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Foster, H. D. (1988). Multiple hazard mapping: A technique for reducing life loss and injury. In L. R. Martin & G. Lafond (Eds.), Risk assessment and management: Emergency planning perspectives (pp. 3-19). Waterloo: University of Waterloo Press.

Multiple Hazard Mapping: A Technique for Reducing Life Loss and Injury

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ABSTRACT

The earth's surface is an intricate risk mosaic, the description and appreciation of which should necessarily form an essential ingredient in reducing the adverse consequences of both natural and man-made disasters. The data required to produce risk maps are often available from a variety of sources, including national and regional government agencies, universities, newspapers and television studios, city or telephone directories, insurance agencies, police, fire and hospital records and diaries. Oral histories, archaeological information and geological and biological data can also be used to extend records.

Once such data are collected they can be used to produce a variety of maps that are essentially predictive tools. Their aim is to show spatial variations of risk, based on expected frequency and intensity of hazard impact. The paper which follows describes in some detail how they can be used to simulate disasters such as earthquakes and how, given a common unit of measurement, such as the economic loss associated with an event, a total risk map can be produced. This illustrates expected losses from all hazards for any location.

Multiple hazard maps may also be used to provide information on the causes of death even when the nature of the hazard involved is not fully understood. Cancer is used to illustrate this point. Maps of death from specific cancer can be produced and the data correlated with possible causal variables. When this was done for the United States, industrial and agricultural activities and bulk and trace element imbalances in the soil showed highly significant correlations. Selenium in particular appears protective. Evidence is also presented from California to show that such multiple hazard mapping and associated risk conscious land use planning have very positive benefit-cost ratios.

RÉSUMÉ

La surface de la terre présente une mosaïque complexe de risques dont la description et l'appréciation devraient nécessairement constituer un élément essentiel dans la réduction des conséquences défavorables faisant suite à des désastres naturels et causés par l'homme. Les données requises pour produire des cartes de zones de risque sont souvent disponibles à partir d'une variété de sources, dont les agences gouvernementales nationales et régionales, les universités, les journaux et les studios de télévision, les annuaires de téléphone ou de municipalité, les compagnies d'assurances, la police, les dossiers et annuaires des hôpitaux et des pompiers. Les histoires transmises oralement, l'information archéologique et les données géologiques et biologiques peuvent également être utilisées pour étendre les archives.

A partir du moment où ces données sont recueillies, elles peuvent être utilisées pour produire une variété de cartes qui sont essentiellement des outils de prédiction. Leur but est de montrer les variations spatiales du risque en se basant sur la fréquence et l'intensité prévues du péril. Cet exposé décrit en détails comment ces cartes peuvent être utilisées pour simuler des désastres comme les tremblements de terre, et comment, en utilisant une unité de mesure stable comme les pertes économiques associées avec un tel incident, une carte de risque total peut être produite. Cette dernière illustrerait les pertes prévues pour toutes sortes de périls, et ce, pour tout endroit.

Des cartes de périls multiples peuvent aussi être utilisées pour apporter de l'information sur les causes de décès, même lorsque la nature du péril impliqué n'est pas complètement comprise. Le cancer sert d'exemple pour démontrer ce point. Des cartes de décès à la suite d'un cancer spécifique peuvent être produites, et les données corrélées avec les causes possibles. Lorsque cela a été fait pour les États-Unis, les activités industrielles et agricoles ont démontré des corrélations fortement significatives avec les débalancements d'éléments chimiques en trace et en grandes quantités dans le sol. Le sélénium, en particulier, apparaît comme élément protecteur. On présente également le cas de la Californie où l'on démontre que l'utilisation de telles cartes de périls multiples pour la planification de l'utilisation des terres en tenant compte des risques présente des avantages écomoniques très positifs.

1. INTRODUCTION

On September 19, 1985 an earthquake with a Richter magnitude of 7.8 occurred off the west coast of Mexico. Nearby towns including Zihuatanejo and Ixtapa, only some 80 kilometres from the epicentre, suffered relatively little damage. In contrast, Mexico City, over 320 kilometres distant, was badly affected. Zihuatanejo and Ixtapa, however, are built on bedrock, whilst Mexico City rests on alluvial deposits of gravel, sand, silt, clay and deep volcanic ash (Legget, 1973). As a consequence, seismic waves were amplified in the capital city, causing some tall buildings to resonate sympathetically with their frequency. Approximately 250 structures collapsed, including the gynecology-obstetrics wing of the General Hospital, 50 towers were close to falling, whilst 1,000 were rendered unsafe. An estimated 20,000 inhabitants were killed and up to 150,000 left homeless (Angier, 1985; Russell, 1985).

Unfortunately, two months later a second major disaster struck Latin America when the Columbian volcano, Nevado del Ruiz erupted. Pyroclastic flows surged outwards from the crater, scouring and melting the northern half of the Ruiz ice cap. Melt water, ice and pyroclastic debris spilled from the summit into a network of shallow streams, which carried the resulting lahars down both the east and west flanks of the Cordillera Central. Surging down the Lagunillas River they overtopped the modern channel and followed the former river course into Armero, obliterating its lower lying southern sector. Over 20,000 died, whilst thousands more were injured, or left homeless. Ironically, many of the survivors escaped by fleeing to Armero's highest ground, its hilltop cemetery (Russell, 1985; Herd, 1986).

