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ABSTRACT

In recent years the area around Houston and Baytown, Texas, has been affected to an increasing degree by land subsidence. Sinking of the land surface has reached critical proportions in many areas, and subsidence of as much as eight feet has occurred. The severity of this phenomenon has been aggravated by the proximity of much of the affected area to bay waters, and tidal flooding has resulted in significant damages and property loss.

Subsidence has been linked by engineers to the decline of subsurface water levels due to heavy ground water withdrawals in the area. An alternative source for water demands has been introduced, although price differentials have slowed its acceptance.

Major objectives of this study included estimation of historical costs attributable to subsidence, projecting estimated costs, and examining the economics of the two alternatives for water supply. A study area of 300 square miles was identified and sampling of residences, businesses, and public officials was carried out. The cost data resulting from those samples formed the basis for economic analysis.

Historical costs and property losses that were attributable to subsidence were estimated to be $60.7

million and $48.9 million, respectively, or $109.6 million total. Of the $109.6 million, $53.2 million were incurred in 1973, principally due to a six foot tide. Probability of the occurrence of a six foot tide in any one year is 20 percent. Given five additional feet of subsidence in the study area the occurrence of a six foot tide was projected to cause an estimated $63.5 million in costs and losses, $10.3 million more than were incurred in 1973.

Estimated annual subsidence-related costs and losses of $14.6 million for the study area, based on 1969 to 1973 data, were used to evaluate total costs associated with supplying water needs from two alternative sources. A break-even analysis indicated that to minimize total water costs, pumping only that quantity of water that would result in no subsidence could be economically justified; i.e., water needs or demand above that rate would need to be purchased from an alternative source. This implied that when pumping is continued to the point that subsidence occurs, the cost of pumping plus associated subsidence-related costs and losses exceed water costs from an alternative source, per unit of water.

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INTRODUCTION AND STATEMENT OF THE PROBLEM

The Texas Gulf Coast is being affected to an increasing degree by land subsidence, a term generally applied to compaction of subsurface strata resulting in a lowering of surface elevation. The phenomenon has beenoobserved in other areas, including California and Arizona in this country [8]. A detailed geological explanation of subsidence is beyond the scope of this analysis, but briefly, subsidence of the surface in the area of Harris County, Texas, has been linked to the withdrawal of groundwater [5,6,7].

Within the affected area of approximately 3,000 square miles (Figure 1) subsidence has been substantial--as much as eight feet since 1943. The city of Houston is within the subsiding area, as are Baytown, Galveston, Kemah, Pasadena, Texas City, and other municipalities. In many communities facing Galveston Bay and the Houston Ship Channel, tides encrouch further inland every year. If withdrawals remain unregulated or continue to climb, further subsidence of the land may be expected.

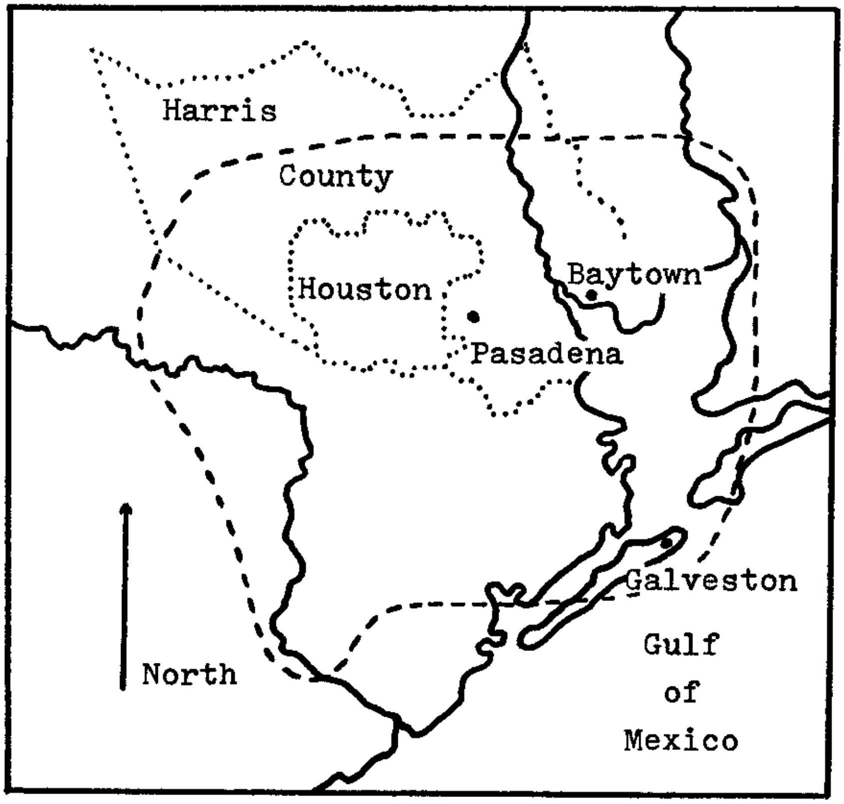

Figure 1. The approximately 3,000 square miles (within dashed line) affected by land surface subsidence in Texas.

Serious problems are thus created for property owners and municipalities. Frequent inundation renders many formerly dry areas virtually useless for residential or commercial purposes, and often results in abandonment of property. Local authorities must continually raise the elevations of roads, repair damages, and construct dikes and drainage facilities. So far the evaluation of alternatives for protective or preventive action for the area has been hampered by a lack of information as to the costs of subsidence.

An initial effort to reduce pumping of groundwater by the diversion of surface water into the area has met with only limited success. The direct cost of the diverted (and treated) surface water to major users is high relative to costs of pumping groundwater. Since no estimates of the private and public costs of subsidence now exist, the real total (direct and indirect) costs of continued unregulated pumping cannot be ascertained. Without such cost information, it is unrealistic to assume that potential purchasers of imported water will be willing to bear the added expense involved.

This and other alternatives for minimizing the effects of subsidence obviously cannot be effectively evaluated without some estimates of subsidence-related costs and projections of estimated future costs attributable to subsidence. There is thus a clear need for such information, and it is anticipated that it might be found useful by federal, state, and local planners; as well as being of interest to private persons and firms directly affected by subsidence.

The general status of the land subsidence problem in Texas is that far more is known about the physical aspects and extent of the phenomenon than is known about its economic impact in the affected area. This general lack of information with respect to economic effects may act to retard effective action to correct the situation.

Review of Literature

Although numerous articles and reports have been directed at the problem of land subsidence in general, and to subsidence on the Texas Gulf Coast in particular, only minor reference has been made to the kinds and extent of damages and associated costs.

In 1956, Poland and Davis reported on the subsidence of land in the San Joaquin Valley in California [8]. In this case, subsidence was a result of groundwater withdrawal for irrigation. Damages were minor due to the inland location. Poland and Ireland recorded a specific effect of subsidence in the shortening and protrustion of a well casing in 1965 [9].

Lockwood examined the phenomenon in the Houston area in 1954, citing declining artesian pressure as a cause [7]. Also in 1954 Winslow and Doyel reported on land subsidence in the Houston-Galveston area [12], attributing the problem at that time to the withdrawal of groundwater for agricultural and industrial uses. Later, in 1959, Winslow and Wood reported further observations in the upper Gulf Coast region [13]. In the past decade Gabrysch has made extensive studies of subsidence in the Texas Coastal areas and has published some projections of future subsidence and other findings with respect to the causes, extent, and physical effects of the phenomenon [4,5,6].

In addition to these and similar publications, numerous newspaper articles have appeared in the Houston area in recent years; and several private consulting firms have prepared studies for use of municipal governments and state agencies. The U.S. Army Corps of Engineers has also been involved in planning for corrective action, resulting in several unpublished reports.

Most of these reports and articles concentrate on the physical causes of subsidence. Some extend their analysis to include effects and cite instances of damage or loss. Some feasibility studies for potential corrective action include cost estimates for putting the plan into effect. With few exceptions, however, no estimates of dollar costs due to subsidence damages are given; and to the knowledge of the author no attempt has been made to isolate and identify these costs on an area wide scale.

Objectives of the Analysis

The purpose of this study is to estimate the costs, both public and private, that are associated with the land subsidence phenomenon in the area of Houston and Baytown, Texas. The specific objectives of this analysis are:

1. To identify the physical effects of subsidence on property in the affected area, and to establish and describe, within the subsiding area, a study area of 300 square miles that exhibits a representative range of land uses, elevations, and relative depths of subsidence.
2. To obtain data from this study area in order to derive estimated public and private costs attributable to land subsidence for the periods 1943-54, 1955-64, and 1965-73.[1]
3. To derive estimates of subsidence-related costs and property losses associated with the storm and tide of September, 1973, and to project estimated future costs and losses

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[1] These particular intervals were chosen because they correspond to periodic leveling surveys performed by the National Geodetic Survey with subsidence maps published by the U.S. Geological Survey (USGS).

for a similar storm and tide under two different assumptions as to the future rate of subsidence.

4. To relate estimated subsidence costs within the observed area to the concept of a "maximum acceptable withdrawal level" in order to consider the economic justification for purchasing surface water as an alternative to withdrawing groundwater.
5. To derive some general implications for the subsiding area as a whole, based on the findings from the sample area, and to relate these implications and some summary comments to suggestions for further research needs.

SOME PHYSICAL ASPECTS OF SUBSIDENCE

In the Houston-Baytown area of Harris County, Texas, where sinking of land due to subsidence is quite critical, the principle cause has been linked to the lowering of pressure heads due to the removal of groundwater [5,6,7].

Geologic formations underlying much of this area are composed of unconsolidated deposits of sand and clay. Subsurface layers of sands and clays are saturated with water, but vertical movement of water is retarded by the clays, Withdrawal of water results in decreases in hydraulic pressure which partially supports the overburden. As a result, permanent compaction takes place in the relatively inelastic clays [5].

