

# Estimating Societal Impacts of Infrastructure Damage with GIS

Steven P. French and Xudong Jia

**Abstract:** This paper describes a GIS model designed to estimate the societal impacts of infrastructure damage from earthquakes. The model links physical components of a water delivery system to population data from the U.S. Census. A prototype model has been developed and implemented for the water distribution system of Memphis/Shelby County, Tennessee. There are three components of the model: the simulation module, the assessment module, and the repair module. In the simulation module, damage to the system is specified in one of two ways: the user can indicate the damaged links interactively, or the output of a separate damage model can be downloaded into the module. Once the simulation module is run, the assessment module presents the impacts of the damage in terms of a selected set of demographic variables. The repair module generates a priority list of water lines to be repaired to maximize service to the user-selected population. This paper combines recent research on the societal impacts of disaster with research on the behavior of lifeline systems in earthquakes and state-of-the-art GIS technology.

Current earthquake infrastructure damage models typically produce damage estimates that are expressed in terms of physical damages. For the water-distribution systems, for example, the Applied Technology Council approach produces estimates of the number of breaks per kilometer (Applied Technology Council 1985). While this type of damage estimate represents a large step forward in understanding the impact of an earthquake on infrastructure systems, it does not fully meet the needs of emergency preparedness and hazard-mitigation planners. What is needed is a way to translate this physical damage into its resultant impact on society. The purpose of this research project is to develop techniques for estimating the size and characteris-

tics of the population impacted by earthquake damage to urban infrastructure systems. Such demographic information is the first step toward a complete accounting of the full dimension of the societal impacts caused by natural hazards.

The type of damage information produced by this model can help decision-makers allocate emergency response resources in the most effective manner after an earthquake. Knowing the number and demographic characteristics of those impacted by the disaster can help emergency response officials determine food, shelter and support services. Running the model with likely-scenario earthquakes can also help decision-makers identify critical components of their infrastructure systems and set priorities for their hazard-mitigation efforts.

Most state-of-the-art infrastructure damage models use geographic information systems to estimate earthquake damage. For an excellent review of current damage-modeling techniques, see Risk Management Software (1994). The GIS provides a number of features that are important to the damage-estimation process. Since infrastructure systems are spread over fairly wide areas that include a variety of geologic conditions, the geographic information system's ability to store and manipulate large amounts of spatially distributed information is helpful. The GIS uses a relational database to store characteristics of system components that are important in determining their response to ground shaking and other earthquake-induced effects. It also provides the spatial analysis tools needed to combine geotechnical information with system characteristics based on location.

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Typically, this type of modeling produces an estimate of the number of physical breaks in the system or an estimate of direct costs associated with repair of the system. Existing models do not consider the service population associated with various parts of the system.

The research project highlighted by this paper developed a GIS-based system (called PIPELINE-FIX) which links components of the physical system (e.g., individual water lines or pump stations) to small-area population characteristics. PIPELINE-FIX associates demographic information from the 1990 Census of Population and Housing with nodes on a water-distribution network. It can then estimate the number and characteristics of people impacted by infrastructure damage at various locations based on the topological relationships of the distribution network. Once we know the number and characteristics of the affected population, we are better able to understand the societal impacts caused by damage to the system. PIPELINE-FIX then develops a repair strategy based on user-selected demographic characteristics. Thus, this system moves from physical measures of damage to societal impacts defined by the size and type of population being served.

PIPELINE-FIX provides the user with several alternative ways to determine the damaged condition of the water-system network. The user may indicate the links that have been damaged interactively. This mode will be most useful in a real-time application in a post-earthquake situation. The system can also accept a damage scenario generated by a separate water-system damage model. In this prototype application we have linked PIPELINE-FIX to the LIFELINE-W(I) model developed by Shinozuka and his associates for the Memphis/Shelby County metropolitan area (Shinozuka *et al.* 1992). PIPELINE-FIX has been developed in such a way that it should be possible to link it to other damage models, if desired.

To support real-time system repair or to prioritize earthquake-mitigation expenditures, the societal-impact model includes an optimization routine that rank-orders the pipe segments to be repaired or strengthened based on the service population of each segment. This allows an emergency manager or hazard-mitigation planner to identify those pipe segments that are most important in terms of their societal impact. The system allows the user to focus not only on the size of the service population, but also on population characteristics such as age, income or ethnicity. For example, the system can identify those pipe segments that serve the largest number of elderly people. Thus, the system can inform decision-makers on the characteristics of users subject to service interruption. It allows them to develop mitigation strategies that minimize the impacts on particularly vulnerable segments of the population.

This paper begins by summarizing key research in the methodologies and techniques for lifeline-damage modeling. It also examines research on the societal impacts of earthquakes and other natural disasters. The review presents the foundations of this research from a variety of disciplines and develops the approach used for modeling social impacts. We then describe the data used in the societal-impact modeling process and the spatial-analysis techniques used in linking demographic characteristics to the infrastructure system. We then describe the three modules of the GIS-based system for estimating the societal impacts. The final section summarizes the research results and highlights issues related to further development of this modeling approach.

## Literature Review

Urban infrastructure systems that are susceptible to damage by earthquakes are often referred to as lifelines. Lifelines, including water and sewer systems, electric power lines and telephone systems, are crucial to supporting human activities. Damage to lifelines after an earthquake, flood, or other natural disaster has physical, social, economic and technological impacts. Over the past 20 years there has been a significant amount of research directed toward developing methodologies to estimate the lifeline damage likely to occur after an earthquake or other natural disaster.

Most early damage studies focused on the building stock and paid little attention to infrastructure systems. The classic work by Algermissen *et al.* (1978) is typical of these early studies that classify the building inventory into a number of categories and apply separate loss functions to each category. In the early 1980s lifelines began to get more attention. A pair of studies by the California Division of Mines and Geology (Davis *et al.* 1982a; Davis *et al.* 1982b) considered the infrastructure damage of a magnitude 8.3 event on the San Andreas fault in Los Angeles or the San Francisco Bay Area. These studies used manual mapping techniques and expert opinion to estimate the likely service interruption impacts resulting from a major scenario earthquake.