These two case studies illustrate the necessity of risk mapping to town planning. The earth's surface is an intricate risk mosaic, the description and appreciation of which should necessarily form an essential ingredient in any rational attempt to reduce the social disruption and economic loss commonly accompanying both natural and man-made disasters. Before risk levels can be effectively utilized to control development, several tasks must be accomplished. Firstly, differing hazard zones must be established for specific disaster agents and then integrated to form multiple, or if possible, total risk maps. Secondly, the loss potential of alternative combinations of land use and structural designs within these zones must be established. Finally, selection must be made between alternative uses on the basis of standards set for unacceptable risk to life and property (Puget Sound Council of Governments, 1975a, 1975b). This paper deals with the first of these steps, the production of maps defining spatial variations in risk, a process that requires data from a very wide variety of sources (Foster, 1980).

2. DATA COLLECTION

Ideally all risk maps should attempt to show which areas are threatened by a hazard(s) and how often, and with what intensity its impact is likely to occur. The production of multiple hazard maps, illustrating numerous threats, requires a wide variety of data. Fortunately, much data may already have been collected for other purposes. For many significant hazards, such as avalanches, floods, tornadoes, hurricanes and toxic waste sites, for example, there is often a national or regional agency which has been involved in data collection for many years. Industrial associations may also play a similar role. Data from these organizations are often freely available in either published or computerized form. Other possible sources of information include academic, business and government scientific papers, maps and records. Many municipalities and drilling companies also maintain borehole records which include data on well location, changes in stratigraphy and the height of the watertable. This information is extremely valuable in producing earthquake microzonations (Wuorinen, 1976) and prediction risks from waste disposal sites (Fenge, 1976). Published accounts of bedrock geology, soil type, vegetation patterns and land use can also be a major input into the microzonation process.

Other key data sources include historical visual information, such as photographs, films, sketches and diagrams, which may be available from government and university archives, newspaper files, television studios and private collections. Since disasters are newsworthy, spatial patterns of destruction, and hence the magnitude of impact of past events can often be established with surprising accuracy from such visual sources.

Private and public records of past and present industrial activity are also pertinent. Old city or telephone directories, for example, may be of value in pinpointing premises where hazardous materials may have been used, or dumped without adequate safeguards. The records and logs of insurance agencies, police, fire, hospitals and disaster-related agencies or societies, such as the Red Cross, are further potential sources of data. Newspapers and magazine articles and the diaries of local inhabitants can also prove very valuable. In 1595, for example, a Spanish monk, Father Pedro Simòn witnessed a major eruption of Nevado del Ruiz. In many ways it was extremely similar to the 1985 event, sending a major lahar down the Lagunillas River. Had his description of the eruption been given more attention, recent casualties at Armero might have been greatly reduced (Angier, 1985).

In regions where monitoring networks are relatively new, data may also be supplemented by oral history. Two major sources exist, namely eyewitness accounts and legends of catastrophe (Vitaliano, 1973). Although legends may be very distorted descriptions of actual events, they can still often be useful in identifying threats with long-term return periods.

Archaeological information may also be of great significance. Excavations on the volcanic island of Santorin and elsewhere around the Mediterranean, for example, indicate that a major eruption, which created an enormous tsunami, probably took place approximately 1450 to 1480 B.C. Archaeological evidence indicates that this event, and numerous associated earthquakes was largely responsible for the destruction of the Minoan civilization (Vitaliano, 1973).

The landscape and its vegetation may also carry the scars of former periods of geographical or meteorological violence. Differences in type and height of vegetation have been used, for example, to predict the magnitude and frequency of avalanches to be expected in Rogers Pass, British Columbia, which is used by the TransCanada Highway to cross the Selkirk Mountain Range (Schaerer, 1972). The interpretation of geomorphological features and their associated deposits can often provide information on spatial differences in risk that may extend the instrumental record by thousands of years. This approach, for example, is useful in identifying previous periods of volcanic eruption and catastrophic flooding (Crandell and Waldron, 1969).

Where direct observation is lacking and other evidence unavailable, the magnitude and frequency of potential disaster agents may have to be predicted by the application oı mathematical formulae or the use of scale models (Allen, 1947).

3. HAZARD MAPPING

Once such data have been collected, it can be used to produce a variety of maps that are useful as predictive tools for reducing disaster losses. The simplest microzonations are one hazard/one purpose maps, designed to show the probable areal extent of a single event or phenomenon. Many such maps are required by fiat since they are needed to implement legislation or agency policy. Examples include microzonations showing areas of potential tsunami inundation in the San Francisco Bay region, compiled by the United States Geological Survey in cooperation with the Department of Housing and Urban Development in 1972. These risk maps assume a runup of 20 ft. at Golden Gate and indicate the areal extent of the resulting flood (Ritter and Dupre, 1972). Similar maps showing the potential for tsunami inundation in Oahu have been prepared by the Hawaiin Civil Defense and Macdonald, Shepard, and Cox (1947).