At the surface, physical effects of subsidence are largely dependent on the location. Contrary to what might be expected, almost no damages occur as a direct result of subsidence. There are a few isolated reports of damages to well casings, pipe lines, and other structures. Some instances in which subsidence might have aggravated damages due primarily to surface faulting do exist, but generally, direct physical damage due to subsidence is slight.[1] Reports on subsidence in other areas [8] and results of surveys and observations in the study area bear this out.

Almost all costs and losses associated with subsidence in the Houston-Baytown region are indirect in nature. Tidal and freshwater flooding, either temporary or permanent, is reported to be the chief cause of subsidence-related damages. It is convenient to consider these indirect effects in terms of those due to tidal flooding and those due to freshwater flooding.

The subsidence-related effects of tidal flooding are of two major types -- temporary and permanent. Temporary tidal flooding refers to unusual inundation of normally dry areas due to storm tides. Flooding of this kind was quite severe during Hurricane Carla in 1961 and again on a more limited scale during Tropical Storm Delia in 1973. It is obvious that larger areas are being made susceptible to such tides as subsidence continues in the area. Increases in population in many of the subsiding coastal regions plus the

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[1] The subsiding area is also plagued by numerous surface "faults" and any relationship between subsidence and faulting is yet to be conclusively determined.

incidence of subsidence is placing ever greater property values within reach of temporary tidal flooding.

Permanent tidal flooding generally results in total or near total loss. This refers to the actual loss of the use of formerly dry land areas and improvements thereon due to encroachment and inundation by normal tides. As subsidence continues in these coastal areas, more and more property is being overtaken by the sea. Evidence of this is seen in many areas in the Houston-Baytown region and in the subsiding area as a whole, wherever land is adjacent to bodies of water that are affected by the tides.

Subsidence-related effects of freshwater flooding are generally a result of changes in surface slopes that introduce or aggravate drainage problems during heavy rains. Streams, drainage canals, and the watersheds themselves may be affected in this way by subsidence. While damages that are indirectly attributable to subsidence do occur as a result of freshwater flooding, such damages probably comprise a small share of the total, relative to those incurred in tidal areas.

All of these general forms of subsidence-related damages occur within the study area. These damages and costs further give rise to losses in property values, reflecting the susceptibility of more and more areas to flooding damage.

METHODOLOGY AND DATA DESCRIPTION FOR ECONOMIC ANALYSIS

The indirect costs that accrue to the study area as a result of subsidence may be considered negative externalities of the process of groundwater withdrawal. This and the alternative water supply situation suggested the general approach, and the specific techniques for sampling and analysis followed.

Analytical Framework

Theory for Analysis of Alternative Supply

The concept of externalities rests upon consideration of the distribution of social benefits and costs resulting from some economic activity [3]. A demand schedule for a product reflects the prices that consumers will pay for various quantities of the product. Under perfect competition price is equated with marginal cost, and in the absence of externalities marginal cost is the marginal social cost that society must incur to have one more unit produced. Social welfare is at a maximum when the marginal social benefit equals the marginal social cost. However, in some cases, marginal social cost does not equal marginal private cost. In these cases, externalities exist, either positive or negative. Profit maximization implies that price equals marginal private cost under perfect competition. However, maximum social welfare can be achieved only if marginal private cost also equals marginal social cost, for only under this condition are marginal social benefit and marginal social cost equal. An externality arises from a divergence between marginal social costs and benefits. If marginal social cost is greater than marginal social benefit, that externality is negative.

Initially within the affected area, industrial and municipal consumers are using a common water resource. Pumping costs of the last unit of this resource comprise the marginal private cost or direct costs to these consumers. However, there is a set of indirect costs involved. Direct costs plus indirect costs of the last unit of resource used comprise the marginal social costs of pumping water. These indirect costs of pumping are the costs and property losses attributable to subsidence in the area, and can be considered negative externalities.

There exists an alternative source for water supplies which has no negative externalities associated with its use, but the direct costs are higher relative to the common groundwater source. That is, if P_p is the per unit cost of pumping water and P_a is the per unit cost of an alternative water source, then $P_a > P_p$.

To minimize the direct and indirect costs to the area as a whole, a comparison of costs of the two sources of water is made. The approach is to assume the existence of some "maximum acceptable withdrawal rate" at which water pressure and subsidence would be stabilized. This maximum acceptable withdrawal rate (MAWR) is not known, and its estimation is a physical rather than an economic problem. Of greater immediate interest to this analysis is the amount of groundwater withdrawn in excess of this rate, since it incurrs the additional indirect costs of subsidence-related damages. This quantity of water withdrawn in excess of MAWR is called the critical quantity of water demand, Q_c.

If pumping water from an underground source incurred no indirect costs then the total costs of water demanded would be:

$$TC_p = P_p(Q_D) \quad , \qquad (1)$$

where:

TC_p = total cost of water pumped assuming no indirect cost,

P_p = per unit cost of pumping groundwater,

Q_D = total quantity of water demanded.

Equation (1) is represented in Figure 2 by the curve TC_p whose slope is P_p. However, there is an unknown MAWR beyond which any additional critical quantity (Q_c) pumped will incur an indirect cost per unit for land subsidence, P_s. Including indirect costs, equation (1) becomes:

$$TC_{ps} = P_p(Q_D) + P_s(Q_c), \text{ if } Q_D > \text{MAWR}^1 \qquad (2)$$

where:

TC_{ps} = total direct and indirect costs of pumping water,

P_s = subsidence-related costs per unit of ground water,

$Q_c = Q_D$ - MAWR, (critical quantity of water).

A necessary assumption is that all per unit costs be constant at all levels of water demand. Thus, the total quantity of water has a per unit cost of P_p and the additional quantity of water demanded beyond MAWR (Q_c) has an added per unit cost of P_s. This situation involves a kinked total cost curve as shown in Figure 2. Between points 0 and MAWR on the Q_D axis, TC_p is the appropriate total cost curve with slope of P_p.

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[1] $P_s(Q_c) = 0$, if $Q_D \leq$ MAWR.

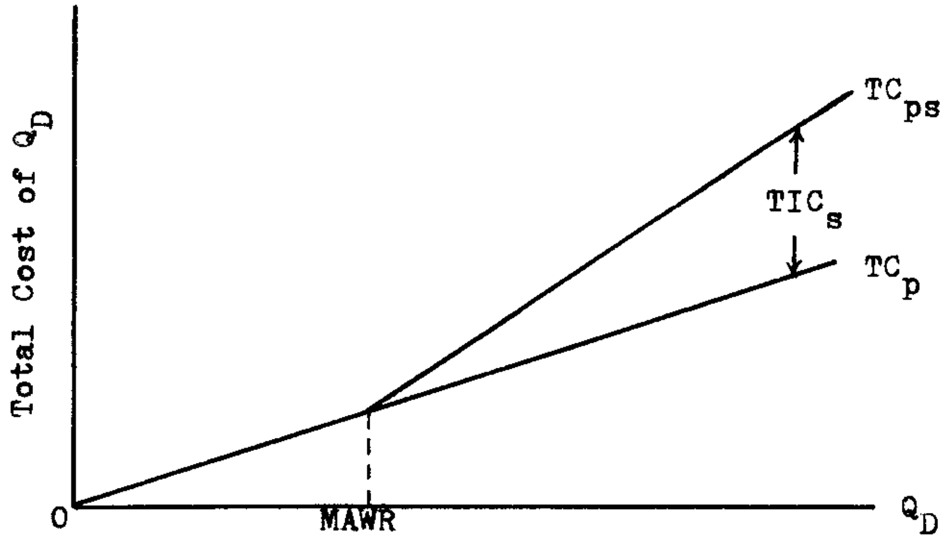

Figure 2. The relationship of MAWR to direct, indirect and total costs of pumping the quantity of water demanded.

Beyond MAWR, TC_{ps} is the appropriate cost curve with a slope equal to $P_p + P_s$.

The total cost equation for the alternative source is:

$$TC_{pa} = P_p(MAWR) + P_a(Q_c), \text{ if } Q_D > MAWR \qquad (3)$$

where:

TC_{pa} = total cost of water demanded when Q_c is obtained from an alternative source,

P_a = per unit cost of water from alternative.

Thus, the per unit cost up to MAWR is P_p and the added quantity demanded beyond MAWR has a per unit cost of

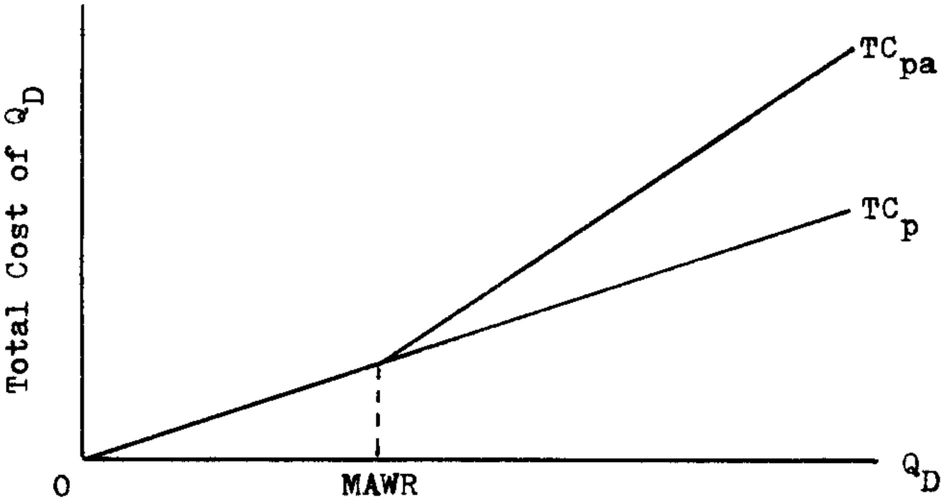

Figure 3. The relationship of MAWR to total costs if the critical quantity of water is purchased from the alternative source.

P_a. This situation is illustrated in Figure 3. Between points 0 and MAWR on the Q_D axis, TC_p is again the appropriate total cost curve, and beyond MAWR, TC_{pa} is the total cost curve.

