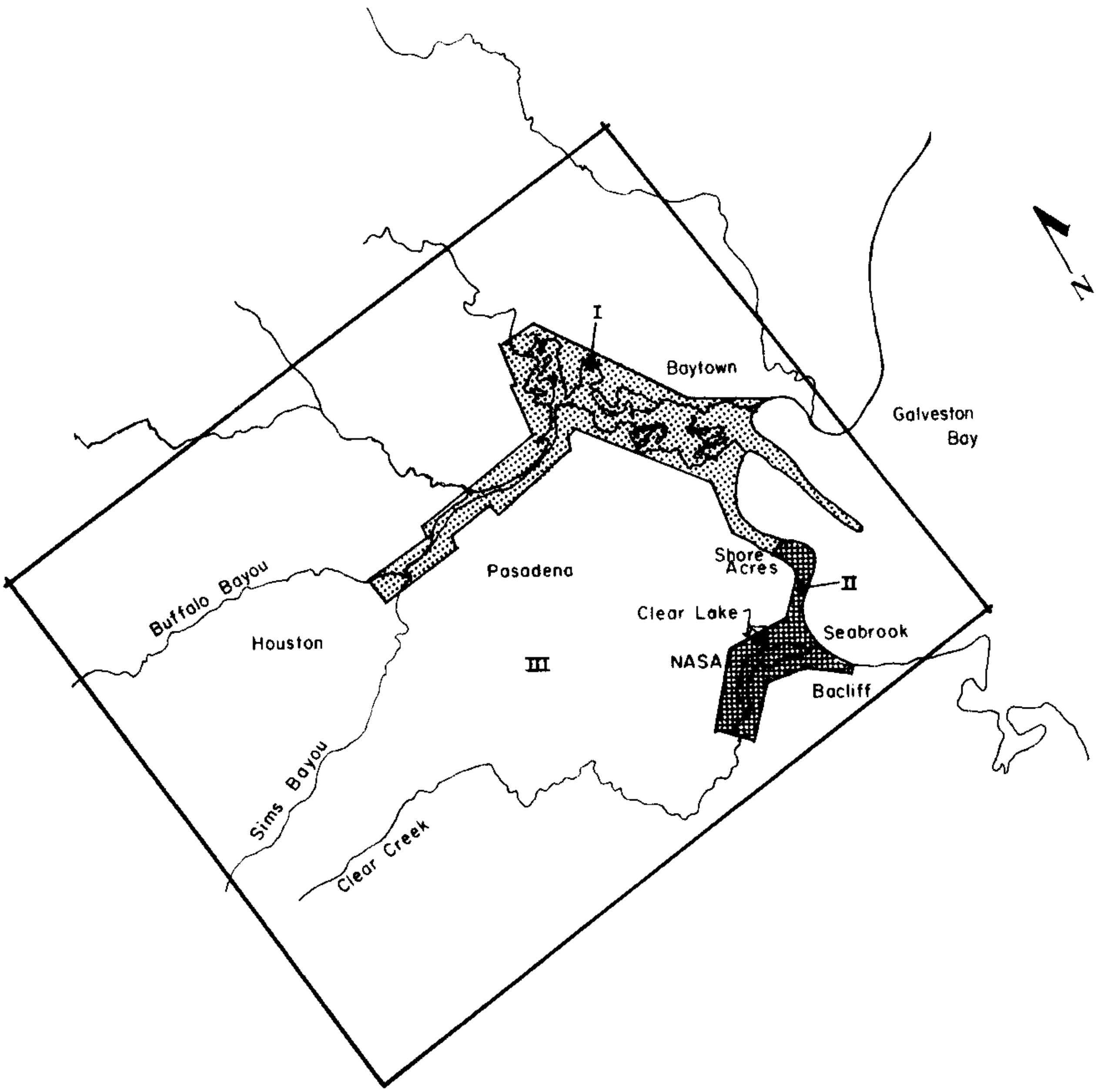

Figure 2. Approximate location of the study area and sub-areas I, II and III.

lies at elevations below 25 feet, including the Brownwood subdivision of Baytown and others that have experienced relatively severe damages from permanent inundation and temporary flooding.

Sub-area II

This sub-area includes 25 one square mile blocks that immediately surround Clear Lake and Taylor Lake and extends along the coastline of Galveston bay to include the Shore Acres development to the north and Baycliff to the south (Figure 2).