Slightly more sophisticated are single hazard/multiple purpose maps which display the anticipated extent and intensity of impact of a single disaster agent, but on several occasions. To illustrate, repeated experience has shown that earthquake damage varies greatly, even within small regions. It is believed that constructional factors being equal, buildings on deep wet clays, sands, or especially fill, particularly if on or near an active fault, will suffer the most damage during an earthquake. It is possible, therefore, to collect such hydrological and geomorphological data and use this information to microzone urban areas according to their seismic vulnerability. Numerous examples are available including maps of Santiago, Chile (Lastrico and Monge, 1972) and Boston, Seattle, Santa Barbara in the United States (Olsen, 1972). Vancouver and Victoria in Canada (Wuorinen, 1974) and Wellington, New Zealand (Adams, 1972), have also been mapped to illustrate differences in seismic risk. Such maps permit spatial variations in the intensity of seismic ground disturbance to be predicted for earthquakes of differing magnitudes. They are also an essential component of computer simulations of disaster. When combined with land use and structural data they can be used to predict life loss and injury from earthquakes of differing magnitude and intensity. The same procedure can be applied to most other hazards. Figure 1, for example, illustrates simulated damage in Victoria from an earthquake reaching a Modified Mercalli Intensity VIII on normal ground (Foster and Carey, 1976). It is one of a series illustrating anticipated losses for earthquakes varying in intensity from VII to IX. It could not have been produced without earlier completion of the seismic microzonation of Victoria shown in Figure 2 (Wuorinen, 1976).

The most useful microzonations, from a planning perspective are the multiple hazard/multiple purpose maps that seek to show the total risk picture. Communities must consider all risks, rather than concentrating on a narrow range of hazards. There is, for example, little point in strenuously preventing development on the flood plain by encouraging construction on avalanche runout zones or abandoned toxic waste sites. To produce such maps, a common unit of com-

