USE OF A GEOGRAPHIC INFORMATION SYSTEM TO EVALUATE THE POTENTIAL FOR DAMAGE FROM SUBSIDENCE OF UNDERGROUND MINES IN ILLINOIS

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ABSTRACT

This paper describes the use of geographic system information (GIS) technology to evaluate the risk of damage to structures from mine subsidence in Illinois. Since the early 1800s, about 3000 underground mines (all but 40 of which are abandoned), have been operated in Illinois to recover coal, minerals, and earth materials. Mine subsidence, the sinking of ground over a collapsed mine, can cause damage to homes and other structures. Maps and tables created with the GIS are used to show the coincidence of underground mines with urban areas and to estimate the number and total value of housing units exposed to subsidence risk. The GIS provides capabilities that solve challenging technical aspects of this project, including compilation of data and the synthesis and presentation of large, diverse data sets. Digitizing, in conjunction with other computer software, provides efficient means for encoding mine locations from source materials having a variety of scales, formats, and degrees of cartographic accuracy. Buffer zones around mine boundaries compensate for uncertainties in the locations of mine boundaries and show surface areas that could be affected by subsidence. Boundaries of urban land are buffered to allow for potential growth. A map library data structure provides efficient handling of large data sets on land cover and mines. The flexibility of the GIS will make it relatively easy to update the study with future census, land cover, and mine data.

INTRODUCTION

This paper describes the use of geographic information system (GIS) technology to help evaluate the risk of damage to structures from mine subsidence. The GIS provides a number of capabilities that help to solve the challenging technical aspects of this project, including the compilation of data and the synthesis and presentation of many large, diverse data sets.

Mine subsidence, the sinking of the ground surface after the collapse of an underground mine, can take place gradually over a large area, or can be quite sudden, opening as a pit at the surface (DuMontelle et al., 1981). This ground movement can result in damage to overlying structures and loss of property value. In Illinois, mine subsidence has occurred over all types of underground mines. Most subsidence events are related to coal mines because of the large number of coal mines and their proximity to urban areas. The largest subsidence event to date, however, was over a lead and zinc mine. More than 2660 underground coal mines have operated in Illinois since 1810; all but 30 are now abandoned. Another 350 underground mines have operated to extract clay, flourspar, lead, zinc, dolomite, limestone, ganister, and tripoli; all but 10 of these mines are abandoned.

Damage caused by "ground movement" is not insured under conventional property insurance. With the inception of the Illinois Mine Subsidence Insurance Fund (IMSIF) in 1979, Illinois became the second state in the country to provide protection against mine subsidence damage to structures. IMSIF reimburses private insurance companies for claims paid for mine subsidence damage.

IMSIF needed information that could be used to evaluate their potential exposure to claims for damage due to mine subsidence. Initially, the only information available was the percentage of each county undermined by coal mines. This information was of little value because in some areas mines are directly under urban development while in other areas mines underlie land having no insurable structures, such as water bodies and cropland. IMSIF also needed to know what areas are undermined by non-coal mines, as there has been mine subsidence over lead and other mines.

This study provides statistics on the proximity of mined areas to urban development and housing. The product of primary interest to IMSIF is a tabulation by township showing acreage of mined areas underlying and adjacent to urban areas, the approximate number of housing units undermined, and the approximate value of those housing units. This information can be derived relatively quickly and cheaply from existing digital data sets: coal mines (Treworgy et al., 1988), land cover (Loelkes et al., 1983; Fegeas et al., 1983), and housing (U.S. Department of Commerce, 1980; Geographic Data Technology, Inc., 1982; Donnelley, 1986). The only data that had to be compiled and digitized were outlines of non-coal mines.

The project was divided into two tasks: 1) to compile and digitize the data on non-coal mines, and 2) to merge the mine information with the data on land cover and housing and present it for IMSIF to analyze.

DEVELOPMENT OF A DIGITAL DATABASE ON NON-COAL MINES

The development of a digital database on non-coal mines involved two problems that were solved by GIS techniques: 1) compilation of mine outlines and mine shaft locations from source maps having a variety of scales and degrees of cartographic accuracy, and 2) documentation of uncertainties of mine location, orientation, and configuration to be tracked and properly considered in later modeling.

Original mine maps were the preferred source for the compilation and digitizing of mine boundaries. We found maps that varied from page-size to wall-size and were drawn on paper (sometimes folded), linen, and tracing paper. Some maps had no scale or reference points. Other maps had incomplete mine boundaries or boundaries that were drawn before mining operations ceased.