In ATC-13, the Applied Technology Council (1985) developed a comprehensive methodology for estimating damage from earthquakes. This approach used expert opinion to develop damage probability matrices for 80 classes of buildings and infrastructure components. For linear facilities, such as pipelines, the matrices expressed the likelihood of experiencing a given number of breaks per kilometer for earthquakes of Modified Mercalli Intensities from VI through XII. Network connections between system components were not explicitly treated; therefore each component was considered independently. The method was extended to include estimated

restoration times in ATC-25 (Applied Technology Council 1991).

In the late 1980s there was increased research on the performance of individual infrastructure components, particularly water and natural gas pipelines (O'Rourke 1989). Component level studies of water-system performance were undertaken by O'Rourke (1991) and others. Thus, we see the state of knowledge regarding infrastructure system performance increasing rapidly during the 1980s with more attention focused on component-level analysis.

In the mid-1980s geographic information systems began to be used to estimate damage to building stocks (French and Isaacson 1984). It was not long before the advantages of the GIS damage-modeling approach began to be applied to infrastructure systems. O'Rourke (1989) developed a program entitled GISALLE to estimate the reliability of water-delivery systems. Sato and Shinozuka (1991) developed a GIS-based model for the Memphis area water distribution system. The standardized loss-estimation methodology currently being developed for the Federal Emergency Management Agency (FEMA) by the National Institute of Building Sciences (1994) uses a GIS to combine seismic hazard and inventory information at the census tract level. The GIS provides a way to integrate knowledge about the causes of physical damage with characteristics of the distribution network to estimate both system damage and performance.

While large strides have been made in our ability to model the physical dimension of earthquake damage, this technical work has remained largely separate from the research on societal impacts of earthquakes and other natural hazards (Tubbesing 1992). In part, this separation may be the result of an information gap on the specific societal impacts of infrastructure damage and the loss of service from lifelines. Currently, the lifeline-infrastructure research is expanding to include the social and economic impacts of disasters and the process of recovery from them.

The short-term social impacts of an earthquake include the need for food, water, shelter, and medical and psychological services. Haas *et al.* (1977) identified social networks as important components in supporting the recovery process. It is now widely recognized that earthquake damage differentially impacts various age, income, and ethnic groups. These impacts are caused not only by direct damage, but also by interruption of important lifeline services. The National Academy of Sciences (Panel on Earthquake Loss Estimation 1989) suggests that these differential sub-population impacts should be considered in emergency planning and response. Rubin and Palm (1987) have documented that immigrant populations were disproportionately impacted by the Whittier Narrows earthquake. Bolin (1993)

found that Hispanic victims were less likely to relocate after the Loma Prieta earthquake, even if their homes were heavily damaged. Greene and Schulz (1993) found that the emergency shelter and replacement housing impacts of the Loma Prieta earthquake disproportionately impacted low-income residents. Bolin also found there was a shortage of housing available for low-income residents after the earthquake. Comerio (1995) found that many of the low-income residents impacted by the Northridge earthquake seemed to disappear.

Bolin (1982) discovered that the elderly recover quickly from the initial emotional impact relative to other age groups, but they experience a substantial decline in their standard of living. Other researchers differ on whether the elderly experience disproportional impacts from disasters. The existing research clearly indicates that the impacts of natural disasters differ among population subgroups. Therefore, our models must distinguish who is impacted by earthquake damage.

The separation of social and economic impacts from physical-damage estimates affects the determination of repair strategies. The current process of infrastructure repair can be characterized as one in which the least-damaged lines are fixed first. Seligson (1990) has calculated time to repair as a function of number of breaks per square mile. Lines with few breaks and heavy demand are usually repaired first, and lines with many breaks and low demand are repaired last. Several attempts have already been made to computerize existing repair strategies (Iwata 1988), but these methods generally do not take societal impacts into account. Tobin *et al.* (1995) report that a GIS model (EPEDAT) was used extensively to manage the response to the Northridge earthquake. For the purpose of this research, it is a given that lifeline repair will occur quickly, but the criteria for repairing lines should be based on the characteristics of the service population.

Based on our current understanding of societal impacts, methods of modeling physical damage, and current approaches to repair, it is desirable to develop a model that combines social and technical knowledge. The common link between these various elements is the demographic characteristics of the service population. If we can develop a model that estimates how infrastructure damage affects different social groups, especially low-income families, the elderly, and particular ethnic groups, we can begin to understand the societal impacts of infrastructure damage. The model developed in this research attempts to make this connection.

## Modeling Societal Impacts

The modeling approach developed in this project characterizes societal impacts in demographic terms. Its basic premise is that societal impacts are a function of the

number and type of population and housing that are affected by infrastructure damage. The modeling is done within the ARC/INFO GIS. The societal impact modeling system, PIPELINE-FIX, consists of three basic modules: 1) the damage simulation module, 2) the assessment module, and 3) the repair priority module (Figure 1). This section discusses the development of the PIPELINE-FIX system in terms of data preparation and the integration of the demographic data with the water distribution system. Issues related to the implementation of the three modules are discussed in the next section.

### Data Requirements

The PIPELINE-FIX system requires information about the water-supply network, demographic data, and information about earthquake impacts over the affected study area. The water-supply network is often considered the most critical lifeline system because it supports many essential human needs. A functioning water-distribution system is also necessary to fight fires following the earthquake.

The water-supply network can be characterized as a series of links and nodes. Each link represents a water pipeline that connects two adjacent nodes. Each node represents an intersection of two or more pipe segments. Other components of the system, such as valves, pump stations and storage tanks, are also represented as nodes on the network.

The demographic data provide the basic description of societal structure. In this system, the demographic data provide variables for estimating societal impacts of the water supply system damaged by an earthquake.