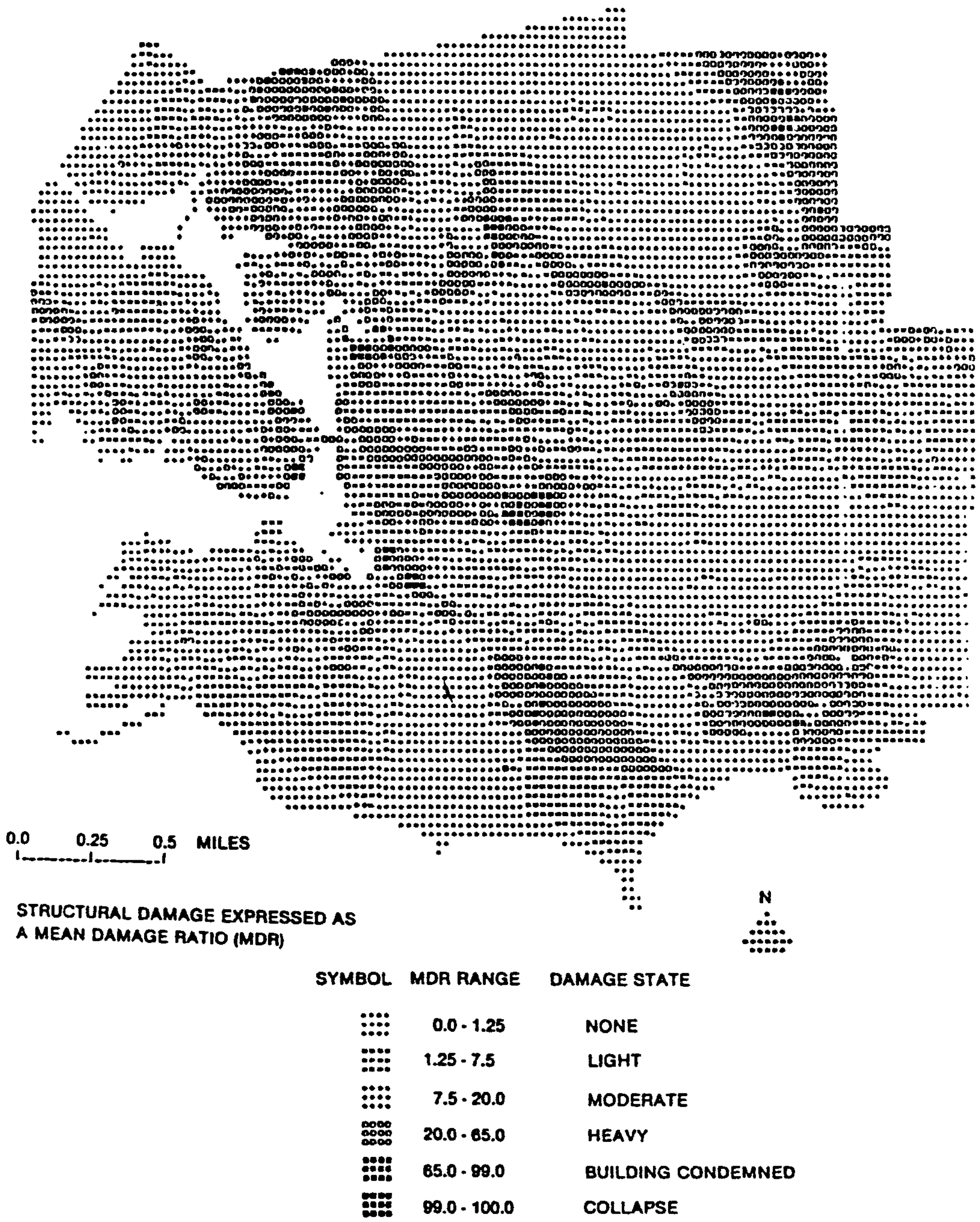

Figure 1: Victoria, BC: Simulated earthquake damage in intensity VIII (Foster and Carey, 1976).

parison must be established for all disaster agents, such as the fatality or injury potential, probable stress caused, or the dollar losses to be expected. Since such mapping is likely to be computerized, the production of a series of maps, using all three of these units of measurement, is almost as simple a procedure as that involved in the use of a single basis of hazard comparison. Where a selection must be made, monetary units have certain advantages over other alternatives since they allow benefit-cost relationships to be established and permit potential losses due to risk to be compared with other locational costs, such as those connected with transportation. However, there are many difficulties associated with assigning a monetary value to life loss and injury. To produce multiple hazard/ multiple purpose microzonations, individual disaster agents must be evaluated independently, using the techniques previously described, to produce a series of single hazard/multiple purpose microzonations. For each hazard mapped in this way the anticipated annual, or other time period, dollar losses per unit area are then calculated. The final total risk map is then the summation of all such values.

One of the most detailed total risk map produced to date was compiled by Wuorinen, under this author's supervision (Wuorinen, 1979). In the Saanich Peninsula, British Columbia, Wuorinen mapped the spatial distribution of threat from individual hazards, such as coastal and soil erosion, flooding, and earthquakes. In the case of earthquakes, for instance, three hazard zones were established and the frequency with which seismic events in each reached specified intensities was established by consulting the Canadian National Building Code. This first step was essentially the production of a single hazard/multiple purpose map. To estimate the losses that might be anticipated it was also necessary to know the value of the land and improvements affected by such events.. It was, therefore, decided to calculate the value of one average hectare of developed land in the Greater Victoria region. This was possible because data collected for taxation purposes were available from the B.C. Assessment Authority (Wuorinen, 1979) (Table 1). It was necessary to calculate independent mean values for land and public and private improvements separately, since different disaster agents result in losses to various combinations of investments. Earthquakes, for example, generally destroy buildings, while coastal erosion results in loss of both land and property.

It was also necessary to know what percentage of this property value would be lost in earthquakes or other disaster agent impacts of differing intensities. Fortunately, Steinbrugge (1970) had already established such damage ratios, based on the cost of repairs for seismic events. These were determined from damage suffered in the San Francisco-Oakland metropolitan statistical area but were considered fairly applicable to Victoria.

These three types of information, the value of land and its developments, anticipated earthquake intensities and frequencies and the associated potential damage ratios, were then used to calculate what the total anticipated loss per hectare per year would be in each earthquake risk zone if the Saanich Peninsula became fully urbanized (Table 2). In the zone with the lowest risk, annual earthquake related losses might be expected to be $266 per hectare, rising to $767 in moderate

