LAND SUBSIDENCE AND ASSOCIATED EXTERNALITIES IN THE COASTAL AREA OF TEXAS*

John P. Warren and Lonnie L. Jones

Texas Gulf Coast areas near Houston have been affected to an increasing degree by land subsidence in recent years. Sinking of the surface has reached critical proportions in many areas, and subsidence of as much as nine feet has occurred since 1943. Physical effects have been extensive, affecting over 3,000 square miles, and economic effects have been aggravated by the approximity of much of the area to bay waters. Subsidence has resulted in significant damage and property loss, from both permanent salt water inundation and temporary flooding due to storm-related tides and rains.[1]

Industrial, municipal and agricultural demands for water have increased sharply in recent years. Engineers have linked subsidence to the decline of subsurface water levels due to heavy groundwater withdrawals [3, 4, 5, 6, 9]. An alternative water source, the importation and treatment of surface water, has been introduced, but relatively high prices have slowed its acceptance. This economic obstacle to limiting withdrawals, plus the time lag between water pressure decline and corresponding subsidence [2, 3], suggest that for the immediate future, continued subsidence can be expected.

Costs associated with subsidence may be viewed as negative externalities to the area that arise from private withdrawals of underground water. Research has been limited to quantifying physical relationships between withdrawals and subsidence. There has been a lack of research to quantify related economic effects.

The purposes of this article are: (1) to estimate historical damage and property losses associated with subsidence, (2) to project future damages and losses with continued subsidence, and (3) to examine the economic justification for using an alternative water source as a means of limiting subsidence and associated external costs.

DATA DESCRIPTION

Within the subsiding area, a 15 by 20 mile study area was delineated. Preparatory to sampling, the 300 square miles within this area were plotted as one-mile squares on maps and stratified into areas above and below 25 feet elevation. Questionnaires were designed for residential, municipal and commercial responses. In general, all three were designed to allow an accounting by year, type, and extent of those damages and losses in property value that could be identified as attributable to land subsidence.

Areas above 25 feet were randomly sampled at a 10 percent rate, and sample areas so chosen were enumerated at the rate of five percent. Since it was hypothesized that greater damages would occur at lower elevations, a 20 percent random sample was withdrawn from areas below 25 feet, and enumeration was at the rate of 10 percent. Property owners within each strata were selected randomly for interviews. Five student enumerators completed 411 private sector questionnaires, and 30 public (municipal) questionnaires. These responses provided the data for analysis. Damages

John P. Warren is research associate, Texas Water Resources Institute, and Lonnie L. Jones is associate professor, Department of Agricultural Economics, Texas A&M University.

* Technical Article No. 11497, Texas Agricultural Experiment Station, Texas A&M University. The authors wish to acknowledge the editorial assistance and critical contributions of Dr. Ronald D. Lacewell and Dr. Wade L. Griffin, and the cooperation and comments of Dr. Jack R. Runkles and Mr. K. Gabrysch.

[1] Throughout this analysis damage refers to physical harm to property or improvements and property loss refers to declines in market value of property or improvements.

and losses reported by interviewers were assumed to be representative of those of property owners within sample areas of each strata. Sample responses were first expanded to estimate total damages and losses within sample areas. Then, assuming that the square-mile sample areas were representative, these estimates were expanded to estimate total damages and losses for the 300 square mile study area.

METHOD OF PROJECTING EXTERNALITIES

Projections of estimated damages were made in terms of 1973 dollars under the assumption that (1) subsidence continues, (2) total additional depth of subsidence at some future time [T′] is constant across the study area, and (3) a storm and a six foot tide similar to those that took place in the study area in 1973 occur at [T′]. A six foot tide occurred in 1973 in association with Tropical Storm Delia, providing recent data on tide-related costs. On average, such a tide can be expected in the study area about every five years [1].