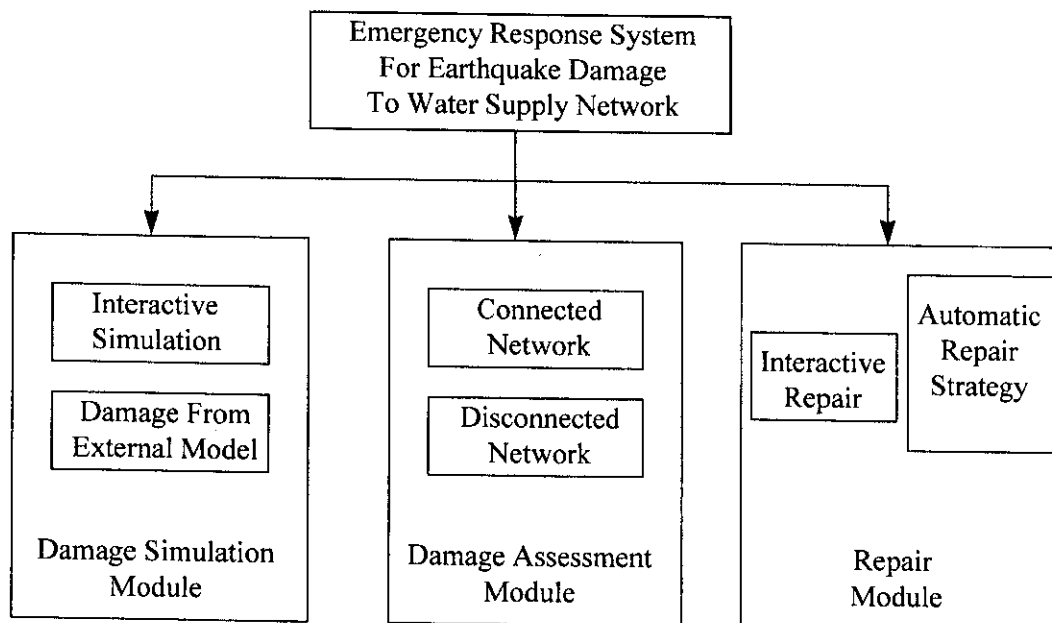
### Study Area and Data Sources

Shelby County, Tennessee, which has nine cities including the city of Memphis, was selected as the study area for this project. Shelby County faces a significant earthquake hazard due to its location in the New Madrid seismic zone. The selection of Shelby County also allowed this project to be integrated with ongoing work of other researchers supported by the National Center for Earthquake Engineering Research (NCEER).

Digital information related to the county, including information about the water distribution network, the population and housing stock and various real and simulated intensities of earthquake, is used in this system. The water distribution network was originally digitized by Memphis State University. It is represented as network coverage in the ARC/INFO GIS. A number of important characteristics of the components of the water system, such as pipeline diameter and roughness, are also stored in the ARC/INFO attribute database.

Coverages that describe Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) for selected earthquakes are stored in the system. This model does not simulate physical damage to the infrastructure, but is linked to other models that perform this function.

FIGURE 1. Conceptual design of the PIPELINE-FIX system



Currently, PIPELINE-FIX relies on damage scenarios generated by the LIFELINE-W(I) model developed by NCEER researchers in the Department of Civil Engineering at Princeton University (Tanaka and Shinozuka 1993). PIPELINE-FIX also allows the user to interactively designate damage to the system without relying on a simulation model.

The demographic information used in the project is drawn from the 1990 Census of Population and Housing. The model uses various categories of data about population and housing available at the block and block-group levels of aggregation. A block is the smallest geographical area defined for data reporting in the 1990 Census. Each block is a small area bounded on all sides by visible features such as streets, roads, streams, and railroad tracks or invisible boundaries such as city, town, township and county limits. In urban areas it is typically one city block. Each block record in the database has a unique identification number and coordinates of its centroid assigned to it. These coordinates can be used to locate the centroids of the blocks within the county.

The block-level information is drawn from the Summary Table Format (STF-1B) CD-ROM published by the

U.S. Census Bureau (U.S. Department of Commerce, 1991). The major variables used in the project include population and housing counts (Table 1). The data collected at the block level are derived from a set of basic questions asked by the Census Bureau of the entire population and about every housing unit (also known as the short form). The greatest weakness of the block-level data is the lack of information about income or educational attainment. Median value of homes and contract rent can be used as surrogates for income, but are obviously imperfect substitutes. Similarly, the data on age and ethnicity do not provide much detail at the block level. The block level is, however, appealing because it is at a fine geographic grain. This is important in linking the data to the water network, which is also geographically detailed.

The Census Bureau publishes a richer set of data at the block-group level. These data are derived from more detailed census questionnaires that are administered to a 1-in-6 sample of the population. As with the blocks, each block group also has a unique identification number and the coordinates of its centroid. The block-group level information is available on the Summary Table Format (STF-3A) CD-ROM published by the U.S. Census Bu-

**TABLE 1. Variables at the block level (STF-3B)**

Variables	Variable Items
Persons	Total
Race	White Black American Indian, Eskimo or Aleut Asian or Pacific Islander
Persons of Hispanic Origin	Total
Age	Under 18 years 65 years and over
Housing Units and Units in Structure	Total 1 Unit Detached or Attached 10 or more units
Mean Number of Rooms	Average Number of Rooms per Household
Tenure	Owner Occupied Housing Units Renter Occupied Housing Units
Mean Value	Average Sales Price
Mean Contract Rent	Average Rental Value
Housing Units with more than one Person/Room	Total Occupied Renter Occupied
Persons in Occupied Housing Units	Total
Housing Unit Occupants	One Person Households Family Householder no Spouse Present with one or more Persons under 18 Present

reau (U.S. Department of Commerce 1991). The block-group level variables used in the project include not only the population and housing counts available at the block level, but also information about education, occupation, income and more detailed categories of age and ethnicity (Table 2). More detail is also available on the housing stock. Some of this, such as the amount of group housing (e.g., nursing homes) and source of water supply (e.g., private wells versus the public system) may be important in determining societal impacts. The key problem is that this richer set of data is only available for much coarser geographic areas because a block group is a collection of individual blocks, typically 8 to 12 blocks containing 250-500 housing units.