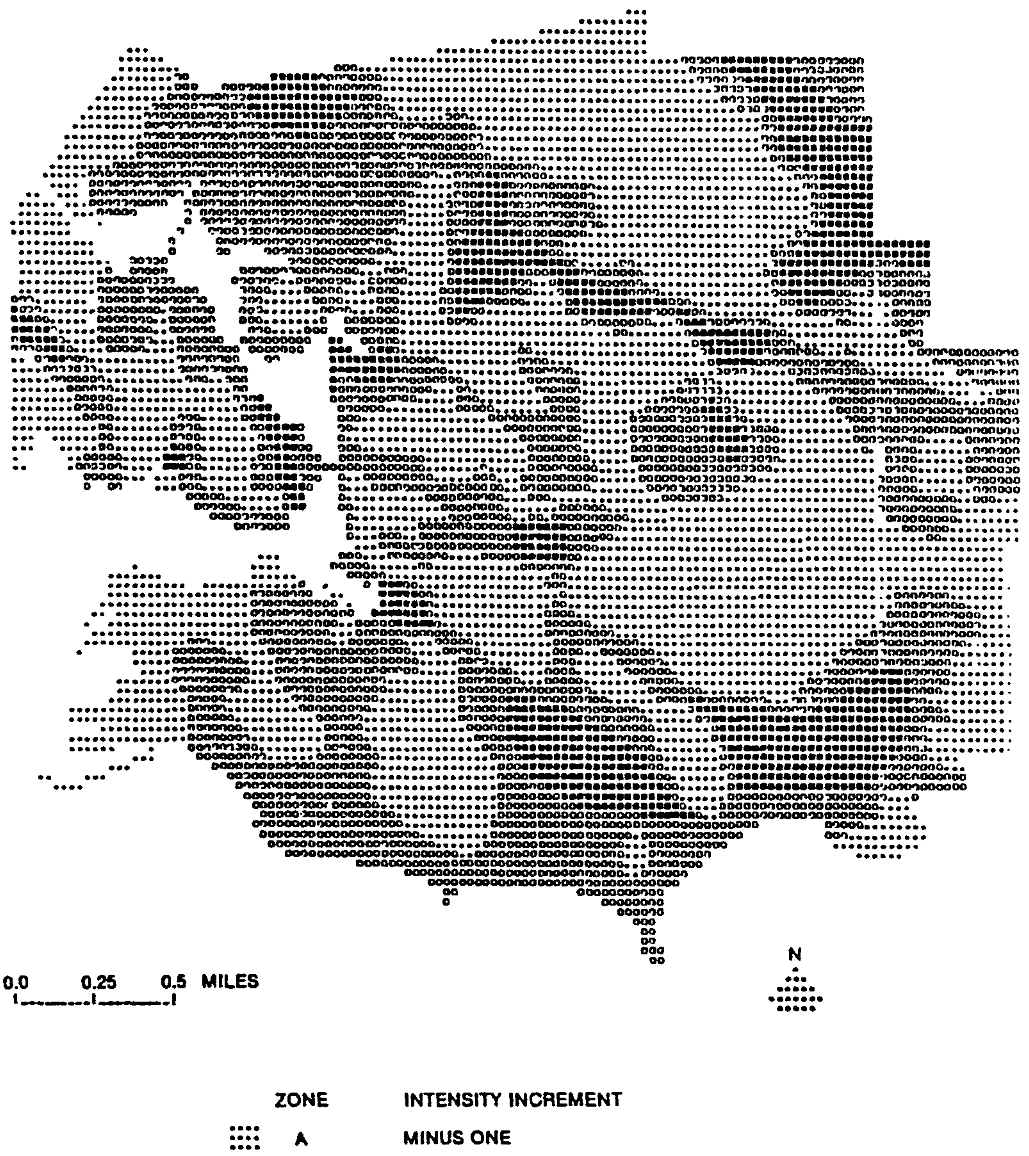

Figure 2: Victoria, BC: Computerized earthquake microzonation (Foster and Carey, 1976).

Table 1: Value of land and improvements: Greater Victoria area.

	Land area (ha)	Land ($)	Private improvements ($)	Total improvements ($)	Grand Total ($)
Victoria	1,878	152,033,160	280,137,800	348,146,273	500,179,422
Oak Bay	1,046	261,464,089	182,234,550	227,793,198	489,257,287
Esquimalt	631	222,506,880	141,889,734	235,153,334	457,660,214
Total	3,555	636,004,129	604,262,084	811,092,805	1,447,096,934
Value/ha	-	178,879	169,975	228,123	407,002

Source: Wuorinen (1979).

risk and $1,817 in high risk areas. In a similar manner, the annual losses to be anticipated in low, medium, and high risk flood, coastal, or soil erosion zones were also calculated (Table 3).

Table 2: Earthquake losses by zone.

	Zone 1		Zone 2		Zone 3	
Annual frequency	MMI	Loss/ ha ($)	MMI	Loss/ ha ($)	MMI	Loss/ ha ($)
.150	III	-	IV	-	V	70
.065	IV	-	V	30	VI	141
.036	V	17	VI	78	VII	413
.015	VI	32	VII	172	VIII	564
.0081	VII	93	VIII	305	IX	447
.0033	VIII	124	IX	182	X	182
Total loss/ ha/year		266		767		1,817

Source: Wuorinen (1979)

Individual single hazard/multiple purpose maps, showing the anticipated annual dollar loss, were then produced by computer using SYMAP for each disaster agent. Summing these values for each hectare resulted in a map showing total annual expected disaster losses for the Saanich Peninsula should it become fully developed (Figure 3). The data collected suggested that for the four natural haz-

Table 3: Summary of potential annual dollar losses per hectare for the Greater Victoria area.

Hazard	Zone 1	Zone 2	Zone 3	Zone 4
Earthquake	266	767	1,817	-
Flooding	0	227	910	-
Surface erosion	0	3	9	-
Coastal erosion	0	960	1,920	2,880

Source: Wuorinen (1979)

ards examined, mean annual disaster losses per hectare would range from $156 to some $4,600.

