SOCIETAL VALUE OF GEOLOGIC MAPS

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An economic analysis by the U.S. Geological Survey's National Geologic Mapping Program that describes (1) geologic maps and their use as a fundamental data base, (2) a rigorous benefit-cost model for valuing geologic map information, and (3) the economic issues associated with determining whether or not a geologic map is a public good

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Societal Value of Geologic Maps

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People frequently regard the landscape as part of a static system. The mountains and rivers that cross the landscape, and the bedrock that supports the surface, change little during the course of a lifetime. Geologic and hydrologic processes are, however, dynamic. Earthquakes, landslides, floods, and drought, to name a few examples, shape the societies that suffer through them. Society can, in turn, alter the geologic history of an area and affect the occurrence and impact of such natural hazards. For example, changes in land use can induce changes in erosion, sedimentation, and ground-water supply. As the environmental system is changed by both natural processes and human activities, the system's capacity to respond to additional stresses also changes. Information describing the physical world is critical for identifying solutions to land use and environmental issues. Geologic maps are known to provide useful information for these purposes. This report describes a method for estimating the economic value of applying geologic map information to land use decisionmaking.

Economic development decisions at all levels from local to global are influenced by their potential for causing environmental change. Addressing environmental concerns presents decisionmakers with choices that have far-reaching societal implications. Deciding to preserve certain tracts of land, for example, may limit economic opportunities and lessen or enhance the value of nearby lands. Conversely, inappropriate development may provide short-term benefits while creating long-term problems that could present future generations with extremely costly consequences.

Detailed, publicly available information concerning the nature and origin of the geology of an area is essential for informed public-policy decisionmaking and for economic development. Many public-policy decisions and commercial enterprises require a specific kind of earth science information, which is spatially based information that is linked to geologic materials and geologic structures. The earth science product that best captures and displays this kind of information is the general purpose **geologic** map.

This report describes the purpose, uses, and value of geologic maps. It contains an evaluation and quantification of the net benefits of different levels of detail and improvements in interpretive models contained on geologic maps. The analysis uses a geographic information system (GIS) that includes earth science, engineering, and economic information to transfer the geologic map information into the decisionmaking framework. We develop and apply a model of decisionmaking that makes explicit use of geologic maps. In particular, the benefits of using improved geologic map information in a regulatory environment are compared to existing or dated geologic map data. The report includes the results of a pilot study in Loudoun County, Virginia, that illustrate how geologic map information can be used in siting a waste disposal facility and a transportation corridor. We show that improvement in geologic map information has a net positive value to society that can enable planners to make superior land use decisions. *Principles developed in this pilot study are generally applicable to the many other possible uses of geologic map information.*

Specific topics are developed in detail in the three chapters of the report. Chapter I provides a definition of a general purpose geologic map and a discussion of the use of a geologic map as a data base. Chapter II details the rigorous development of an economic model for valuing geologic map information. Chapter III identifies specific hypotheses that can be tested to determine whether or not general purpose geologic map information is of public benefit and also contains a partial documentation of the need for geologic maps.

GEOLOGIC MAPS: THE BASICS

Most people are familiar with highway maps or topographic maps that depict forms on the surface of the Earth (fig. 1*A*). A geologic map, unlike a topographic map,

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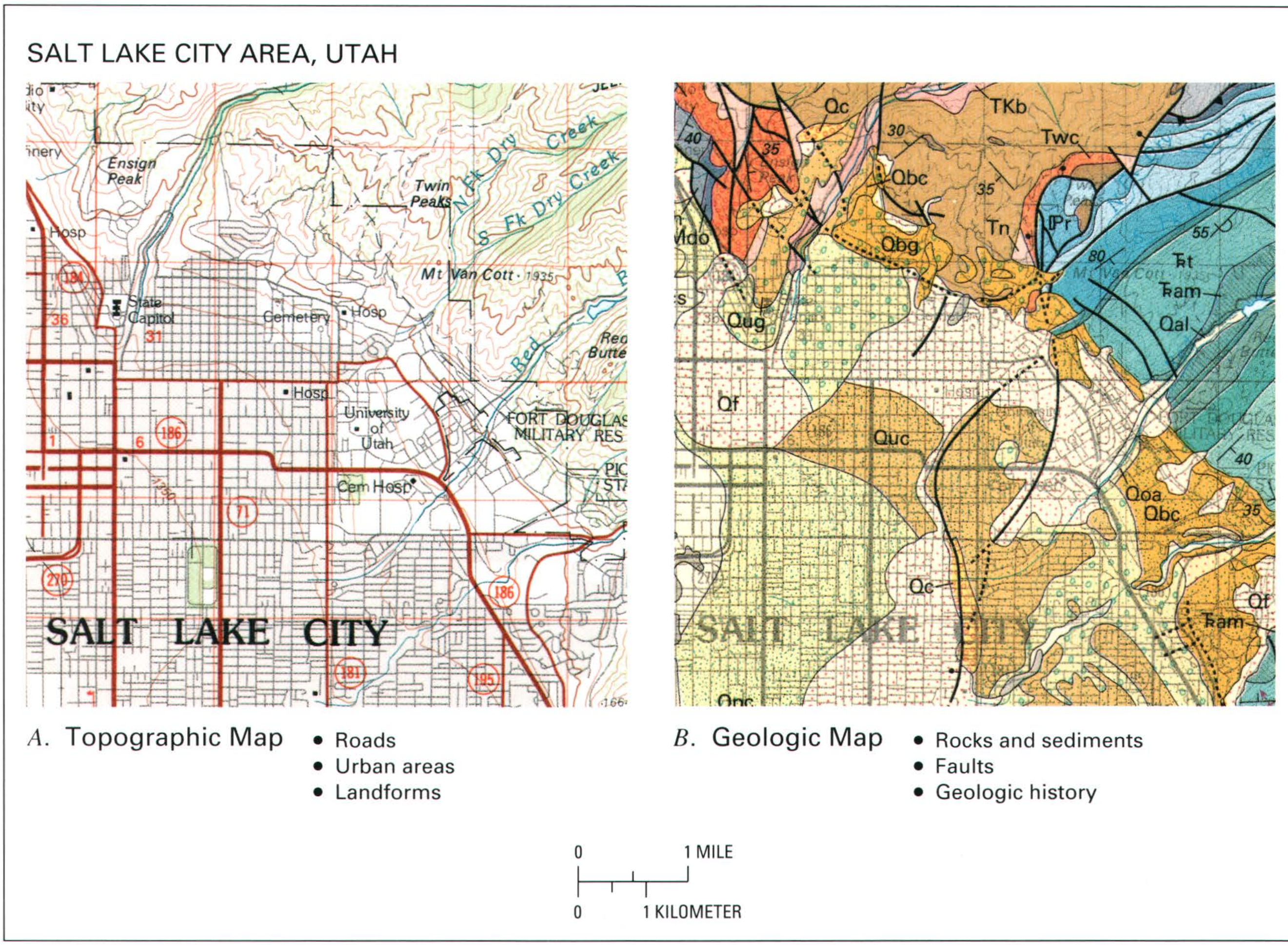

Figure 1. A comparison of sections of (*A*) topographic and (*B*) geologic maps of the Salt Lake City area, Utah. Scale 1:100,000.

uses a combination of colors, lines, and symbols to depict the composition, structure, and history of geologic materials that support the landscape (fig. 1*B*).

Geologic maps contain *descriptive information* about the solid earth. A geologic map commonly identifies the spatial distribution of **bedrock materials** like granite, limestone, sandstone, or shale; **surface materials,** which are deposited by wind, water, and ice; **deposits** such as landslide debris and debris flow materials; and **geologic structures** like faults, fractures, and folds. Geologic maps also provide an *interpretation* of how these materials and structures are related in space and time.

This combination of description and interpretation provides a conceptual framework relating all the geologic elements of an area together. For example, geologic maps commonly describe the physical properties of geologic materials and structures and can help someone determine their strength, porosity, and continuity. They can also depict the timing and sequence of events that produced the geologic materials and structures displayed on the map. This may help identify, for example, geologically recent earthquake or volcano activity, in areas lacking historic records of such activity, that may raise safety concerns. The geologic map thus forms a fundamental data base for environmental decisions, including land use and zoning, that require a forecasting capability. A geologic map made and published by the U.S. Geological Survey (USGS) is a publicly available general purpose document that provides all of these types of information.

GEOLOGIC MAPS: SUPPLIERS, USERS, USES, AND DISTRIBUTION

The USGS generally produces areal and regional geologic maps. Site-specific geologic maps, which are more commonly prepared by State geological surveys and consulting geologists, generally begin with the information contained in one of the USGS geologic maps.

The USGS has been the major supplier of general purpose, regional geologic maps since its creation through the Organic Act of 1879 (43 U.S.C. 31(a)). The Organic Act charges the USGS with providing the geologic knowledge base associated with all Federal, State, and private lands. The Director of the USGS is assigned responsibility for:

> classification of the public lands and examination of the geological structure, mineral resources and products of the national domain. (p. 6)

The *distribution* of geologic information also is prescribed by the Organic Act as follows:

> The Director . . . is authorized . . . to dispose of the . . . geologic maps . . . at such prices and under such regulations as may from time to time be fixed by him . . . and a number of copies of each map . . . shall be distributed gratuitously among foreign governments and departments of our own Government to literary and scientific associations, and to . . . educational institutions and libraries . . . . (p. 8)

Further, the Organic Act requires that maps be distributed at costs below those of production and distribution:

> Three thousand copies of each shall be published for scientific exchanges and for sale at the *price of publication* . . . (p. 7) (emphasis added)

Through the Organic Act, Congress dictated that earth science information should be widely available and clearly recognized that no social benefit accrued from restricted access to geologic information. Regional geologic information thus becomes a "public good."

Given the growing debate concerning the need to privatize goods and services currently provided by the government (and thus reduce government expenditures), it is necessary to ask whether production of regional geologic map information should be reassigned to the private sector. Answering this question requires analysis of several related issues that are raised and discussed in depth in chapter III.

Many governmental issues require the use of a general purpose geologic map. Federal agencies, for example, have diverse use requirements for geologic maps (table 1). Federal, State, and local governments use USGS geologic map information for policy development and enforcement in all of these areas. For example, the U.S. Environmental Protection Agency (EPA) and most States require geologic map information to establish guidelines for selecting safe waste disposal sites. Highway planners also begin their site-selection process with regional geologic map information. The need for site-specific information for highways and landfills arises only when rights-of-ways or potential landfill sites have been identified. This more detailed information, or even a site map, commonly would not be provided by the USGS but by another, more specialized source.

The Departments of Interior (DOI) and Agriculture (USDA) also use geologic map information to fulfill their land and resource management missions. DOI's Bureau of Land Management (BLM) and Minerals Management Service (MMS) use geologic map information to assist in managing energy and mineral resources as required by provisions of Federal law. The National Park Service (NPS) needs geologic map information to manage the mineral resources or geothermal resources found in and around the national parks, as law requires. The NPS also uses geologic map information to communicate the geologic history and landforms to national park visitors. Like the BLM, the Forest Service utilizes geologic map information to manage

Table 1. Selected Federal users of USGS geologic map information

USER	APPLICATION
Department of Interior (DOI): Bureau of Land Management (BLM) Bureau of Mines (BOM) Bureau of Reclamation (BOR) Office of Surface Mining (OSM) Minerals Management Service (MMS) National Park Service (NPS) Fish and Wildlife Service (FWS)	Energy and mineral resource assessments of wilderness areas and other public lands; resource management plans; multiple-use plans; dam and reservoir development; ground-failure stability analysis.
Department of Defense (DOD): Army Corps of Engineers	Development planning; waste repositories; geologic-hazards analysis; siting of water works.
Department of Energy (DOE)	Energy resource assessments; waste repository developments and cleanup; seismic evaluations; siting of nuclear tests.
Environmental Protection Agency (EPA)	Assessment of naturally occurring toxins; ground-water assessments; multiple-use land use plans; waste site evaluations.
Nuclear Regulatory Commission (NRC)	Nuclear plant and waste site evaluations.
U.S. Department of Agriculture (USDA): Agricultural Research Service (ARS) Forest Service (FS) Soil Conservation Service (SCS)	Toxic substance evaluation; ground-water resource evaluation; wilderness assessment; Resource Management Plans.
Department of Transportation (DOT)	Transportation and utility corridor evaluations; airport and facilities siting; geologic-hazards evaluation.
Housing and Urban Development (HUD)	Transportation and utility corridor evaluations; geologic-hazards evaluation; urban area zoning.
Federal Emergency Management Agency (FEMA)	Geologic-hazards evaluation.
Tennessee Valley Authority (TVA)	Geologic-hazards and ground-water resource evaluations.

mineral and renewable resources in the national forests. In addition, most Bureaus in DOI and many Federal and State agencies need geologic map information to help address issues related to hazardous materials on public lands.

Beginning in 1988, the National Geologic Mapping (NGM) Program of the U.S. Geological Survey asked selected Bureaus in the Department of Interior and other Federal agencies to prioritize their needs for geologic mapping. The Bureaus were surveyed to guide the program in its long-term planning and to begin closer coordination among the USGS and other Federal agencies to produce and utilize geologic maps. The long-term goal of the NGM Program is to systematically build an archival geologic-map information base for the Nation. Priorities identified by Federal agencies are among the factors that help shape long-term program continuity.

ENVIRONMENTAL DECISIONMAKING WITH GEOLOGIC MAPS

Costs

The costs of producing geologic maps can be grouped into five categories: (1) data collection in the field, (2) data compilation and interpretation, (3) data presentation such as drafting, digitizing, and data-base construction, (4) printing and publication, and (5) distribution. This process is labor intensive and requires a highly skilled staff. Therefore, producing uniform geologic map coverage for the Nation, at a scale detailed enough for nearly all perceived uses, will be extremely expensive and thus should be a long-term goal that is systematically approached by establishing mapping priorities that represent shorter term goals (milestones).

A geologic map of the United States exclusive of Alaska and Hawaii was published by the USGS in 1974 at a scale of 1:2,500,000 and is the most detailed geologic-map information base that uniformly covers the contiguous States. Assuming that the geologic information it contains is as accurate as the cartographic base map used for compilation, a resolution of only about 5 km (kilometers) is possible for any individual geologic datum. Geologic maps at more detailed (larger) scales exist for various parts of the Nation, and the geologic-map information base of the Nation is improved continually as more detailed geologic map data are gathered, as new analytical techniques are developed, or as new models are proposed and adopted to interpret the distribution and structure of geologic materials.

Geologic maps commonly are constructed from both new and existing information. Gathering new information is the dominant cost and may determine the priority among candidate map areas. The cost of acquiring new geologic map information for a particular area will depend on the quality of the existing geologic map information for that area, on the geological complexity of the area, and on the level of map detail needed for the perceived application. For some regions, the available geologic map data consist only of reconnaissance-quality information. For these areas, new information of greater density and accuracy must be acquired at significant cost. For other regions, the available data consist of modern, interdisciplinary, detailed-scale geologic map information. In these instances, existing geologic map information needs only be revised slightly and published in a form that compiles this existing information in a new format or in the context of new interpretive models. Geologic-map production costs will be relatively low in such cases.

Benefits

It is commonly accepted that geologic maps provide benefits to society. The specific societal benefits considered in this study are the savings (defined in terms of economic losses avoided) realized when geologic map information is considered in a public-domain land use decision. Benefits accrue when regulatory decisions are made from geologic maps that contain improved information. These benefits are realized as a reduction in the level of uncertainty of information (geologic map information in this case) that serves as the basis for implementing land use regulations. This concept is explained in the following paragraphs.

Any economic decision is accompanied by some level of uncertainty. Is enough scientific information available to make the best decision? This study examines how geologic map information might enter the framework of such a decision. For the Nation, the available geologic maps vary widely in detail and in vintage. Differences in the amount and the detail of geologic maps in an area considered for a land use decision have an impact on financial decisions, because newer, more detailed geologic maps would be expected to provide a better data base for decisions than older, less detailed maps. Improvements to the quality of the geologic information for an area, therefore, should yield societal benefits that can be described as economic losses avoided. Expected reductions in property values due to adverse environmental impacts can be minimized. This study addresses this societal issue in a rigorous, quantitative fashion and finds that society indeed benefits from decisions based on improved geologic data.

Financial decisions that rely in part on geologic map information include issues related to environmental preservation, hazard mitigation, and mineral extraction. We examine two issues, landfill siting and major highway construction, relevant to an area of rapid urban growth, the Washington, D.C., metropolitan region. Landfill siting is a significant environmental and economic issue because of the potential shortage of available sites and the threat to water supplies from leakage of hazardous substances from landfills. Selection of a transportation corridor is also an important long-term decision that has a geologic component: right-of-way, construction, and maintenance costs for these corridors are influenced by local variations in near-surface geology, which affects, for example, cut-and-fill requirements that ensure slope stability. The study area was selected in part because new geologic mapping by the USGS provided the opportunity to compare land use decisions made with the new and improved geologic map information to decisions that would have been made without the information. The method outlined in this report is not, however, specific to these two issues or to this single location. The report develops a general model that can be applied to other issues and in other parts of the United States.

A fundamental consideration in this model is: What impact does the application of geologic map information have in the process of land use decisionmaking? We examine how geologic map information can provide input to a financial decision, at what stage of the decisionmaking process the information is useful, and if that information would be compelling enough to alter a decision. We test the relevance of geologic map information in an economic framework. This is known as an "ex ante" approach because future decisions are evaluated. A contrasting approach would utilize an "ex post" analysis: improvements that have actually accrued from the use of a geologic map would be evaluated and compared to a hypothetical situation that predicts economic conditions if that map information had not been available. That approach examines the cost effectiveness of using geologic map information in a known decision. By contrast, this study examines the more fundamental question, what is the *future* economic impact of the application of geologic map information in land use decisions?

An analytical approach has been developed to evaluate the monetary value (the benefits) of utilizing geologic maps in future land use decisions. The net benefit of any geologic map can be described as the "expected loss avoided" that arises from using the geologic map, minus the cost of producing and disseminating the map. However, the societal value of improved geologic map information (improvement of a geologic map consists of a greater density of geologic observations per unit area and (or) the use of more up-to-date concepts relating to geologic processes) is the difference between the net benefits associated with using improved geologic map information and the net benefits associated with using existing geologic map information of the same area.

Benefit Estimation

In the remainder of this section, we briefly discuss certain technical prerequisites and assumptions for the development of the economic model used to value geologic map information. Discussion is expanded later in this Introduction and in chapter II. Technical considerations include the manner in which we treat the geologic map information and execute the model. For the land use issues to be studied, both improved maps and preexisting maps were evaluated for information uncertainty in a computerized GIS. The geologic map information was converted into a probability or likelihood map of an environmental hazard such as ground-water contamination from a leaking landfill. To evaluate the role of this information in a decision and to forecast net benefits, we examined the existing regulations (in which the decision is framed) by use of geologic maps. In addition, we developed hypothetical regulations based on geologic criteria to supplement existing regulations. Implementation of these hypothetical regulations for the improved and for the preexisting geologic map information, when combined with economic data, yields two estimates of expected property losses that could be avoided for the hazard. Comparison of expected losses avoided for the improved and preexisting geologic map information provides a measure of net benefits of the improved geologic map information. Discussion of the results of the pilot study begins with consideration of public risk and the need for regulation.