The PIPELINE-FIX system uses both of the above data sets to estimate the societal impacts of earthquake damages to the water supply network. Each data set has its own strengths and weaknesses. The block-level data have a small number of variables. Using this set of variables, PIPELINE-FIX can determine the impact of an earthquake on the overall population and on various broad social groups (white, black, under 18, over 65). The block-group level provides a more extensive set of

variables. There is more information on the breakdown of ages, houses that utilize wells, sewage disposal, education and occupation. This additional set of variables affords the opportunity to analyze the consequences of infrastructure damage on different groups in more detail.

The size of geographic area is important in the assessment of societal impacts of water system damage and the development of emergency response plans. The block-level data represent the population and housing characteristics of the small areas with high accuracy. The block groups are significantly larger than the blocks. Therefore, there are a smaller number of centroids used to represent the patterns of population and housing in the same study area. While the census block-group level includes a more extensive set of variables, its lower level of spatial resolution makes it less accurate spatially.

### *Integrating Demographic Data with Water Pipeline Network*

Integration of demographic data with the water network is critical to the assessment of social impacts of water pipeline damage and the development of emergency-response plans. It converts the direct damage of the water network into description of various service populations that are not connected to the pump stations or water tanks.

The first task for such integration is to convert the demographic data into a form that could be used by the PIPELINE-FIX model. The data sets at the block and block-group levels were originally stored in the dBASE databases. These data sets are converted and moved from dBASE databases to INFO attribute tables. Using the centroid coordinates of the blocks and block groups, we generated two point coverages that locate the demographic data in the INFO tables.

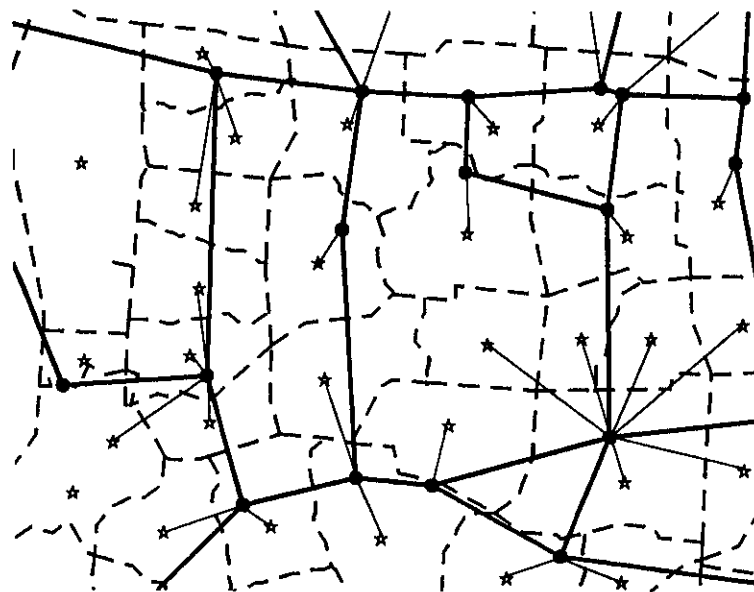
Given the demographic data available for use in ARC/INFO, the next important issue is how to link it to the water distribution network. A number of alternative techniques, including various types of buffering and line-to-polygon overlay, were investigated in this research. A centroid-to-node aggregation technique was finally chosen for this linking purpose. This approach links and aggregates the demographic information from each block to the closest node in the water system (Figure 2). Block centroids are shown as stars in the figure. The demographic attributes from the block centroids are aggregated to the closest water-network nodes (depicted by the heavy circles). The process can be described as follows:

- Locate the closest node for each block centroid and assign the node number to it. Increase the search radius to a proper distance, so that all the centroids find at least one node.

**TABLE 2. Variables at the block-group level (STF-3A)**

Variable	Variable Items
Persons	Total
Race	White
	Black
	American Indian, Eskimo
	Asian or Pacific Islander
Households	Total
	Families
Age	All ages
	Less than 10
	Less than 18
	Less than 60
Housing Units	Total
	Group Housing
Occupation	SIC Classifications
Income	Various Income Groups
	Poverty Status
	All Household Income
	Median Household Income
Water Supply	Public Supply
	Well
Sewage Disposal	Public Sewage Disposal
	Septic Tank or Cesspool/other
Structure	Median Building Age

FIGURE 2. Aggregation of block level population to water network nodes








### Point-to-Node Aggregation

$$\text{PopNode} = \sum_j \text{Pop of Block Centroids}$$

where  $j$  is the total number of block centroids within close proximity of a node.

### LEGEND

-  Water Delivery Network
-  Block Boundary
-  Connectors
-  Network Nodes
-  Block Centroids

- Sum the demographic variables (including population and housing units) within all the blocks with same node number and assign the results to the corresponding node. The results represent the characteristics of the population served by each node.

This approach allocates all of the population within a block or block group to a single node. This is obviously an approximation that has some limitations. Where parcel-level tax assessment data are available, housing units can be assigned their adjacent water line based on address matching or parcel adjacency. The service population associated with each pipeline can then be estimated based on the number and size of the housing units. Such an approach is preferable where detailed demographic characteristics of the service population are not needed or in rural areas where small area census data is not available. While the land-parcel approach is likely to improve the model's spatial accuracy in allocating population to the network, it cannot provide the rich description of the service population characteristics (e.g., age, ethnicity) that can be accessed using census data. The accuracy problems associated with inferring detailed social characteristics from housing data are at least as great as the spatial aggregation problems associated with using the coarser census data. Given these issues and the quality of land parcel information available for Shelby County, the research team chose to use the centroid-to-node aggregation approach using small area census data as the best way to link detailed societal data to the network.