Hard copies of original mine maps were made from microfilm of original mine maps acquired through the Federal Office of Surface Mining. Large maps were divided onto two or more microfilm frames. Locations for mines without outlines were taken from maps and legal descriptions in publications and from shaft and mine tunnel symbols on USGS 7.5-minute quadrangles. Although there were 29 different scales ranging from 1:120 to 1:63,360, the majority of maps were at the scales of 1:2400, 1:4800, and 1:24,000.

Compilation of Mine Outlines into a Digital Database

Three basic methods were used to enter the mine locations or outlines into the database: 1) digitizing directly from the mine map, 2) transferring the mine outline to a mylar overlay of a 7.5-minute quadrangle and digitizing the mylar, and 3) using a computer program to convert legal descriptions to X-Y coordinates. Maps in good condition that had at least four reference points (section corners or 1/4-section corners) were digitized directly into the database. About 30 percent of the mines were entered in this manner.

Some mine maps had no section corners, or only one. These mines were digitized along with any landmarks that could be used for orientation (north arrows, roads, railroad tracks, landforms, streams, or mine shafts). The mine outlines and landmarks were plotted at 1:24,000 and overlain on the appropriate USGS 7.5-minute quadrangle. Using the reference points and features digitized from the original map, the mine outline was registered to the topographic map and transferred by hand onto mylar overlays. Mines that were too narrow to digitize as polygons were drawn onto mylars as lines. Mine shaft and mine tunnel symbols found on quadrangles or other maps were also transferred to the mylars as point locations. The mylars were digitized after all mines for that quadrangle were compiled. About 50 percent of the mines were entered in this manner.

When the only information available for a mine was its legal description (township, range, section, quarter section or footages), X-Y coordinates were calculated from the legal description using a computer program and a database of section corner coordinates (Swann et al., 1970). The computed coordinates were entered directly into the non-coal mine database.

Documentation of Uncertainties

Documentation maintained for each mine includes date and source of the maps showing the mine outline or point location, and other sources of information. Possible errors in the source map or compilation process were also recorded. Every mine polygon, line and point entered into the database was assigned a code to indicate the accuracy of the source map and the method used to digitize or enter the data (Table 1). For example, polygons digitized from the original mine maps received a code of 1. Mine locations calculated from a legal description that located the point to the nearest quarter-quarter section were given a code of 8. These location-uncertainty codes were used during data synthesis to create buffer zones that covered the area where mines might be located.

SYNTHESIS AND EVALUATION OF DATA

The ARC/INFO GIS software is used to process the digital data (Morehouse, 1985). Areas at risk of subsidence damage are calculated by merging data from five spatial data sets and one tabular data set (Table 2). These data sets are physically large (76 Megabytes total), derived from source materials of different scales, and stored in different geographic subdivisions. The GIS provides a mechanism to 1) manage the data by extracting it in standard subunits of manageable size, 2) represent the proximity of certain features and account for uncertainties in boundary locations, 3) adjust and register spatial features from small-scale maps to features from large-scale maps, 4) merge spatial features and link to tabular data organized in different statistical areas, and 5) present complex information in a comprehensible manner.

Table 1. Location-uncertainty codes and buffer distances

Code	Buffer distance (ft.) proximity	uncertainty	Source of mine outline or location
1	500	1000	Original mine map, four reference points
2	500	1000	Original mine map, registered using landmarks
3	500	1000	Topographic map
4	500	1000	Map with topography OR with scale larger than 1:24,000
5	500	2320	Map without topography AND scale smaller than 1.24,000
6	500	1000	Legal description with footages or good landmark
7	500	1660	Legal descriptions; section 1/4 1/4 1/4 or CE1/4 or CE1/2 1/4 or CE1/2 or CE1/2 1/2
8	500	2320	Legal description; section 1/4 1/4
9	500	3640	Legal description; section 1/4 or 1/2 1/4
10	500	6280	Legal description; section only

Table 2. Original scale, size and geographic subdivision of digital data sets

Data set	Scale of Source maps	Size of file (Mb)	Unit of storage
Coal mines	1:1200 - 1:62,500	11 0	county
Non-coal mines	1:1200 - 1:63,360	2.5	county
Land cover	1:250,000	15.3	USGS 1° x 2° quadrangle
Census tracts	1:62,500	10.0	SMSA*, county
Political townships	1:500,000	0.8	state
Census statistics	tabular data	36.0	state

*SMSA is Standard Metropolitan Statistical Area.