When individuals perceive a risk in their daily lives, one possible response is to require the public sector to remove this risk through regulation. Regulatory agencies such as the EPA employ geologic map information in setting environmental safety standards. The public agency chooses to implement the safety standard after evaluating, on the basis of the best available information, whether a hazard could be present in a specific location. However, uncertainty regarding the true geologic conditions at a location remains. As such, the required regulatory safety standards for a specific land use could be either lower or higher than ideal because of a lack of suitable geologic map information.

In the case of natural hazards, the prevailing approach is for broad-based standards. For instance, the Uniform Building Code, which is a minimum standard for residential and commercial construction, distinguishes three risk zones for earthquakes in California. Buildings are constructed on the basis of this standard of information. If more detailed or improved geologic map information and seismic data were available to improve the determination of site response, these restrictions might need to be adjusted, either up or down, in order to achieve a desired level of safety at a minimum cost.

The presence of geologic uncertainty means that the regulatory process is capable of generating errors involving either underregulation or overregulation of land uses within a geographic region; either case must result in a welfare loss to society. From the economic point of view, this is a departure from the optimal level of regulation (zero net marginal expected loss avoided—losses that could be avoided with geology-based standards). The benefits of the improved geologic map information can be expressed as the change in the expected loss avoided through regulations and the costs expressed as the costs associated with acquiring the improved information.

An economic model, presented in depth in chapter II, was developed to calculate the expected loss avoided that results from using improved geologic map information. This model was applied in Loudoun County, Virginia, for two actual land use decisions involving (1) the potential locations for a county waste disposal facility and (2) the choice of a route for an interstate-type highway known as the Washington Bypass. Use of the model suggests that when geologic-map-based regulations are implemented, there is an incremental change in expected property loss and mitigation cost avoided between using the existing county geologic map information and using a new, more detailed county geologic map. This incremental change represents the value of the improved geologic map information.

The model is designed to consider a land area that could be used for many different purposes. In order to frame our analysis, a single use of the land is assumed, for example, as a waste disposal facility or as a transportation corridor. For statistical analysis, the geologic maps of the area were divided into even-sized square cells. Subdividing, or "gridding," a map into blocks or cells is the commonly used approach to derive map information for a statistical analysis. For the maps used in this study, grid cell size was dictated by map scale (larger cells for the map of less detailed scale, and smaller cells for the more detailed map). Within each of these cells, the geology can be characterized by a variety of criteria. In our example applications, the available geologic map information at different vintages and scales for the same land area is used to produce derivative maps of geologic attributes such as rock permeability (a measure of the ease of fluid flow) and shear strength (a measure of the internal resistance to shear stress).

The model assumes that regulations have been promulgated that depend on the geologic map information for each cell. Depending upon the geologic attributes of materials within the cell, implementation of the regulation can eliminate the location from further consideration for a particular land use such as a site for a waste disposal facility. The regulations, in effect, define a level of safety that places restrictions on land use. In the case of the waste disposal site, safety increases as the amount of inappropriate land subjected to consideration decreases. Thus, safety is linked implicitly to the amount and quality of available information.

For some data, such as geologic map information, a probability of encountering an unsafe condition can be derived; however, this probability includes a random error component. Using traditional statistical techniques, we estimate the mean and standard deviation for geologic attributes that are derived from a geologic map. The geologic attributes and their statistical parameters are an integral part of applying the hypothetical regulation. The agency can regulate by accepting those cells that meet the regulatory standard within some confidence level (such as 95 percent, which allows for two-standard deviations from the predicted mean for the geologic characteristic covered by the regulations). This practice allows the agency to "err" on the side of accepting cells that have a mean that *exceeds* the regulatory standard but for which the mean plus or minus two standard deviations meets the regulatory standard.

The vintage and scale of a geologic map affect its use in the decision process. New regional geologic maps are commonly produced at more detailed scales than existing maps. At the new map scale, faulting may be more clearly delineated and boundaries between different rock units better defined than on the older, less detailed maps. This enhanced precision is possible because the newer map is generally based on more detailed, systematic observations of rock units. Access to a more detailed and modern geologic map yields better information (a reduction in uncertainty), and as a result a different number of cells are acceptable according to the regulatory standard.

For this demonstration study, regulations were developed by applying hypothetical (but realistic) rules based on geologic attributes. All cells within the study area are considered acceptable for a proposed land use unless they are determined not to be in conformance *solely due to geologic conditions*. The assessment is based on the hypothesis that the regional geologic setting influences the likelihood of hazard occurrence and that geologic map information can improve regulatory decisions. Other regional and site-specific variables such as hydrologic and topographic attributes also exert influence on the problem, in addition to the geologic attributes.

THE LOUDOUN COUNTY PILOT STUDY

A model was implemented for the siting of a waste disposal facility and the siting of a new interstate-type highway route in Loudoun County, Virginia (fig. 2). We assumed that these projects will go forward. We did not consider the benefits and costs of the projects themselves, but we restricted consideration to the benefits and costs of utilizing geologic map information in the site-selection procedure.

The Loudoun County population, commercial base, and road network are each divided in a manner that mirrors the underlying geologic framework. The western portion of the county (west of U.S. 15) is largely an upland region underlain by a complex group of igneous and metamorphosed sedimentary rocks of the Blue Ridge province. East of U.S. 15, the county plan has delineated large tracts of land for intensive regional growth. These tracts are underlain by part of a Mesozoic basin (Culpeper basin) filled with a sedimentary sequence of conglomerates, red siltstones,

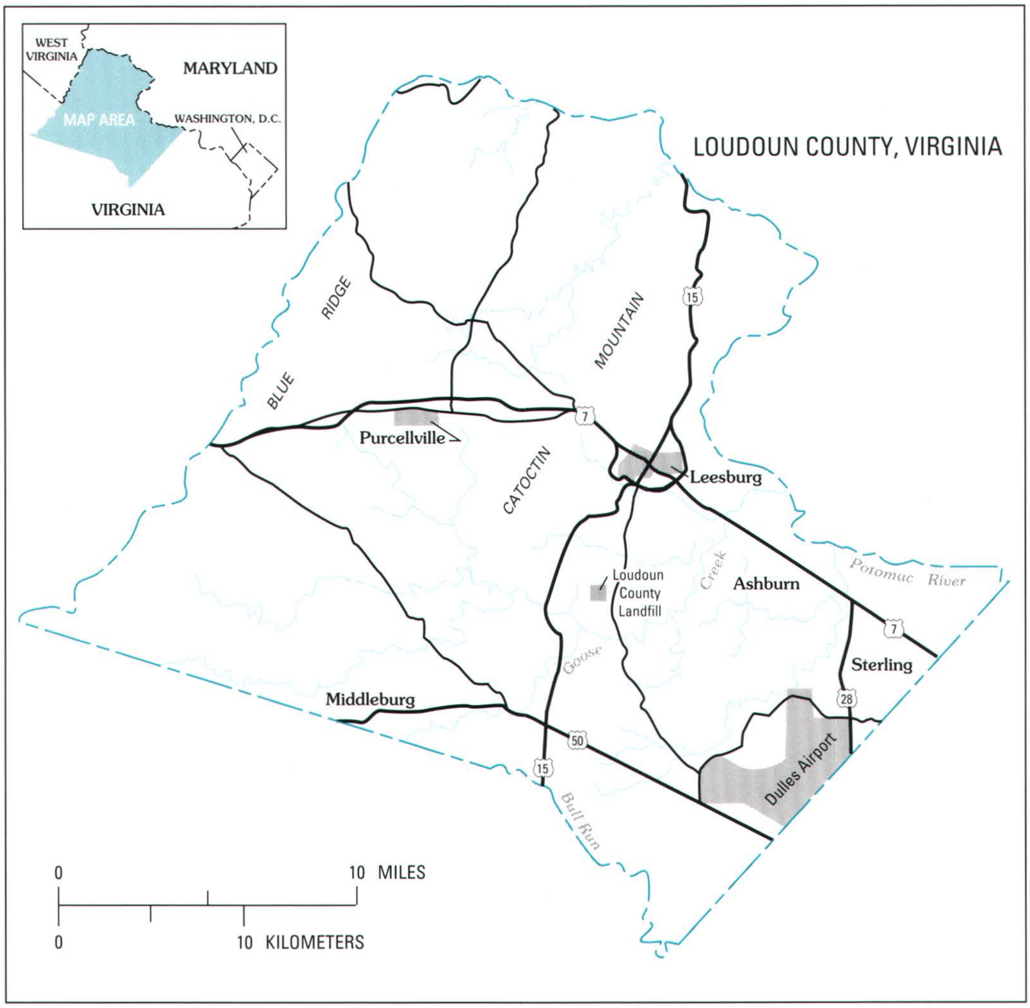

Figure 2. A location map of Loudoun County, Virginia, showing the position of various cultural and geographic features.

claystones, and sandstones that are faulted and interlayered with massive basalt or intruded by diabase dikes and sills. This geologic setting provides opportunities for the development of ground-water well fields, the construction of public and private waste facilities, and the extraction of construction materials. Both the current landfill and the proposed routes for a Washington Bypass are located in the eastern part of Loudoun County, so this part of the county was selected as the study area.

For this analysis, land use choices were based on two geologic maps of different scale and vintage (fig. 3), a geologic map of Virginia compiled and published at 1:500,000 scale in 1963,[3] and a preliminary version of a geologic map of Loudoun County prepared by the USGS at 1:100,000 scale in 1992.[4]

The 1963 geologic map of Virginia shows the *general* distribution of *three* different rock units in eastern Loudoun County. The rock units on the map and the boundaries (contacts) between them are approximately located and in many instances are accurate only to the nearest 1.5–2 km. The spatial distribution of rock units on the 1963 map was derived by extrapolation from previously published maps and reports on the area, not from new, onsite observations.

The preliminary version of the 1992 USGS-prepared geologic map of Loudoun County, Virginia, shows the *specific* distribution of 16 separate rock units in the eastern

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[3] Geologic Map of Virginia, 1963, compiled by R.C. Milici, C.T. Spiker, Jr., and J.M. Wilson. Charlottesville, Virginia Division of Mineral Resources.

[4] Geologic Map of Loudoun County, Virginia, 1992, Burton, W.C., Froelich, A.J., Schindler, J.S., and Southworth, C.S., U.S. Geological Survey Open-File Report 92–716.

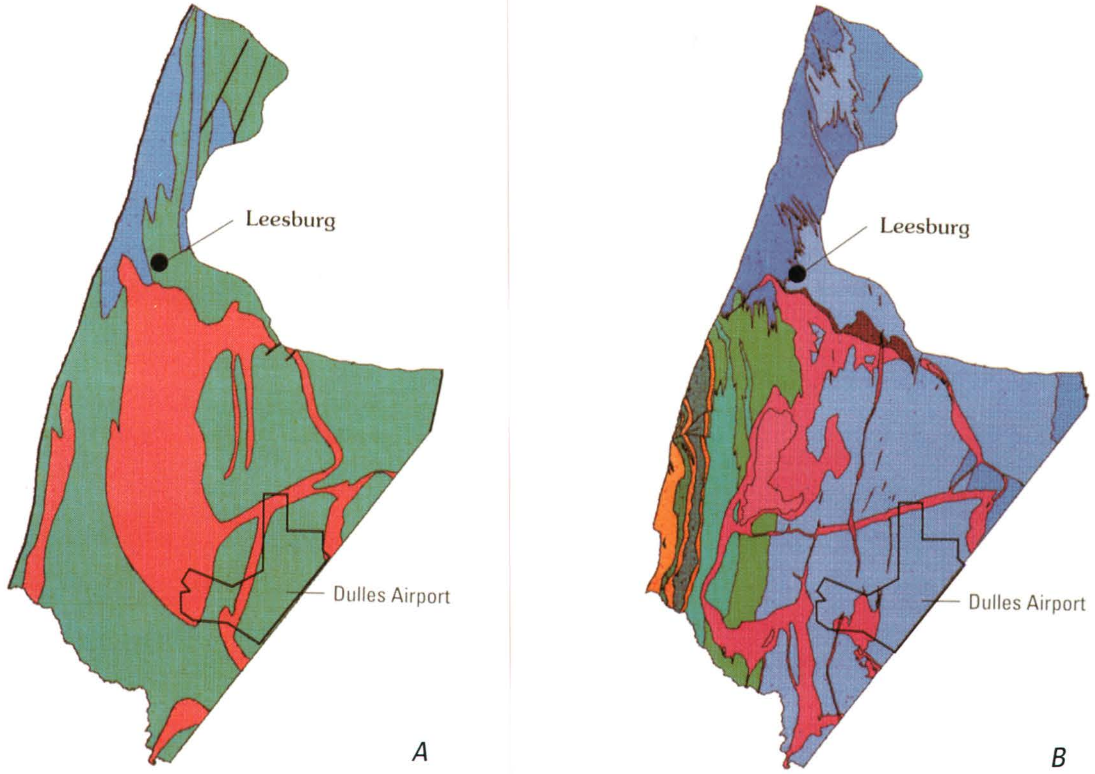

Figure 3. Geologic maps of eastern Loudoun County, Virginia. *A,* Part of the 1963 Geologic Map of Virginia (Virginia Division of Mineral Resources). Green = sedimentary rocks (sandstone and shale undivided), pink = igneous rocks (diabase and gabbro undivided), and blue = conglomerate (a coarse-grained sedimentary rock). *B,* Part of a preliminary version of the 1992 USGS Geologic Map of Loudoun County, Virginia (Open-File Report 92–716). Greens and blues = sedimentary rocks (sandstones, siltstones, and conglomerates), pinks and orange = diabase and basalt rock units, and darkest blue = limestone conglomerate of particular importance to this study.

part of the county.[5] These 16 separate rock units and the boundaries between them are located with an average spatial resolution of about 60 m (meters). This map is based on at least 16 actual onsite observations per square kilometer for the approximately 500-km^2 area of eastern Loudoun County.

In our analysis, both geologic maps of eastern Loudoun County were first converted to digital format. Next, the permeability (as average ground-water yield in gallons per minute) and average shear strength were calculated for each rock unit. *These geologic-map based attributes are only one subset of the earth science data needed to conduct comprehensive land use analyses.* If the approach developed in this study were to be incorporated into an actual regulatory process rather than a demonstration, more precise measures would be obtained and used, such as water migration through the rocks. To treat the geologic map data quantitatively and to conduct the statistical analysis, we intersected the derivative maps of average yield and average shear strength with a grid of 1-km × 1-km cells for the 1:500,000- scale map and a grid of 250-m × 250-m cells for the 1:100,000-scale map. Formatting and manipulation of all the data layers used for these statistical and spatial analyses required geographic information system (GIS) relational data-base techniques.

Case A: The Siting of a County Landfill

Leakage of hazardous materials from waste facilities and landfills poses a threat to the Nation's water supply. There is a direct correlation between the rate of transport of dissolved and suspended contaminants away from a site and the permeability, faulting, and fracturing of the surrounding geologic materials. Changes in subsurface conditions that reflect local variations in the geology near a disposal facility can affect both the rate of transport of contaminants and the areal extent of contamination.

[5] Some of the rock units are not discernible on this map (fig. 3) because the subtle color changes between rock units are difficult to reproduce in the printing process.

Substantial costs are incurred in reducing the risk of water contamination. To protect ground-water supplies from irreversible or irreplaceable losses and to protect surface-water supplies from contamination, Federal and State regulations require the use of a variety of engineering solutions at waste sites. These solutions range from construction of lined sites with buffer zones to highly sophisticated integrated engineering and monitoring techniques to clean up contaminated sites.

In 1989, Loudoun County received results of a contracted engineering analysis that evaluated all areas of the county for suitable landfill sites. Recommendations to the county about suitable sites are based on the size of the landfill required for the projected quantity of waste through the year 2015; this estimate is based on the population growth rate in Loudoun County. According to the report, Loudoun County will generate at least 3.3 million tons of solid waste for a population of 246,000 in the 20-year period from 1995 to 2015. The disposal of this quantity of waste requires a landfill with a capacity of over 9 million cubic yards. Assuming the need for this capacity in a single landfill site, the consultants concluded in their report that less than 15 percent of the total land area of the county seems capable of surviving the permit process.

In our demonstration study, we assumed the consultant's report had not been prepared, so as not to bias the site-selection process. Further, we assumed that the waste disposal site must be located in the eastern portion of the county to minimize transportation costs and traffic congestion.

In the following discussion, we describe an expanded role for geologic map information in the decisionmaking process for potential sites for waste disposal facilities. In contrast to the general approach of promulgating environmental regulations that use demographic and cultural protocols as well as scientific data, our approach uses physical measures derived exclusively from geologic map information as the initial basis for regulatory decisions.

We implement the following procedures to estimate the value of the improved geologic map information relative to the existing information in siting a landfill. For this application, we assume that a regulator will have a tendency to underregulate in his approach to this issue. With improved geologic map information, better siting decisions can be made, meaning that more environmentally sensitive areas would be restricted.

Step 1: The suitability of a cell on each geologic map for a landfill is determined on the basis of rock permeability (average ground-water yield).

A cell is considered unsuitable if any or all of the following physical conditions exist:

a. presence in the cell of the limestone conglomerate geologic map unit (a highly permeable material prone to sinkhole development and currently used as a restriction under Virginia State Regulations for siting waste disposal facilities);
b. presence of other rock units that have high ground-water yields;
c. presence of faults and associated intense fracturing of rock units in the cell (generally increases the ground-water yield).

The implementation procedure for step 1 is detailed in chapter II of this report. The results of step 1 are shown in figure 4.

Using the test for suitability in step 1, we estimate the potential property losses that could be avoided (steps 2–4).

Step 2: For each cell on each geologic map, a probability of contamination is estimated as a function of the average yield.

Step 3: The monetary value of the property in each cell is estimated for each map.

In this application, only property value losses are estimated. We do not attempt to quantify the expected value of health effects or economic disruption that would ensue from a contamination incident in the county. On the basis of recent real estate transactions, an average residence in the eastern part of the county is assigned a value of $150,000.

Step 4: For each cell identified as unsuitable for a landfill in step 1, the expected property loss avoided by not placing a landfill in or near the cell is estimated as the product of the probability of a loss and the monetary value of the loss (total property value) in a cell.

Step 5: Summing the expected loss avoided from each geologic map and then taking the difference between the two, we obtain the value (marginal benefit) of the improved geologic map information.

Proceeding on the basis that the county will need to construct one new waste disposal facility, we use this analysis to estimate the value of the improved geologic map information for selecting one site in the study area. The site is assumed to occupy a 1-km^2 area to conform with the proposed sites described in the 1989 engineering report.

The average difference in expected property loss avoided between the two geologic maps for a 1-km^2 area in eastern Loudoun County is slightly over $1.50 million, which is the societal value of the improved geologic map information in this application.[6]

[6] Discounting issues are not explicitly considered. If one assumes a discount rate of 10 percent and an inflation rate of 10 percent, a formal annualizing and discounting step is not necessary. Because this is a demonstration, we have made these assumptions.