For areas affected by tides (situated on a bay, bayou, or channel) a topographic approach was employed to project subsidence related damage.[2] First, the coastal area inundated in 1973 was estimated, using U.S. Geological Survey maps showing elevation contours, and a polar planimeter.[3] Areas that would be inundated by a similar tide with an added increment to subsidence were then estimated with the same technique. Subsidence related damages were projected using a ratio of these two areas. For example, if "a" represented the area inundated by a six foot tide in 1973, and "b" the area inundated by a similar tide given "x" more feet in subsidence, then 1973 damages were multiplied by the ratio (b/a) to project damages associated with a six foot tide at time T′. This procedure was repeated for each sampled land area adjacent to tidal waters. Damage in areas not affected by tides was assumed to remain constant. This procedure provided estimates of tidal damages that can be expected at some future time T′ only if subsidence continues.

Losses in property values were expressed as a function of subsidence damages and estimated using least square regression.

HISTORICAL AND PROJECTED COSTS AND LOSSES

Physical effects of subsidence are largely dependent on location. Most costs and losses associated with subsidence were found to be indirect in nature, and caused by tidal or freshwater flooding, either temporary or permanent. As identified in this study, direct damages such as structural breaks were minor since subsidence is gradual and relatively uniform over the study area.

As land subsides, more property becomes susceptible to permanent inundation or temporary flooding due to storms or high tides, creating serious problems for property owners and municipal officials. Often property is abandoned or frequent inundation renders it virtually useless. Private and public expenditures for protection and repair continue to rise. It was estimated that subsidence resulted in private damages of $60.7 million and property losses of $48.9 million in the study area between 1943 and 1973. Public costs were conservatively reported at $4 million for the same period, but were not included in projections due to incomplete response.

Reported private damages and losses of $53.1 million were associated with the six foot tide that occurred in 1973 (Table 1). Of this total, $9 million was due to damages and $44 million to losses in property value.

Table 1. HISTORICAL AND PROJECTED ESTIMATES OF SUBSIDENCE RELATED DAMAGES AND PROPERTY LOSSES ASSOCIATED WITH A SIX FOOT TIDE IN 1973, AND AT SOME FUTURE TIME T′, GIVEN FIVE MORE FEET OF SUBSIDENCE IN THE HOUSTON, TEXAS, AREA

Subsidence	Damages	Property Losses	Total
1973 level	$ 9,275,780	$43,912,235	$53,188,015
1973 plus five feet	13,488,340	50,014,258	63,502,598

According to Gabrysch [4, 5], five additional feet of subsidence could occur in the area by about 2000, given continued significant declines in water

2 The discussion pertaining to projections has been adapted with some alteration from [8, pages 24-26].

3 A planimeter is a mechanical device used by engineers and cartographers to compute areas on a map or plane.

pressure. Clearly, the return of a six foot tide would temporarily inundate more area than was inundated in 1973, assuming such additional subsidence. Flooding damages resulting from such inundation were projected to reach $13.5 million within the study area (Table 1). This represents a 50 percent increase over the $9 million in damages reported in 1973.

Losses in property value, like damages, were assumed to remain constant for those sample areas not affected by tides. However, those areas subject to the effects of tides are expected to experience increasing property losses as more related damages occur. Loss in property value was expressed as a function of subsidence related damages in 1973, and equation (1) was estimated:

$$PLOSS_i = \$97{,}746 + 2.82(DAMAG_i) \quad (1)$$

where

$PLOSS_i$ is estimated property loss in sample block i in 1973, and

$DAMAG_i$ refers to damages in sample block i in 1974.[4]

Projected damages were substituted into the equation to estimate projected property losses at time T′. Property loss is assumed cumulative up to the value of the property. It is understood that part of the property loss associated with a six foot tide and five more feet of subsidence will already have occurred prior to the time T′, since as subsidence takes place in intervening years, more property becomes susceptible to permanent and temporary tidal flooding.

Equation (1) was used to project property losses within each of the 14 sample blocks affected by tides and reporting damages in 1973, and results were expanded to the study area. Estimated losses in property value, given the return of a six foot tide and five additional feet of subsidence, were $50 million (Table 1), representing a 14 percent increase over the 1973 estimates. Total costs and losses for the area were projected at over $63 million, compared to $53 million in 1973, an increase of nearly 20 percent.