The accuracy of the aggregation process is significantly affected by the number and spatial distribution of the centroids being aggregated. A large number of densely packed centroids (as in the case of census blocks) results in a small average distance between any centroid and its nearest node. In this case, most water-system nodes are likely to be allocated a service population from one or more centroids. When larger demographic units, such as block groups or tracts, are used, there are fewer centroids to be allocated. As a result, some water-system nodes may not be allocated a service population. The use of fine-grained demographic units results in a more accurate allocation of population to the network nodes.

To characterize the match between the nodes and centroids, we developed a simple measure. We used the ratio of nodes with data to total nodes as a measure of fit. We called this ratio the "snap ratio." For census blocks in Shelby County the snap ratio is 13/14, which means that over 90 percent of the water-system nodes were allocated with population. For block groups the snap ratio drops to 8/14 because the relatively large size of the block-group polygons makes many water-system nodes not allocated with demographic data. Thus, the coarser block-group data may cause problems in the application of the PIPELINE-FIX system.

### The PIPELINE-FIX Software

The PIPELINE-FIX software implements the conceptual framework described in the previous section and inte-

grates the three primary modules using a graphical user interface (Figure 3). The user interface consists of two windows: the main window containing the simulation, assessment and repair components; and the report window displaying background information and system processing status. The functions in the main window can be easily modified or updated. The software is generic in the sense that it can be applied to any water system as long as the graphic and database format is consistent with the software's requirements. The report window provides information (such as maps of soils, streams, geology, contours, and roads) for users to understand the study area and the analysis. This section describes the modules that pertain to the analyses of earthquake damage to the water network and highlights their applications to the data sets described in the previous sections.

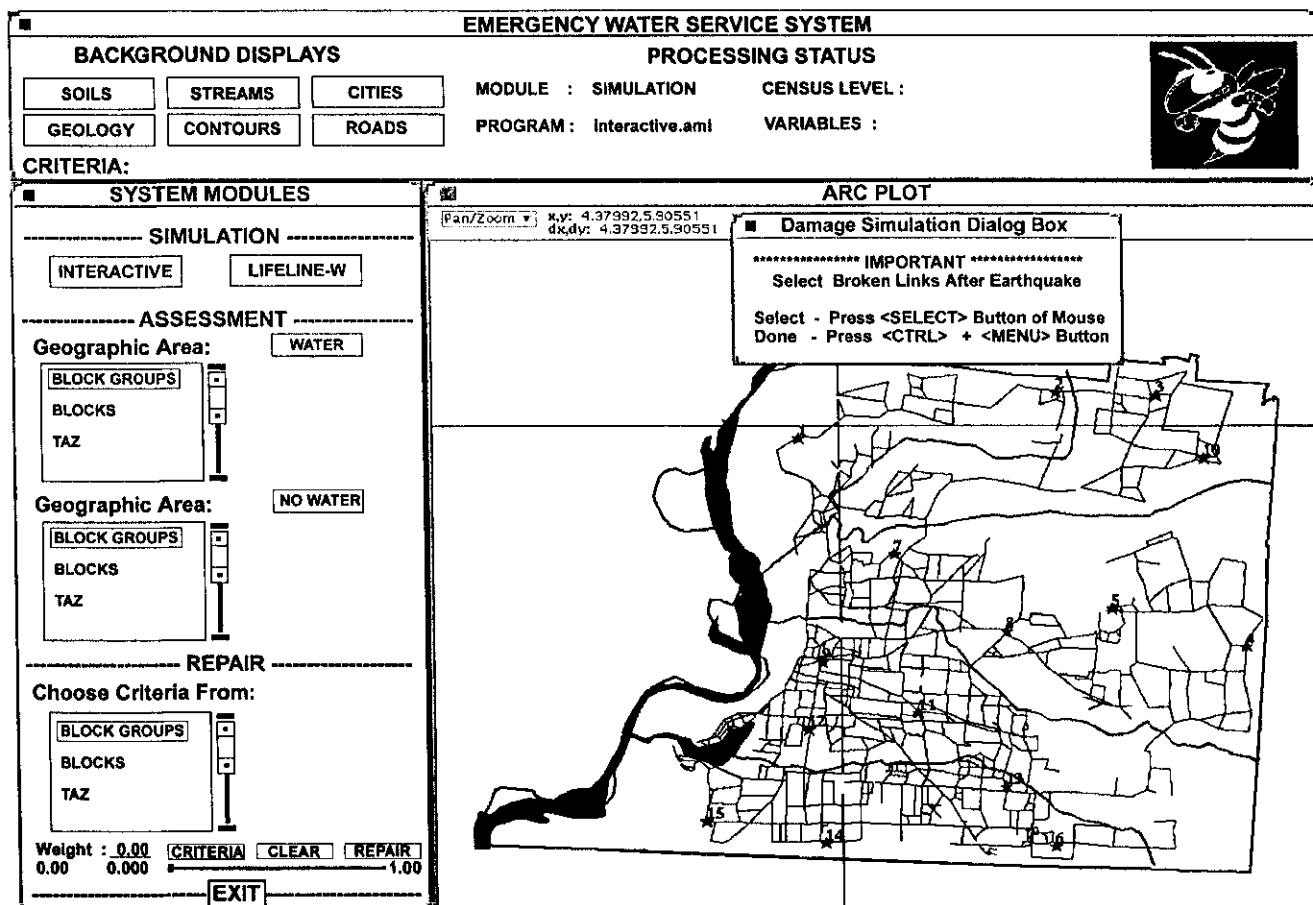
### The Simulation Module

The simulation module is designed to depict earthquake damage states for the water-distribution network. It can

generate the damage pattern based on interactive input by the user or can accept damage scenarios calculated by external damage models. The interactive method allows the user to select pipelines damaged by the earthquake based on the information he or she receives from the site investigation, public reports, or a predetermined scenario. Once the operator makes his or her selections, the system displays the locations of the broken pipelines on the water network. This type of simulation can be particularly useful for directing real-time emergency response. Immediately after an earthquake or other natural disaster, the damaged pipelines can be located by field investigation. The user then indicates the broken lines on the system. Using the assessment and repair modules, the system can estimate the population no longer receiving water service and suggest an order of repair to restore service.