Most of this sub-area is developed, primarily with residential and commercial properties, although some land along the Galveston bay coastline remains undeveloped. Sub-area II includes the communities of Seabrook, Kemah, Nassau Bay, El Lago and others. The NASA Lyndon B. Johnson Space Center is also included within this study area.

Sub-area III

This sub-area consists of the remaining 837 square miles contained in the total study area. Most of this sub-area is remote from the Galveston bay coastline and consequently is affected less by saltwater encroachment, temporary saltwater flooding or permanent inundation, although some areas along bayous are influenced by tidal surges. Since these are the primary causes of subsidence-related damages, the incidence of subsidence-related damage (per square mile or property unit) within sub-area III is relatively slight. Some structural damages resulting from subsidence aggravated faults, temporary freshwater flooding and costs incurred to repair public facilities damages appear to be the most important subsidence costs within this area.

METHODOLOGY

Private damages and property losses associated by property owners with subsidence were estimated separately for each of the sub-areas within the total subsidence study area. These were then aggregated for the 945 square mile area. Public costs were aggregated for the total area by the governmental entity incurring the costs, i.e., federal, state, county or municipal. These estimates are reported in the results of this analysis.

Questionnaires, survey techniques and estimation methods developed for an earlier study were utilized to estimate private subsidence costs in this study. Procedural details are contained in an earlier report of the Texas Water Resources Institute [Warren, et. al.].

However, the method of selecting sampling blocks for this study differs from the initial study. Based on information gained from the earlier analysis the decision was made to classify square mile sample blocks into <u>waterfront</u> and <u>non-waterfront</u> sub-areas and to concentrate sampling most heavily in sample blocks adjacent to waterfronts (high damage areas) while limiting sampling in others. Within each of the waterfront blocks, a 10 percent random sample of all residential and commercial property was drawn and property owners were interviewed to gain estimates of costs of damages and losses in property values that they attributed to subsidence. In sub-area III, a smaller sample of 25 square mile blocks was used to represent the total sub-area of 837 square miles and property owners were interviewed at a rate of 5 percent within each sample block.

Estimates of public costs incurred by the various government entities were obtained from interviews of municipal, county, state and federal agencies. This enumeration was as complete as feasible given the resources and time available for this study. Both past and expected expenditures were obtained from governmental officials.

For the analysis of costs of water from alternative sources of supply (ground or surface), information concerning current groundwater costs by the various municipalities of the study area using groundwater was obtained. These rates were then compared with rates that might be expected if the municipalities switched from the groundwater source to surface water source at a cost of surface water that is currently being used in negotiations by municipalities.

The method of expanding sample data to estimate total costs was the same for both residential and commercial property in all sub-areas. Estimates of property values, property losses and damages were first expanded to totals for each square mile sample block. For example, if a 10 percent sample had been drawn within a sample block of 96 residences, 10 completed questionnaires provided the basis for expansion. If the ten sample residences had an estimated total property value of $200,000, then the average value per residence of $20,000 was multiplied by 96 to estimate total residential property value within the sample block. This same procedure was used to estimate subsidence-related costs and losses in property value for both residences and commercial businesses. In sub-area III where sampling rate used was 5 percent, expansion factors were adjusted to reflect the different sample size.

Once estimates were obtained for each square mile sample block, the estimates were expanded to totals for each respective sub-area. These totals were derived as the product of the estimated average total per sample block times the ratio of the total number of one square mile blocks to the number of sample blocks within the sub-area. Since all square mile blocks within sub-area II were sampled, a simple summation of totals over all estimated sample blocks provided the estimate for the sub-area.

Interviewing for this study extended over a period of about 18 months. For sub-area I, 128 questionnaires were completed in the early spring of 1974. Sub-area II interviewing was completed in the spring of 1975 and sub-area III in the summer of 1975. A total of 1051 residential and commercial questionnaires, designed for reporting subsidence-related damages and losses in property values, was used in the analysis.

PHYSICAL EFFECTS OF SUBSIDENCE

Physical effects of surface subsidence to real property are largely dependent upon location of the property. The most obvious problem caused by subsidence is the loss of land in low-lying tidal areas and the submergence of homes, buildings and structures located on the immediate coastline. Also damaging is the loss of surface elevation and the potential subjection of more land and property to the natural hazard of temporary flooding either from tidal surge or temporary runoff. As is revealed in this study, these hazards (temporary tidal flooding and permanent inundation) account for most of the costs and losses in property value that have been associated historically with subsidence. Furthermore, it has been estimated that approximately 20,000 acres (about 31 square miles) of land may be lost by the year 2020; and, that if storm tides with the same surge height as those generated by Hurricane Carla in 1961 had struct the upper Galveston bay in 1974, an additional 70 square miles of subsiding land, much of it highly developed, would be flooded by hurricane-surge waters [Brown]. Potential hazards are clearly intensified by subsidence. Consequently, estimates of historical costs contained in this report are probably quite conservative since they include no estimate of potential damages. For example, an important exclusion of the work is the lack of information on the impact of a major hurricane.