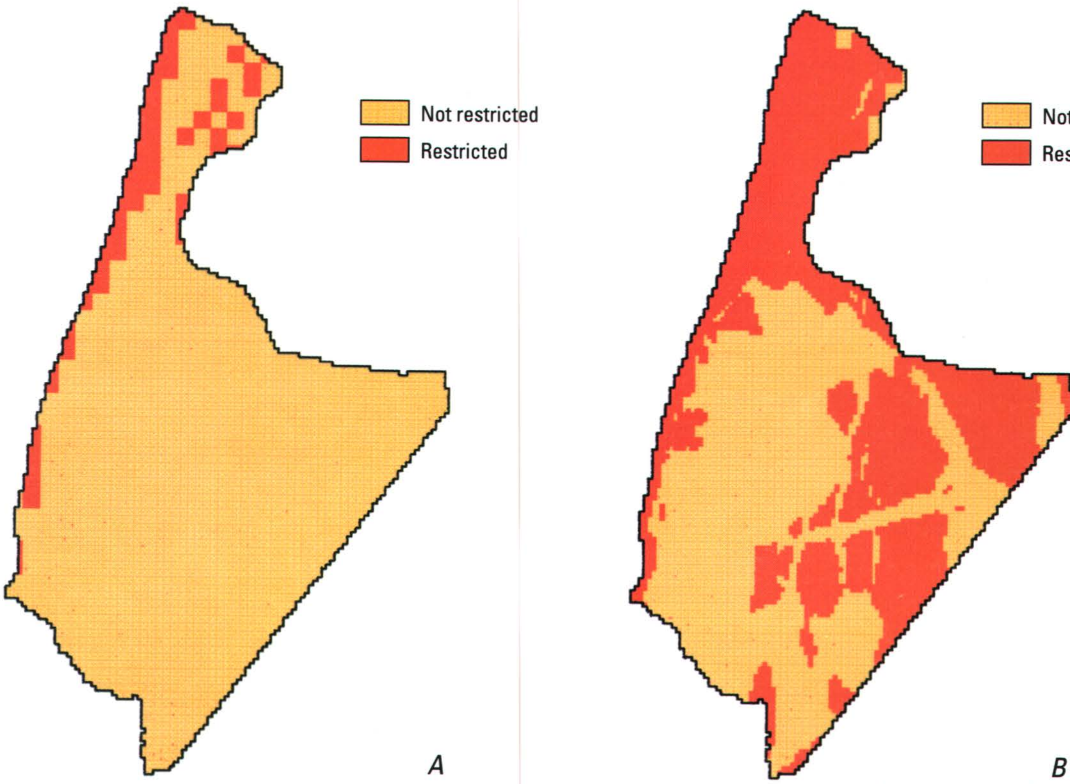

Figure 4. Distribution of cells unsuitable for further consideration as possible sites for a landfill based on (*A*) the 1963 Geologic Map of Virginia (Virginia Division of Mineral Resources) and (*B*) a preliminary version of the 1992 USGS Geologic Map of Loudoun County, Virginia (Open-File Report 92–716).

Case B: The Washington Bypass

In any part of the Nation, the geologic framework affects choices for transportation corridors. Right-of-way, construction, and maintenance costs for these corridors are influenced by local variations in near-surface geology and topography. Depending on the selected location of the corridor, mitigation costs due to geologic variability can be significant. Engineering solutions for mitigation range from cut-and-fill requirements for slope stability described in the Uniform Building Code, Chapter 70, to alternative engineering construction techniques such as building retaining walls.

A draft environmental impact statement (DEIS) for a proposed new transportation corridor that would pass through Loudoun County, known as the Washington Bypass, has been prepared by the U.S. Department of Transportation, Federal Highway Administration (FHWA), the Maryland State Highway Administration, and the Virginia Department of Transportation. According to the FHWA, the Washington Bypass is a proposed interstate-type highway that would bypass the Washington, D.C., region, provide additional roadway capacity to the region, improve truck and traffic safety, and provide improved facilities for both through-traffic and local traffic.

All proposed Washington Bypass corridors cross the eastern part of Loudoun County. Along the many alternative routes within the bypass corridor in Loudoun County, the length of road varies from 13.2 km to 42.1 km over flat to rolling terrain. The variation in engineering characteristics of geologic materials along any proposed corridor means that the possibility of slope failure induced by construction also varies along any proposed corridor. The possibility of slope failure induced by construction along a corridor route is directly related to the shear strength of near-surface geologic materials. In a manner similar to the one used in the landfill application, expected mitigation costs avoided for slope failure induced by construction are estimated for all cells in the study area. For this application we assume only that a highway route must be selected in the study area. In the following discussion we describe an expanded role for geologic map information in the siting of such a transportation corridor.

In contrast to the current practice of using construction guidelines based on topographic as well as other scientific data, our approach (similar to the landfill siting application) uses a physical measure, shear strength,

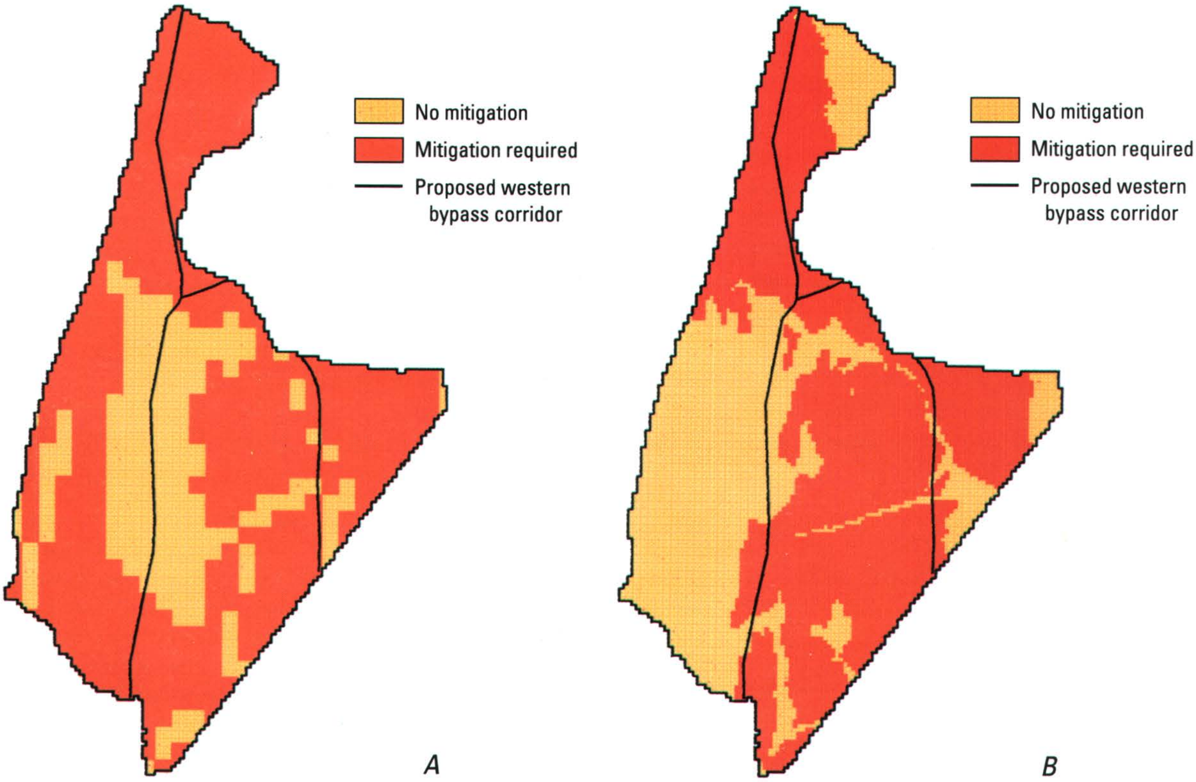

Figure 5. Distribution of cells requiring mitigation of slope failures arising from road construction, as based on (*A*) the 1963 Geologic Map of Virginia (Virginia Division of Mineral Resources) and (*B*) a preliminary version of the 1992 USGS Geologic Map of Loudoun County, Virginia (Open-File Report 92–716).

derived exclusively from geologic map information as the initial basis for regulatory decisions.

We implement the following procedure to estimate the value of the improved geologic map information relative to the existing information in siting a transportation corridor such that expected mitigation costs for slope failures arising from construction would be minimized. For this application, we assume that a regulator will have a tendency to overregulate in his approach to this issue. With improved geologic map information, better siting decisions can be made (fewer locations along the transportation corridor would be expected to require mitigation for slope failure arising from construction).

Step 1: Cells that would require mitigation are identified for each geologic map (based on a procedure detailed in chapter II).

A cell is considered to require mitigation if there is low shear strength for a given slope angle. The results of step 1 are shown in figure 5.

In steps 2–4, we use the test for mitigation of slope failure that is due to construction (step 1) to estimate the potential mitigation costs that could be avoided.

Step 2: For each cell, on each geologic map, a probability of slope failure that is due to construction is estimated as a function of the shear strength and topographic variables.

Step 3: The cost of the required mitigation in each cell is estimated for each geologic map.

For the study area, the savings in road construction costs (retaining walls) and repairs is calculated for the cells that require mitigation by the implementation of the geologic-map-based protocol. The mitigation cost avoided is assumed to be a $2,000 per meter cost (this figure is based on the assumption that both sides of the road would require mitigation) for constructing a retaining wall to prevent road damage (estimated cost for retaining wall construction similar to that along the I–66 corridor in northern Virginia).

Step 4: For each cell identified as requiring mitigation in step 1, the expected mitigation cost avoided is estimated as the product of the probability of a slope failure due to construction and the cost of mitigation in a cell.

Step 5: Summing the mitigation cost avoided from each geologic map and then taking the difference between these values, we obtain the value (marginal benefit) of the improved geologic map information.

Depending on the final choice for the location of a proposed transportation corridor in eastern Loudoun County, the difference in expected mitigation cost avoided between the two geologic maps for any cell in the study area varies considerably but on average is about $11,000 per 250-m × 250-m cell. Assuming that any corridor selected will cross a minimum of 85 cells and a maximum of 287 cells (number of cells crossed by the shortest and longest proposed routes in the DEIS), the societal value of the improved geologic map information in locating an interstate-type highway corridor in eastern Loudoun County ranges between $935,000 and $3,157,000.

NET BENEFITS OF GEOLOGIC MAP INFORMATION

The purpose of this analysis has been to develop and implement a methodology for estimating the societal value of improved geologic map information. We have derived the benefits of using the improved geologic map information for two applications. In this section, we estimate the net benefits (benefits minus the cost of producing the improved information) of this improved geologic map information.

Cost To Produce Geologic Map Information for Loudoun County

Loudoun County occupies approximately 1,400 km^2, an area equivalent to about ten 7.5-minute (1:24,000-scale) quadrangles, or about one-third of a 30 × 60 minute (1:100,000-scale) quadrangle. A number of areas within the county have been mapped geologically for other purposes in the past with varying quality and density of observations; these areas have been interpreted and reinterpreted over the last century as different paradigms for geologic understanding were developed, tested, and refined or abandoned. The current USGS geologic mapping project in Loudoun County, therefore, requires both new geologic mapping and compilation and reinterpretation of existing geologic map information. Total costs for the improved geologic map information, the 1:100,000-scale USGS geologic map, are projected to be about $1,160,000 distributed over 6 years. These costs include an opportunity cost of capital compounded semiannually at 10 percent during the production period. The project cost is about $968,000, and interest is $189,000. For the project, the capital and operating costs are $913,000 and $55,000, respectively. Capital costs include utilization of plant and equipment and personnel, while operating costs include daily expenses and supplies.

Net Benefits of Improved Geologic Map Information

The expected net benefit of using the improved geologic map information (the modern USGS 1:100,000-scale geologic map), derived from just two of the many situations that require geologic data in Loudoun County, is the gross benefit derived from the use of the improved geologic map information ($2.44 to $4.66 million for the two case studies described above) minus the cost of producing that geologic map ($1.16 million). Therefore, the expected net benefit (societal value) for the two applications of the 1:100,000-scale Loudoun County geologic map ranges from about $1.28 million to $3.50 million.

The United States covers an area greater than 17,000 times the area of eastern Loudoun County, Virginia. Two out of many possible applications of improved geologic map information in this small area have been shown to be of significant value to society. An improved geologic map data base for the Nation will result in enormous savings if properly applied to balanced land management decisions. The issue of whether all applications of improved geologic map information will yield positive net benefits is unknown. We do know that in regions that exhibit economic growth, improved geologic maps will be increasingly important for making decisions that relate to the revitalization of the Nation's infrastructure, for avoiding irreversible environmental impacts, and for mitigating effects of natural hazards.

ACKNOWLEDGMENTS

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Chapter I

Geologic Maps: Fundamental Data Base for the Earth Sciences

INTRODUCTION

This chapter describes what geologic maps are, why they are needed, what kinds of information they contain, how they are used, and how much it costs to make them.

What Is a Geologic Map?

A geologic map is a graphical information display that uses a combination of colors, lines, and symbols to depict the composition and structure of geologic materials and their distribution across and beneath the landscape. The graphical display contains both *descriptive information* about geologic units and structures and an *interpretive model* of how they were formed. This combination of descriptive and interpretive geologic map information provides a conceptual framework that relates all the geologic elements of an area together so that the position, characteristics, and origin of each element are understood in relation to all other elements. Such a unique synthesis of descriptive and interpretive information makes the geologic map a powerful research tool for understanding the Earth's composition and structure, internal and external processes, and history.

The standard geologic map is a general purpose product; that is, it conveys essential information about many aspects of the geologic setting, not just one or a few aspects. For a prescribed area, such a map might identify **bedrock formations** like granite, limestone, sandstone, or shale and their altered or mineralized equivalents; **surficial units** like soils, landslides, and sediment deposited by streams, wind, glaciers, and hillslope processes; and **geologic structures** like folds, faults, and fractures. A single general purpose geologic map thus provides a comprehensive record of a diverse suite of geologic features, and this characteristic makes the map a primary data base for a broad range of societal and scientific applications.

Why Are Geologic Maps Needed?

The regional geologic map is universally recognized as the instrument of choice for planning and executing research and decisions that involve earth science information (National Research Council, 1987, 1988). Its utility and value derive from the fact that the unique information content of a geologic map can be used to characterize the geologic setting of a specific site in the context of the surrounding region. Scientists, decisionmakers, and managers can extrapolate the results of site-specific investigations outward to adjacent sites or regions where investigations have not been conducted and thereby forecast or predict geologic conditions where data are limited. The regional geologic map forms a fundamental data base for earth science applications that require a predictive capability (geohazards evaluation, resource assessment, environmental analysis).

In order to understand why geologic maps are needed, we must first understand and appreciate the role that solid-earth materials and structures play in day-to-day activities. Consider the following situations:

1. You are a home buyer. You and your family are moving to a part of the United States where you have no first-hand information concerning the nature of the land—its water hazards, atmospheric hazards, and geologic hazards. You probably would not have the time, resources, or inclination to pursue such information through your own independent research, so you might turn to some publicly accessible source such as a municipal, county, or State planning or regulatory commission that already has incorporated technical information into zoning and setback provisions. But where did these surrogates acquire their information, and what assurances do you have that their information was comprehensive, well documented, and up to date?
2. You are on the seismic-safety panel of the planning commission for a county undergoing rapid urban expansion. What planning tool do you use to develop countywide hazard-zonation maps that extrapolate regionally the results of a small set of site-specific investigations that indicate the potential for landslides, liquefaction, subsidence, and strong ground shaking?
3. You are a land use planner for a municipal, county, State, or Federal commission charged with the balanced use of lands that must accommodate multiple demands, which include agricultural, residential, recreational, commercial, industrial, and mineral-, energy-, and water-resource uses. What planning tools do you turn to in order to evaluate solid-earth factors that contribute to multiple-use decisions?

4. You are a mineral-, energy-, or water-resource exploration manager. What planning tool do you use to identify terranes that are likely to host earth resources? Once you have identified favorable terranes, what planning tools do you use to select exploratory drilling or grid-sampling sites, given that your exploration budget does not have room for a trial-and-error strategy and given that you must project your limited site-specific information across areas or regions where information is sparse?
5. You are a research scientist who develops new models for how the solid earth is formed. What research tool do you turn to that illustrates three-dimensional relations among geologic materials and structures so that you can examine the position and origin of each geologic element in relation to the others? Without some means of displaying spatial and geometric relations among geologic materials, would you be able to formulate a complete model for how these materials formed?

Answers to these questions depend to a large degree upon spatially based geologic information that is linked to geologic materials and geologic structures. The geoscience product that captures and displays this kind of information is the geologic map.

What Kinds of Scientific Information Does a Geologic Map Contain?

Geologic maps display a broad range of information attributes.

Physical properties.—Geologic maps provide geotechnical information about each geologic unit and structure, including attributes such as mineralogic composition and physical properties, weathering or chemical alteration, thickness, degree of consolidation or hardness, relative density, and the orientation and spacing of fractures, faults, and folds. These attributes are important because they determine characteristics such as the strength, transmissivity, and continuity of geologic materials and structures.

Three-dimensional geometry.—Through information attributes that describe the geometric orientation of geologic materials and structures at the Earth's surface, a geologic map interprets the three-dimensional shape of geologic materials in the subsurface, including (1) the lateral distribution of rock bodies and geologic structures and (2) changes in orientation that occur between measurement stations.

Relative age relations.—Geologic maps provide information about the timing and sequence of events that produced the geologic materials and structures displayed on the map. The timing of one geologic event relative to another is important because many basic- and applied-research applications keyed to a particular geologic unit or structure depend on the chronology of the formation of a unit or structure relative to other units and structures.

Relation between geologic form and geologic process.—A geologic map allows the map user to understand the geologic processes that produced the materials and structures portrayed on the map. As the user understands the genetic processes that gave rise to the physical properties and geometric configuration of geologic map units or structures, the scope and usability of a given piece of geologic map information increases.

How Is a Geologic Map Used?

Because of its comprehensive information content, a geologic map is the primary data base for a broad range of societal and scientific applications. A graphic representation of the primary data is shown in figure I–1. Each specialized application extracts one or more information attributes from the general purpose geologic map and combines these attributes into special purpose derivative maps that address specific geologic features, processes, or applications. Derivative maps can be generated by distilling selected information from the primary data base or by developing and expanding a particular part of the primary data base through follow-on specialized investigations. The geologic map thus should be viewed as a first-order information layer that can be combined with information layers from other geologic, geographic, hydrologic, or demographic disciplines.

ENVIRONMENTAL ANALYSIS

Waste Repository Siting

Issue: How does geologic map information help select the threshold level of acceptable risk in siting a waste repository facility?