Management of Data

A number of complex processing steps are required to merge the data sets and to compile township-level statistics for mine subsidence potential. The full data sets are too large for the hardware and software to conveniently handle and too complex to for us to effectively monitor the results of incremental processing steps. To alleviate these problems, we process the data on a county basis. The county subsets of the main data sets are referred to here as coverages. The procedure for extracting the data for each county is transparent and relatively efficient with the use of map libraries.

A map library is a special data structure supported by the ARC/INFO software (Keegan and Aronson, 1985). Conceptually, the library consists of layers and tiles. The layers can be thought of as maps of individual data sets such as coal mines, non-coal mines, and land cover. All layers are divided into the same set of geographic subdivisions called tiles. We use two libraries. The mine data library has counties for tiles and five layers: coal mine polygons, coal mine points, non-coal mine polygons, non-coal mine lines, and non-coal mine points. The second library has one layer, land cover, which is divided into tiles corresponding to 1- by 2-degree quadrangles. To process a county we create an outline of the county that extends one mile beyond the actual boundary, to allow for nearby urban land or mines. Given this outline, the GIS librarian software automatically determines which tiles are intersected in each library, retrieves the data from those tiles, and creates a single coverage for each layer.

Representation of Proximities and Uncertainties

Modeling to evaluate the exposure of structures at risk of subsidence must include consideration of the proximity of mines to urban areas and the uncertainties of the position of mine areas and urban boundaries. In this study, proximities and uncertainties are represented by buffer zones of various distances created around mines and urban areas.

Mine buffers. The GIS is used to create two buffer zones around mines. A small buffer (the proximity buffer) delineates the adjacent land that could be affected by subsidence; a larger buffer (the uncertainty buffer) represents the uncertainty in the position of the mine. Although the buffer distances for mines, if considered individually, would vary depending on the depth of the mine, nature of the geologic strata, quality of the available mine maps, and other criteria, the regional scope of this study makes it necessary to assign standard buffer distances to all mines.

Structures on land adjacent to a mine are at risk because the subsidence from the collapse of an underground mine can spread sideways as it moves upward to the surface. This lateral ground movement is not highly predictable, but is a function of the depth of the mine and the local geology, among other factors. Generalizing these factors statewide, we estimate that the maximum distance of lateral subsidence movement will be 500 feet, and use 500 feet as the proximity buffer distance on all mines.

Uncertainties in the positions of mine boundaries come from two sources: 1) incomplete or imprecise maps of mine workings and 2) errors in compilation and digitizing. We estimate that for all coal mines and many non-coal mines the error from these two sources generally would not exceed 1000 feet. This uncertainty is represented by creating a buffer zone extending 1000 feet beyond the proximity buffer zone.

The uncertainty buffer is expanded for mines located by small-scale maps and for mines with no map (Table 1). Because government regulations differ for non-coal mines, information on these mines is more difficult to obtain; maps of the workings are less likely to be kept on file and may not be available at all. When the legal description is the only source for the mine location, the uncertainty buffer distance is expanded according to the size of the area in which the mine might be located.

Urban buffers. A 1-mile buffer is created around all urban land areas (except for the transportation category). This buffer is to allow for uncertainties in the boundaries of the urban areas (some of them were based on mapping that occurred more than 10 years ago) and to identify areas where nearby mines will underlie future urban expansion.

Adjustment of Features

Before the spatial features for a county are overlain, township boundaries must be merged with census tract boundaries where they should coincide. Because the township lines and the census tract lines come from different source maps, there are slight offsets in some areas where the lines should be coincident. Using the GIS, township lines that are within a specified distance of tract lines are automatically shifted to match the tract lines.

Merge Spatial Features and Link to Tabular Data

After the extraction of the data into manageable county areas, the creation of buffer zones, and the adjustment of township lines to tracts, the coverages are merged into a single county coverage containing urban land, buffered urban land, buffered mined areas, townships, and census tracts. To calculate the number of homes at risk of mine subsidence damage, the merged spatial coverage must be linked to the tabular data set of census statistics. Also, the census statistics, which are organized on a tract basis, must be recomputed on a township basis for the final tabulation. The merged county coverage, still containing data on townships and tracts, provides a means for this calculation. The relational database management capability of the GIS is useful for linking and recomputing these elements.

The county coverage of census tract polygons is constructed from a DIME file of lines of tract boundaries. A program relates the lines in the DIME file to the census tract coverage and assigns tract numbers to the polygons. The polygons in the final merged coverage then have both a township number and a tract number. Each township may contain several tracts or sections of tracts. Another program uses the township and tract numbers to pick out the appropriate polygons for each statistical area, summarize and save the data for each township and for each tract into new files. Data on number and value of housing units per tract are stored in separate tabular files and are linked to the saved files. Through several relates of saved files and tabular files, statistics for each township are extracted.