In areas more remote from immediate coastlines, subsidence can result in changes in land slopes, stream gradients and stream drainage patterns. Such changes can cause problems in gravity transport systems, such as water and sewage lines [Brown]. Streams, drainage canals and watersheds have been affected in this way by subsidence within the study area. Since the rate of subsidence is not uniform, temporary flooding from freshwater runoff has increased in some parts of the subsiding area. Gradual widening of streams and bayous, slow drainage and more frequent flooding was reported by numerous respondents remote from the coastline and at relatively high elevations.

Research by the Bureau of Economic Geology at the University of Texas indicates that subsidence may activate and aggravate surface faults along the Texas Gulf Coast. According to a recent Bureau report:

> Geologic evidence suggests that fault activity today should be a relatively minor process. The frequency and activity of fault movement, nonetheless, is increasing. These are clear indications that certain of man's activities, such as groundwater withdrawal and oil and gas production, are causing this increase in fault activation. In the Houston-Galveston-Baytown area, where there has been heavy withdrawal of groundwater, oil and gas and extensive concomitant subsidence, several faults have become active. Nearly all faulting has occured in areas where the potentiometric surface has dropped over 100 feet and where there has been at least one foot of land-surface subsidence. Of course, the areas of heavy groundwater usage are also the areas of greatest land use and, hence, the presence of active faults and their effect is more likely to be noticed than in areas of less intense use [Brown].

This geologic research indicates a relationship between intensity of faulting and land subsidence. Hence, structural damages to properties surveyed in this study were recorded and used in the analysis. These damages are manifested primarily as cracking, shifting and separation in residential and commercial structures and attachments such as sewer and waterlines. Along the water frontage, these costs constitute a relatively minor share of total subsidence costs.

Losses in property value may arise from two interrelated sources. These are: (1) the actual loss of the use of property and improvements, such as land, homes or commercial structures because of permanent inundation or frequent inundation as the property subsides and (2) losses in the value of property due either to a history of flooding in other subsidence-related damages or a potential of such damages. In either case, the dollar value of flood-proned property will be discounted to take into account this undesirable feature, resulting in a capital loss to owners of such property. In this study, losses in property value refers to the property owner's estimate of the value loss of improvements attributed to subsidence damages. Such losses were highest in areas subject to frequent inundation and/or permanent inundation.

ESTIMATED SUBSIDENCE COSTS

Subsidence-related damages and property losses were reported throughout the study area. However, neither the incidence nor intensity of losses was uniform. For this reason damages and costs to private property are reported separately for the three sub-areas of the selected study area. Comparisons of costs among these study areas provide insight into the incidence of subsidence costs to private property in the greater Houston area. Public costs are reported only for the entire study area taken as a whole.

Costs in the Houston-Pasadena-Baytown area (sub-area I)

Total estimated costs and losses in property value for the period 1969-1973 within sub-area I are presented in Table 1. Subsidence-related costs reported by residential and commercial property owners are summarized under four major types: structural, bulkheading and landfilling, temporary flooding, permanent inundation, and property value losses. Temporary flooding comprised most of the damages to residential property within this sub-area with a total estimated cost from flooding damages of about $5.87 million. Much of this total was the result of Tropical Storm Delia that struck the upper Galveston coast in 1972, temporarily inundating a large area of residential developments in Baytown-Pasadena area. No commercial damages from temporary flooding were reported by the sample of commercial property owners.

Permanent inundation was a major cause of damage for both residential and commercial property owners in sub-area I, resulting in estimated costs of $6.91 million over the five year period from 1969-73. This total is comprised chiefly of losses due to inundation of improvements such as homes, businesses, loading docks, piers, boat houses, etc. Virtually all square mile sample blocks contained damages from permanent inundation.

Total estimated damage costs to residential and commercial property in sub-area I were $14.33 million in the 1969-73 period. Both structural damages and costs for bulkheads and landfill made up a relatively small share of the total subsidence costs within sub-area I.