Geologic-map-based information bears directly and indirectly on factors that are used to site waste repository facilities: (1) geologic maps depict the areal distribution of geologic hazards likely to threaten a repository site (earthquake faults, slope failures, ground subsidence); (2) they depict the surface and subsurface distribution of permeable geologic materials whose transmissivity potential would exacerbate the effects of leakage from a waste repository; (3) they depict the distribution of geologic materials whose geotechnical properties are compatible with the engineering specifications of the repository facility; (4) they identify the potential for co-located geologic resources (clay, sand, and gravel resources, energy resources, ground-water resources) whose development might be compromised by siting a waste facility in an area for which the multiple-resource potential had not been determined; (5) they depict the distribution of geologic materials and structures that would affect the size and spacing of buffer zones; and (6) they depict the distribution of geologic materials more or less likely to shake strongly in response to earthquake energy.

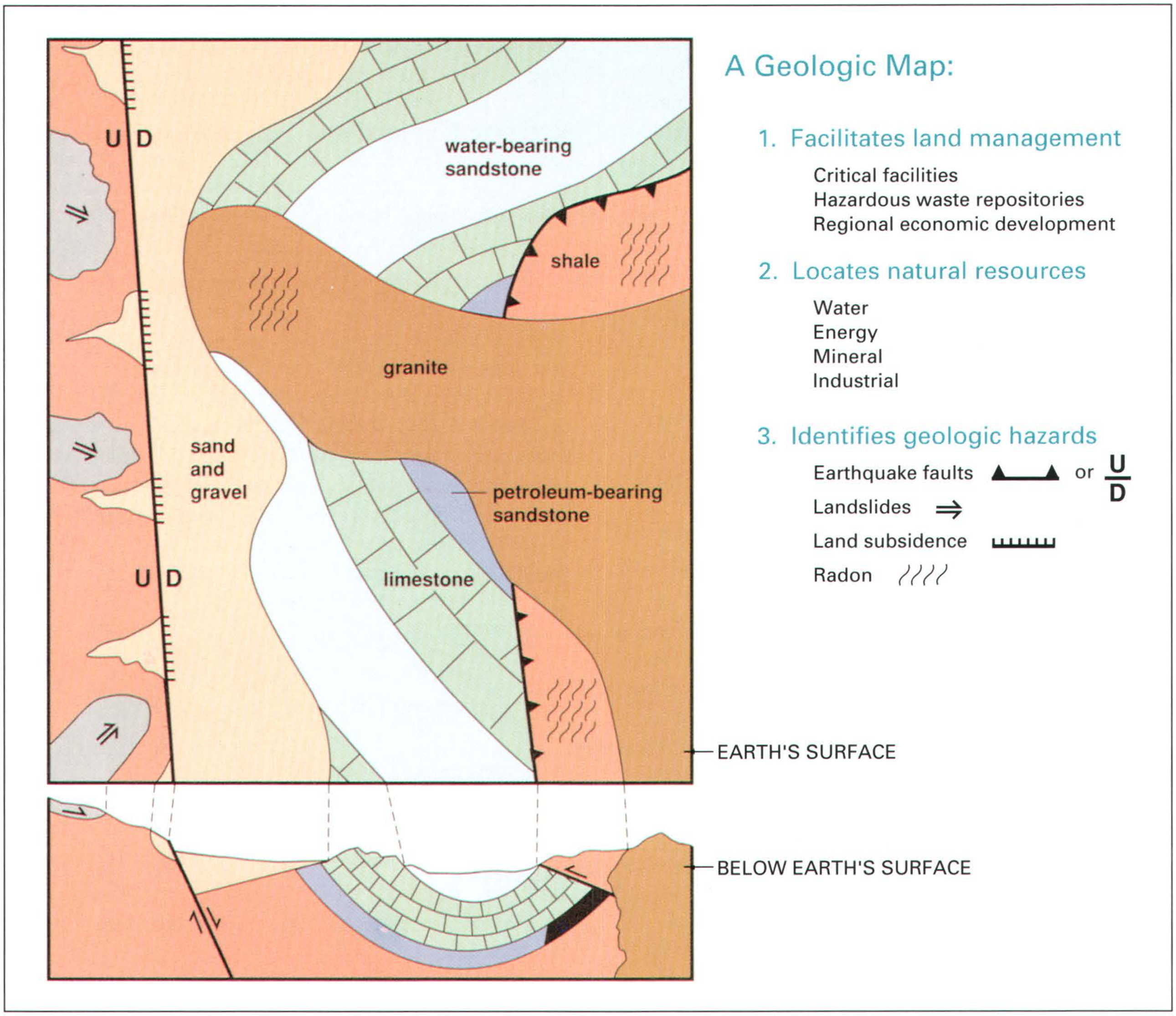

Figure I–1. A graphic representation of some of the typical information contained in a general purpose geologic map and some of the many applications of that information. A geologic map can be used to identify geologic hazards, locate natural resources, and facilitate land use planning.

Regional Ground-Water Quality at Risk from Point-Source and Nonpoint-Source Contamination

Issue: How does geologic map information help identify the threshold level of acceptable risk for ground- and surface-water contamination?

Geologic-map-based information is essential to the estimation of the vulnerability of regional ground-water reserves to point-source and nonpoint-source contamination: (1) on a regional basis, geologic maps depict the areal distribution and subsurface configuration of geologic materials that store ground water or that recharge the ground-water reservoirs; (2) geologic maps depict the areal distribution and subsurface configuration of geologic materials whose layering characteristics and geotechnical properties are conducive to the transmission of ground-water contaminants and to the trapping and storage of contaminants; and (3) geologic maps depict the areal distribution and subsurface configuration of geologic materials that form barriers to the flow of ground water, which is the source of dissolved mineral constituents, or that lead to perched ground-water conditions.

Site-Specific Ground-Water Sources

Issue: How does geologic map information help locate site-specific ground-water sources?

Geologic-map-based information forms the basis for locating site-specific ground-water sources: (1) geologic map information defines the local distribution and subsurface configuration of geologic materials that contain ground water; (2) geologic maps depict the distribution and subsurface configuration of geologic materials that form barriers to and conduits for the flow of ground water or that lead to perched ground-water conditions; (3) geologic maps portray the distribution of geologic materials and structures that affect the size and position of buffer zones; and (4) geologic maps portray the distribution and types of materials in potential ground-water recharge areas and may improve estimation of recharge rates or long-term reliability of a ground-water source.

GEOLOGIC-HAZARD RECOGNITION

Earthquake Potential and Earthquake Hazards

Issue: How does geologic map information help identify the threshold level of acceptable risk for earthquake-induced property damage and loss of life?

Geologic maps provide three kinds of information essential for the evaluation of *earthquake potential*: (1) they identify faults whose field characteristics indicate geologically recent activity; (2) they demonstrate geometric relations among different faults so that they can be analyzed as an integrated system rather than as isolated features, because seismic activity in a region is a product of faults whose dynamic interaction must be understood before meaningful forecasts can be made about earthquake potential; and (3) through geometric relations between faults and other geologic units, geologic maps can document the long-term geologic history of faults so as to provide a context for instrumentally determined estimates for future earthquake activity. Geologic maps provide three kinds of information essential for evaluating *earthquake hazards*: (1) they identify the areal and subsurface distribution of geologic materials that have different ground-shaking and ground-response potential; (2) they identify active fault lines that are likely to yield ground rupture; and (3) they distinguish different types of faults that are likely to generate different kinds and amounts of seismic energy.

Landslide Potential and Landslide Hazards

Issue: How does geologic map information help identify the threshold level of acceptable risk from landslide hazards?

Geologic maps provide three kinds of information essential for the evaluation of landslide potential and landslide hazards: (1) they identify geologic materials that are conducive to slope failure because of their intrinsic geotechnical properties; (2) they identify geologic terranes that have generated landslides in the recent geologic past; and (3) they demonstrate geometric relations between landslide-prone terranes and other geologic structures (faults, folds) so that landslide potential can be understood as a product of geologic processes other than simply a product of parent material and slope conditions.

Volcanic Potential and Volcano Hazards

Issue: How does geologic map information help identify the threshold level of acceptable risk from hazards imposed by volcanic activity?

Geologic maps provide three kinds of information essential for the evaluation of volcanic potential and volcano hazards: (1) they identify the general geologic setting of a region that thereby allows volcanologists to forecast one of three or four major types of volcanic activity that could be expected to occur in the map area; (2) they identify geologic terranes that have been produced by volcanic activity in the recent geologic past; and (3) they depict the kinds of volcanic processes (high-velocity downhill-flowing hot ash clouds, lava flows, mud and debris flows, catastrophic slope failures) that have formed the volcanic map units and that could be expected to occur during future volcanic activity.

RESOURCE EXPLORATION AND EXTRACTION

Energy Strategy

Issue: How does geologic map information help define a develop-or-preserve energy strategy in a multiple-use environment?

Geologic maps provide three kinds of information essential for evaluating energy-resource policy: (1) they identify the distribution of geologic materials that are hosts for various energy commodities (coal, oil and gas, uranium); (2) they identify geologic terranes that hold greater potential for the occurrence of an energy commodity of a particular quality and quantity; and (3) they provide a basis for defining exploration and development strategies and for projecting operational costs that depend upon the complexity and scale of the geologic setting.

Minerals Strategy

Issue: How does geologic map information help define a develop-or-preserve minerals strategy in a multiple-use environment?

Geologic maps provide three kinds of information essential for evaluating mineral-resource policy: (1) they identify the distribution of geologic materials that are hosts for various mineral commodities (precious and base metals, industrial minerals); (2) they identify geologic terranes that hold greater potential for the occurrence of a mineral commodity of a particular type and grade; and (3) they provide a basis for defining exploration and development strategies and for projecting operational costs that depend upon the complexity and scale of the geologic setting.

BALANCED LAND MANAGEMENT

Regional Economic Development Decisions

Issue: How does geologic map information help define a develop-or-preserve land strategy in a multiple-use environment?

Geologic, hydrologic, and topographic features and processes interact in a generally predictable way in a dynamic environmental system. Some of these physical variables are *static* in the time frame of human activities: even though the variables play a critical background role in guiding cultural, political, and economic development, they neither trigger dramatic changes in human activities nor are they themselves altered by such activities. However, other physical variables are more *dynamic* in relation to human activities: they can induce dramatic responses in cultural, political, and economic development (the social and economic impact of earthquakes, ground- and surface-water cycles, landscape evolution), and, additionally, the variables themselves can be altered by human activities. For example, patterns and rates of land use can induce changes in resource availability, rates and patterns of runoff and recharge, and rates of landscape erosion, sediment transport, and sediment accumulation. As the environmental system is modified by natural processes and human activities, the system's capacity to respond to additional perturbations also changes.

Environmental changes resulting from either natural or human causes influence decisions regarding regional economic development, environmental preservation, and resource allocation. Options proposed for preservation and development each have associated opportunity costs (opportunities foreclosed by taking a particular action): (1) a decision to preserve an environment may cause delays in regional development and thus may alter the value of specific parcels of land and (2) alternatively, development may provide short-term benefits to the current population while causing irreversible effects on the natural environment in the long run. These long-term impacts could impose extremely high costs on future generations.

How Much Does it Cost To Produce a Geologic Map?

Several factors contribute to geologic-map production costs:

1. Original investment costs (costs already assumed in order to acquire a certain background level of geologic map information for the Nation).
2. Operational costs (costs to acquire interdisciplinary geologic map information of a particular scale and quality).
3. Data-base costs (data-base management, publication, distribution, and archival costs).

Original investment costs: a multigeneration national geologic map data base.—Geologic map information at some level of accuracy and data density exists for all parts of the Nation: for some regions, the available data base consists only of reconnaissance-quality information; for other regions, the available data base consists of modern, interdisciplinary, detailed-scale geologic map information. The cost of acquiring new geologic map information for a prescribed area will depend upon the technical quality of the available data base for that area and upon the demands of the perceived application. For some areas, the available information need only be revised slightly and released in a form that compiles the older information in a new format or in the context of new interpretive models for the geologic materials and structures. In such instances, geologic-map production costs will be relatively low. For other areas, the available archival geologic map information is sparse or obsolete in terms of modern geologic theory or analytical techniques, and new information of greater density and accuracy must be acquired to accommodate the perceived application. Of importance is the notion that geologic map information is not static: as new analytical techniques are developed or as new models for how geologic materials and structures are formed, the geologic map information in a given region must be reexamined for its accuracy and precision.

For this analysis, the geologic information base that already exists at the time a geologic mapping investigation is initiated is an original investment cost, which is a cost that has been underwritten by earlier funding initiatives and has produced some previous benefit.

Operational costs.—These are the costs associated with acquiring new geologic map information beyond that which already exists in the data base. Operational costs are of two kinds: (1) the costs required for the geologic map lines and polygons and their associated information attributes and (2) interdisciplinary data required for age, physical properties, and origin of geologic materials and structures.

Data-base costs.—These are the costs associated with managing all aspects of the archival geologic-map data base, including cartographic production, data-base management and distribution, publication, and translation to information users.

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Chapter II

The Societal Value of Geologic Map Information: Use in a Regulatory Application

INTRODUCTION

The Issue

The economic value of scientific information is determined within the framework of the decision process: the greater the value of the resources to be protected, the greater the value of the information. In this chapter we develop and apply a model of decisionmaking that makes explicit use of modern geologic maps. We compare the benefits of using improved geologic information relative to existing map data in a regulatory environment. We show that improvements in geologic map information have a net positive value to society that enables superior land use decisions to be made. As a result, greater economic and environmental losses can be avoided than if the improved information were not available. The value of the information is shown to be the net value of the losses avoided.

Geologic maps are applicable to many policy-related issues and concerns. We concentrate on the use of geologic information for risk assessment. Despite the fact that environmental hazards have been a major policy concern, their translation into regulatory policies is difficult because of the considerable uncertainty surrounding these risks and the physical processes that produce them (Lichtenberg and Zilberman, 1988). Depending on the accuracy of the risk assessment and the stringency of the regulatory actions taken to avoid a loss, uncertainties remain that are due to the physical attributes not adequately considered in the implementation of generalized regulations governing the planning and engineering of a project (Shavell, 1984). To appreciate the role of geologic maps in the decisionmaking process requires a full description of the decision problem, the geologic map information, and the decisionmaking institution, including the preferences of the decisionmaker. We consider each of these issues.

Background and Economic Concepts

Land use decisions commonly are made with some level of uncertainty regarding actual geologic conditions. Errors can be costly. An inappropriate land use may result in the failure of a particular investment project or in potential adverse environmental impacts.

There have been a few studies of the value of information gathered by public agencies for land use decisions. For example, Lind (1973) addresses the optimal assignment problem: which land use should be assigned to which parcel of land in order to maximize social surplus. The benefits of this information derive from the superior land use allocation. We do not consider the optimal assignment problem. Our focus is to evaluate the effect of improved geologic map information for permitting a particular land use in terms of threshold geologic conditions.

Roe and Antonovitz (1985) analyze the value of publicly gathered information in agricultural applications. The paper demonstrates that this information is a public good in the sense that it may be usefully applied in more than one decision without the value of the information being impaired. Roe and Antonovitz focus on the case in which there is uncertainty concerning one attribute, and information is made available for this attribute. They do not consider the value of this information in a regulatory decisionmaking process.

Lichtenberg and Zilberman (1988) and Lichtenberg and others (1989) explicitly incorporate the impact of the uncertainty of the information gathered by public agencies when policy is being set. In their framework, there is a risk associated with an action, and this risk has uncertainty associated with it (that is, the hazard has both an expected value and a nonzero variance). The uncertainty is an important element of the decisionmaking process. A hazard is defined by both the *risk*, which is the expected value, and the *uncertainty*, which is the dispersion. The decisionmaker's problem is to set a regulatory safety standard that will be violated not more than some given fraction of the time. That is,

$$\text{Prob}\ \{R < R_0\} > P$$

where R_0 is the regulatory standard, R is the actual level of risk exposure, and P is the margin of safety defined as the inverse of the frequency with which the standard is violated. P functions much like the confidence interval in statistical hypothesis testing. The level of safety can be increased by raising R_0 or by lowering P. In the Lichtenberg and Zilberman framework, the level of information is constant. Information is useful in this environment because it allows the safety standard to increase without necessarily raising the regulatory standard. Lichtenberg and others (1989, p. 31) note, "The mechanism by which a consensus value of the margin of safety could or should be established deserves further study." In this chapter we explicitly incorporate improved geologic map information into the regulatory decisionmaking process and show that the value of the improved information is determined by its impact on the outcome of the process.[1]

A regulator is charged with enforcing land use regulations by allowing or disallowing certain uses of parcels of land. On the basis of engineering and epidemiological information of an adverse land use impact, a regulatory standard can be defined, for example, in terms of a particular geologic characteristic. The regulation defines the level of the safety that can be achieved.

One view of the behavior of regulatory agencies is that they attempt to maximize social welfare by imposing an optimal level of safety (Scherer and Ross, 1990). The optimal level of safety is achieved by permitting a land use to occupy a site only when the expected value of the regulatory criterion is below (in the case of minimum standards) or above (in the case of maximum standards) the mandated standard. Behaviorally, regulatory agencies choose to ignore the uncertainty (variance) inherent in information and focus solely on the risk (expected value) when evaluating a parcel of land.

Not all regulatory agencies can be expected to behave in this fashion. There is a considerable body of literature suggesting that regulatory agencies are "captured" by the very groups they regulate and that they produce regulations that benefit or, at least, do little harm to the groups being regulated (Stigler, 1971; Peltzman, 1976).[2]

In the absence of perfect information, the decisionmaker may have a general perspective (a prior) of the possible geologic characteristics of an area. This prior is formed from existing available geologic map information. As the quantity of information increases or the quality improves, the uncertainty (variance) of this prior is reduced.[3] This new level of information may be used to reduce exposure to risk in decisions concerning the allocation of resources. Further, this improved information reduces the risk faced by the decisionmaker by decreasing the variance around the mean of the geologic characteristic being measured. Thus, land use decisions become more precise because parcels are rejected as inappropriate on the basis of probability distributions that are less diffuse.

If the decisionmaker is risk neutral, he or she allows land use types on the basis of expected values, and the information that reduces uncertainty (reduces the mean-preserving spread) has no value. If the decisionmaker is averse to risk, then such information does have value (see Rothschild and Stiglitz, 1970; Theil, 1971). Finally, if the process yields a bias in favor of a certain type of land use, the uncertainty regarding the true state of the geology may be exploited to defend an allocation that the decisionmaker prefers.

In the case we address, geologic map information contributes to the measurement of several physical and environmental attributes of a site. Further, the uncertainty about the attributes of a site may be reduced as improved geologic map information is acquired. We focus on the use of information in the application of an existing set of standards rather than in the setting of standards. Geologic map information pertaining to the geologic characteristic used to determine whether a parcel of land meets the regulatory standard is available with some variance. We consider the value of improved geologic map information (a reduction in the variance) to be derived from the fact that it permits a more accurate application of the existing regulatory standard.