So long as Q_D is less than MAWR, there exists no economic problem with indirect subsidence costs associated with pumping of underground water. Therefore, the analysis isconfined to a comparison of equations (2) and (3) both of which include a term for the critical quantity of water Q_c. Equation (2) can be rewritten as:

$$TC_{ps} = P_p(Q_c) + P_p\ (MAWR) + P_s(Q_c), \qquad (4)$$

since: $Q_D = \text{MAWR} + Q_c$. (5)

Subtracting P_p (MAWR) from equations (3) and (4), the critical quantity of water may be evaluated in terms of the following relationship:

$$P_p(Q_c) + P_s(Q_c) \lesseqgtr P_a(Q_c) \quad (6a)$$

or $$TC_{ps} \lesseqgtr TC_a. \quad (6b)$$

The three possible situations for this relationship are presented in Figures 4 and 5. Now, as Figure 4 shows, MAWR is assumed known and constant over time, and total demand is Q_{D1}. An underlying assumption is that of linearity of indirect costs per unit of water pumped.

TC_{ps3} assumes that total costs of pumping are less than total costs for purchasing Q_c. This situation implies that continued pumping is justified.

TC_{ps2} is equal to TC_a, suggesting indifference as to the source of Q_c. If this relationship is found to exist, the question of the source of Q_c becomes a legal one, since economics does not suggest a solution.

TC_{ps1} assumes that total costs of pumping Q_c are greater than the total costs of purchasing Q_c, and implies that there is economic justification for the purchase of Q_c from the alternative source.

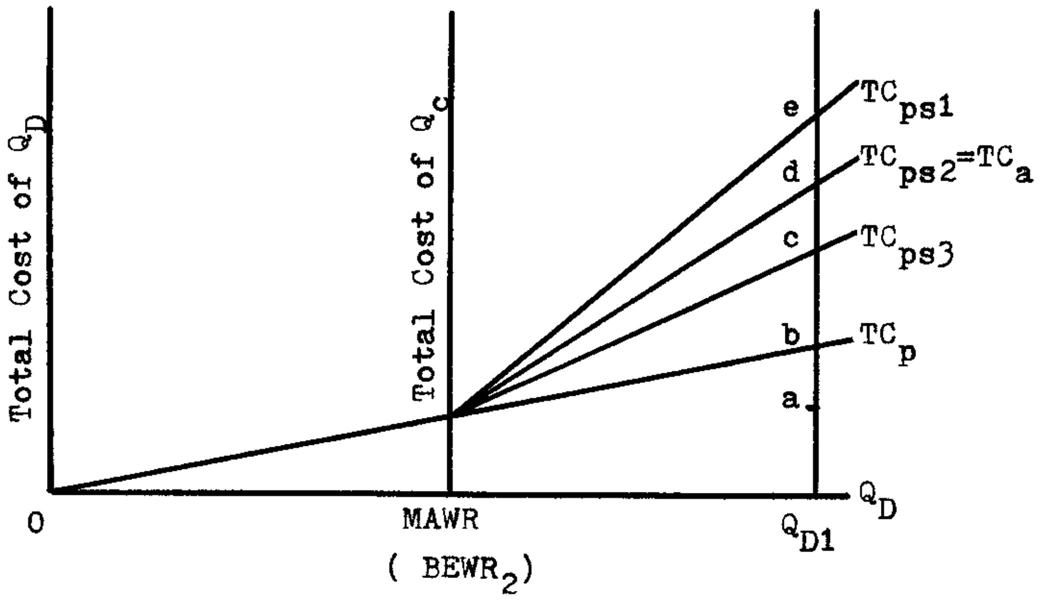

Figure 4. Total costs of pumping related to total cost of purchasing the critical quantity under three conditions.

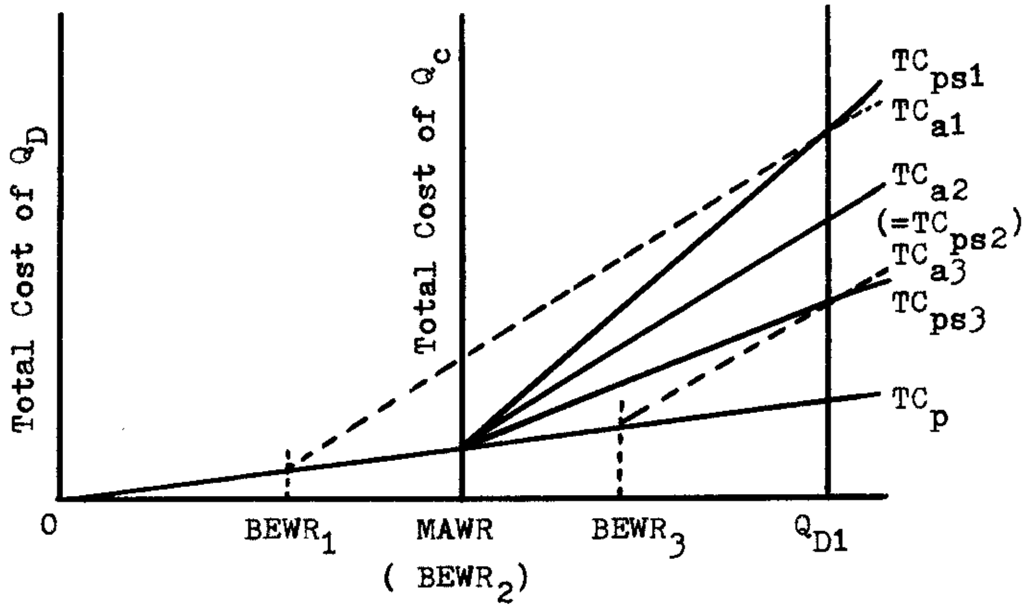

Figure 5. Break-even withdrawal rates and total cost curves as related to alternatives for meeting water demand.

For a hypothetical total demand of Q_{D1}, the direct cost of pumping the critical quantity is ab, and the direct cost of purchasing Q_c from an alternative source is ad. Total direct and indirect costs of pumping Q_c may be ac, ad, or ae, depending on whether TC_{ps} is less than, equal to, or greater than TC_a, respectively.

MAWR and Q_c are not known, but P_a and P_p will be given, and TIC_s which is related to a given Q_c, will be estimated as an annual average of subsidence-related costs. It will be possible to use break-even analysis to estimate an equilibrium critical quantity, Q_{ce}, by holding TIC_s, P_a, and P_p constant. Once Q_{ce} has been estimated, it may be used to estimate a break-even withdrawal rate (BEWR). Since $P_s(Q_c)$ is TIC_s, we can express relationship (6a) as the equation:

$$P_a(Q_c) = P_p(Q_c) + TIC_s, \tag{7}$$

which can be further reduced to:

$$(P_a - P_p)Q_c = TIC_s, \tag{8}$$

or $$Q_{ce} = TIC_s \;/\; (P_a - P_p). \tag{9}$$

In Figure 4, MAWR is equal to $BEWR_2$ if TC_{ps2} is true. That is, if TC_{ps} equals TC_a then Q_c is at an equilibrium and the corresponding MAWR is BEWR.

The procedure for finding BEWR if TC_{ps1} or TC_{ps3} holds true is presented in Figure 5. The reader is reminded that there can be only one TC_{ps}, one TC_a, and one BEWR for any given Q_D, even though three alternatives are presented in Figures 4 and 5. Given total demand Q_{D1} and MAWR, if TC_{ps} is greater than TC_a at Q_{D1}, then BEWR exists to the left of MAWR. The point where TC_{ps} equals TC_a at Q_{D1} determines $BEWR_1$. The slopes of the three TC_a curves in Figure 5 are equal, so for TC_{ps1}, the TC_p curve will be intersected by TC_{a1} to the left of MAWR.

If TC_{ps} is less than TC_a for Q_{D1} and MAWR, then BEWR will be found to the right of MAWR. This cost relationship is illustrated by TC_{ps3}, TC_{a3}, and $BEWR_3$.

Since MAWR is not known and must be determined by engineering research, the estimated BEWR becomes an important tool for comparing the costs of pumping Q_c with the costs of purchasing Q_c. For example, consider TC_{ps2}. $BEWR_2$ is the break-even withdrawal rate. A MAWR exists somewhere to the left of Q_{D1}. If engineers set MAWR to the left of $BEWR_2$, TC_a would shift up to TC_a', a level above TC_{ps2}, and continued pumping of groundwater would be economically justified for all of Q_D. If MAWR is set to the right of $BEWR_2$, then TC_a, since its slope must remain constant, would shift down (to the right) and there would be economic justification for purchasing surface water to meet Q_c.

Techniques for Projecting Costs and Property Losses

Projections of estimated costs are made for the future assuming additional subsidence, since most experts [5,6] expect continued subsidence. The total additional depth of subsidence at future times is assumed to be constant across the study area, to make economic analysis simpler, although the accumulated (1943 to 1973) depth of subsidence varies widely.

The projections estimate subsidence-related damages and property losses at future subsidence levels given the occurrence of a storm and tide similar to those which took place in the study area in 1973.

Quite complete cost data were associated with Tropical Storm Delia in 1973, since memory loss and post-storm changes in residency among respondents had not yet become factors in the reliability of the responses.[1] Since these data were available, and since

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[1] These two factors probably resulted in significant underestimates of damages associated with the Hurricane (Carla) which occurred in 1961.

they were associated with Delia, a six foot tide was chosen as a condition for the projections.

Two procedures were used to project estimated costs due to subsidence-related damages to private property. First, since most of the base year (1973) cost data were associated with flooding by six foot tides, the sampled areas were divided on the basis of location relative to tidal waters. This process is demonstrated in the hypothetical cross-section of an area affected by subsidence, as diagrammed in Figure 6. At time T the land surface is at elevation E. Some subsidence is assumed to have already occurred, causing some related permanent tidal flooding at point A, temporary tidal flooding at point A', and minor damage from freshwater flooding at point B. At A'' no subsidence-related damages are occurring at time T.