Table 1. Estimated private costs and losses associated with land subsidence in the Houston-Pasadena-Baytown area (sub-area I), 1969-73.

category	units	residential	commercial	total
Structural	dol.	595,490	349,091	944,581
Bulkheading & Landfill	dol.	608,000	-0-	608,000
Temporary Flooding	dol.	5,870,544	-0-	5,870,544
Permanent Inundation	dol.	1,089,553	5,818,180	6,907,733
Total Damages	dol.	8,163,587	6,167,271	14,330,858
Property Losses	dol.	22,195,193	2,152,727	24,347,920
Total Damages plus Losses	dol.	30,358,780	8,319,998	38,678,778
Property Value	dol.	163,005,523	277,157,732	440,163,255
Property loss as a % of Value	percent	13.6	0.8	5.5

Losses in private property values were estimated to be over $24 million (Table 1). Of this, over $22 million were estimated losses in residential property value. Commercial property value loss was estimated at just over $2 million. As a percentage of total estimated property values, property value losses were 13.6 percent and 0.8 percent for residential and commercial properties, respectively. Overall, losses were estimated to be 5.5 percent of total private property values.

Total damages and property losses to residential and commercial property for the five-year period amounted to an estimated $38.7 million in sub-area I. In addition, industrial damages in the amount of $37,186 were estimated for study area I during this same period [Warren, et. al.]. As indicated by Warren, this value for industrial damages is almost certainly an underestimate.

Costs in the NASA-Clear Lake area (sub-area II)

Total cost estimates for residential and commercial properties in sub-area II by type of damage are presented in Table 2. Estimated costs for this area cover the six year period from 1969-74. Total estimated damages and property value losses for residential and commercial property in the 25 square mile area were just over $30 million for the six year period. Predominant among the types of costs were expenditures for bulkheading and landfilling--a total estimated cost of over $5 million. This cost was primarily for raising piers, boat docks, constructing bulkheads and other remedial action against flooding and permanent inundation.

Temporary flooding was also a significant cause of damage to both residential and commercial property. In total, an estimated $12.65 million in property damages was attributed to land subsidence.

Table 2. Estimated private costs and losses associated with land subsidence in the NASA-Clear Lake area of the Texas Gulf Coast (sub-area II), 1969-74.

category	units	residential	commercial	total
Structural	dol.	961,500	1,039,740	2,001,240
Bulkheading & Landfill	dol.	2,714,570	2,347,500	5,062,070
Temporary Flooding	dol.	682,400	3,430,000	4,112,400
Permanent Inundation	dol.	910,000	564,000	1,474,500
Total Damages	dol.	5,268,470	7,381,740	12,650,210
Property Losses	dol.	4,202,000	13,200,000	17,402,000
Total Damages plus Losses	dol.	9,470,470	20,581,740	30,052,210
Property Value	dol.	189,872,100	271,818,500	461,690,600
Property Loss as a % of Value	percent	2.2	4.9	3.8

Losses in property value were estimated at $17.4 million, or about 3.8 percent of estimated property value. Residential property value losses as a percentage of total residential value were somewhat lower in sub-area II than in sub-area I, while commercial losses as a percentage of commercial values were higher. These differences are likely the result of differences in the age of property improvements, recent growth trends and location of properties. Most of the developments in sub-area I (Baytown and Pasadena) are older and growth has stabilized as compared to sub-area II which has grown rapidly in recent years. The more rapid growth in sub-area II and consequent higher demand for private property, especially residential property, could mask the detrimental influence of subsidence-related damages on property values in the area. Differences in commercial property value losses are largely due to the fact that more commercial property is located on or near waterfront in the Clear Lake area than in the Baytown-Pasadena area.

Costs in Non-waterfront Areas (sub-area III)

Costs associated with land subsidence in the remainder of the 945 square mile study area (study area III) are presented in Table 3. The absolute magnitude of damages and property losses are highest in this sub-area. However, the intensity of damages, as measured by costs per value unit of property, is relatively low since most of the area is remote from the immediate coastline which is subjected to permanent inundation and saltwater flooding. Total damages and losses in property value were estimated to be just over $86.8 million for the five year period 1969-73. Of this total, about $46.6 million were estimated

Table 3. Estimated total private costs and losses associated with land subsidence (sub-area III), 1969-73.