A regulatory agency can base its decision on both the risk *and* the uncertainty surrounding this risk. Even though the regulatory standard (an acceptable level of risk) is defined as some specific value or level for a geologic criteria, the true state of the geologic information is known only with some certainty (geologic map attributes can be represented as a probability distribution). On the basis of credible scientific information, the regulator would be able to accept or reject parcels of land for a given use if the standard lies within some interval around the mean. Typically, an acceptable interval is defined as being within the 95-percent confidence level (or two standard deviations). While there is an optimal level of safety based on the expected value of the losses avoided, the actual regulatory process may lead to a level of regulation that departs from this optimal level when the uncertainty is incorporated into the decision process. The regulatory agency cannot, however, set a standard arbitrarily low (or high), because the oversight committee responsible for the agency's authorization will demand justification for standards that are too lax (or too stringent).[4]

Specifically, the uncertainty inherent in scientific measurement could lead a regulatory agency to make implementation errors. For a particular land use issue, regulations could be applied to accept parcels of land for which the geologic attribute in a specific location plus (minus) two standard deviations falls below (above) the regulatory standard. For example, in the case of waste facility siting, the potential for contamination can be assumed to increase as rock permeability increases. In this particular example, the regulation might be that the geologic attribute *minus* two standard deviations is less than the

[1] The value of risk reduction is lower for risks that are less well understood (have a higher variance). Reducing the variance will also increase the return to raising R_0.

[2] It is beyond the scope of this paper to demonstrate all of the forces at work in particular settings.

[3] Rothschild and Stiglitz (1970) develop a definition of increasing risk as a mean-preserving spread in the variable being observed.

[4] See Weingast and Moran (1983) for a discussion of the behavior of regulatory agencies under oversight.

standard in order for the location to be acceptable. Because contamination is an adverse environmental impact, the regulation dictates that waste disposal facilities avoid environments in which the rocks near the surface are highly permeable. As improved geologic map information becomes available, and the variance of the geologic attribute likely decreases, we can reduce the number of locations that are presumed to be acceptable by using less precise geologic maps. Thus, as the geologic map information becomes more specific, we would tend to restrict more locations from this land use. We will refer to this situation as a case of underregulation. Alternatively, the regulator could determine to be acceptable only those parcels for which the geologic attribute *plus* two standard deviations is greater than the standard. We will refer to this as a case of overregulation. Regardless of whether the agency chooses to underregulate or overregulate, improved geologic map information will lead to the application of regulatory rules that approach an optimal level of safety.

The Empirical Evaluation

We undertake two applications that involve hypothetical land use regulations in which geologic map information is applied in the decisionmaking process: the location of a landfill and the routing of a highway. In each case the regulatory standard is described in terms of particular geologic characteristics. This standard is applied as a threshold condition for permitting a certain land use. The regulatory decision for parcels with existing geologic map information and with improved geologic map information are compared. From the resulting change in land use restrictions, expected losses can be avoided with the improved geologic map information. These expected losses avoided can be calculated to yield a measure of the benefits of the improved geologic map information. The net benefits of this improved information are found to be positive for the two applications considered. There are many potential applications of the information that can be derived from a single geologic map. As such, the net benefits reported here may be viewed as a conservative estimate.

THE ROLE OF GEOLOGIC MAP INFORMATION IN THE MAKING OF A DECISION

Reducing Information Uncertainty with Geologic Maps

Chapter I describes geologic map information. For purposes of this chapter, we provide a brief description of the nature of geologic map information as it applies to regulatory decisionmaking. The geologic characteristics of a parcel of land are based on the type, structure, and engineering characteristics of the rock that are identified during the geologic mapping. This activity involves observation, sampling, analysis, and interpretation. The resolution of geologic map information generally increases with larger scale maps (more detailed) and with newer vintage maps.

Geologic maps can be interpreted to provide the basis for statistics that infer quantitative attributes about the geologic characteristics of a particular parcel of land. More detailed (larger scale) maps provide more accurate statistics (provide a likely reduction in the variance). In the demonstration of our applications, the available geologic map information (at different vintages and scales) for a region is used to produce derivative map information showing rock permeability and shear strength. A geologic map's vintage is an important consideration because it represents the status of interpretations, concepts, and models that continue to evolve over time. These geologic characteristics are considered important for our applications. Suppose a new geologic map of a region is produced at a scale that is more detailed than the existing geologic map, as is commonly the case. For instance, at the new map scale, perhaps faulting is delineated more clearly and boundaries between different rock types (contacts) are defined better than on the older, less detailed geologic map. Better delineation of the geologic attributes results because the newer and improved geologic map is based on more detailed, systematic observations. If this improved geologic map information leads to a different number of restricted parcels, then we have a measure of the value of the improved geologic map information. The net benefits of this improved information are the changes in the expected loss avoided, and the costs are the costs associated with acquiring the improved geologic map information.

Gathering geologic map information is a challenging process because of the scarcity of geologic outcrops, scarcity and expense of drill-hole data, and complexity of possible geologic interpretations. In general, the density of data required for the appropriate level of geologic resolution is a function of map scale. At any map scale, geologic information has an inherent uncertainty because observations cannot be made everywhere, and extrapolations must be made. Thus, the true value of a geologic attribute for a location is described by a probability distribution. The central point of the probability distribution is the expected value of the geologic attribute in a specific location. The variance of the attribute corresponds to the variability of the geologic attribute over the entire mapped area. This concept is illustrated in figure II–1, in which the probability distribution of a geologic attribute is plotted for two different levels of information, d_1 and d_2, corresponding, for example, to existing and improved geologic information. R in figure II–1 denotes a regulatory standard (threshold), and $\bar{g}_k$ denotes the expected value of the geologic attribute for a given locality or parcel of land. The 95-percent confidence interval (2σ) about the expected value is indicated for the

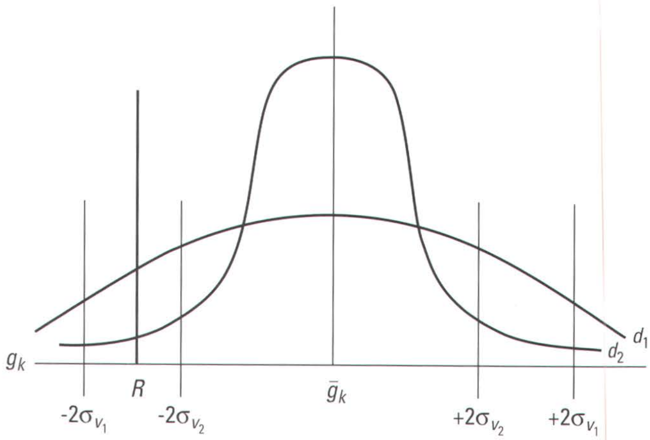


Figure II–1. The probability distributions, d_1 and d_2, of a geologic characteristic, g_k, for two geologic maps of different vintages and different scales, v_1 and v_2, for the same area. R represents a regulatory standard. $\bar{g}_k$ denotes the expected value of the geologic attribute for a given locality or parcel of land. 2σ is the 95-percent confidence level about the expected value for the distributions.

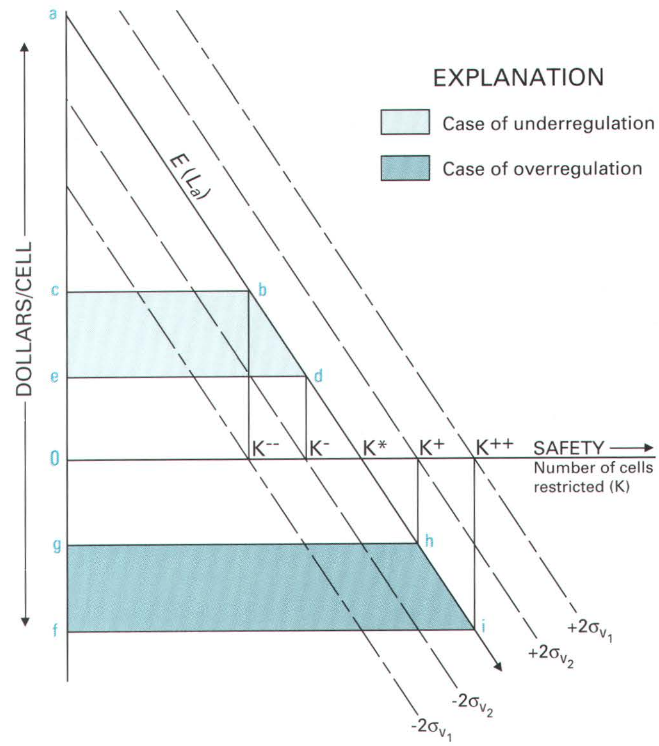


Figure II–2. Economic impact of a regulation based on geologic map information. $E(L_a)$ is the marginal expected loss avoided; K* is the optimal level of safety. See text for in-depth discussion.

distribution d_1 as $2\sigma_{v_1}$. With this information, we fail to reject the hypothesis that the allowed standard, R, is met for this parcel of land, because it is within two standard deviations of the expected value, and H_0: $\bar{g}_k - 2\sigma_{v_1} < R$.

With improved geologic map information, based on larger scale maps or newer field data, we have distribution d_2. The improved information is more precise and more detailed. As such, distribution d_2 has less uncertainty (in this case, a smaller standard deviation, $2\sigma_{v_2}$ than d_1. The null hypothesis is rejected because the expected value of the geologic attribute minus two standard deviations is greater than the standard, R.

The rejection of a particular parcel by use of information from d_2 occurs because the information in d_2 is more precise, not because there is a bias in the original data, d_1. Additionally, note that the expected value of the geologic attribute has had the effect only of reducing the variance of the statistic.

The Inclusion of Geologic Map Information in Regulations

Hypothetically, a regulatory agency could employ the following procedure to determine the number of parcels available for a given land use.[5] Each parcel is tested for whether the average value of the geologic attribute ($\bar{g}_k$), minus two standard deviations, is greater than or less than the regulatory standard. The rule in equation II–1 is applied to each parcel.

$$\bar{g}_k - 2\sigma_v \lesseqgtr R \qquad \text{(II–1)}$$

where $\bar{g}_k$ is the average value of the geologic attribute in k, where k=1, . . ., K, σ_v is the standard deviation of g over the mapped area for a given vintage geologic map, v, and R is the regulatory standard.

The economic impact of a regulation based on the improved geologic map information can be seen in figure II–2. This figure is a representation of the changes in the number of parcels restricted or mitigated when new, more detailed information becomes available. Safety (horizontal axis) is denoted as the fraction of land (parcels or cells) in the region that is rejected (require mitigation) for a partic-

[5] There are additional issues related to each parcel that go beyond the question of optimal information and the value of the information. For instance, there is the question of the optimal scale of the geologic map information for a specific land use application. In this study we are limited by the availability of the existing geologic maps. One could easily envision a study to address the question of the optimal scale for resolving a land use issue. In addition, there is the question, in a regional geologic mapping program, of prioritizing the schedule for creating geologic map information. Which geologic maps should be produced first? Again, this is beyond the scope of the study but is an important question in the overall issue regarding the "best" geologic mapping program.

ular land use type.[6] Losses avoided through implementation of regulations are measured in terms of a money metric (dollars) on the vertical axis. As the vulnerable, or "at risk," cells are eliminated, society's exposure to that risk is reduced. As the level of safety increases, there is an increase in expected losses avoided. The change in expected losses avoided is shown in the figure as the marginal expected loss avoided, $E(L_a)$, for restricting each additional cell. The $E(L_a)$ curve represents the *net* marginal expected loss avoided (the cost of avoiding losses is constant), which is normalized on the figure by representing the $E(L_a)$ as deviations from zero. Therefore, an optimal level of safety is shown as the intersection of the $E(L_a)$ curve and the horizontal axis (net marginal expected loss avoided is zero) at the point labeled K* in the figure.

There is uncertainty regarding the actual losses to be avoided by restricting cells, because there is uncertainty concerning the true state of the geology underlying a cell. We have indicated this uncertainty in figure II–2 by the dashed lines above and below $E(L_a)$. We have indicated two levels of uncertainty, each of which is consistent with a different level of geologic map information (d_1 and d_2 in terms of fig. II–1). In each case, the dashed lines enclose the 95-percent confidence interval.

The presence of information uncertainty leads to a tendency in the regulatory process to generate errors involving either underregulation or overregulation of land uses. Since the optimal level of safety is that which results in net marginal expected loss avoided being zero, either underregulation or overregulation must result in a welfare loss to society.

These losses may be shown by reference to figure II–2. Consider the case in which the regulator sets the standards to restrict K^{--} cells. With K^{--} cells restricted, the social loss is given by the area bc0K*. This area is the amount of the potential consumer surplus that is foregone when the regulatory standard is set at K^{--} rather than the optimal level of K*. Improved geologic map information results in the level of regulation being increased so that K^{-} cells are now restricted (this is the 95-percent confidence level with this improved information, d_2). The welfare loss is now given by the area de0K*. The value of the improved geologic map information is the gain in consumer surplus (the reduction in the welfare loss) shown as the area cbde in figure II–2.

Consider now the case in which the regulator sets the standards at K^{++} (this is overregulation compared with the social optimal level of K^{*}). The welfare loss associated with this amount of overregulation is the area if0K^{*}. With the improved information, the regulator reduces the number of cells restricted to K^{+}. The gain from this information is the area fihg.

The role of the improved geologic map information in a regulatory decision process can be shown explicitly. At any geologic map scale, there is a lower limit to the resolution of geologic attributes and hence a minimum cell size in a rectangular grid. In this demonstration, we assume that geologic maps at 1:500,000 and 1:100,000 scales have minimum cell sizes of 1 km × 1 km and 250 m × 250 m, respectively.[7] In the case of the 1:500,000-scale geologic map, it is assumed that the geologic attribute has one measurement per 1-km × 1-km cell, while at the 1:100,000 scale, the attribute is assumed to have 16 measurements covering the same area. Figure II–3 illustrates the difference between the size of a cell and the delineation of a geologic attribute at the two map scales. In figure II–3*A*, the attribute takes on one value (an average of the attribute over the area) while in figure II–3*B*, the attribute has 16 discrete observations for the 1-km × 1-km cell. The implication of applying a regulatory standard can be explained using an example.

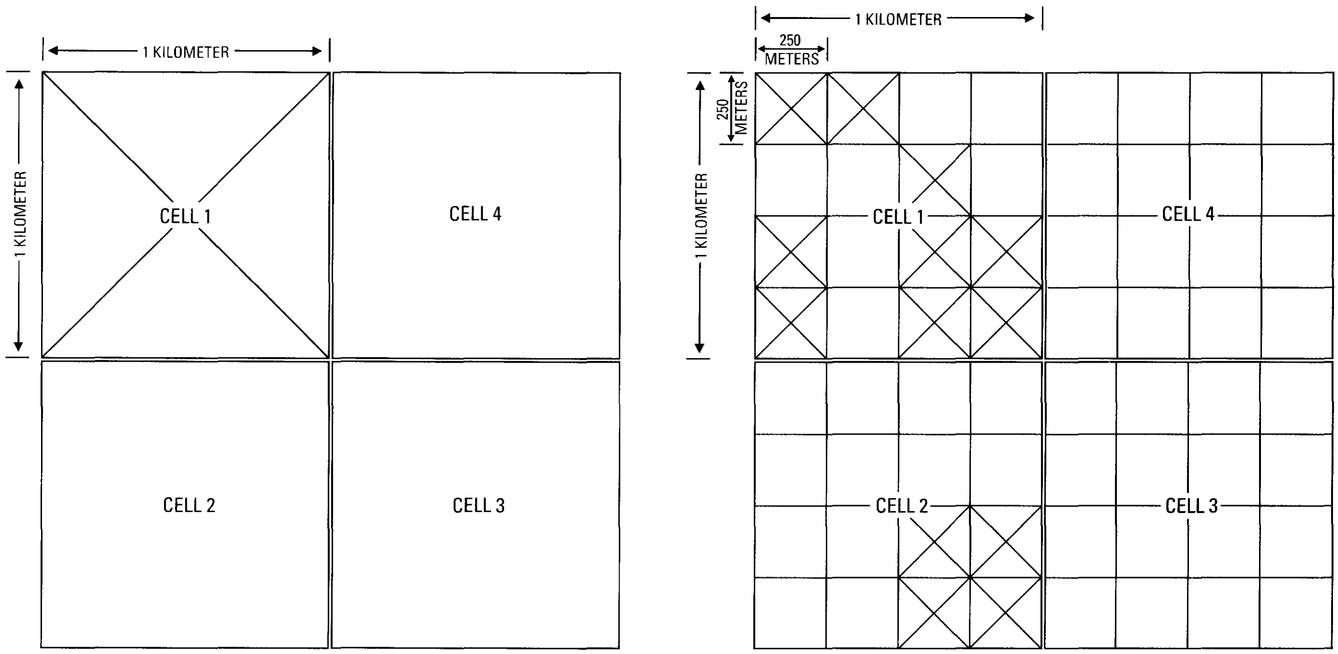
Suppose a regulator is inclined to permit a land use unless geologic information in cell k suggests that an unacceptable adverse environmental change could occur. Figure II–3 depicts possible combinations of acceptable and unacceptable cells under two distinct levels of information. In comparing the possible outcomes for the two grids, we will make the assumption that if any part of a 1-km × 1-km cell is considered unacceptable and, therefore, is restricted, then the whole 1-km × 1-km area is restricted.[8] There are four possible outcomes:

Outcome 1: The cell *is* restricted if the earlier geologic map is used and *is* restricted if the improved geologic map is used.

[6] Henceforth, we shall refer to parcels of land as "k" rectangular cells in an equal-area grid to conform with the empirical work to be presented in this chapter.

[7] Grid sizes are selected by considering limitations in geologic map data accuracy and in digital data-base size; too small a grid size results in unmanageable file sizes, whereas larger grid sizes result in excessive averaging, or smoothing, of the geologic data. For the improved geologic map (1:100,000 scale), the minimum grid size is dictated by the 60-m spatial resolution of the geologic contacts for this map. However, a grid of this dimension would yield nearly 146,000 cells, which was considered an unworkable number of cells for this application. Therefore, a somewhat larger cell size (250 m) has been selected; in most cells only one geologic unit is represented, with a file containing 8,671 cells. To project a grid cell size for the existing geologic map (1:500,000 scale) would, based on map scales alone, increase the cell size by a factor of five, to 1.25 km. An even larger cell size might be warranted on the basis of the fact that geologic information on this geologic map was not gathered with the same level of detail as on the improved geologic map. However, we have chosen a more conservative approach for the existing geologic map by selecting a cell size of 1 km.

[8] This is a simplifying assumption only. Relaxation of the assumption would not affect our argument or the resulting empirical estimation.



A. 1963 MAP

B. 1992 MAP

Figure II–3. Comparison of the size of a grid cell for the 1:500,000-scale 1963 map (Milici and others, 1963) and the 1:100,000-scale 1992 map (Burton and others, 1992) and the delineation of a geologic attribute at the two geologic map scales. In *A*, the attribute takes one value for the 1-km × 1-km cell. In *B*, the attribute has 16 observations for the same 1-km × 1-km cell. In both *A* and *B*, a cell with an × in it is deemed unacceptable.

Outcome 2: The cell *is not* restricted if the earlier geologic map is used and *is* restricted if the improved geologic map is used.

Outcome 3: The cell *is* restricted if the earlier geologic map is used and the cell *is not* restricted if the improved geologic map is used.