The second method for generating a damage simulation is to directly incorporate output from a stand-alone damage model. This method uses the damage model to convert the earthquake intensities to the ground motions and ultimately to the damage of the water pipeline

FIGURE 3. Interactive simulation of the water pipeline network damage



network. Currently, PIPELINE-FIX system uses the LIFELINE-W(I) system developed by Shinozuka, Hwang, and Murata (1992). Although this system is primarily intended to calculate the water pressure under different conditions, it also generates pipeline damage data that can be used in the PIPELINE-FIX system for assessment of societal impacts.

In the LIFELINE-W(I) system, ground motion is considered the major cause of breaks in underground pipes. Ground motion can be represented in two types of scenarios. The first scenario assumes the earthquake intensity is the same everywhere in the study area, and can be measured by the Modified Mercalli Intensity (MMI). The second scenario assumes ground motion intensity varies from place to place, and it estimates the intensity at selected locations within the study area in terms of peak ground acceleration (PGA). Ground motion for the entire study area is then interpolated spatially from site PGA values. The LIFELINE-W(I) system estimates the occurrence rates of pipeline failure and calculates water flows in terms of pressure and water head. The occurrence rates of pipeline failure are stored in an ARC/INFO database that the PIPELINE-FIX system can easily access.

The LIFELINE-W(I) system was originally developed as a FORTRAN program. It was then linked into the ARC/INFO environment. Since it works within the ARC/INFO environment, the PIPELINE-FIX system can easily integrate the LIFELINE-W(I) system for use in societal impact analysis. Other third-party systems may not be developed for the ARC/INFO platform; therefore additional software interfaces would be required to link them to PIPELINE-FIX.

### *The Assessment Module*

The assessment module calculates the first-round societal impacts using the damage state produced by the simulation module. It translates the physical damage produced by the simulation module into societal variables such as population, housing units or the number of elderly people. It can report either the number of people or housing units of selected characteristics that are without water service or the number that retain adequate service.

Using the topological structure of the water distribution network, the model identifies those nodes that have been disconnected from the network by the pipeline damage. Because the nodes of the water system have been linked to the service population and its demographic characteristics as described earlier, the model can estimate the number and character of the impacted population. The ARC/INFO system provides a powerful connectivity-searching routine for use with networked systems. The assessment module uses this rou-

line, identifies the nodes isolated by damaged pipes, extracts the characteristics of the population served by each node from the associated database, and aggregates them to estimate overall societal impact. In this approach, the pipelines are treated as pathways that allow the water to reach its service population located at the nodes. It should be noted that some critical pipes may service a number of nodes depending on the topological structure of the network. This approach accounts for this network characteristic.

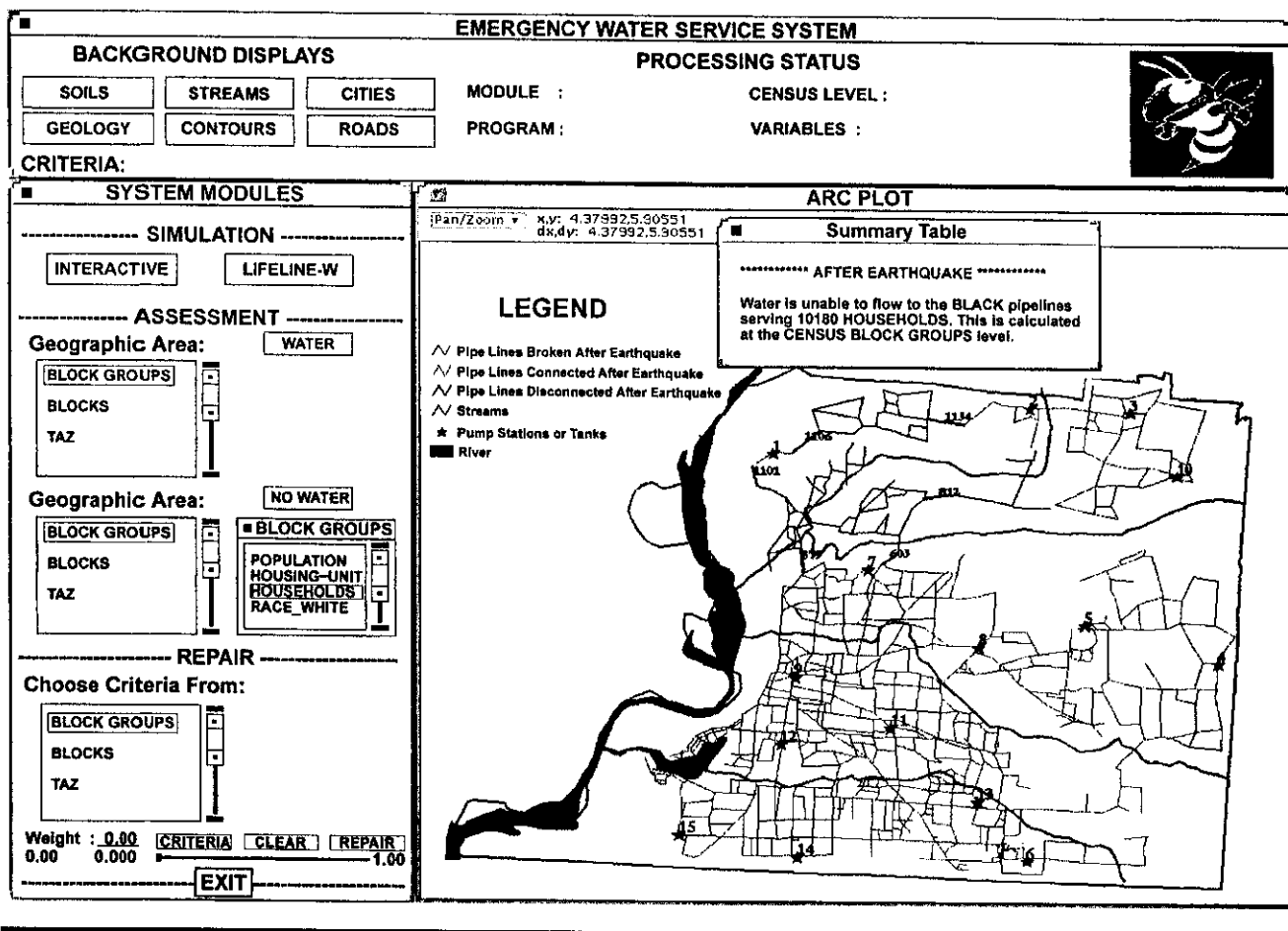
To calculate the impacted population, the PIPELINE-FIX system analyzes the damaged network to determine which nodes are still connected to pump stations or storage tanks by undamaged pipelines. The nodes connected to the pump stations or tanks are assumed to receive service after an earthquake. The nodes that have been disconnected from the pump stations or tanks are considered out of service. It is important to realize that population located alongside an undamaged pipe will lose its water service if there is no network link to a pump station or storage tank. Thus, each node is analyzed to determine if it can be connected to a source of water by the network.