ECONOMIC ANALYSIS OF ALTERNATIVE WATER SUPPLIES

Estimates and projections of subsidence-related costs can be of considerable interest to area planners and affected individuals. However, to be useful in decision making for action to prevent future damages and property losses to the affected area, the analysis must include comparisons of costs of alternative strategies for meeting the area's water needs. An alternative water supply is available to area consumers as a substitute for groundwater, but its unit cost is high relative to groundwater. Since the relationship between subsidence and groundwater withdrawals has been well established [3, 4, 5, 6, 9], a comparison of groundwater pumping and subsidence costs to costs of the surface alternative provides information useful in minimizing total area water costs.

Ideally, subsidence-related externalities would be estimated as a discounted future stream of projected annual total costs that could be compared directly with current annual costs of the alternative water supply. Unfortunately, reliable data from which projections of damages and property losses by future years or differing tidal surges were not available at the time of this study. Hence, an alternative analysis, using annual average external costs for the most recent five year period, was developed to evaluate the economic feasibility of importing surface water in order to avoid externalities associated with land subsidence.

Engineers generally agree that some maximum acceptable withdrawal rate (MAWR) exists at which water pressure and subsidence would be stabilized [5, pp. 24-25]. This maximum annual rate is not known, and its estimation is a physical rather than an economic problem. Of immediate interest to this analysis is the amount of water withdrawn in excess of this maximum acceptable rate, since this critical quantity of water (CQ) incurs the added external costs of subsidence-related damages. The analysis can be limited to consideration of this critical quantity of water because MAWR can be pumped at a lower cost and without causing land subsidence. Although total water demand (QD) is known, its make-up (MAWR + CQ) is unknown, and it is useful to solve for the equilibrium critical quantity of water (ECQ), where total costs are equal regardless of the water source used to obtain CQ. The equilibrium critical quantity is estimated by the break-even equation:

$$ECQ = TSC/(A - G) \quad (2)$$

where

TSC = total annual subsidence related costs to the area,

A = per unit cost of water from the alternative source, and

G = per unit cost of water from groundwater supply.

[4] Analysis of variance indicated an F value of 50.137 and an R-square of .82 associated with this regression equation.

The maximum acceptable withdrawal rate will have to be estimated by engineers, but a break-even withdrawal rate (BEWR) can be estimated by subtracting ECQ from total demand (QD). BEWR is important for comparing costs of the critical quantity of water from the ground and surface sources. For example, if MAWR, as estimated by engineers, is lower than BEWR, then continued pumping of CQ from the underground source is justified—at such levels water costs to the area are greater for the alternative source. If MAWR equals BEWR, there is economic indifference as to the source of CQ. However, if the maximum acceptable rate is estimated to be greater than the break-even withdrawal rate, then there is economic justification to purchase the more expensive surface water to satisfy that part of total demand above MAWR.

The economic feasibility of using alternative water sources to avoid externalities was analyzed by comparing direct plus external (subsidence-related) costs of pumping groundwater to the costs of purchasing surface water for the critical quantity of water as expressed in equation (2).

Because the analysis was made on an annual basis, it was convenient to make computations in billion gallons per year (bgy). The data base for these estimates was the five-year period from 1969 to 1973.[5] Subsidence related costs and losses were estimated at about $14.6 million annually during this period [8].[6]

Reported prices for surface water (A) and groundwater (G) were approximately $160,000 and $50,000 per billion gallons, respectively. TSC was estimated at $14.6 million. Hence, using equation (2), ECQ was estimated at 132.7 bgy. This implied that under current prices and with constant estimated annual subsidence-related costs, the purchase of CQ of up to 132.7 billion gallons of surface water a year would be justified in terms of total costs to the area.