Outcome 4: The cell *is not* restricted if the earlier geologic map is used and *is not* restricted if the improved geologic map is used.

Of specific interest is outcome 2. Cells would not be restricted if the earlier, 1:500,000-scale geologic map (1-km × 1-km grid) is used but would be restricted if the improved 1:100,000-scale geologic map (250-m × 250-m grid) is used. The higher resolution of the 1:100,000-scale geologic map information prevents a certain land use where, given the additional detail of the geologic map information, it should not be allowed. If only the earlier, less-detailed information were available, this would represent the case of underregulation and a level of safety below the optimal level as depicted in figure II–2. Outcome 3 represents the case of overregulation in figure II–2. On the basis of the earlier map information, a land use is not allowed; with the addition of improved geologic map information, the land use would be allowed.

FRAMEWORK FOR EMPIRICAL ANALYSIS

Study Area and Background

The model is implemented in a demonstration study in Loudoun County, Virginia (fig. II–4). To show the diverse nature, use, and value of geologic map information, we apply the model in two different ways: in locating a waste disposal facility and in locating a new interstate-type highway route.[9] In considering these two case studies, we begin with the perspective that the value of geologic map information is the sole issue to be evaluated. We do not address the net benefits of the projects themselves. In order to estimate the benefits of an improved geologic map relative to existing geologic map information, we use a benefit-cost framework to evaluate the information content on both the old and the new geologic maps.

The Loudoun County population, commercial base, and road network are distributed in a manner that reflects the underlying geologic framework. The western portion of

[9] The 1963 geologic map has been used in a number of ways in Loudoun County and elsewhere in Virginia. Geologic map information contained in the 1963 Geologic Map of Virginia has limited application in a decisionmaking environment. Two documented applications of this geologic map have been as a teaching tool for the geologic framework of Virginia and for the general distribution of rock units that are potential sources for building stone, aggregate, or road metal.

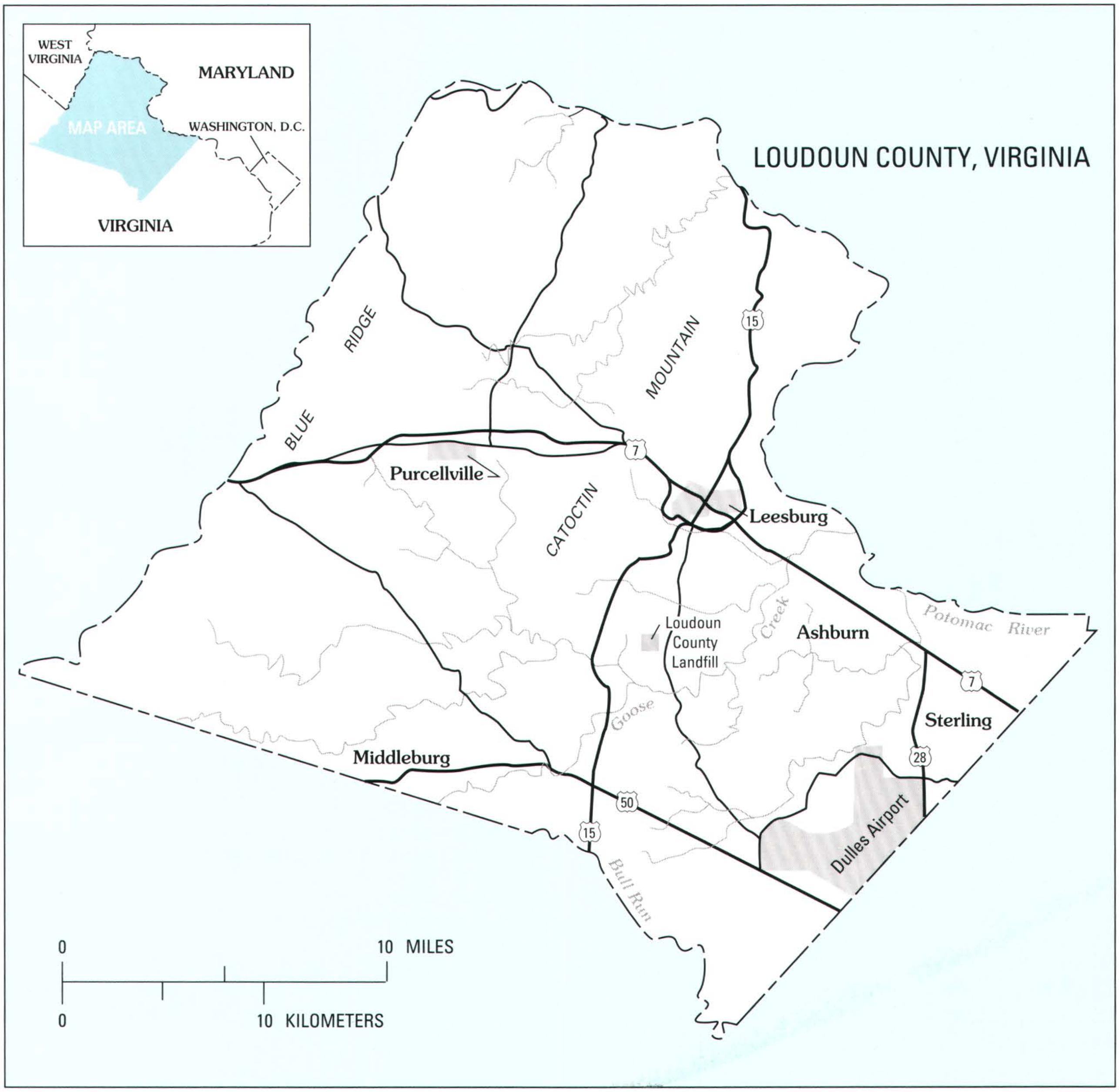
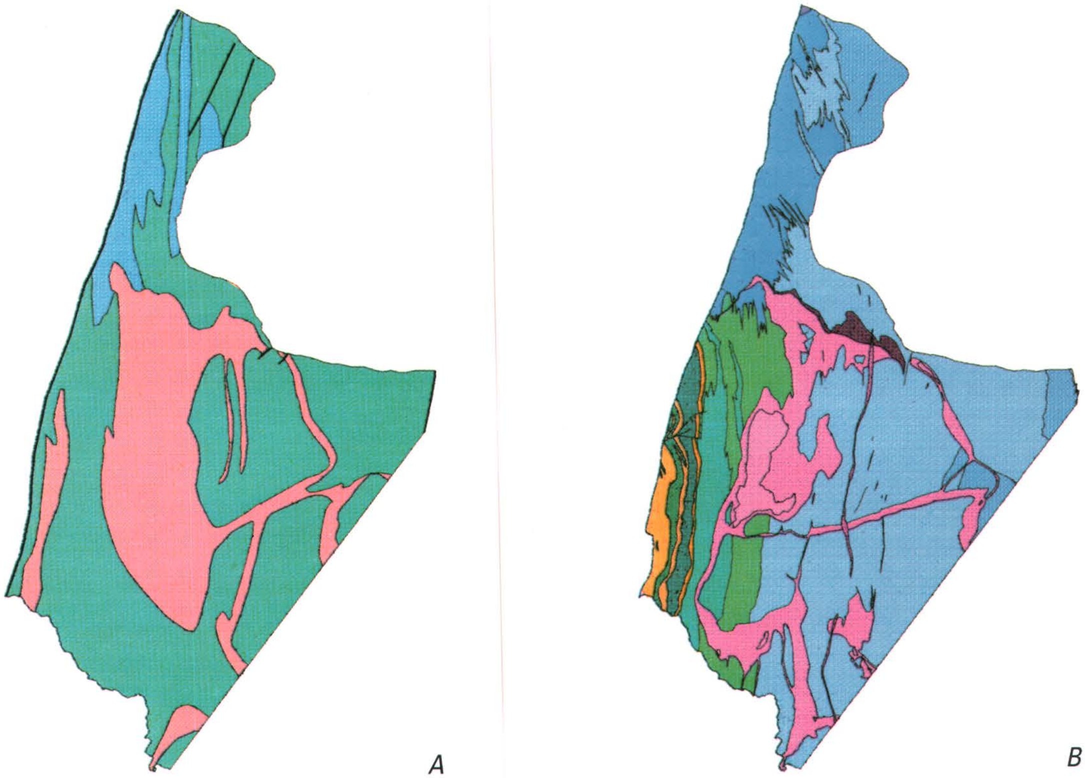


Figure II–4. Location map of Loudoun County, Virginia, showing selected geographic and cultural features.

the county (west of U.S. 15) is underlain by a complex group of igneous and metasedimentary rocks of the Blue Ridge province. East of the U.S. 15 corridor, the county plan has delineated large tracts of land for intensive regional growth. These cells are underlain by part of a Mesozoic basin filled with a sedimentary sequence of conglomerates, red siltstones, claystones, and sandstones that are faulted and interlayered with massive basalt or intruded by diabase dikes and sills. This geologic setting provides opportunities for the development of ground-water well fields, construction of public and private waste facilities, and extraction of construction materials. Given the location of the current landfill and the proposal for a Washington Bypass in the same (eastern) part of Loudoun County, the part of the county underlain by rocks of the Mesozoic basin was selected as the study area.

The Land Use Decisions

The net benefits of improved geologic map information are determined by comparing the land use decisions that would be made when using two geologic maps of the same area that are different in scale and vintage (fig. II–5). The existing geologic map information is from the 1963



A B

Figure II–5. Geologic maps of eastern Loudoun County, Virginia. *A*, Part of the 1963 Geologic Map of Virginia (Milici and others, 1963). Green = sedimentary rocks (sandstone and shale undivided), pink = igneous rocks (diabase and gabbro undivided), and blue = conglomerate (a coarse-grained sedimentary rock). *B*, Part of the preliminary version of the new USGS Geologic Map of Loudoun County, Virginia (Burton and others, 1992). Greens and blues = sedimentary rocks (sandstones, siltstones, and conglomerates), pinks and orange = diabase and basalt rock units, and darkest blue = limestone conglomerate of particular importance to this study.

Geologic Map of Virginia compiled and published at 1:500,000 scale (Milici and others, 1963). The improved geologic map information is a preliminary version of the USGS Geologic Map of Loudoun County, Virginia, which was compiled at 1:100,000 scale (Burton and others, 1992). For purposes of demonstration and analysis, the eastern Loudoun County portion of each geologic map was converted to digital format in a geographic information system (GIS). GIS relational data-base techniques were required for handling and formatting the data for statistical and spatial analyses.

The 1963 geologic map of Virginia shows the *general* distribution of *three* lithologic units in eastern Loudoun County (fig. II–5*A*). These lithologic units and the boundaries (contacts) between them are generally located in many instances only to the nearest 1.5 to 2 km. The spatial distribution of rock units was derived by extrapolation from previously published maps and reports. Because there are no onsite observations, we assume a uniform distribution for describing the geologic attributes of a cell when regulatory standards are applied.

The preliminary version of the new USGS Geologic Map of Loudoun County, Virginia, shows the *specific* distribution of *sixteen* lithologic units in the eastern part of the county (fig. II–5*B*). (As stated in the Introduction, some of the new map's rock units are not discernible here (fig. 5*B*) because the subtle color changes between rock units are difficult to reproduce.) The sixteen lithologic units and the contacts between them are located with an average spatial resolution of about 60 m. The observational data base for the map contains, on average, at least one actual onsite observation per cell. As such, given the existence of on-site observations and systematic sampling, we assume a normal distribution for describing the geologic attributes in a cell when regulatory standards are applied.

We used the information on the two geologic maps to derive some basic geologic attributes that bear on our applications. The ground-water yield (in gallons per minute), a measure based in part on rock permeability, is estimated for each rock unit on the geologic map. Information on yield for the rock types came from Albert Froelich and Ronald Parker (USGS, personal commun., 1991) and was supplemented by information in Laczniak and Zenone (1985). For faulted and intensely fractured areas, the value of the ground-water yield is doubled on the basis that these features serve to markedly increase the rate of water flow. Also, the shear strength of each rock unit on the geologic map, a measure of resistance to slope failure, is calculated; standard values and information in Froelich (1985) and Leavy and others (1983) were used. **These two geologic-map-based attributes are only a subset of the information that would be necessary to actually conduct these two land use analyses.** However, these data are pertinent to the analyses and can be applied when using both geologic maps. If the approach developed in this study were to be incorporated into an actual regulatory process rather than a demonstration, more precise measures of, for example, water migration through the various rock units would be obtained and used.

To treat the geologic map data statistically, the geologic maps of eastern Loudoun County were intersected in the computer with a grid of 1-km × 1-km cells for the 1:500,000-scale (existing) map and a grid of 250-m × 250-m cells for the 1:100,000-scale improved map. For the 1:500,000-scale map, there are 605 1-km × 1-km cells, while for the 1:100,000-scale map, there are 8,671 250-m × 250-m cells. For each cell, an area-weighted average yield was computed from the average yields of geologic map units intersected by the cell. In the same manner, area-weighted average shear strengths were computed. Census block data of the number of dwelling units from the TIGER files of the 1990 U.S. Census were intersected with the cells. A 1990 census block commonly is larger than one 250-m cell. The proportion of each census block in a cell forms the basis for the calculation of the number of dwelling units per cell. Figure II–6 shows the dwelling density per cell. In addition, for each cell, the average and maximum topographic slope also was computed, and the presence of faulting, flood plains, municipal wells, airport-exclusion areas, and geologic map units prone to sinkhole development was recorded.

Central to our analysis of the net benefits of geologic map information is the demonstration that the two geologic maps of the same area represent distinct information that is statistically different. From the previous discussion, we know that the probability of the value of a particular geologic attribute in cell k is randomly distributed with a mean and a variance. Figures II–7 and II–8 contain the uniform and normal distributions for average ground-water yield and shear strength, respectively. We argue that when a newer vintage and larger scale (more detailed) geologic map is available, the geologic condition in any map location is more precisely known. This is fundamental to our analysis and is a testable hypothesis:

H_o: The geologic information content of both geologic maps is the same.

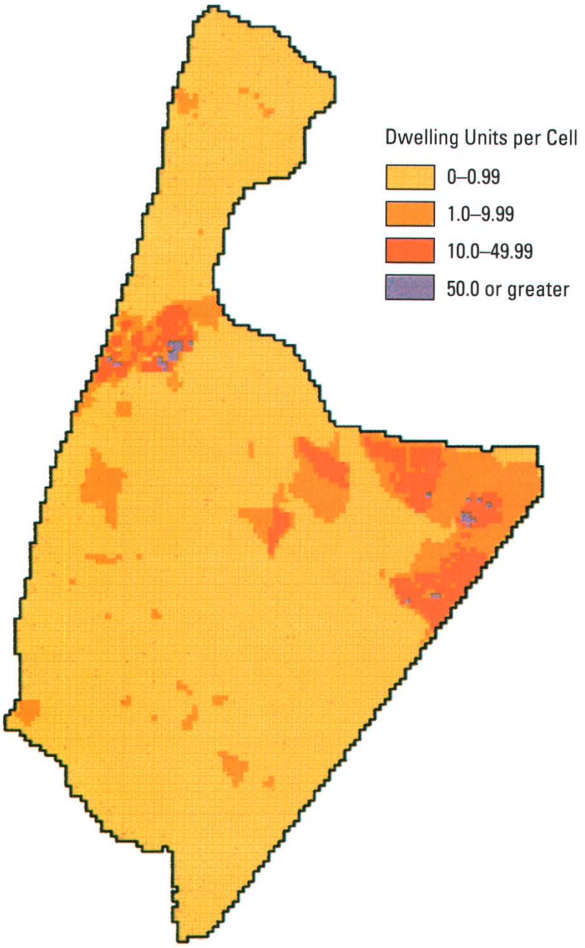


Figure II–6. Dwelling density per 250-m grid cell in eastern Loudoun County, Virginia, based on 1990 U.S. Census data.

If the information in the geologic maps is statistically identical, then the value of the new geologic map information is zero, by definition. This hypothesis can be tested by using non-parametric statistical tests such as the Mann-Whitney test for the difference between means and the squared ranks test for equal variances (Conover, 1980). These non-parametric statistical tests are conducted to determine whether the two geologic maps come from the same statistical population.[10]

We tested for a statistical difference between the geologic maps, using the Mann-Whitney test (comparison of the means, μ's, of the geologic attributes for all cells on both maps; in other words, does $\mu_{100} = \mu_{500}$?). The test is

[10] It is not hard to imagine geologic maps that are fundamentally the same. For example, if a geologic map is updated to a minor extent, a statistical comparison of the original and the updated version might show that the maps are essentially the same and thus would be inappropriate for a demonstration such as we have undertaken here.

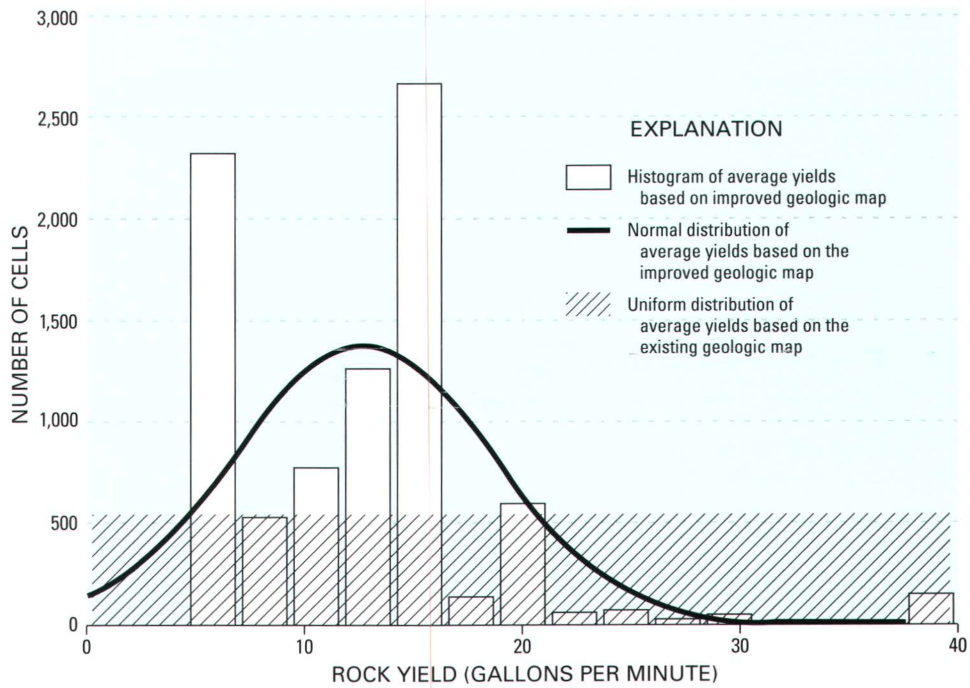


Figure II–7. Frequency distributions for average ground-water yields based on the two different geologic maps.