The system then characterizes the societal impact in terms of the demographic variables chosen by the user. For example, the system can estimate the number of elderly residents or the number of high-density apartment units that will lose service for a given damage pattern. These variables are aggregated for all disconnected nodes to estimate the total societal impact.

The assessment module allows the user to choose a set of particular demographic variables that will be used to determine societal impact. As discussed in the previous section, these variables are drawn from two different levels of census geography - blocks and block groups. A scroll window is provided for selecting variables from different levels of geography. The user first chooses the level of geography for the analysis, either the block or the block group. Once the level is specified, the PIPELINE-FIX system displays the set of demographic variables available for that level. The user then selects a particular variable and allows the system to use the variable for subsequent analyses.

The assessment model can generate either of two types of first-round results. The first shows the population or housing units that are no longer served by the water network. Conversely, the system can calculate those that retain service even though the system is partially damaged. The assessment results of each type can be represented in a thematic map (Figure 4). In this map, the gray links represent the operative pipelines after the earthquake, the numbered dotted links represent the broken pipelines, and the black links indicate undamaged lines that are out of service because they have lost connection to their supply nodes. This map displays the

FIGURE 4. Example output of the assessment module



total population and number of housing units without service given that five pipelines—579, 591, 604, 610, and 812—have been broken.

Thus, the assessment module informs damage assessors of the total number of users that will lose service in a given damage scenario. The user can select what particular variables best characterize societal impacts in a particular situation and can choose the appropriate level of geography to use in measuring those impacts.