category	units	residential	commercial	total
Structural	dol.	16,997,796	33,480	17,031,276
Bulkheading & Landfill	dol.	703,080	-0-	703,080
Temporary Flooding	dol.	28,876,500	77,004	28,876,500
Permanent Inundation	dol.	-0-	-0-	-0-
Total Damages	dol.	46,500,372	110,484	46,610,856
Property Value Losses	dol.	40,206,132	-0-	40,206,132
Total Damages plus Losses	dol.	86,706,504	110,484	86,816,988
Property Value	dol.	5,819,910.8	6,920,425.9	12,740,336.7
Property Loss as a % of Value	percent	1.49	0.002	0.68

damages and $40.2 million were property value losses. The major cost component was from temporary flooding--$28.9 million or about 62 percent of all damages. Temporary flooding in sub-area III occurred chiefly in relatively low areas and along bayous such as Sims and Little Vince that are affected by unusually high tidal surges. Respondents reported a gradual worsening of drainage problems in recent years throughout the study area, but primarily along creeks and bayous. Also, in areas of relatively low elevation respondents reported increases in water encroachment and more frequent flooding. Such damages appear to be increasing throughout the area, evidently the result of changes in land slope, stream gradients and stream drainage patterns.

Structural damages were also important in sub-area III, causing an estimated $17 million in costs to residential and commercial property owners.

Public Costs

Costs incurred by governmental agencies and municipalities to repair and prevent damages from land subsidence were obtained from public officials throughout the study area. These estimated public costs are presented in Table 4 by the governmental entity incurring the costs. Expenditure estimates are limited to those that correspond with damages occurring within the study area. Hence, they are limited to expenditures by Harris County, municipalities within the study area and state and federal agencies for projects relating directly to the study area. Costs are reported as both past and anticipated expenditures.

Total past and anticipated expenditures by all public entities to

Table 4. Estimated public costs within the subsidence study area due to land surface subsidence, 1969 to 1973.

category	dollars spent	estimated dollars to be spent	total
Federal	-0-	12,700,000	12,700,000
State	500,000	3,061,000	3,561,000
County	1,800,000	15,500,000	17,300,000
Municipal	388,000	4,675,000	5,063,000
TOTAL	2,688,000	35,936,000	38,624,000

[a]Federal expenditures for research and monitoring of subsidence have been incurred. These are not included in either past or anticipated public cost.

repair or prevent subsidence damages for the period of 1969-74 were estimated to be over $38.6 million. Most of this total (over $35.9 million) was anticipated expenditure estimates for damages already incurred but not yet repaired. Nevertheless, these were specific expenditure items either budgeted or estimated by public officials as needing to be spent. Estimated expenditures to date were reported to be $2.7 million by all governmental entities. Of this, $1.8 million, the largest component, was spent by Harris County for elevation of public roads, ferry landings and other items. The municipal costs of $388,000 were primarily for roadwork, water and sewer lines, abandonment of water wells, drainage, etc. Similarly, state goverment costs were for elevation of state highways, tunnel entrances and other such expenditures.

Direct federal government expenditures were not reported separately. However, considerable sums of federal monies have been spent as a result of the land subsidence problem in Texas Gulf Coast area. To date these have been limited chiefly to expenditures for research on the problem by the Corp of Engineers, U.S. Geological Survey and other agencies. No federal projects for repair or prevention have been implemented as yet. The estimated $12.7 million to be spent are for the purpose of purchasing properties in the heavily impacted areas on the immediate waterfront to create a public park and provide relief to property owners affected by subsidence [U.S. Corps of Engineers].

Other anticipated expenditures include about $3 million by the State of Texas, $15.5 million by Harris County and $5.1 million by municipalities in the study area. Anticipated expenditures are for similar items as previous expenditures with somewhat heavier expenses anticipated to deal with increasingly difficult drainage problems. Just under $3.2 million were anticipated expenses to the city of Baytown--its share of the cost to create a public park in the Brownwood sub-division [U.S. Corp of Engineers].

The fact that most public expenditures are anticipated for future projects indicates that remedial action is just now being undertaken against a problem that has existed over a long period of time. It is likely, therefore, that anticipated expenditures of just over $35.9 million are a conservative estimate. It should be noted that the $2.7 million expenditure for the 1969-74 period is probably an underestimate of actual subsidence costs. In many cases, public officials reported damages attributable to subsidence but they were unable to isolate the costs involved in repairs or replacement.