If at time T' the land surface subsides by x feet uniformly throughout the area to elevation E', the land surface from A to A' will experience permanent tidal flooding, and unusual tides will result in temporary tidal flooding at point A''.

Heavy rainfall associated with such a tide may result in practically the same minor amount of freshwater flooding and damages at point B as occurred at

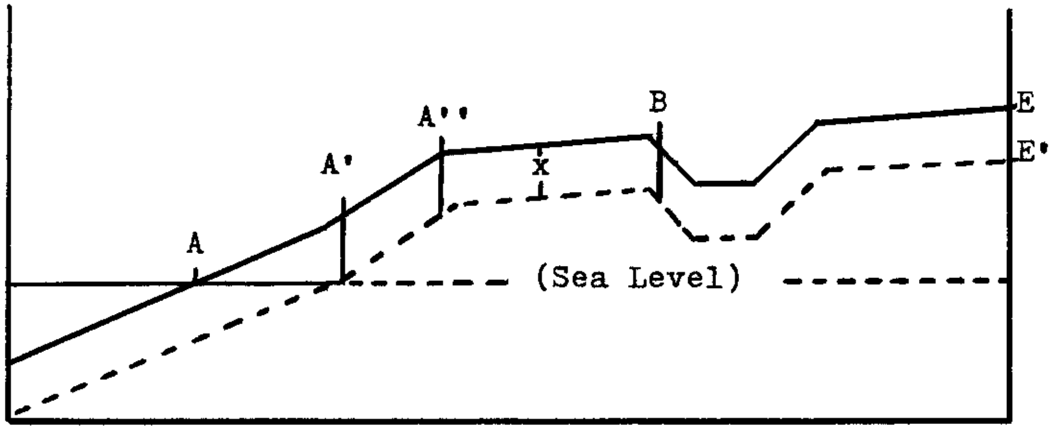

Figure 6. Schematic diagram of effects of a unit increment to subsidence on areas affected by tidal flooding and freshwater flooding.

time T. This is based on the assumption that the increment to subsidence is geographically uniform. Hence, for the purposes of this analysis, the subsidence-related damage associated with a tide and storm in areas not affected by tides is assumed to be constant regardless of time period or depth of subsidence.

For those areas affected by the tides (situated on a bay, bayou, or channel) an "engineering" or topographical approach is used to project subsidence related costs (Figure 7). The projections relate to damages within land areas experiencing flooding conditions in the 1973 tide. The area inundated in 1973 is first estimated, using USGS maps showing elevation

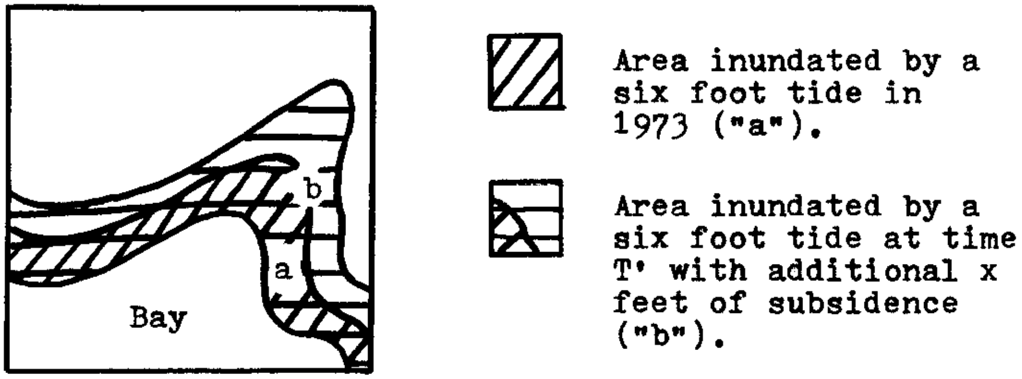

Figure 7. Procedure for applying engineering approach to projecting relative areas of inundation, 1973 and time T'.

contours, by use of a polar planimeter.[1] The planimeter is then used to estimate the area that would be inundated by a similar tide with an additional increment to subsidence. The ratio of the latter area to the original area is used as a multiplier of 1973 costs to project estimated costs associated with a six foot tide and some new level of subsidence at time T'.

From Figure 7, area "a" may be represented by z and "b" can be expressed as y. Damages associated with the six foot tide in 1973 are multiplied by the ratio y/z to obtain the projected estimate of damage associated with a six foot tide at time T'. This

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[1] A planimeter is a mechanical engineering device that can be used to compute areas on a map or plane.

procedure is carried out for each of the sampled land areas that is adjacent to waters affected by tides. It should be recognized that since variations in the depth of the water across temporarily inundated areas are ignored, these projections probably underestimate costs.

Those property losses associated with the areas which become subject to permanent tidal flooding with the added subsidence are partially reflected in the original (1973) and projected property loss estimates.

Property losses for those areas affected by the tides were expressed as a function of subsidence related damages associated with the six foot tide in 1973. This function may be expressed as:

$$PLOSS_i = f(DAMAG_{73i}), \qquad (10)$$

where:

PLOSS is estimated property loss and $DAMAG_{73}$ is estimated damage attributable to subsidence for 1973. The subscript i refers to the sample area.

Under the assumptions of this analysis, property loss in those areas not affected by the tides remains constant as long as subsidence remains uniform. All computations are in terms of 1973 dollars.

The Data

In order to identify the economic effects of subsidence in the study area, discussions were held with various municipal, county, and federal authorities with respect to the delineation of a satisfactory sample area within the overall subsiding area. Their suggestions were also solicited in regard to the most practicable method of sampling within that area, and the construction of the survey questionnaires. A study area of 300 square miles was selected from the affected area of over 3,000 square miles.

The Study Area

The study area from which samples were drawn is located near the geographical center of the affected area (Figure 8). The area is a fifteen by twenty mile rectangle extending from eastern Houston to the center of Baytown on its longest (East-West) axis. Subsidence ranges from about 3.0 feet to approximately 7.9 feet in the vicinity of the Washburn Tunnel. Elevation in the area ranges from sea level to over 50 feet. A wide range of land uses are represented, including

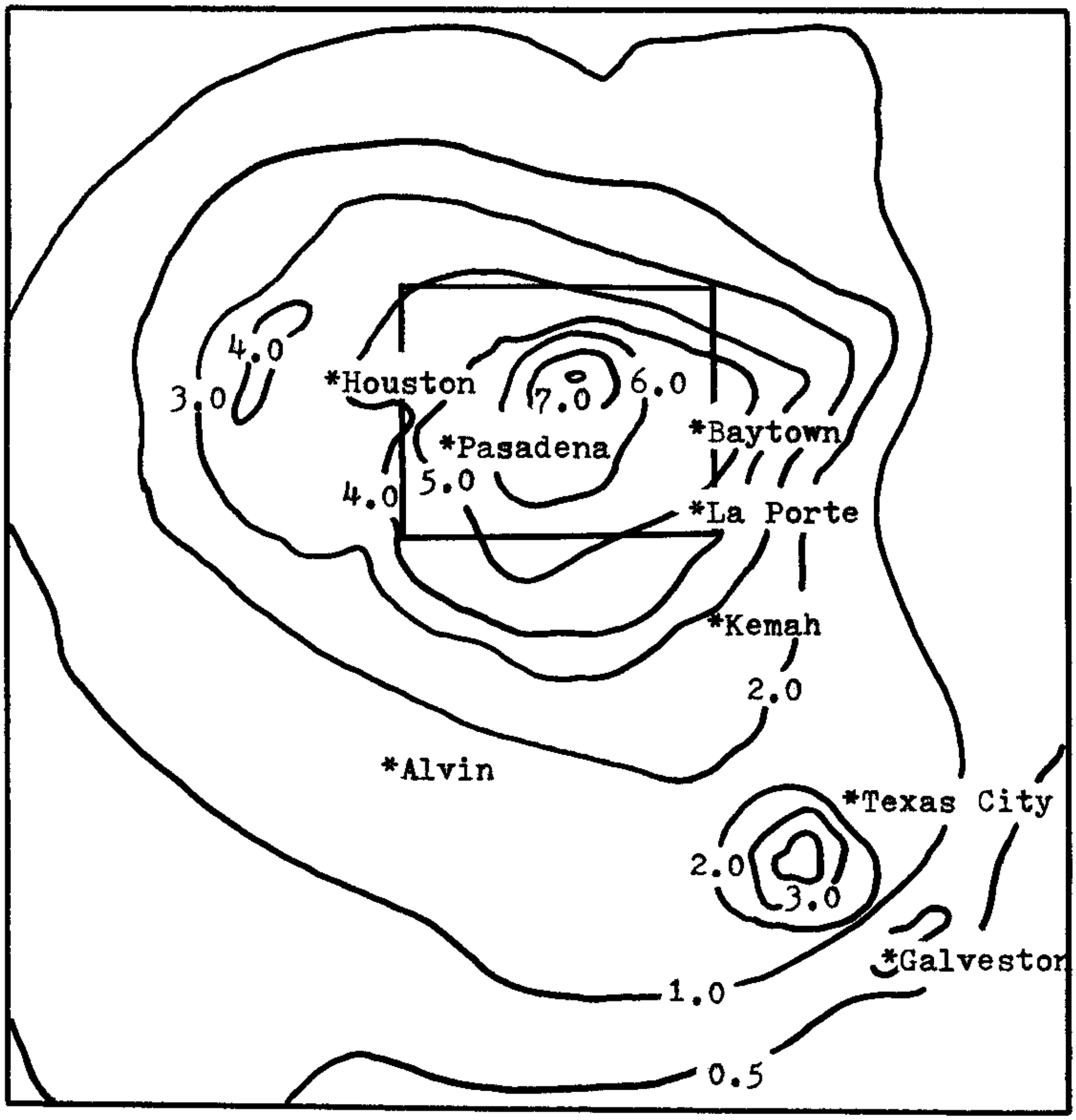

Figure 8. Subsidence of the surface (contour lines in feet) in the area of Houston and Baytown, 1943 to 1973, and the approximate location of the study area.