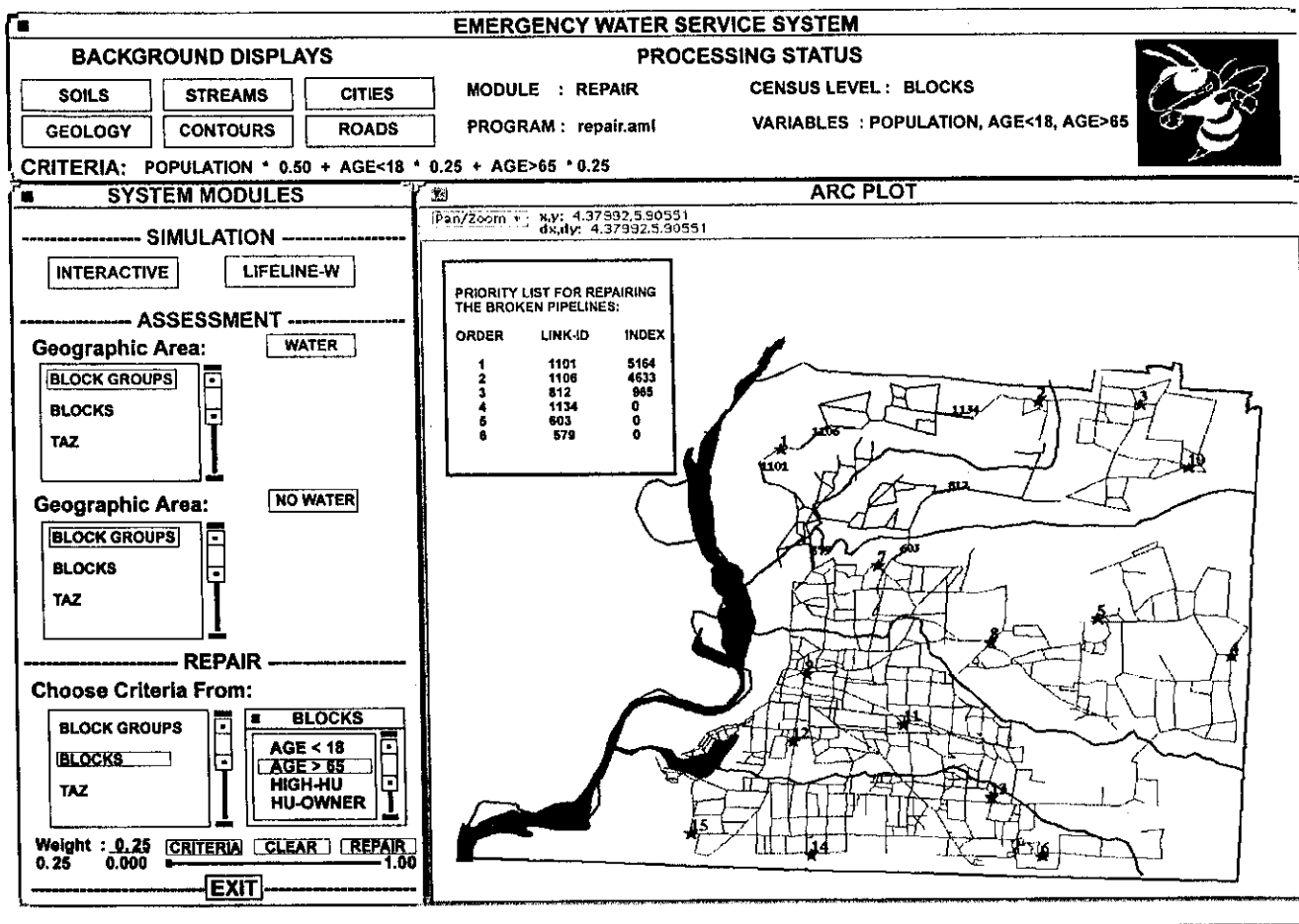
### The Repair Module

Managing the emergency response effort immediately after an earthquake can be viewed as a sophisticated optimization task. It involves a thorough understanding of characteristics of the damaged water supply network and an understanding of the societal costs of the damage. The PIPELINE-FIX repair module generates a response plan based on maximizing the social benefits with each pipeline restored to service. The repair module utilizes information on system damage and related

population produced by the simulation and assessment modules.

The repair module develops a prioritized repair strategy based on the societal benefits associated with the restoration of each pipe segment. The societal benefits are measured by a user-defined combination of societal variables or impact criteria. These variables are combined into a societal impact index based on weights proportional to their relative importance. The repair module includes a criteria editor that allows the user to create indices to guide the repair strategy. The user first selects one or more societal variables to include in the index, then assigns each a weight between 0 and 100 percent, such that all weights total 100 percent. The system then uses this index to select the order in which to repair the damaged pipes. An example would be an index that includes total population (50 percent), the population under 18 (25 percent), and the population over 18 (25 percent). The model would thus consider the population served by a particular link, but would give added weight to those links that served children and the el-

FIGURE 5. Repair strategy generated by the repair module



derly—populations that might be especially vulnerable. Any of the variables available at the block or block-group level can be used to construct a repair index.

The repair module uses the index constructed with the criteria editor to generate an optimal repair strategy. It simulates the repair process by selecting one broken pipeline at a time and evaluating the connectivity of the water network if that pipeline is repaired. It then estimates the changes in the service population that the restored water line will provide. For example, if the societal impact index is population only, the number of people for whom service will be restored is calculated for each broken pipe. The broken pipeline that restores service for most people is selected for repair. The repair module notes that this pipeline has been repaired, and repeats the repair analysis for the remaining broken pipelines. When completed, the system displays a priority list of pipelines. Those that yield the most benefits in terms of the social impact index are repaired first. For example, pipeline 591 should be repaired first in an example priority repair list (Figure 5).

Thus, the repair module develops a priority list for repairing the network based on the service provided by each pipe in the network. The module bases this analysis on the connectivity of the network and the population served by each link. The user determines the combination of demographic variables that will be used to define social impact.

## Conclusions and Future Research

This paper demonstrates an approach that incorporates societal impacts into earthquake damage modeling. The GIS-based system, PIPELINE-FIX, utilizes a modular approach to analyze the societal impacts of earthquake damage to an urban infrastructure system, specifically a water-pipeline network. The system links demographic characteristics of the service population to the physical components of the water network. In addition, it uses the topological characteristics of the network to estimate the type and amount of population that will lose service for any specific pattern of damage to the network.

The system also uses the societal impacts as measured by the demographic characteristics of the affected population to generate a repair strategy that minimizes societal impact. In generating a repair strategy, this system considers the connectivity characteristics of the damaged water-pipeline network as well as the societal cost of the damage. It does not, however, consider the difficulty of restoring a broken pipeline or the time required for the repair.

The prototype model developed in this research demonstrates that it is possible to use the capabilities of a GIS system to integrate societal impact variables with a damage model of an infrastructure network. The model can be used in an emergency response mode where actual damage has been identified based on field reports. The Northridge earthquake experience demonstrates that simulation models can provide important damage estimates that can be quite useful in response management until actual damage information is available. This model can extend this use to provide estimates of the number and characteristics of service populations impacted by the event.

The model can also be used in conjunction with other simulation models to test hypothetical earthquake scenarios. In this simulation application, the model can be useful in identifying critical components of the water system, which, if damaged, have the greatest societal impact. Once identified, these components can be strengthened or provided with redundant capacity to minimize societal impacts. In this way, the model provides the capability to develop mitigation strategies that take account of societal impact.

Future research will extend the basic model to account for economic as well as societal impacts. To effectively estimate the economic impacts of infrastructure damage, it is first necessary to locate the various economic activities with enough precision to determine their relationship to the infrastructure network. This research suggests that aggregate data for areas larger than the census block level is unlikely to provide sufficiently reliable results. Since the U.S. Bureau of the Census does not provide economic data at the block level, address matching of local records maintained for tax assessment and business licenses provides the best method of locating economic activity. Once located, economic activities can be associated with support infrastructure using the same basic techniques developed in this research for linking demographic data to the network. By making this link we can identify those activities that will be without fire protection after an event. We can also identify those businesses and critical facilities that are likely to experience significant service interruption. This information can be used to support more elaborate interruption and input/output modeling efforts. These economic impacts can then be integrated

and balanced with the social impacts currently produced by the model.

Future research will investigate the feasibility of extending the basic approach developed here to similar infrastructure networks. Road networks and telecommunication systems appear to be the most fertile areas for further investigation. Both of these systems exhibit some characteristics that are quite different from the water distribution network considered in this project, but many of the same principles should apply.

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