Of the $20.2 million public costs (county and municipal) anticipated within the immediate subsidence area, $15.5 million are at the county government level. County expenditures are important because they are shared by taxpayers throughout the county whether or not they reside in the areas heavily impacted by subsidence; i.e., there clearly are equity implications.

ESTIMATED ANNUAL COSTS

Estimated total costs and property value losses for each sub-area are expressed in an annual average basis and presented in Table 5. Annual estimates for sub-area II (NASA-Clear Lake) are derived from the six year period 1969-74 while the other areas are derived from the five year period 1969-73. These costs represent only the reported costs for this period for which property owners had made expenditures. Hence, they should be

Table 5. Estimated annual average costs and property losses associated with land subsidence in the subsidence study area.

area	approximate area size	estimated annual average costs			percent of total
		damages	property losses	total	
	-sq. miles-	---dollars---			%
I[a]	83	3,925,758[d]	4,869,584	8,795,342	27.7
II[b]	25	2,108,368	2,900,333	5,008,701	15.8
III[a]	837	9,322,171	8,041,226	17,363,397	54.8
Public Costs[c]		537,600		537,600	1.7
TOTAL		15,893,897	15,811,143	31,705,040	100

[a]Annual average costs and losses for the five year period 1969-73.

[b]Annual average costs and losses for the six year period 1969-74.

[c]Annual average costs for the five year period 1969-73. This estimate includes actual expenditures only.

[d]Includes $37,186 estimated costs to industry.

considered a conservative estimate of subsidence-related damages and property value losses. They represent costs to property owners resulting from the day-to-day, gradual encroachment of saltwater and flooding from "normal" weather phenomenon that may be expected to occur frequently. These estimates do not include "potential" damages and costs from hurricanes that may be expected to occur infrequently, but with a devastating impact. The most damaging tropical storm to occur within the study period was Delia in 1972. However, similar storms have an estimated return frequency of about five years [Bodine]. Hence, a tropical storm of a similar force would not be considered abnormal for any selected five year period.

Estimated annual costs and property value losses totaled over $31.7 million for the study area as a whole. These were primarily costs to private property owners, but included just over $.5 million per year in public costs. The largest costs were in sub-area III, with about $17.4 million. Estimated costs for sub-areas I and II were over $8.79 million and $5 million, respectively. Although the totals are less than for sub-area III, these two sub-areas experienced a much higher intensity of subsidence costs. For instance, sub-area I makes up about 8.8 percent of the total study area and experienced 27.7 percent of the costs due to subsidence damages and property value losses. Sub-area II experienced 15.8 percent of total costs but occupies only about 3 percent of the total study area. Hence, subsidence damages and losses in property value are concentrated heavily in the areas in close proximity to the immediate coastline of Galveston bay, Buffalo Bayou, Clear Lake and Taylor Lake. Other sections throughout the study area experienced damages and property losses but less frequently and less intensively.

ALTERNATIVE WATER SOURCES AND COST COMPARISONS

Since subsidence has been linked to groundwater withdrawal, one of the primary purposes in estimating costs associated with land subsidence in the Texas Gulf coastal area is to provide information that may be used in evaluating alternative sources of water for municipal, industrial, agricultural and other uses.

Sources of Water

Two immediate sources of water are available to the subsiding area. One of these is the continued withdrawal of groundwater from the Evangeline and Chicot aquifers. The other is surface water from several surface sources including Lakes Houston, Livingston and Conroe.

Surface water is currently used from Lake Houston and plans for delivery of water from Lake Livingston (Trinity River) via facilities under construction by the Coastal Industrial Water Authority are planned for completion in 1976 [Munson]. Ample quantities of surface water are available to meet the needs within the subsiding area. It is estimated that about 1.2 billion gallons per day are available from Lakes Livingston, Houston, Conroe and other surface sources. The greater Houston water distribution systems completed or nearing completion have a total capacity of some 1.27 billion gallons per day [Munson]. Lake Houston (150 mgd) should not be considered a new source of surface water since the reservoir is already fully committed. Nevertheless, the addition of Lake Livingston surface water in 1976 and potential future supply from Lake Conroe and Wallisville reservoir provides quantities well in excess of current needs.

At present, as in the past, the subsiding area relies primarily on groundwater and withdrawals have increased steadily in recent years. Table 6 shows average daily groundwater pumpage for major areas, as delineated by Gabrysch for the five years 1969-73. Total pumpage increased steadily up to 1972 when groundwater withdrawals reached 364.2 million gallons per day (mgd). Pumpage in 1973 was somewhat lower at 353.9 mgd. According to Gabrysch, average daily withdrawals varies among years depending upon amounts of rainfall, season of rainfall and other factors.