The entire mapping system was computerized and is capable of illustrating expected losses of up to sixteen hazards, although it could easily be expanded to handle more. Such multiple hazard/multiple purpose maps can, of course, be prepared for as many disaster agents as a region or municipality is subjected to. These hazards may be natural or man-made. Once their impact has been reduced to a common unit of measurement, risks from any source can be summed to give a comprehensive overview of potential losses. At this point a major policy decision is required since agreement must be reached on what constitutes unacceptable risk. This varies with the activity involved and should reflect a very careful balancing of potential losses and benefits to the community (Foster, 1980). Ideally, the most significant and vulnerable activities should be located on lowest risk sites.

It is possible to produce such multiple hazard maps even when the nature of the hazard is not fully understood. Inadequate knowledge about carcinogens, for example, does not preclude the production of maps which illustrate mortality from either a specific cancer, or from malignant neoplasms as a whole. Mason and his colleagues (Mason et al., 1975) mapped United States mortality, at the county or state economic area scale, for some 30 specific cancers or groups of cancers. Two of the illustrations in the resulting *Atlas of Cancer Mortality for U.S. Counties: 1950-1969* show death from cancer for all types combined and can be considered multiple hazard maps.

Similar illustrations have been produced by this author for the 4.6 million deaths occurring in the United States from cancer, during the period 1950 through 1967 (Foster, 1986). As can be seen from Figure 4, which illustrates age adjusted death rates, the cancer "peak" in the United States was found to lie in Rhode Island, with very high total mortality in neighbouring states such as Connecticut, New York, Maryland and the District of Columbia, Pennsylvania, Massachusetts and Delaware. In contrast, the lowest cancer mortality occurs in New Mexico

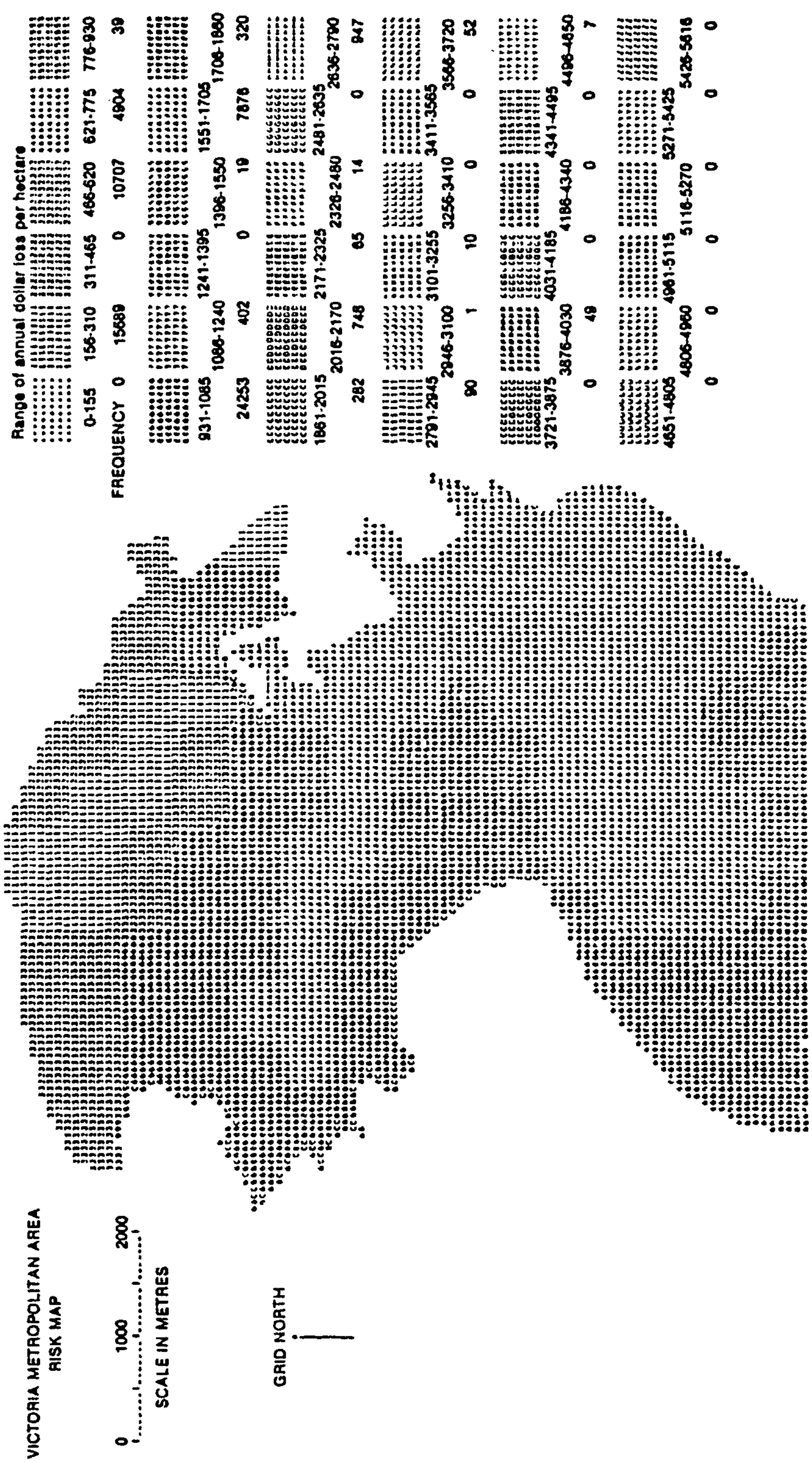

Figure 3: Total risk from geophysical hazards, Saanich Peninsula, BC (Wuorinen, 1979).