The magnitude of this calculated equilibrium critical quantity was a most significant finding. A break-even withdrawal rate (BEWR) corresponding to ECQ could be estimated for this case by subtracting ECQ from total demand. However, a recent five-year annual average of total groundwater pumped was 118.8 billion gallons [8], well below the 132.7 billion gallons estimated as equilibrium critical quantity. This implied that, even if MAWR were zero, the purchase of surface water would have been justified in terms of minimizing total costs to the study area.[7]

For example, if all annual water needs had been pumped from groundwater sources, total direct costs would have been about $5.9 million during the 1969-73 period. Added to total external costs of about $14.6 million, the total costs of pumping QD would have been approximately $20.5 million. If MAWR were zero and all of QD 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 the area's recent water demands above MAWR from the surface water source would have been economically justifiable, and that even if all total demand had been purchased total costs to the area would have been lower. Since annual subsidence-related costs and property losses are projected to increase with continued subsidence, this analysis suggests the economic feasibility of using surface water as a means of avoiding subsidence-related externalities and minimize total water costs of the area.

CONCLUDING REMARKS

The substitution of surface water for groundwater would result in higher internal costs to users, implying that some form of inducement will 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.

Methods of controlling groundwater pumping may range from purely administrative to purely economic. In this case, since the externalities can be associated directly with the quantity of water withdrawn from the groundwater aquifer, control measures that focus on internalizing external costs within the cost structure of the user would seem

[5] The 1969 to 1973 period was a particularly applicable base, since data from the more recent years were considered more reliable and since the occurrence of a tide such as that which took place in 1973 can be expected about once in every five years [1]. Annual average costs from this base period were utilized since sufficient data were unavailable for development a continuous functional relationship between future annual costs and annual subsidence as well as future costs of surface and groundwater.

[6] This estimated annual average cost is higher than subsidence-related cost projected in the previous section since continuous costs of permanent tidal inundation, structural damages and freshwater flooding are included. Sufficient data were not available for projecting these components of subsidence-related costs.

[7] Sensitivity analysis using equation (2) suggests that at current relative water prices ECQ exceeds QD so long as TSC exceeds $13.1 million per year.

desirable from the standpoint of economic efficiency. It is interesting to note that, for the 1969-73 period, the subsitution of surface water for groundwater would have had the effect of totally internalizing to water users the subsidence-related costs within the area.

This analysis does not consider changes in demand for water, and calculations of break-even withdrawal levels 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 adoption of water recycling by some users, that could contribute to neutralizing the effects of increases in the demand for water.

REFERENCES

[1] Bodine, B. R. "Hurricane Surge Frequency Estimated for the Gulf Coast of Texas," Technical Memorandum No. 26, U.S. Army Corps of Engineers, February 1969.

[2] Gabrysch, R. K. "Development of Ground Water in the Houston District, Texas 1966-69," Texas Water Development Board, Report 152, June 1972.

[3] ————————. "Land Surface Subsidence in the Houston-Galveston Region, Texas," an open file report of the U.S. Geological Survey, published in the proceedings of the *International Symposium on Land Subsidence,* Tokyo, Japan, 1969.

[4] ————————. "Preliminary Report on Land-Surface Subsidience in the Area of Burnett, Scott, and Crystal Bays near Baytown, Texas," U.S. Geological Survey, February 1973.

[5] ————————, and C. W. Bonnet. "Land-Surface Subsidence in the Area of Burnett, Scott, and Crystal Bays near Baytown, Texas," Water Resources Investigations 21-74, U.S. Geological Survey, September 1974.

[6] Lockwood, M. G. "Subsidence from Declining Artesian Pressure Can No Longer Be Ignored in Houston Area, Texas," a paper presented before the *Spring Meeting, Texas Section, ASCE,* Midland, Texas, April 1954.

[7] Poland, J. F., and G. H. Davis. "Subsidence of the Land Surface in the Tulare-Wasco (Delano) and Los Banos-Kettleman City Areas, San Joaquin Valley, California," *Transactions of American Geophysical Union,* Vol. 37, No. 3, pp. 287-296.

[8] Warren, John P., Lonnie L. Jones, Wade L. Griffin, and Ronald D. Lacewell. "Costs of Land Subsidence Due to Groundwater Withdrawal," Technical Report No. 57, Texas Water Resources Institute, Texas A&M University, July 1974.

[9] Winslow, A. G., and W. W. Doyel. "Land Surface Subsidence and its Relation to the Withdrawal of Groundwater in the Houston-Galveston Region, Texas," *Economic Geology,* Vol. 49, No. 4, pp. 413-422.