Average daily groundwater pumpage for the 1969-73 period by type of user are presented in Table 7. Average daily water use in the subsiding area was estimated at 347.3 mgd. Over half of this pumpage (198.8 mgd) was for public supply uses, including households, commercial businesses and other municipal purposes. Industries within the area were the second largest users with an average of 147.1 mgd over the five year period.

Comparison of Costs of Alternative Water Sources

The economic feasibility of importing surface water to substitute for groundwater may be analyzed by comparing the pumping (internal to the user) and subsidence-related (external to the user) costs of groundwater withdrawal to the cost associated with purchasing and conveying water from surface sources. The internal pumping costs of groundwater is low relative to the cost of acquiring and conveying surface water. Current estimates of costs within the subsidence area are about \$.06 per thousand gallons for pumping groundwater and about \$.22 per 1,000

Table 6. Groundwater pumpage in million gallons per day in the subsidence study area, 1969-1973.

area	year				
	1969	1970	1971	1972	1973
	mgd				
Houston	160.4	170.7	195.9	194.5	188.6
Pasadena	122.8	121.2	120.4	119.5	116.3
Baytown-LaPorte	27.8	28.0	28.4	31.8	30.3
NASA-Clear Lake	11.2	15.6	14.7	18.4	18.7
TOTAL[a]	322.2	335.5	359.4	364.2	353.9

Source: R. K. Gabrysch, Development of Groundwater in the Houston District, Texas, 1966-69, report no. 152 of the Texas Water Development Board and U.S. Geological Survey, June, 1972; and updated information from R. K. Gabrysch, U.S. Geological Survey.

[a]This total does not include the Katy, Alta Loma, Texas City and other Galveston County areas reported by Gabrysch.

Table 7. Average groundwater pumpage in million gallons per day in the subsidence study area, 1969-73.

areas[a]	public supply	industrial	irrigation	total
	---mgd---			
Houston	170.7	10.4	0.9	182.0
Pasadena	14.9	105.1	0.1	120.1
Baytown-LaPorte	7.4	21.8	0	29.2
NASA-Clear Lake	5.8	9.8	0.4	16.0
TOTAL[b]	198.8	147.1	1.4	347.3

Source: Calculated from R. K. Gabrysch, Development of Groundwater in the Houston District, Texas, 1966-69, report no. 152 of the Texas Water Development Board and U.S. Geological Survey, June, 1972; and updated information from R. K. Gabyrsch, U.S. Geological Survey.

[a]Area deliniations used in this table are those reported by Gabrysch.

[b]This total does not include the Texas City, other Galveston County or Katy areas reported by Gabrysch. Average groundwater pumpage in all areas in 1969-73 was 497.8 mgd.

gallons for purchase of surface water.[1] Hence, a user cost differential of approximately $.16 per 1,000 gallons in favor of groundwater exists between the two sources. However, since groundwater pumping results in additional costs due to surface subsidence that are not associated with surface water use, the external costs (damages and losses in property values) must be considered in the cost comparison.[2] The external, subsidence-related costs are estimated to be about $31.7 million per year (Table 5).

In this comparative analysis, a break-even equation is used to calculate the quantity of surface water that could be purchased with an internal cost differential of $.16 per thousand gallons of water that would just equate the total cost of surface water with the total cost (internal and external) of groundwater.[3] The equation used may be expressed as follows:

$$Q_e = TEC_S/(P_s - P_p) \qquad (1)$$

where

Q_e = the break-even quantity of surface water

TEC_S = total external cost of subsidence

P_s = internal cost of surface water

P_p = internal cost of groundwater

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[1]The survey of public officials indicated that $.06 and $.22 were typical costs estimated for groundwater and surface water respectively.

[2]The external costs from damages and losses in property values are incurred by groundwater users as well as non-users. Such costs are external in the sense that an individual within the areas cannot avoid the costs by varying the quantity of groundwater used. Avoidance of the external costs must be accomplished by collective action within the area.

[3]For a detailed derivation of the break-even equation used, see Warren, et. al.

The quantity of water (Q_e) calculated from equation (1) provides an estimate that may be compared directly with total water use (Q_d) to arrive at the least cost source to the entire subsiding area.[1] That is, if Q_e is less than total water use, continued pumping of groundwater is the least cost source of water to the area; if Q_e is greater than Q_d, surface water is the least cost source and if they are equal, the two sources will cost the same considering both internal and external costs.