Presentation of Data

The final step of this study is to produce and present statistics that can be used to evaluate the potential for damage from mine subsidence. For purposes of this study, undermined areas and areas within the proximity buffer are considered areas of highest risk. Areas within the uncertainty buffer are considered areas of moderate risk. Areas outside of both buffers have the lowest risk. Urban areas, particularly those classed as urban residential, are considered to have the highest concentrations of insurable structures. Areas within the urban buffer may have significant concentrations of insurable structures now or in the future. Areas outside of the urban buffer are assumed to have a low density of insurable structures.

Assumptions must be made about housing values and the distribution of housing units within a township. A comparison of figures from census tracts and census places in this county indicated that 80 to 90 percent of the housing units are in the residential areas. Therefore, for this example we assume 90 percent of the housing units to be in residential areas and the remaining 10 percent to be evenly distributed throughout the rest of the township. All housing units are assumed to have equal value. The GIS calculates the number and value of housing units undermined based on the total number and value of units in the township and the percentage of residential land undermined.

Table 3 shows some of the statistics produced for a county in Illinois. Although less than one percent of the county is in the highest category of subsidence risk (i.e. land within the proximity buffer), more than 7 percent of the residential and other urban land is in this category. An additional 5 percent of residential land (4 percent of all urban land) is in the moderate risk category. In this particular county, 66 percent of the buffered mine area falls within the urban land and an additional 28 percent within the urban buffer. Six percent of the buffered mine area underlies water areas and does not present a risk of subsidence damage.

The data can also be effectively depicted in map form. Figure 1 shows most of the map features used for the evaluation of subsidence for this county; the tract boundaries and proximity buffers are not shown. The coincidence of mines with urban areas and urban buffers is readily apparent. Maps like this could be used to show the need for proper building practices and regional planning. Figure 2 shows the estimated number of housing units in the high and moderate zones of subsidence risk. Figure 3 shows the estimated percentage of housing units in the township that fall in these two zones. These graphics show the statistics of Table 3 in a spatial context, and present at a glance the geographical areas most at risk of mine subsidence damage.