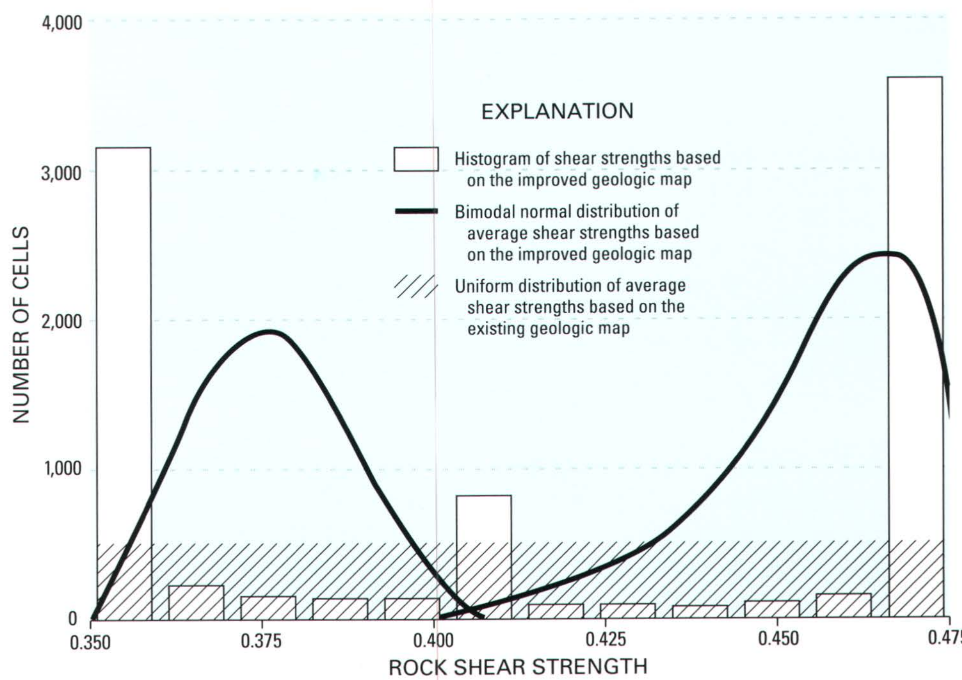


Figure II–8. Frequency distributions for average shear strengths of geologic materials based on the two different geologic maps.

significant at greater than the 99-percent confidence level ($T = 67.22$ for a two-tailed test) (see Conover, 1980); this means that $\mu_{100} \neq \mu_{500}$ and that the rock units on the two geologic maps are statistically different. We also conducted a non-parametric test for equal variances, comparing the variances (σ^2's) of the geologic attributes for all cells on

Each implementation protocol is applied to determine the acceptability or unacceptability of a cell in the economic evaluation. This is referred to as a zero/one decision setting; the cell either passes or fails the standard. In other words, the threshold screen states that there is a geologic characteristic of a cell that exceeds the regulated standard and that we are 95 percent confident of the value of that characteristic.

Step 2: For each cell in the study area, a probability of loss, $P(L_k)$, is estimated as a function of the geologic attribute of the cell.[12] For the cells identified in step 1, these probability values become the basis for estimating expected losses avoided in step 4.

The probability of loss is estimated in equation II–2 for each land use.

$$P(L_k) = P(H_k|g_k) = f(g_k, V_k) \qquad \text{(II–2)}$$

This conditional probability is a qualitative choice regression where the estimate of the hazard is based on geologic-map-based attributes such as average yield (a surrogate for rock permeability) or shear strength (a resistant force to slope failure).

Step 3: The appropriate monetary value in each cell for each map is estimated. This value, L_k, represents the property at risk.

Monetary measures for property values are developed from 1990 Census data in the demonstration for the waste facility siting, and measures for mitigation costs are developed from an engineering cost estimate in the highway slope-failure application.

Step 4: For *each cell identified* in step 1, the expected loss avoided (the savings), $E(L_a)_k$, is estimated in equation II–3 as the product of the probability of a loss (eq. II–2, step 2) and the monetary value of the loss (step 3) in cell k:

$$E(L_a)_k = P(L_k)L_k \qquad \text{(II–3)}$$

Step 5: The benefit of the improved geologic map information is calculated as the difference in expected loss avoided between the two geologic maps.

This is the benefit of the new geologic map information as defined by the regulatory standards. If more geologic characteristics were included and (or) the standards were changed, variations in the benefits would be likely.

[12] Varnes (1974) argues that a given geologic map is not necessarily suitable for all purposes. Thus, we include the type of land use subscript in the recognition that different maps will be required for different land uses.

Step 6: The marginal cost of the improved geologic map is determined.[13] The marginal cost of the geologic map information is the total cost (capital and labor) of producing a new geologic map, including the time value of money (an opportunity cost of capital), C.

Step 7: The net benefits of the new geologic map information are calculated as the difference between the benefits of the new geologic map information and the marginal cost of producing the new geologic map.

We apply equation II–4 to estimate the net benefits of improved geologic map information for each land use application of the geologic map.

$$NB_{v_2} = \sum_j [E(L_a)_{j_{v_2}} - E(L_a)_{j_{v_1}}] - C_{v_2} \quad j=1, \ldots, J \qquad \text{(II–4)}$$

where NB_{v_2} is the marginal net benefits (expected loss avoided) derived by using the new, more detailed (1:100,000 scale) versus the 1963 vintage geologic map (v_1) (1:500,000 scale), j is the land use, and C_{v_2} is the cost of producing the new geologic map. As discussed earlier, we assume the new geologic map "builds" upon the knowledge base of the existing geologic map.[14]

THE LOUDOUN COUNTY, VIRGINIA, LANDFILL SITING DEMONSTRATION STUDY

The Regulatory Standards

Leakage of hazardous materials from waste facilities and landfills potentially poses a threat to the Nation's water supply. Substantial costs are incurred in reducing the risk of water contamination (Raucher, 1986). There is a direct correlation between the rate of transport of dissolved and suspended contaminants away from a site and the permeability, faulting, and fracturing of the surrounding geologic materials. Changes in subsurface conditions that reflect local variations in the geology near a disposal facility can affect the rate of transport of contaminants and the extent of contamination. Avoidance of irreversible or irreplaceable losses of ground water and contamination of surface-water supplies requires engineering solutions for mitigation ranging from construction of lined sites with buffer zones to highly sophisticated integrated engineering and monitoring techniques for remedial action.

An engineering analysis prepared by HDR Engineering (1989) evaluated all areas of Loudoun County for suitable landfill sites. Recommendations to the county

[13] Because we are interested in the value of the new geologic information, we do not need the cost of the old map.

[14] Discounting issues are not explicitly considered. If one assumes a discount rate of 10 percent and an inflation rate of 10 percent, a formal annualizing and discounting step is not necessary. Because this is a demonstration, we have made these assumptions.

Table II–1. Hypothetical regulations applied to cells in the study area

Land use	Impact	Protocol[1]	Screen (threshold standard)
Waste disposal facility	Contamination	Rock permeability	
		Sink holes	Restrict when limestone conglomerate is present.
		Highly permeable rock units	Restrict when average yield is ≥15 gal/min.
		Faulting and associated intense fracturing	Restrict when faulting and associated intense fracturing are present.
Transportation corridor	Slope failure due to construction	Rock shear strength	Mitigate when rock shear strength <0.49.

[1] Protocols are defined as geologic attributes used in implementing regulations.

each map. For the newer map, variance should be reduced compared to the older map ($\sigma^2_{100} < \sigma^2_{500}$). Using the distributions in figure 11–7 for the average yield attribute, the test finds a significant variance at the 99-percent confidence level ($T = 2.63$ for a one-tailed test), and using the distributions in figure II–8 for the bimodal shear strength attribute, the test finds there is also a significant difference in the variances at the 99-percent confidence level ($T = 4.23$ and $T = 2.65$ for one-tailed tests[11]). These tests suggest that the geologic characteristics represented in the two maps are statistically different and do not come from the same population. Thus, we are able to derive estimates of the value of the improved geologic map relative to the existing geologic map of the same area.

The Regulatory Standards

Current regulatory standards regarding waste site location typically are represented in terms of demographic and cultural characteristics, and there are no current highway construction regulations that incorporate geologic criteria. Leakage from waste facilities and landfills threatens the Nation's water supply. Variations in regional geology near such a facility affect the rate of transport of contaminants and the extent of contamination. Also, the costs of constructing and operating transportation corridors are influenced by regional variations in near-surface geology and topography. In addition, a transportation corridor can have an impact on the regional geology by contributing to slope failure, excessive runoff, and altered drainage patterns.

[11] The shear strength distribution for the eastern portion of the recent, 1:100,000-scale Geologic Map of Loudoun County, Virginia, is bimodal. Two normal distributions for the shear strength variable are, by definition, independent of each other (Agterberg, 1974). The test for variances was run for both samples and compared to the uniform distribution for the eastern Loudoun County portion of the earlier, 1:500,000-scale Geologic Map of Virginia. The sample is split at a shear strength of 0.415.

Table II–2. Variables used in empirical demonstration of value of geologic map information

Variable	Definition
$\bar{g}_k$	Geologic attribute of rock materials in cell k such as faulting, permeability, and shear strength of rock materials.
L_k	Monetary loss in cell k.
$P(L_k)$	Probability of a loss L_k in cell k.
R_j	Safety standard for land use j, defined as restrictions on allowed land uses or requirements for a given land use, for example, building codes.
$E(L_a)_k$	Expected loss avoided for cell k.
$P(\bar{g}_k)$	Expected value of a geologic attribute in cell k; k = 1, . . ., k.
$E(L_a)_j$	Expected loss avoided for land use j.
H_k	Hazard in cell k.
V_k	Additional physical attributes in cell k.

An example of hypothetical regulations that are based solely on geologic characteristics is presented in table II–1 for these two land uses. The regulations consist of one or more implementation protocols relating to geologic attributes (for example, for the waste disposal facility's regulation, we apply three rock permeability protocols as shown in table II–1). For each protocol, a specific action, or threshold standard, is given; this is referred to as a screen. Our protocols are not meant to be exhaustive in the existing regulatory environment, only illustrative.

The Method

In table II–2 we provide definitions of the variables used in this analysis. Implementation of our demonstration studies requires seven steps that are outlined below:

Step 1: For each cell on each map, the value of the geologic attribute, g_k, at the 95-percent confidence level (2σ) must have a finite value (greater than zero). If the cell meets or exceeds this condition, the value of $\bar{g}_k$ is compared to the regulatory standard.

about suitable sites are based on the size of the landfill required for the projected quantity of waste through the year 2015, which is based on the population growth rate in Loudoun County. According to the HDR Engineering report, in the 20-year period from 1995 to 2015, Loudoun County will generate at least 3.3 million tons of solid waste for a population of 246,000 (HDR Engineering, 1989, p. 2–5).[15] The disposal of this quantity of waste would require a landfill having a capacity of over 9 million cubic yards.[16] Depending on the actual parcel attributes, the total size of a landfill to accommodate the disposal needs of the county for a 20-year period starting around 1995 probably would have to be at least 600 acres (about 2.5 km^2) to adequately buffer the site and to mitigate community impacts.

According to conventional practice, the HDR study used current regulations based on demographic, cultural, and scientific criteria to identify potential landfill sites. To more completely illustrate the effects of these regulations, we applied the following parts of the Virginia standards to identify areas that could be restricted from landfill development:

1. Landfills shall not be sited in geologically unstable areas where inadequate foundation support for structural components of the landfill exists. Factors to be considered when determining unstable areas shall include:
   a. Presence of sinkholes within the disposal area.[17]
2. No sanitary landfill disposal area shall extend closer than:[18]
   a. 10,000 feet of any airport runway used for turbojet aircraft or 5,000 feet of any airport runway used by only piston type aircraft, unless the facility operation does not pose a bird hazard to aircraft;
   b. 100 feet of any regularly flowing surface water body or river;
   c. 500 feet of any well, spring, or other ground-water source of drinking water.

These regulatory screens are implemented and intersected with a 1-km × 1-km grid as shown in figure II–9*A* for the eastern Loudoun County study area as background information to indicate the extent of the restrictions of the current regulatory standard. Application of the current Virginia regulations to the area leaves 162 1-km × 1-km cells still available for a waste disposal facility (fig. II–9*B*). Although commonly used, this approach to code enforcement considers geologic map information in but a cursory manner.

However, in the following discussion, we describe an expanded role for geologic map information in the decision-making process. In contrast to the current approach of promulgating environmental regulations that use demographic and cultural protocols (alternative policies for code enforcement) and scientific data, our approach uses *physical measures derived from geologic map information* as the initial basis for regulatory decisions.

Because this analysis is a demonstration that estimates the value of geologic maps, we do not consider all of the possible protocols. For this study, threshold standards based upon the application of rule 1 above (rule 2d of the current Virginia regulations), and additional hypothetical rules based on geologic attributes, are implemented. Thus, all cells within the Loudoun study area are considered acceptable unless they are determined not to satisfy the threshold standard for a particular geologic attribute.

Empirical Implementation

In what follows, we implement the model described above. For the landfill siting application, we assume a tendency to underregulate.

> Step 1: For each cell on each geologic map, the value of a geologic attribute related to rock permeability (for example, average yield[19]) is compared to the regulatory screens in table II–1 to identify those cells potentially suitable for siting a waste disposal facility.

The suitability test for a cell as a potential landfill site based on geologic attributes is a two-part procedure:

1. For any cell to be considered unsuitable, the value of the average yield, $\bar{g}_k$, at the 95-percent confidence level

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[15] Population projections based on Metropolitan Council of Governments Round 4 Cooperative Forecast, November 4, 1987, using the Intermediate Level of Anticipated Growth. Annual waste quantity projections are based on a per capita waste generation rate of 5 lb per person per day. This figure is consistent with actual data for 1989.

[16] The entire county was screened by HDR; they used 21 criteria pertaining to the landfill regulations and to technical issues that usually are addressed in permit hearings. One of the criteria used in the decisionmaking process is the "Constraints imposed by physical characteristics pertaining to permitting" (HDR, 1989, p. 3–2). This specific criterion is the only geologic input in the engineering study. As a result of this analysis, less than 15 percent of the total land area of the county appears to be capable of surviving the permit process. Within the reduced land area, three potential sites were selected for further examination. The sites were selected because of their physical setting and size, potential community impacts, traffic impacts, and other waste transportation issues. These three locations were designated "Primary Search Areas" and all other areas of the county were excluded from further consideration.

[17] We used the occurrence of the limestone conglomerate map unit as a surrogate for this protocol because sinkhole (karst)-forming processes affect this unit.

[18] The following rule was applied to show the extent of the current restrictions. This specific screen is for demonstration purposes and was not used in the estimation of the benefits of geologic map information.

[19] The definition of average yield has two parts: (1) we calculate a ground-water yield in gallons per minute for a specific rock unit on each map and (2) for each grid cell, an area-weighted average yield is calculated from the rock units contained in the cell.

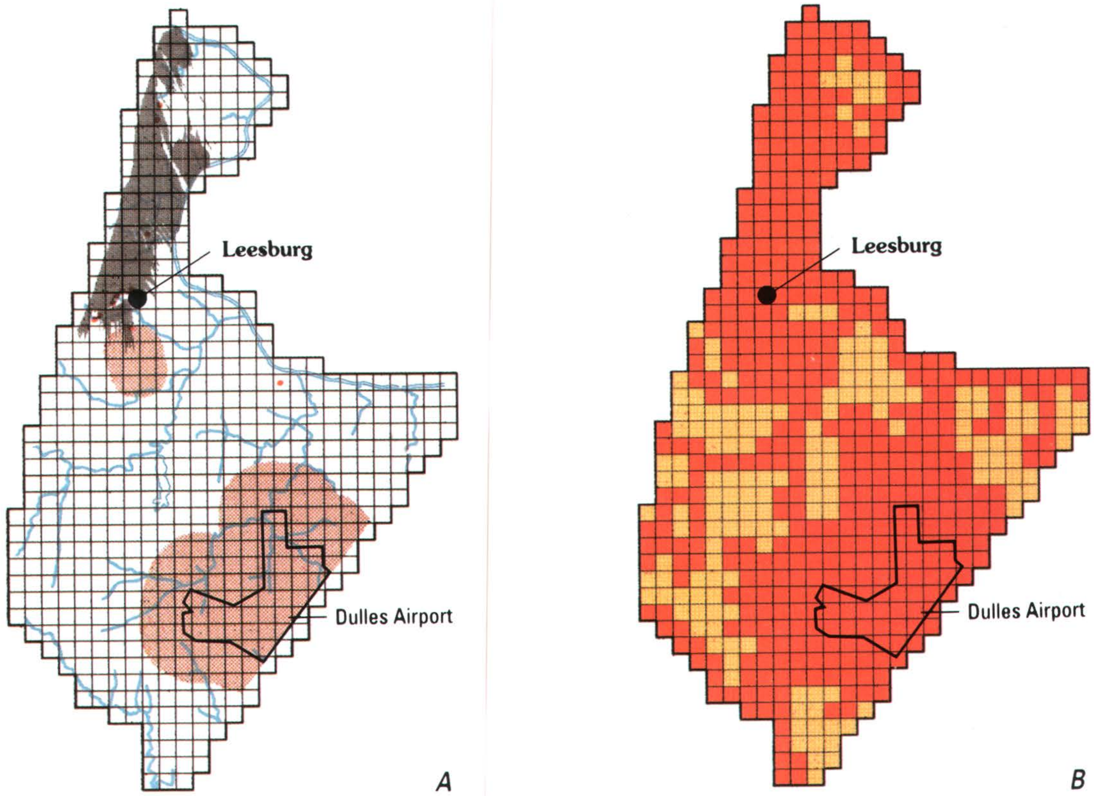

Figure II–9. Areas in eastern Loudoun County, Virginia, excluded from consideration for possible waste disposal facilities on the basis of current State regulations (1-km grids). *A*, Regulatory screens. Gray = area susceptible to presence of sinkholes, brown = airport exclusion areas, red dots = municipal water wells, and blue = streams. *B*, Excluded (red) and nonexcluded (yellow) cells.

(2σ) must be a finite value (greater than zero). For the cells that meet this condition, the regulatory standard is applied.

2. The regulatory standard consists of three screens:
   a. the cell is unsuitable if it contains the limestone conglomerate geologic map unit (a highly permeable material prone to sinkhole development and currently used as a restriction under Virginia State regulations for siting waste disposal facilities);
   b. the cell is unsuitable if it has an average yield equal to or greater than 15 gallons per minute (a relatively high value for rock units in the study area); and
   c. the cell is unsuitable if faults and associated intense fracturing of rock units are present (generally increases the ground-water yield).

A simple example using equation II–1 ($\bar{g}_k$ represents the average yield in cell k) illustrates how our model works. Consider the values: $\bar{g}_k$ = 20 gal/min; the regulatory standard for average yield, R_j, =15 gal/min; for the earlier geologic map, v_1, $2\sigma_{v_1}$ = 10 gal/min; and for the improved geologic map, v_2, $2\sigma_{v_2}$ = 4 gal/min. For the earlier geologic map, v_1: $20 - 10 = 10 < 15$, the standard for R_j, so the cell cannot be restricted for locating a waste disposal facility. For the improved geologic map, v_2: $20 - 4 = 16 > 15$, the standard for R_j, so the cell should be restricted from development as a waste disposal site.