As indicated, the subsidence-related external costs of groundwater pumping (TEC_S) were estimated at about $31.7 million per year. The internal costs of surface and groundwater were $.22 and $.06 per 1,000 gallons; or, as applied to one million gallons, $220 and $60, respectively. Hence, Q_e, the break-even quantity of surface water, was estimated to be:

$$\frac{\$31,705,040}{\$160} \quad \text{or} \quad 198,156 \text{ million gallons per year.} \qquad (2)$$

This indicates that with current prices and the estimated subsidence-related costs, the purchase of up to 198.16 billion gallons per year (bgy) or 543 mgd of surface water would be economically justified. The magnitude of this break-even quantity is most significant when compared with annual water use within the study area of 126.76 bgy (347.3 mgd, see Table 7), the annual average for the same five year period over which costs were estimated.[2]

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[1] It is generally agreed that there exists a withdrawal rate at which water pressure and subsidence would be stabilized. If some quantity of water can be pumped without causing subsidence, then this quantity should be deducted from total water use in making the comparison with Q_e. However, this withdrawal rate has not been estimated.

[2] Estimates by Gabrysch place total groundwater use in areas "principally in Harris County" at a five year average of 181.7 bgy, still less than the Q_e of 198.16 estimated in equation (2).

This difference of 71.4 bgy (196 mgd) implies that, even if all groundwater pumping were displaced by imported surface water, the surface alternative would be the least-cost source of water needs of the area.

For example, assuming all water demands had been pumped from groundwater sources during the 1969-73 period at a cost of \$60 per million gallons, total pumping cost would have been about \$7.6 million per year. Added to total annual external costs of \$31.7 million, this brings the total cost of groundwater to an estimated \$39.3 million per year. Assuming the area's water use (126.76 bgy) had been supplied with purchased surface water at a cost of \$220 per million gallons, total annual costs would have been about \$27.9 million, or a savings to the area of about \$11.4 million per year.

Since the total cost of acquiring of surface water relative to groundwater pumping costs may vary from that used here ($P_s - P_p = \$160$), it is useful to consider estimates of break-even quantities of surface water at various cost differentials. Such estimates are presented in Table 8. Given an estimated subsidence-related cost of \$31.7 million per year, the break-even quantity of surface water (Q_e) declines as the cost difference between surface and groundwater increases (Table 8). However, for all cost differentials below \$250 per million gallons the break-even quantity (Q_e) exceeds the average annual water use of 126.76 bgy in the study area. Assuming that no groundwater may be pumped without resultant subsidence, the values in Table 8 imply that up to a price differential of \$250 per million gallons could be paid to import surface water in order to reduce costs to the study area as a whole.

Savings in total cost to the subsiding area from substituting surface for groundwater would not be distributed equally over all sub-areas. Since subsidence-related costs are concentrated on the immediate coastline (sub-

Table 8. Estimated break-even quantities of surface water at various selected surface and groundwater cost differentials for a given level of subsidence costs.

(1) TEC_s	(2) $(P_s - P_p)$	(4) = (1) ÷ (2) Q_e
(million $)	($/million)	bgy
31.7	160	198.1
31.7	180	176.1
31.7	200	158.5
31.7	220	144.1
31.7	240	132.1
31.7	260	121.9

areas I and II), property owners within these areas would enjoy the greatest reduction in total cost if the substitution of surface for groundwater halted subsidence. Property owners in areas remote from the coastline would experience higher internal, user costs for water, but may not enjoy comparable cost savings since the incidence of subsidence-related costs are relatively low. Given the substantial difference in cost of surface and groundwater, methods of inducement will likely be required to encourage reductions in the use of groundwater.

Other methods of reducing costs to the area, such as limiting water use by recycling or other methods, were not considered in this study. There was considerable evidence from industrial respondents that the adoption of programs to recycle water used in manufacturing and processing is increasing. Since industrial users consume a large share of total water used in the subsiding area, such programs have potential for reducing consumption use of water in the future.

The implications of this study seem clear. Damages and property value losses associated with land subsidence in the Texas Gulf Coast are high and extensive over a large portion of the coastal area. The resulting costs, as estimated in this study, are so high that continued pumping of groundwater at rates that cause subsidence cannot be justified. The pursuit of alternative sources of water to meet area needs and institutional measures for controlling subsidence are fully justified from a standpoint of reducing total costs to the area.

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