Source: Adapted from [10, Figure 9].

residential, commercial, heavy industrial, and agricultural.

Preliminary consultations with engineers and others in the area suggested that by far the greatest share of subsidence related damages would be due to flooding, either tidal or freshwater. Although, as indicated in Figure 8, subsidence is extensive geographically, direct structural damages therefrom are minor. At surface elevations unaffected by flooding, subsidence levels of several feet may be unnoticed. If detrimental at all it is likely to be so only at a nuisance level with respect to drainage problems. There are exceptions, of course, especially along some of the bayous and canals. But, structural damages due to subsidence are rare, as the differences in the depth of subsidence over a given area of land surface occur gradually. Sharp changes that would cause cracking or shifting of a building, for instance, seldom occur.[1] This pattern strongly suggested a stratification of the sample area based on elevation.

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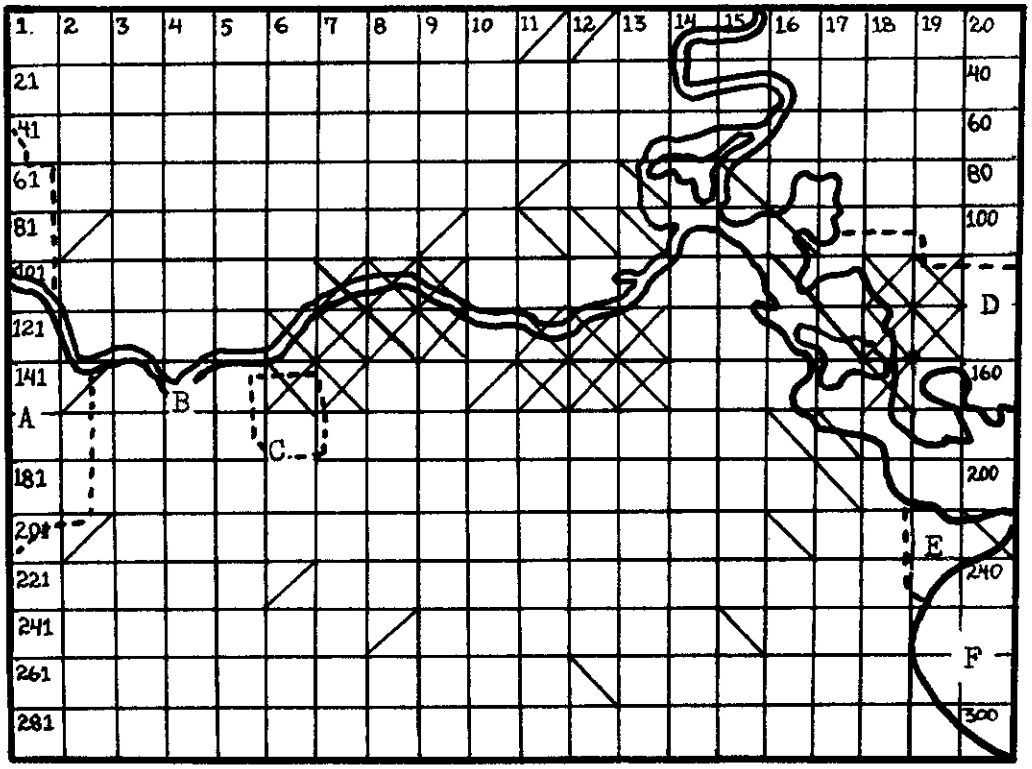
[1] This type of structural damage is often encountered in the area, but is generally attributed to surface faulting.

The Stratification and Sampling Procedure

The sample area was divided into 300 one mile square blocks for purposes of drawing the stratified random sample. Each block was numbered and identified as to the surface elevation of land within the blocks (Figure 9). Two strata were used for the sample - those with significant land areas below an elevation of 25 feet and those with over one-half the land area above 25 feet. Also, three industrial areas containing a total of 19 blocks located along the Houston Ship Channel and in Baytown were withdrawn for 100 percent sampling of the industries located therein. The remaining 281 blocks were divided between the lower and higher strata, 88 of them falling below 25 feet and 193 above that elevation (Table 1). Due to their location in the bay or on "channel dredgings", ten blocks were omitted from the lower elevation stratum.

Sample blocks were drawn in a random manner from the two strata. From above 25 feet, 11 squares were drawn. Since it was hypothesized that more damages would occur at lower elevations, a heavier sample of 16 squares was taken from the below 25



⧅ Sampled areas below 25 feet elevation (16)

⧄ Sampled areas above 25 feet elevation (11)

⊠ Industrial areas sampled (19)

A: Houston B: Ship Channel
C: Pasadena D: Baytown
E: La Porte F: Galveston Bay

Figure 9. The approximate study area, showing the grid, numbering system, and areas sampled in residential, commercial, and industrial areas; and location of major cities.

Table 1. Stratification of the 300 one mile square blocks within the study area.

Below 25' (78)	Above 25' (193)	Industrial (19)	Omitted (10)
13, 14, 33-35, 54, 55, 67, 73, 75, 76, 87, 88, 91-97, 101, 102, 112-114, 116, 117, 120, 122, 125, 126, 130, 135, 137, 140, 144, 145, 156, 159, 176-180, 197-200, 236-239, 252-258, 272-278, 293-299.	1-12, 15-32, 36-53, 56-66, 68-72, 77-86, 89, 90, 98-100, 103-106, 110, 111, 121, 123, 124, 134, 141-143, 148-150, 154, 155, 160-175, 181-196, 201-215, 221-235, 241-251, 261-271, 281-292.	107-109, 119, 127-129, 131-133, 138, 139, 146, 147, 151-153, 158.	74, 115, 136,157, 240, 259, 260, 279, 280, 300.

feet stratum. The 46 squares withdrawn for the survey of private costs are shown in Figure 9.

It appeared from preliminary visits that damages at higher elevations would be extremely small, and that interviewing at the rate of five percent of businesses and five percent of homes within these areas would be satisfactory, especially since a high degree of homogeneity within squares was noted. An interview rate of ten percent was chosen for those areas below 25 feet.

Three questionnaires were developed for interview purposes. Series I (Figure 1, Appendix B) forms were designed for use in surveying residences. The first two questions establish the respondent's awareness of subsidence and the existence (or nonexistence) of damages attributable to subsidence, respectively. A check list of possible damages is presented, with spaces to note the date of appearance, type or extent of damage, date repaired, and cost of repair (or value if not yet repaired). Final questions deal with the type, age, and market value of the dwelling; and estimates of the effects (if any) of subsidence on the market value of the property.

The Series II form (Figure 2, Appendix B) was designed for surveying commercial enterprises. It is basically the same type of questionnaire as the Series I, and seeks the same types of information, although it is somewhat longer and more detailed to allow for the larger variety of size and type among commercial establishments.

The questionnaire for identifying public costs is Series III (Figure 3, Appendix B). The thrust of the questions is similar, but aimed at costs relating to public facilities.

All three forms underwent numerous modifications before reaching the final form. Suggestions were sought from economists, engineers, and statisticians; and although not every suggestion could be incorporated, the questionnaires do reflect the comments of many. In general, all three are designed to allow an accounting by year, type, and extent, of those damages and losses that can be identified as attributable to land subsidence.

Potential enumerators were screened at the University of Houston and four were employed through a commercial interviewing service. Preliminary to interviewing, training sessions were held to familiarize the enumerators with the general objectives of the research and to emphasize the importance of being complete and accurate. Enumeration of residences and businesses began in the fall of 1973.

The 27 randomly drawn squares were sampled systematically, at the five and ten percent rates for areas above and below 25 feet, respectively. Every tenth home and every tenth business was interviewed within each square below 25 feet, for example. Attempts were made to interview all industries within the three industrial areas, and to obtain all public costs for the entire 300 square mile area.

Using the above sampling procedure, 366 Series I (residential) forms, 45 Series II (commercial and industrial) forms, and 30 Series III (public sector) forms were completed. The data obtained from these 441 interviews are the basis for the analysis in this report.

Procedure for Expanding Data

Since most of the data were based on a sample, it was necessary to expand reported costs, losses, and property values in a sample to overall values for the total block. Data expanded to the sample block were summarized on a sample evaluation form (Figure 4, Appendix B). These forms provide a summary of expanded data and a breakdown of information between residential and commercial responses for each sample block.

The expansion procedure was the same for both homes and businesses. For example, if 96 residences were noted in sample area A, and if area A was below 25 feet elevation, a 10 percent sample (ten residences in this case) was interviewed. These 10 interviews or completed Series I forms provided the basis for expansion. If the 10 sampled residences had a total value of $200,000.00, then the average value per residence of $20,000.00 was multipled by 96 to estimate total residential property value in area A. This same procedure was followed for estimating subsidence-related costs within each time period as well as for estimating losses in property value among residences in area A.

This same procedure was applied for those areas above 25 feet, but the sampling rate was five percent instead of ten. Although this technique was more time consuming, it is felt that it was more accurate than the simpler method of multiplying raw totals in each square by 10 or 20, depending on whether a 10 or five percent sample was taken.

In order to estimate values for the 300 square mile study area as a whole, data from the 27 sample evaluation forms were expanded by stratum (above and below 25 feet elevation). With respect to the below 25 foot stratum, 16 blocks were sampled out of a population of 78. Totals estimated by expanding sample data for property value, property loss, damages (by time period), and total damages and losses were summed for the 16 sampled blocks. The sum for each value or cost category was then divided by 16 to derive average estimated values per sample square. This figure was multiplied by 78 to estimate totals for the stratum.

Applying the same procedure to areas above 25 feet, 11 blocks were sampled from a total population of 193 blocks. In a similar manner damages and property value were estimated for the industrial samples. Since a concentrated effort was expended to obtain a 100 percent sample of the public sector for the study area, costs due to subsidence on Series III questionnaires were summed.