and Idaho. Utah and Wyoming also have low mortality rates from total neoplasms, as do Georgia, Arkansas, Alabama, Mississippi and North and South Carolina. Total cancer mortality, therefore, drops away to the north, west and south from a Rhode Island "peak". Maps showing significant variations from national age adjusted death rates from a variety of diseases are also available for Canada. Some, such as those showing mortality from all causes and death from all types of cancer, can be considered multiple hazard macrozonations of Canada (Health and Welfare Canada, 1980 and 1984). Such single and multiple hazard maps, illustrating death or incidence rates for various causes, can be of significant value to community planners. They can be used, for example, to design medical screening programs, ensuring that early detection efforts are concentrated where a particular disease has been traditionally the most common. Similarly, they can be of value in the logical siting of new clinics and hospitals, since they indicate potential demand for services (Meade, 1983; Griggs, 1983; Hellen, 1983).

The data required to produce either single or multiple hazard mortality maps can also be great value in epidemiological and geographical research. In an effort to help explain the distribution of mortality from cancer in the United States, for example, this author (Foster, 1986) developed a computer data bank containing information on a large number of natural and man-made environmental substances, a total of 219 entries. Most of this information was derived from United States government sources, and was restricted to that collected during the period 1950-1970. Data on sunlight, precipitation, groundwater use, DDT and phosphate application, the presence or absence of dieldrin, lindane, cadmium, chromium and arsenic in surface waters, for example, were included. Information on barley, hay, potato, cotton and tobacco production was also used, as were data on a variety of mining and industrial activities. In addition, extensive information on soil geochemistry formed part of this data base.

These data were analyzed using both Pearson correlation coefficients and stepwise multiple regressions. A large number of apparently significant links were found between the patterns of cancer mortality in the United States and various natural and man-made substances and the distribution of several industrial and agricultural activities. In summary, it was discovered that high mortality from cancer had often been associated with manufacturing and coal mining. Very high or low concentrations of certain bulk or trace elements in the soil were also linked to elevated or depressed mortality. Of major importance are levels of calcium, magnesium, sodium, potassium, phosphorus, manganese, iodine, zinc and selenium. Elevated levels of calcium, magnesium, potassium and phosphorus, for example, were apparently associated with reduced mortality from some cancer, yet increased deaths for others. Selenium appeared to play a protective role against many specific cancers, while mercury, which probably reduces the body's ability to utilize selenium, seemed to be very detrimental. High levels of chromium were also often associated with elevated mortalities. In addition, barium, beryllium and strontium, which probably interfere with the body's capacity to utilize specific bulk and trace elements, were also associated with high mortality from many malignant neoplasms. To illustrate, cancer of many parts of the digestive tract appears to be associated with depressed levels of calcium and