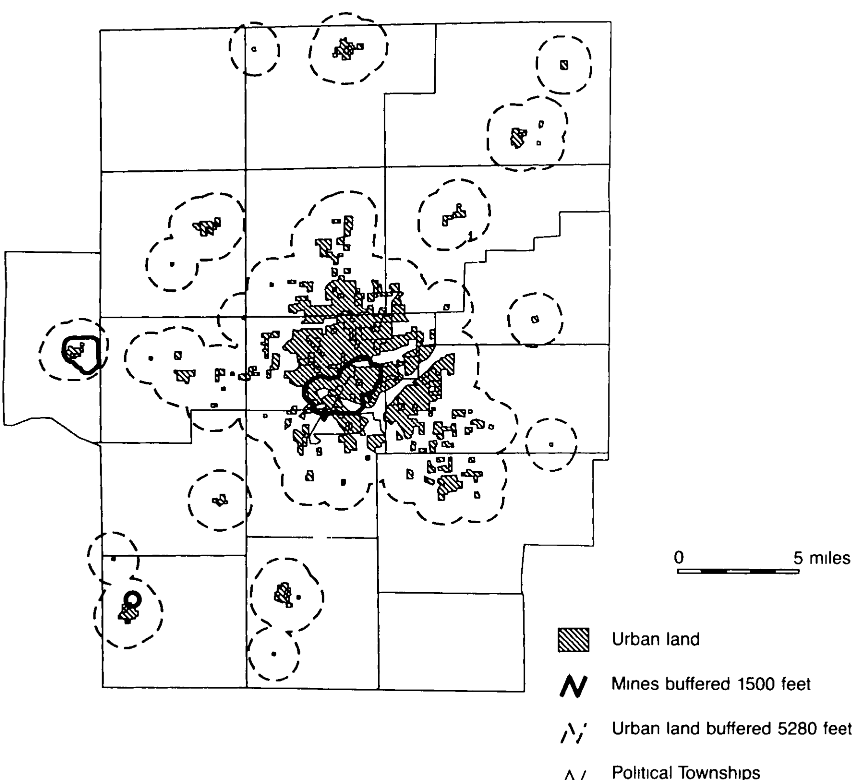

Figure 1 Merged map features

Table 3 Acreage exposed to high and moderate risk of mine subsidence

Twp. no.	Township total area	Township area at risk	Township percent at risk	Residential total area	Residential area at risk	Residential percent at risk	Other urban total area	Other urban area at risk	Other urban percent at risk	Urban buffer total area	Urban buffer area at risk	Urban buffer percent at risk	Housing units at risk	Housing value at risk
High risk (undermined or within proximity buffer)														
8	18,406	568	3.1	135	94	69.7	52	52	100	3,324	422	12.7	225	$5,398,505
10	19,073	1,889	9.9	7,687	1,033	13.4	4,149	567	13.7	6,233	147	2.4	4,031	78,586,892
13	17,262	0	0.0	888	0	0.0	339	0	0.0	8,584	0	0.0	0	0
15	20,466	18	0.1	227	0	0.0	66	0	0.0	4,206	18	0.4	0	0
Totals	371,444*	2,475	0.7	16,427*	1,127	6.9	7,946*	619	7.8	97,952*	587	6.0	4,256	$83,985,397
Moderate risk (within uncertainty buffer)														
8	18,406	518	2.8	135	40	29.6	52	0	0	3,324	479	14.4	96	$2,275,166
10	19,073	1,186	6.2	7,687	763	9.9	4,149	282	6.8	6,233	29	0.5	3,013	65,990,713
13	17,262	7	0.0	888	4	0.5	339	0	0.0	8,584	3	0.0	6	304,822
15	20,466	143	0.7	227	12	5.1	66	0	0	4,206	132	3.1	32	678,425
Totals	371,444*	1,854	0.5	16,427*	819	5.0	7,946*	282	3.5	97,952*	643	0.7	3,147	$69,249,126

* Includes all other townships in county.

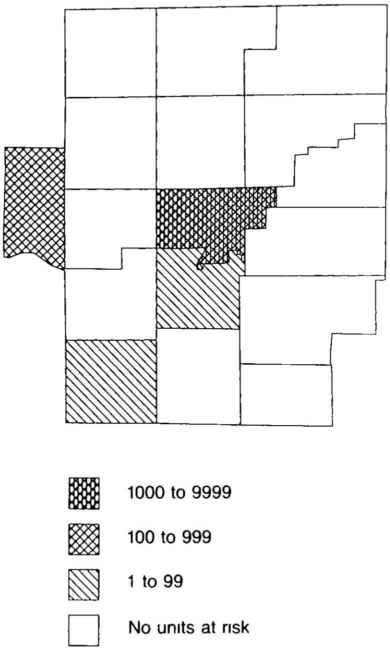

Figure 2 Number of housing units at risk by township

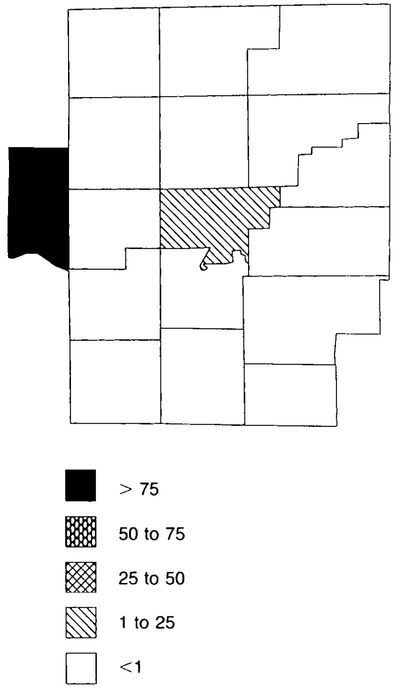

Figure 3 Percentage of housing units at risk by township

CONCLUSIONS

Use of a GIS is providing dramatic new views of the risk of damage to structures from mine subsidence. With GIS capabilities we can efficiently merge a number of large, diverse data sets and evaluate the risk of damage. Although it is up to IMSIF to act on the results of this study, this information will be useful for reviewing and modifying the insurance rate structure and the geographic areas of and procedures for marketing mine subsidence insurance.

The successful application of a GIS to mine subsidence risk could be expanded in several directions. As we learn more about the factors that contribute to subsidence, we can refine the categories of risk by mapping the factors and adding them to the merged county data sets. The GIS could be used to help identify these factors by finding spatial correlations between subsidence events and other parameters. Insurance companies may even be interested in using the address matching capabilities of the GIS to merge mine buffers, DIME (or TIGER) files, and customer lists to identify the homeowners who should be alerted to the need for mine subsidence insurance coverage.

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