RESULTS AND APPLICATIONS

Estimated Private and Public Costs -- Historical

Interviewing for this study was completed in the early spring, 1974. Over 400 questionnaires were utilized during the survey, and the resulting data were expanded by sample square and within strata (above and below 25 feet elevation) to estimate both costs and property losses due to subsidence for the study area.[1]

The estimated damages due to land subsidence, by time period, and losses in property value at the time of the interview as expanded to the total study area are presented in Table 2. Reported damages include primarily those caused by tidal and freshwater flooding. Subsidence-related damages to both real property and personalty, and losses in property value were reported.

These results indicated that the estimated costs of subsidence-related damages in the areas have risen sharply in recent years. From reported damages of

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[1] Costs (damages) were compiled by year of occurrence on questionnaires, and were combined to conform to the three time periods (1943-54, 1955-64, and 1965-73) during expansion. Property losses were all reported relative to 1973.

Table 2. Estimated total private costs and losses attributable to subsidence for the period 1943-1973, in the area of Houston and Baytown, Texas.

Category	Below 25 Feet	Above 25 Feet	Industrial	Overall
	---------------------------------	-------Dollars-------	---------------------------------	
Damages 1943-54	8,775			8,775
Damages 1955-64	1,408,875	4,825,000	600,000	6,833,875
Damages 1965-73	6,446,223	42,875,826	4,512,000	53,834,049
Damages 1943-73	7,863,874	47,700,826	5,112,000	60,676,700
Losses in Value of Property	19,538,025	29,428,112		48,966,137
Total Damages Plus Losses	27,401,899	77,128,938	5,112,000	109,642,837
Property Value	111,396,967	3,987,801,248	1,809,000,000	5,908,198,215
Property Losses as a percent of Value	17.5%	0.74%		0.83%

$8,775 in the period from 1943 to 1954, estimated costs increased to over $53 million for the period from 1965 to 1973. Such large increases probably reflect not only continued subsidence and increasing overall property values, but the fact that memory failure and residency changes affect responses for earlier years.

With respect to the three industrial areas, the goal was a 100 percent sample. However, it was possible to obtain responses from only 33.3 percent of the large industries. Total estimated damages suffered by industry due to subsidence since 1943 were an estimated $5 million. These damages included some permanent flooding of industrial facilities adjacent to the Houston Ship Channel, resulting in the need for raising and rebuilding. Some damages due to temporary flooding during high tides are also reflected in this total. Although there is no basis in this study for challenging this damage figure, it appears to be somewhat understated in view of the large property value and generally low elevation of many of the industrial areas.

Total estimated private damages and losses in property value attributable to subsidence in the area since 1943 total over $109 million, with public costs estimated at over $4 million as a result of subsidence.

The figure for public costs is almost certainly an underestimate, since in many cases public officials reported damages attributable to subsidence but were unable to isolate the costs involved in repairs or replacement. The figure does not include payments made to property owners under governmental flood insurance programs, since such damages are reflected in reports of private costs.

The damage estimates for the period from 1943 to 1973 indicate that total damages and property losses have been higher in areas above 25 feet elevation (over $77 million) than in areas below 25 feet ($27.4 million). However, as a percentage of property value, losses in areas below 25 feet far exceed those from areas at higher elevations (17.5 percent as compared to 0.74 percent). Among the factors reflected in the high total costs for areas in the above 25 foot stratum is that many of the sample blocks in this stratum contain some land areas adjacent to bayous or channels which are affected by the tides. Such areas were shown to be highly susceptible to flooding damages and property losses attributable to subsidence. The analysis shows that in residential-commercial areas below 25 feet the greatest economic impact of subsidence is property loss.

Property loss may result either from physical loss due to permanent inundation or from economic loss due to declining market values. As subsidence causes property to become more susceptible to flooding damages, market value tends to decline. The observed incidence of such losses in sample blocks from the above 25 foot stratum strongly suggested that elevation might not have been the best basis for stratification. A reclassification of samples on the basis of proximity to bodies of water affected by tides was apparently more appropriate, since subsidence-related damages were primarily associated with flooding. This classification became a key to the process of projecting estimated costs and losses which follows.

Comparisons of the relative awareness of respondents with respect to subsidence, and of the incidence of subsidence-related damages are made in Table 2, Appendix A. Over 90 percent of homeowners and all businessmen located below 25 feet elevation were aware of subsidence, compared to 74 percent and 78 percent, respectively, for residential and commercial respondents above 25 feet. About 57 percent of all respondents at low elevations and 34 percent at higher elevations reported damages or losses due to subsidence. Overall, 39 percent of respondents in the study area reported some subsidence-related damages.

Projecting Subsidence-Related Damages and Property Losses

The procedure of projecting costs and property losses was related specifically to the occurence of a six foot tide. This was done for several reasons, but primarily because of the dependability of historical cost data associated with a six foot tide. A six foot tide occurred in the study area just prior to sampling, and reliable estimates of damages and property losses were available. Moreover, since subsidence-related damages are chiefly flood-related, the most significant costs may be expected to be associated with conditions causing high tides. Hence, the projections are limited to those damages and losses that may be expected to occur at different future rates of subsidence and the reoccurrence of a six foot tide. Such a tide can be expected to occur about once every five years (Table 1, Appendix A).

Projections of subsidence made by Gabrysch [5] for the area of Burnett, Scott, and Crystal Bays, near Baytown, were used to develop projections and costs. While not coinciding perfectly, the area treated by Gabrysch lies within and comprises a large part of the 300 square mile study area.

Gabrysch made projections under two different assumptions as to water pressure decline.[1] The first assumption was that artesian pressures in the aquifers affecting the area will decline at a rate of six feet per year until 1980, and that thereafter no further declines will occur. The second was that artesian pressures will be stabilized by 1995, after declining at a rate of six feet per year from 1970 to 1995.

The projected depths of subsidence therefore differ after 1980 (Table 3, Appendix A). Under the assumption of stability in 1980, an average of approximately two feet of additional subsidence is projected to occur between 1973 and 2000.[2] For this analysis,

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[1] Water pressure decline alone is not subsidence, although subsidence is linked to declines in water pressure. For example, one foot of decline in artesian pressures might be associated with one inch of surface subsidence.

[2] Gabrysch applied his projections to a specific case. This procedure assumes a more general application.

the first assumption was associated with an assumed increment to subsidence of two feet by 2000, and this increment was to be uniform across the study area.

Under Gabrysch's second assumption, additional subsidence of about five feet is expected by 2000. For this analysis, a uniform increase in subsidence of five feet was associated with the second assumption.

Projecting Damages

Since projections were to be made based on tidal damages, a classification of sample areas based on proximity to tidal waters was made. Those areas affected by tides were evaluated using an engineering approach to project damages and related costs. For example, suppose sample area B is affected by tides and incurred $1000 in subsidence related damages in the 1973 tide. The engineering approach indicates that under similar tidal conditions but with two added feet of subsidence, 1.45 times as much land in area B will be inundated as was flooded in 1973 by Delia.[1]

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[1] The multiplier 1.45 represents the ratio of the land area expected to be inundated by a six foot tide with two added feet of subsidence to the land area inundated by a six foot tide in 1973.

The projected damage with a six foot tide and two additional feet of subsidence would be an estimated $1450 for area B. If five more feet of subsidence would flood 2.1 times as much land area as was flooded in 1973, then the projected estimate of costs in area B would be $2100.

Sample areas not affected by tides, all of which are above 25 feet elevation, are assumed to be affected by associated heavy rainfall, if at all. For these areas, the damages reported in 1973 are assumed to remain constant regardless of future subsidence, since all projections are made in terms of 1973 dollars.

All areas reporting damages due to subsidence in 1973 were evaluated using these two procedures, and the results from sample blocks were expanded to apply to the study area (Table 3).

Projecting Property Losses

Losses in property value, like damages, are assumed to remain constant for those sample areas not affected by tides (above 25 feet elevation). However, those areas subject to the effects of the tides are expected to experience increasing property losses as more subsidence-related damages occur.

Table 3. Historical and projected estimates of subsidence related damages and property losses associated with a six foot tide in 1973, and at some future time with two and five more feet of subsidence in the Houston-Baytown area.

Subsidence	Damages	Property Losses	Total
1973 level	$ 9,275,780	$43,912,235	$53,188,015
1973 plus two feet	11,110,372	43,308,450	54,418,822
1973 plus five feet	13,488,340	50,014,258	63,502,598

Property losses associated with the six foot tide and added subsidence are calculated using an equation derived through regression analysis. Property loss was expressed as a function of subsidence-related damages, and the estimated equation is:

$$PLOSS_{ij} = \$97,746 + 2.82\ DAMAG_{ij}$$

where:

PLOSS is estimated property loss,
DAMAG refers to damages,
i ($i = 1,2, \ldots 14$) refers to the sample block, and
j refers to the subsidence level (j = 1973, 1973 + 2 feet, 1973 + 5 feet).

Again considering the hypothetical sample area B, if damages with two more feet of subsidence were projected at $1450, then property loss in area B would be estimated at $97,746 plus 2.82 ($1450), or $101,835. Property losses due to five more feet of subsidence and associated with the projected damages of $2100 would be estimated at $97,746 plus 2.82 ($2100), or $103,668.

For every area affected by tides and reporting damage, this equation was applied, and results were expanded to the area as a whole. Several unusually high property losses were reported in 1973, and the expanded total for the base year was therefore slightly larger than the total estimated with two more feet subsidence (Table 3).[1] Estimated property losses increase considerably above 1973 estimates with five more feet of subsidence. Total damages plus property losses increase under both of the subsidence rate assumptions.

Property losses are assumed to be cumulative, up to the value of the property. It is understood that part of the property loss associated with a six foot tide with two and five more feet of subsidence will already have occurred before the tide is assumed to occur. As subsidence takes place in the intervening years, property loss will occur, since more and more property will become susceptible to permanent and temporary flooding by tides.

The Projections

Damages and property loss in 1973 and projected with two and five additional feet of subsidence are

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[1] Minor interpretative value can be attached to this occurrence, as it is a result of statistical error associated with using a regression model for projections.

presented in Table 3. The projections are estimated subsidence-related damages and property losses in the private sector associated with a six foot tide.