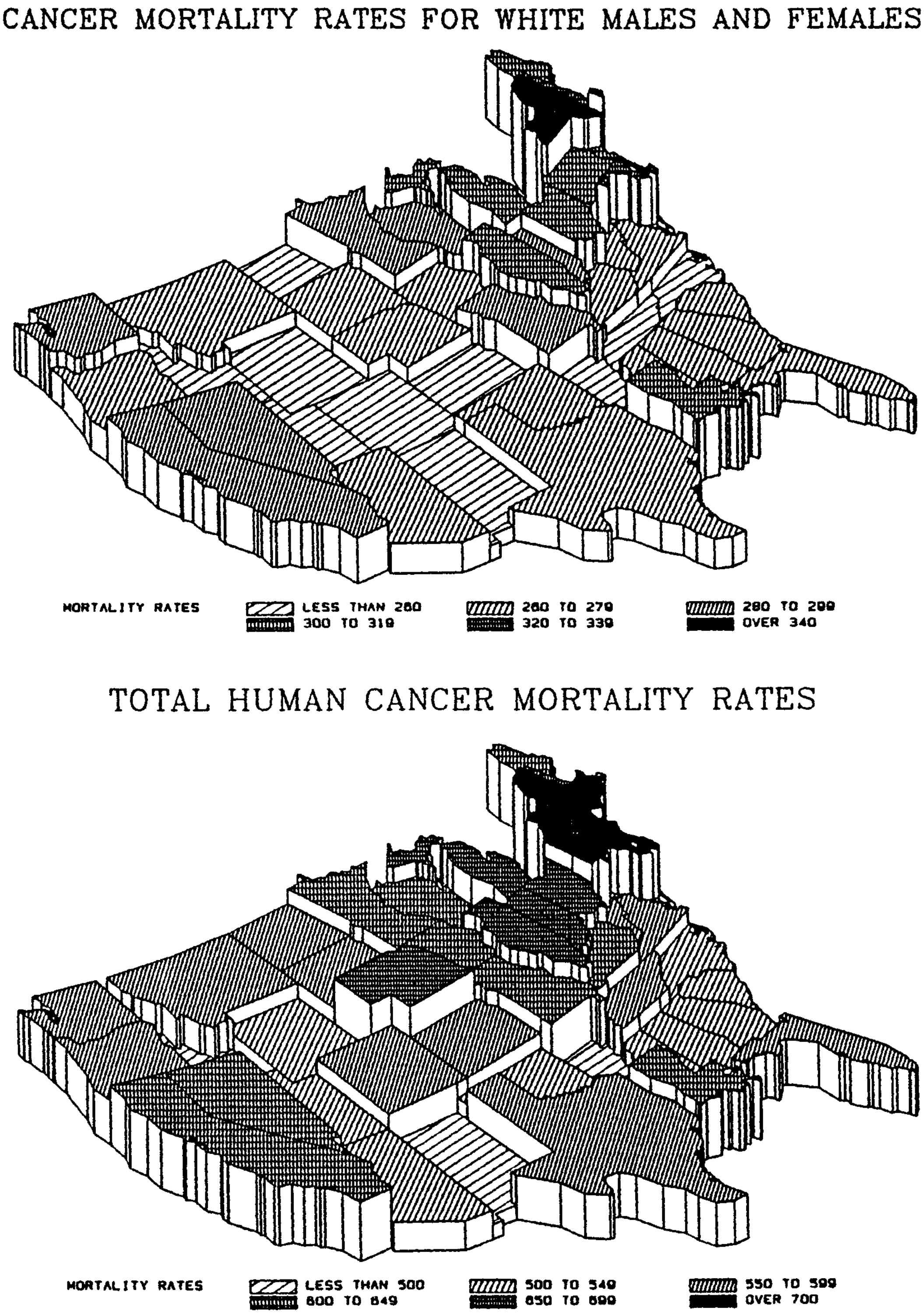

Figure 4: Multiple hazard mapping: Cancer, United States (Foster, 1986).

selenium in the soil. Mortality is especially high where sodium, potassium, manganese, beryllium and mercury concentrations are elevated. As a result, digestive cancer is particularly common in soft water areas, especially if soils are saline. This may be why states that extensively use de-icing salts contain most of the nation's highest mortality rates for cancer of the esophagus, throat, larynx, large intestine, rectum and bladder (Mason et al., 1975).

Since elevated levels of many bulk and trace elements are associated with high mortality from certain cancers and low death rates from others, some cancers show inverted distribution patterns. This is true of melanoma and breast cancer, and cancer of the esophagus and the liver. Melanoma, for example, is relatively common in the south while breast cancer rates peak in the north. In contrast, unlike almost all other cancers, the leukemias do not correlate significantly with the distribution of bulk and trace elements, or with industrial pollutants, but seem to be associated with specific crops, especially hay, wheat, oats, barley and cotton. This association suggests a possible link between various leukemias and the use of agricultural chemicals, possibly herbicides.

The distribution patterns of mortality from malignant neoplasms, therefore, appears to suggest three basic causal mechanisms. The leukemias and lymphomas, for example, seem to be associated with overexposure to agriculture chemicals. The latter, however, demonstrate a link with subsequent bulk and trace element imbalances in diet, whilst the leukemias do not. Virtually all other cancers appear related to both exposure to largely industrial carcinogens and dietary bulk and trace element imbalances. Maps of total cancer mortality in the United States (Figure 4), therefore, seem to reflect both the environmental levels of man-made and natural carcinogens and the presence of bulk and trace elements and their antagonists in local food and drinking water. To a large degree, those naturally occurring substances are geologically controlled, as are so many other natural hazards. While it would be difficult to reduce the impact of such natural elements, it should be possible to reduce road salt use in an effort to establish whether or not it is a major man-made hazard causing digestive cancer.

4. CONCLUSIONS

Once the spatial distribution of risk has been determined and standards of unacceptability adopted, changes in land values or product use begin to occur. This process naturally leads to opposition from owners of adversely affected high risk sites or industries. This occurred, for example, in Anchorage, Alaska (Schoop, 1969) after the 1967 earthquake. Regardless of the strength of pressure to develop in high risk areas, economic studies invariably support the use of microzonation in directing construction. It has been estimated that unless such practices become more widespread in California, losses of over $55 billion are to be expected by the year 2,000 (California Division of Mines and Geology, 1973). Many developers and government agencies resist this rational approach to disaster mitigation on the grounds that it is too costly, yet the resulting benefit-cost ratios in California are 20:1 for expansive soils, 9:1 for landsliding, 5:1 for earthquakes and volcanic hazards and 1.5:1 for subsidence, tsunamis and erosion. Clearly, it is cheaper to avoid disaster than to suffer it. The same is of course true of various diseases, such as cancer, which appear to be strongly related to both nature and man-made environmental pollutants. Their cost to society is clearly far greater than that of preventative measures.

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