A tide such as the one which occurred with Tropical Storm Delia in 1973 and upon which these projections are based can be expected to occur about once in every 5.1 years (Table 1, Appendix A). However, the projections presented in Table 3 are related to additional depths of subsidence, rather than an assigned time period. Variations in water pressure decline could result in the occurrence of two (or five) feet of additional subsidence within any reasonable time period. The magnitude of losses from a six foot tide at those specific subsidence levels is of interest in the projections.

Estimated private damages and losses associated with the six foot tide in the area can be expected to surpass $54 million, given two more feet of subsidence. This includes damages of over $11 million and property loss of over $43 million. Total damages and losses exceed those reported for 1973 ($53,188,015) by over $1 million (Table 3).

Estimated private damages and losses in the area with a six foot tide given five additional feet of subsidence could exceed $63 million, compared to $53 million with two added feet of subsidence. Approximately $13.5 million of the $63 million can be attributed to damages, a 45 percent increase over the $9 million in damages estimated for 1973, and a 21 percent increase over the $11 million estimated for two added feet of subsidence (Table 3). Property losses are estimated at $50 million, representing a 14 percent increase over property loss in 1973 and a 15 percent increase over the estimates for an additional two feet of subsidence and six foot tide. Total damages and property losses estimated at over $63 million for five additional feet of subsidence represent an increase of nearly 20 percent over the damages and losses estimated to have occurred in 1973.

The reader is cautioned that projections based on a six foot tide and two or five feet of subsidence cannot be considered applicable to eight or eleven foot tides at the current time. The reason is that some permanent flooding takes place with the additional subsidence. For instance, an eleven foot tide in 1973 represents about eleven feet of temporary flooding, relative to 1973 elevation. Theoretically, a six foot tide with five more feet of subsidence represents five feet of permanent flooding and six feet of temporary flooding.

The Real Costs of Unregulated Pumping

Groundwater Withdrawals -- Historical

The rate of groundwater withdrawal has increased sharply due to continued urbanization and industrialization within Harris County. In this general area, recent years have been characterized by rapid growth in residential, commercial, and industrial sectors. For example, the population of Harris County increased by over 40 percent, from 1.24 million to 1.74 million, during the ten years from 1960 to 1970; and the populations of Baytown and Pasadena increased by 56 percent and 52 percent, respectively, in the same period [1]. Increases in the rate of groundwater use have accompanied this growth. Groundwater withdrawals in the Houston, Pasadena, and Baytown - La Porte areas have increased dramatically in recent years. A summary of groundwater withdrawals from 1968 to 1972 in these areas is presented in Table 4. Daily withdrawals in the study area have increased from 198.7 mgpd in 1960 to 345.8 mgpd in 1972, a 74 percent increase. The positive relationship

Table 4. Estimated daily and annual groundwater withdrawal in the area of Houston, Pasadena, Baytown and La Porte, Texas, 1968 to 1972.

Item	1968	1969	1970	1971	1972	Five-Year Average
	------------------Million Gallons------------------					
Daily	307.3	311.0	319.9	344.7	345.8	325.74
Annual	112,165	113,515	116,764	125,816	126,217	118,895

Source: Compiled from [4] and updated withdrawal schedules provided with [4].

between groundwater withdrawal and land subsidence has been well established [5,6,7] and alternative sources to meet increasing demand have been proposed. Most prominent among these is the scheme to substitute water from surface supplies for groundwater.

The Coastal Industrial Water Authority (CIWA) project was developed to import and distribute surface water from Lake Livingston, and thus reduce groundwater withdrawals. The objectives of this project include the substitution of surface water for groundwater in quantities sufficient to stabilize declining pressure heads and therefore subsidence. A review of relevant reports did not reveal any professional estimates of the rate of withdrawals at which such stability might occur.

A large quantity of surface water has been made available to the area through the CIWA project. The primary obstacle to the rapid substitution of this surface water for groundwater is cost to the user. The cost of groundwater is from four to six cents per 1,000 gallons, including well operation and maintenance costs. Surface water of equivalent quality costs the consumer from 14 to 18 cents per 1,000 gallons, of which four to six cents is for purchase and 10 to 12 cents for treatment [11].

Economic Analysis and Maximum Acceptable Withdrawal Rate

Although not yet accurately defined, it is generally agreed that there exists a withdrawal rate at which water pressure and subsidence would be stabilized. This rate of withdrawals is most important, since the amount of withdrawals above this rate gives rise to the indirect costs associated with subsidence. Such subsidence-related costs and losses were estimated for the study area for the five year period from 1969 to 1973 (Table 5). The annual average cost of subsidence was estimated to exceed $14 million during this period. These costs are applicable only to that quantity of annual groundwater withdrawal greater than the maximum amount that can be withdrawn with no subsequent decline of water pressure.

The economic feasibility of importing surface water in substitution for groundwater may be analyzed by comparing the direct and indirect (subsidence-related) costs of pumping to the costs associated with purchasing surface water, for that quantity of water that exceeds the maximum acceptable withdrawal rate. Basic to the analysis is equation (9):

$$Q_c = TIC_s / P_a - P_p \, , \qquad (9)$$

Table 5. Estimated costs and property losses related to subsidence in the area of Houston, Pasadena, Baytown and La Porte, Texas, 1969-1973.

Sector	Total Costs 1969-1973	Property Losses	Total Costs and Losses
Residential - Commercial	$21,294,643	$48,966,137	$70,260,780
Industrial	37,186		37,186
Public	2,701,500		2,701,500
TOTAL			$72,999,466
FIVE-YEAR AVERAGE			$14,599,893

which states that the break-even critical quantity (Q_c) is equal to the total indirect (subsidence-related) costs of pumping Q_c divided by the difference between the price per unit of surface water and the price per unit of groundwater. In this analysis, Q_c is expressed in million gallons per year, since TIC_s is an annual cost. It is assumed that prices per 1,000 gallons are 16 cents and five cents for surface water and groundwater, respectively. As applied to one million gallons, P_a is \$160 and P_p is \$50. Since TIC_s is estimated at \$14,599,893 (Table 5), and $P_a - P_p$ is \$110, Q_{ce} is estimated to be:

$$\frac{\$14,599,893}{\$110} \quad \text{or 132,726 million gallons per year.}$$

This implies that under current prices and with the estimated annual subsidence-related costs, the purchase of a Q_c of up to 132.7 billion gallons of surface water a year would be economically justified.

The magnitude of the calculated break-even Q_c is perhaps the most significant finding of this analysis. A break-even withdrawal rate (BEWR) corresponding to Q_{ce} may be estimated for this case by subtracting Q_{ce} from total demand (Q_D). However, Table 4 shows that a recent five-year annual average for total withdrawals is 118.8 billion gallons, a figure well below the 132.7 billion gallons calculated as Q_{ce}. Moreover, the highest reported withdrawal for the area (126.7 billion gallons in 1972) is over six billion gallons below Q_{ce}, the quantity that could have been economically imported based on relative prices and total indirect costs for the period. As indicated earlier, MAWR was unknown. But this analysis implies that so long as total quantity demanded in the area did not exceed MAWR plus the estimated break-even quantity (Q_{ce}) of about 132 billion gallons per year, then at least Q_c should have been purchased to minimize total costs to the area. Further, annual indirect costs (TIC_s) used in equation (9) were associated with annual total pumpage of only about 118 billion gallons. This implies that even if MAWR were zero, the purchase of surface water would have been justified in terms of minimizing total regional costs.

For example, if all water demands had been pumped from groundwater sources, total direct costs would have been about $5.9 million. Added to total indirect costs of about $14.6 million, the total costs of pumping Q_D would have been approximately $20.5 million. If MAWR were zero and all of Q_D had been purchased from the alternative source, total costs would have been about \$18.9 million, representing savings to the area of about \$1.6 million. This suggests that at current prices, the purchase of all of the area's recent water demands above MAWR from the surface water source would have been economically justifiable.

The substitution of surface water for groundwater would result in higher direct costs to users, and at least initially, some form of inducement might be needed to encourage consumption of surface water. Defining equitable distribution of increased costs is a problem that falls outside the scope of this study, but one that will demand the attention of legal and social planners.

This analysis does not consider changes in demand for water, and calculations of break-even withdrawal rates must be made individually for any given level of water demand. Cost estimates with continued subsidence and changes in demand for water cannot be made due to data limitations. However, there are two factors, the lowering of price for the alternative water source and the recycling of water by some users, that could contribute to neutralizing the effects of increases in the demand for water. Theoretically, as greater quantities of surface water are purchased, some economies should be experienced, resulting in lower prices. This lowering of the cost of surface water would provide economic justification for the substitution of an even larger critical amount of water, and would contribute to the fulfillment of increases in water demand.

However, total water demand in the study area may not continue to increase as historical trends would indicate. Several reponses indicate that some industrial consumers are already instituting programs to recycle part of the water they are using in manufacturing and refining processes. Since these users traditionally consume a very large share of area withdrawals, overall demand could decline over a period of several years. This conservation measure by the larger water consumers, if pursued on a reasonably wide scale and combined with surface water purchases, could help to lower groundwater withdrawals and stabilize pressure levels.

SUMMARY AND CONCLUSIONS

Land surface subsidence in the area of Harris County, Texas, affects over 3,000 square miles. The sinking of the surface has been linked by engineers to the withdrawal of groundwater.

In this analysis, 300 square miles within the affected area were identified as a study area. The 300 square miles were plotted on maps and stratified into areas above and below 25 feet elevation preparatory to sampling. Industrial areas containing 19 square miles were also withdrawn for sampling. Questionnaires were designed for residential, commercial, and public responses, and sampling was undertaken, resulting in the completion of 441 questionnaires. These provide the data for this analysis.

Physical affects of subsidence were assessed, and it was established that subsidence causes few direct damages such as structural faulting. In almost all cases, related damages and property losses were associated with either tidal or freshwater flooding. By far the greatest damages were related to temporary or permanent tidal flooding that was attributable to subsidence. Ninety percent of homeowners and 100 percent of businessmen interviewed at lower (below 25 feet) elevations and 74 and 78 percent, respectively, at higher elevations, were aware of subsidence. Overall, 39 percent of respondents in the area reported subsidence-related damages.

Subsidence resulted in estimated private damages of $60.67 million in the study area between 1943 and 1973. In addition, private property losses for the period were estimated at $48.96 million, and total public costs were conservatively estimated at over $4 million. This represents a total subsidence-related cost to the area of an estimated $113 million.

It was estimated that the six foot tide that occurred with Tropical Storm Delia in 1973 resulted in subsidence-related damages and property losses of over $53 million. Projections indicated that a similar tide, which can be expected about every five years, could result in $54.4 million in damages and losses if two additional feet of subsidence occur, and in $63.5 million given five more feet of subsidence. These estimates are considered to be quite conservative.

Groundwater withdrawals in the area were estimated to average about 118 billion gallons per year, and these withdrawals have increased annually. Since subsidence has been linked to withdrawals, an alternative source (surface water) has been introduced into the area. An obstacle in the substitution of surface water for groundwater as a means of retarding subsidence has been price. The application of break-even analysis, based on current prices for ground and surface water and estimated annual subsidence-related costs, implies that the purchase of all of the area's recent water needs (up to 132 billion gallons a year) would have been economically justified, even with the large difference in direct costs. Therefore, if a rate of pumping at which water pressure decline and surface subsidence would be stabilized could be determined, the quantity of current water demand above that level should probably be purchased from the alternative source, if minimizing total costs to the area is an objective.

Some Limitations of the Analysis

Time and money limited the geographic scope of the analysis to 300 square miles out of over 3,000. A more extensive study area including the entire affected area would have resulted in a more universally meaningful report. However, the financial and time requirements for such an undertaking, if the data were to be truly representative, would be prohibitive.

With respect to the residential-commercial sampling, the key to this analysis, all reasonable care was taken to assure random selection of sample blocks within strata and to maintain unbiased systematic sampling within these blocks. The expansion of data from all sectors was carried out in a manner emphasizing statistical accuracy and minimizing the probability of overestimation. Any significant shortcomings of the data are likely to be associated with the initial responses. For example, some respondents may have had a tendency to attribute damages to subsidence that were not a result of that phenomnon. Although all due care was exercised in "allowing" damages to be reported as subsidence-related, some unrelated costs may have entered the analysis.

In addition, due primarily to inconsistencies in survey responses, historical costs could not be inflated to 1973 equivalents. This probably contributes to an underestimation of historical costs.

Also, in reporting events up to 30 years ago, there is quite possibly a high degree of memory failure among respondents, as well as a high incidence of respondents who were not at their present location even a few years ago. To minimize this influence dependence was placed on data from the most recent time period for the analysis of surface water and the projections of costs and losses.

Regarding the estimates of public costs, these are reported with some reservations, since in many cases the respondents were unable to isolate public expenditures on subsidence-related damages. These estimates were probably understatements, and no projections were made, other than suggesting that the costs will increase. In industrial sectors, also, the sampling results were less than satisfactory, and no related projections were made, although the analysis of the real costs of pumping includes these costs as reported in the recent time period.

Some Comments on Future Research Needs

The results of this analysis suggest that the costs and losses attributable to land subsidence are indirect in nature, and more closely related to the proximity of property to tidal waters than to the depth of subsidence. Any research leading to significant contributions to these findings and to the projections of future losses should probably be based upon more extensive sampling procedures. Such steps might be justified at some future date, if the study area could be substantially enlarged.

A pressing need now exists for engineering research leading to the establishment of a "maximum acceptable withdrawal rate" for the area.[1] This would enable planners to apply the estimated costs of subsidence as indirect costs of that amount of groundwater being withdrawn in excess of the acceptable rate, a practice that, as this study has implied, should justify the substitution of surface water for pumped groundwater.

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[1] Mr. R. K. Gabrysch has indicated in personal conversation that the USGS is currently involved in such research.

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APPENDIX A

Table 1. Tidal surge frequency at Baytown, Texas.

Surge Height in Feet	Estimated Tide Frequency Per 100 Years	Expected Interval Between Tides (Years)
1	100 +	< 1
2	100 +	< 1
3	100 +	< 1
4	45.0	2.2
5	26.0	3.8
6	19.5	5.1
7	14.0	7.1
8	11.0	9.1
9	9.0	11.1
10	7.0	14.3
12	4.5	22.2
15	1.5	66.7

Source: Adapted from [2, page 30].

Table 2. Percentages of respondents aware of subsidence and reporting damages, in areas above and below 25 feet elevation.

Sector	Aware of Subsidence	Reported Damages
Residential	91%	58%
Commercial	100%	40%
All below 25'	91%	57%
Residential	74%	36%
Commercial	78%	22%
All above 25'	75%	34%
OVERALL	78%	39%

Table 3. Calculated and projected subsidence in the area of Baytown, Texas, 1940-2000.

	Subsidence in Feet		
Year	Historical	Case I[a]	Case II[b]
1940	2.0		
1945	2.8		
1950	3.7		
1955	5.0		
1960	5.5		
1965	6.1		
1970	7.0		
1975		8.0	8.0
1980		9.0	9.0
1985		9.2	9.8
1990		9.3	11.0
1995		9.4	12.0
2000		9.5	12.3

[a] Assumes decline in water pressure is stabilized by 1980.

[b] Assumes decline in water pressure is stabilized by 1995.

Source : Adapted from [6, page 20.]

APPENDIX B

Figure 1

Series I Questionnaire
Private Costs - Residential

Sample____
Date______

A. Are you aware of land subsidence?_____

B. Do you attribute any damages to your property to land subsidence?_____

1. What kind(s) of damage have you identified?

Date	Damage to:	Extent	Date Repair	Cost*
	a. foundation			
	b. walls			
	c. floors			
	d. outbuildings			
	e. pavement			
	f. plumbing			
	g. utilities			
	h. tidal flooding			
	i. f'water floods			
	j. ______________			
	k. ______________			

* Show estimated value if not yet repaired.

2. Type Dwelling:__________________Age:____________
3. Market value of dwelling:__________Land:_________
4. Has market value been affected by land subsidence in the area?_____ By how much?_____
5. Remarks:____

____

____

____

Figure 2

Series II Questionnaire   Sample______
Private Costs - Commercial   Date________

A. How would you classify this firm?

1) Small business_ 2) Industrial_ 3) Manufacturing__

4) Retail_________ 5) Wholesale__ _______________

B. Type of commercial activity:____________________

C. Years at this location:_______

D. Are you aware of subsidence?____

E. Have you noted damages to company property or losses that you attribute to subsidence?_____

1. What kind(s) of damage have you identified?

Date	Type Damage	Repaired	Cost*	Recurrence
_____	a. Tidal flooding	________	_____	__________
_____	________________	________	_____	__________
_____	b. F'water flooding	________	_____	__________
_____	________________	________	_____	__________
_____	c. foundations_____	________	_____	__________
_____	d. walls___________	________	_____	__________
_____	e. plumbing________	________	_____	__________
_____	f. outbuildings____	________	_____	__________
_____	g. pavement________	________	_____	__________
_____	h. other___________	________	_____	__________
_____	i. ________________	________	_____	__________
_____	j. ________________	________	_____	__________

* Show estimated value if not yet repaired.

2. What kind(s) of business loss or expense has your company incurred due to subsidence?

Date	Loss due to:	Estimated cost	Remarks
______	_____________________	______________	_______
______	_____________________	______________	_______

Figure 2, continued

Series II, page 2.

3. Additional remarks:______________________________

____

____

____

____

F. Do you foresee additional damages if subsidence continues at current rates?________________

What kinds of damages do you expect?____________

____

____

____

G. What is present market value of:

1. Improvements $____________
2. Land $____________

H. Has market value been affected by damage due to subsidence?____ By how much?____________________

Figure 3

Series III Questionnaire
Public Costs

Number_______
Date_________

1. A. Agency, division, unit: ______________________

   B. City of: _____________ County of: _____________

   C. For what activities is this agency responsible

   ____

   ____

   D. What is the general geographic area of responsibility? _____________________________________

   E. Are you aware of land subsidence? ____________

2. A. Have you noted any subsidence-related damages to public property under your supervision? ___

   ____

   Within our sample area? ______________________

   B. What kinds of damages?

Date	Location	Damage to:**	Cost*	Recurrence
		roads		
		roads		
		pipes		
		pipes		
		bldgs		
		bldgs		

* Show estimated value if not yet repaired.

**Indicate whether flooding or other damage.

   C. Has your office been involved in any preventive or remedial activities to protect public or private property from tidal flooding? _____

Figure 3, continued

Series III, page 2.

C., continued. Please indicate the location, date, and estimated costs for each project.

____

____

____

____

D. Remarks: _________________________________

____

____

____

E. Please identify any other subsidence-related public costs that have not been specified.____

____

____

____

Figure 4

Sample Evaluation
Private Costs

Sample______
Category_____

I. Residential (a) Approximate no. homes: ________
(b) Series I forms used_____(c) Percent Sample__
(d) Average value of property________________
(e) Expanded (total) value__________________
43-54 55-64 65-73 total
(f) Subsidence Damages _____ _____ _____ _____
(g) Losses in property value_________________
(h) ___of___were aware of subsidence.
(i) ___of___reported subsidence-related damages.
(j) Remarks_____________________________

II. Commercial (a) Approximate no. firms: ________
(b) Series II forms used___(c) Percent Sample___
(d) Average value of property________________
(e) Total value of property_________________
43-54 55-64 65-73 total
(f) Subsidence Damages _____ _____ _____ _____
(g) Losses in property value_________________
(h) ___of___were aware of subsidence.
(i) ___of___reported subsidence-related damages.
(j) Remarks_____________________________

III. Totals:
43-54 55-64 65-73 Total
Damages: _______ _______ _______ _______
Losses in property value___________________