Table II–3. Number of cells restricted for waste facility siting

[Outcomes are detailed in the section "The Inclusion of Geologic Map Information in Regulations"]

	1:500,000-scale map (old map)	1:100,000-scale map (new map)	Number of 1-km × 1-km cells
Outcome 1	Restriction	Restriction	61
Outcome 2	No restriction	Restriction	321
Outcome 3	Restriction	No restriction	0
Outcome 4	No restriction	No restriction	223

The results of applying the standards for siting a waste disposal facility for the two geologic maps are listed in table II–3; we assume that a landfill will occupy a 1-km × 1-km cell that, as mentioned earlier, is the lower limit of the geologic resolution of the earlier geologic map. Listed in the left-hand column are the possible outcomes of the

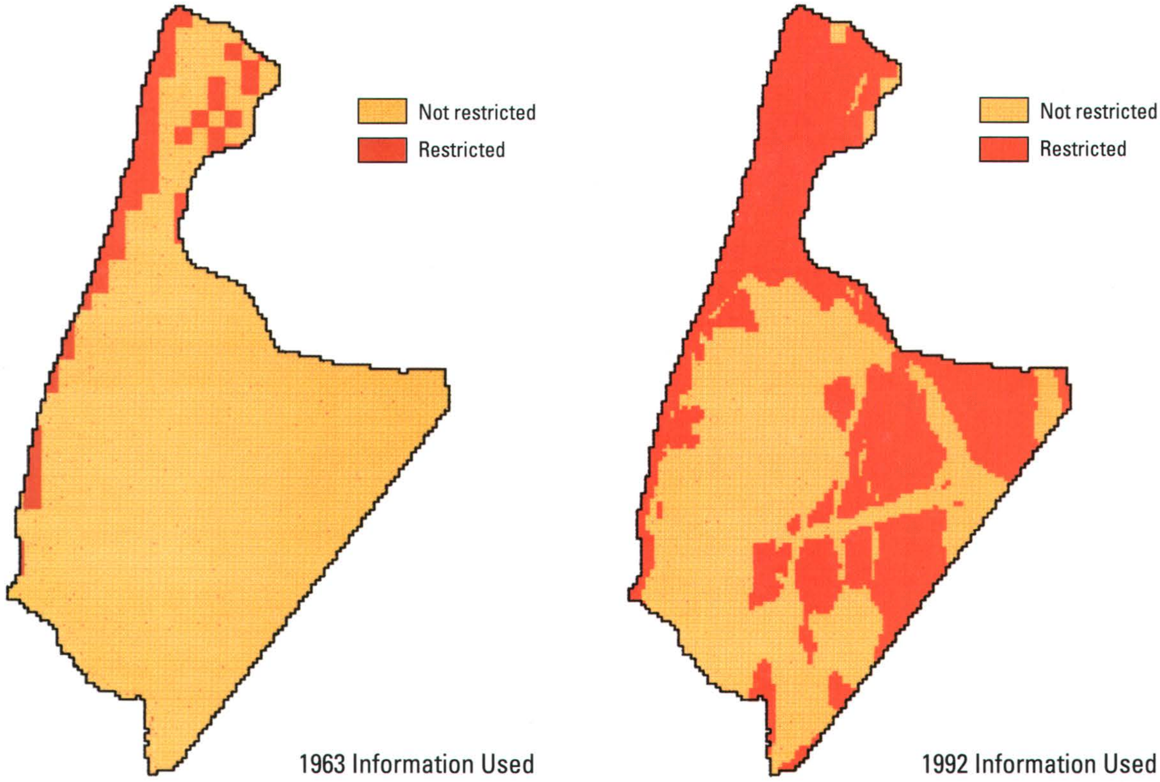

Figure II–10. Spatial distribution of cells in eastern Loudoun County, Virginia, restricted from further consideration as a possible landfill site on the basis of existing (1963) and improved (1992) geologic map information.

process. For instance, outcome 2 represents the case where no cells were restricted when we use the earlier geologic map information but 321 1-km × 1-km areas were restricted when we use the new, more detailed information. Figure II–10 illustrates the spatial distribution of the restricted cells when we use the earlier and the improved geologic map information. This represents the case of underregulation. The improved geologic map information identified areas to be excluded that were not identified with the earlier information. Of note is outcome 3. In this case cells would be restricted when the older information is used but would not be restricted when the improved geologic map information is used. This outcome represents overregulation. Note that no cells fell into this category. As such, it becomes apparent that using the old data results in underregulation, not overregulation.[20]

Step 2: For each cell, a probability of loss $P(L_k)$ is estimated as a function of the geologic attribute of the cell.

For each 250-m × 250-m cell, a conditional probability (log odds) of contamination $P(L_k)$ is estimated by applying equation II–2 as a function of the rock types. The conditional probability of contamination, in equation II–5, is a binary choice logit regression based on the average yield (a surrogate for permeability) of rock materials in locations surrounding sites regulated by the EPA according to the Resource Conservation and Recovery Act and solid waste landfills located in the Mesozoic basin. The estimation of the spatial probability of contamination is:[21]

[20] As indicated in the footnote regarding the HDR study, three primary search areas were identified. One of these is the proposed southward extension of the existing waste site and is within our limited study area. Thus, we ask "are there any cells restricted on the earlier geologic map or the improved geologic map for a 1-km × 1-km area for the landfill extension south of the existing site?" Our investigation indicates that there are no restrictions when the earlier geologic map is used. Of interest, however, is that there are 7 250-m × 250-m cells restricted when the improved geologic map is used. All are based on the implementation protocol of average yield of ground water and the associated screening value. This result supports the conclusion that, in the waste site demonstration, the use of the earlier geologic map leads to underregulation.

[21] Because Loudoun County has only one existing landfill, the probability of contamination is estimated for an analogous geologic terrain, the Mesozoic basin in central New Jersey, where water monitoring data and waste sites are more plentiful. The coefficients from the New Jersey equation are extrapolated to the study area in eastern Loudoun County.

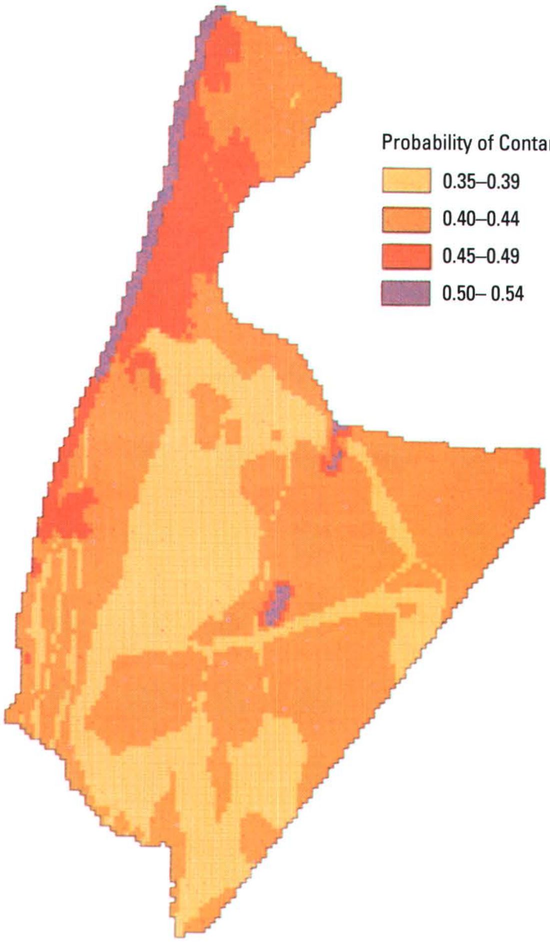

Figure II–11. Conditional probability of contamination of rock materials in eastern Loudoun County, Virginia, determined on the basis of their permeability. Cell size is 250 m × 250 m.

$$\ln\left(\frac{P(L_k)}{1-P(L_k)}\right)=-1.23+0.37(AVGYLD_k) \qquad \text{(II–5)}$$

where $P(L_k)$ comprises contamination incidence H_k ("yes" or "no") given an average yield $(\bar{g}_k)$ = 1 if ground water at the waste disposal site exceeds the state primary drinking water standard for any constituent, and $P(L_k) = 0$, otherwise. *AVGYLD* is equal to the area-weighted average yield of rock units. The *t*-statistic is −1.41 for the constant and 1.95 for the average yield coefficient, $R^2 = 0.1$, and the number of observations $(n) = 83$.

The conditional probability of contamination ranges from 0.37 to 0.53, has a mean of 0.42, and a standard deviation of 0.03 for the 8,671 250-m × 250-m cells on the 1:100,000-scale geologic map (fig. II–11).

Step 3: The monetary value of the property (L_k) in each cell for each map is estimated.

In this study, only property value losses are estimated. We do not attempt to quantify the expected value of health effects or economic disruption that would ensue from a contamination incident in the county. In pursuing this approach, the private benefits associated with residences in the case of the waste site example are captured. However, other private benefits are ignored as well as the public benefits. We acknowledge that this procedure contributes to a bias. However, we know of no practical method for a study of this scale and effort that would allow an alternative assumption. Further, given that we are only considering some of the uses of geologic maps for a region and hence only some of the private benefits, the overall benefit bias of the study is downward, that is, conservative. This issue is developed further in the concluding section of the chapter where the overall net benefits are considered.

The number of residences by census block were taken from the 1990 U.S. Census to estimate the property-value effects in each cell. A census block commonly includes all or part of several grid cells. To estimate the number of dwellings in a cell, the areal proportion of a census block in that cell was multiplied by the total number of dwelling units in the census block. For cells containing more than one block, these products were summed (see fig. II–6 for a spatial representation). On the basis of recent real estate transactions, an average residence in the eastern part of the county is assigned a value of $150,000. Figure II–12 presents a spatial representation of property value per cell.

Step 4: For *each cell identified* in step 1, the expected loss avoided $E(L_a)_k$ (fig. II–13) is estimated by using equation II–3 as the product of the probability of a loss (eq. II–5) and the monetary value of the loss (total property value) in cell k (step 3).

For each 250-m × 250-m cell, the expected loss avoided from a contaminated waste disposal site is estimated as the product of the probability of contamination (eq. II–2) and the property value in cell k. Combining the spatial distribution of the $E(L_a)$ (fig. II–14) with those cells identified in step 1 (fig. II–10) yields the expected loss avoided for each geologic map.

Step 5: Calculation of the benefit of the improved geologic map information is accomplished by taking the difference in expected loss avoided between the two geologic maps.

On the basis of the assumption that the county will need to proceed with constructing one new waste disposal facility, this analysis is used to estimate the benefits of the improved geologic map information for selecting one site in the study area. The site is assumed to occupy a 1-km^2 area (about 250 acres), which roughly conforms to the proposed sites described in the HDR study (sites selected for future landfills ranged from 302 to 978 acres).

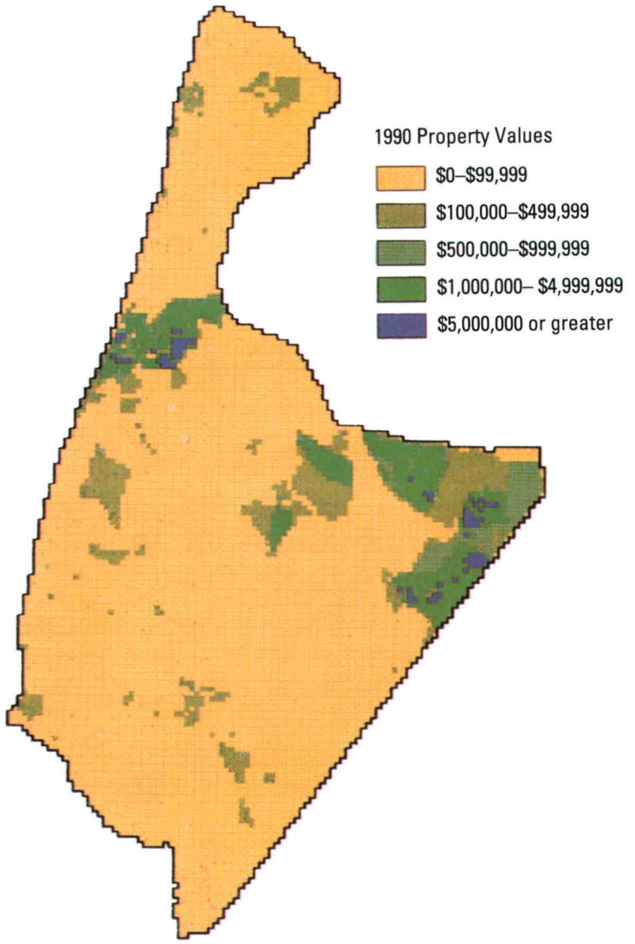

Figure II–12. Spatial distribution of property values, eastern Loudoun County, Virginia.

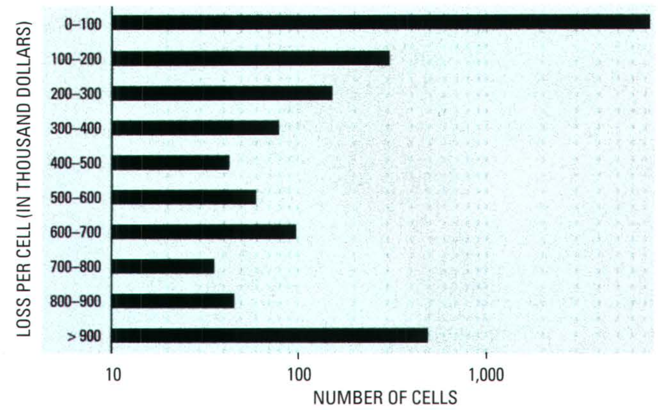

Figure II–13. The expected losses avoided due to landfill contamination for cells in the study area, eastern Loudoun County, Virginia.

Depending on the location of the proposed waste disposal facility, the difference in expected loss avoided, $E(L_a)$, between the two geologic maps ranges from $39,241 per 250-m × 250-m cell to $124,791 per 250-m × 250-m cell. The difference in average expected loss avoided, $E(L_a)_k$, for any cell in the study area is $94,027 per 250-m × 250-m cell.

For a landfill site that requires a 1-km × 1-km area, the average $E(L_a)_k$ is multiplied by 16 (there are 16 250-m × 250-m cells in a 1-km × 1-km area) to estimate the societal value of the improved geologic map in this land use.[22] The 1-km × 1-km areas that would be restricted

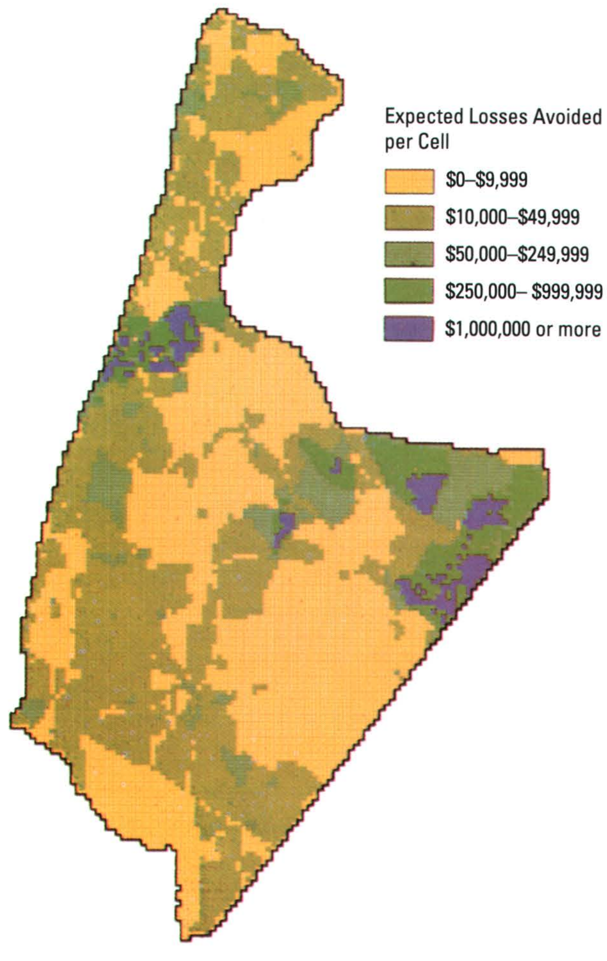

Figure II–14. Spatial distribution of expected losses avoided per cell from a contaminated waste disposal site. Cell size is 250 m × 250 m.

[22] In the study area, there are 321 1-km × 1-km areas that are acceptable for development as a landfill based on applying to the earlier geologic map the implementation protocols that contain at least 1 250-m × 250-m cell that would be restricted when applying the same protocols to the improved geologic map. The existing waste site occupies 147 acres (about 0.6 km^2), or approximately 10 250-m × 250-m cells.

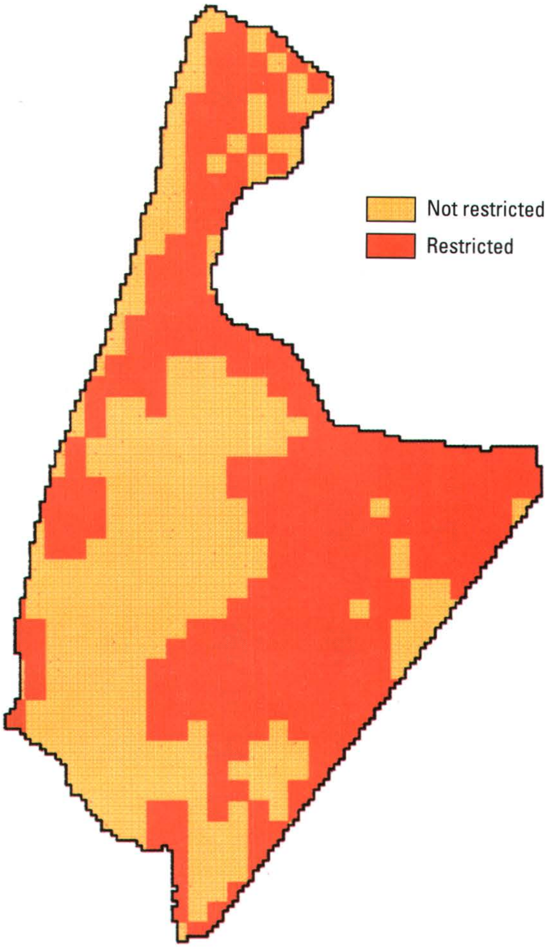

Figure II–15. Areas in eastern Loudoun County, Virginia, that *would* be restricted when the improved geologic map is used but *would not* be restricted when the existing geologic map is used. Cell size is 1 km.

by use of the improved geologic map while not being restricted using the existing map (outcome 2) are shown in figure II–15. The benefit of the improved geologic map in locating a new waste disposal in Loudoun County is approximately $1,500,000.

These geologically based hypothetical regulations, or other regulations more suited to a particular region's geologic setting, could contribute to a comprehensive set of regulations for the siting of waste disposal facilities. We have outlined a method for evaluating geologic risk, including both the probability of a change in physical state and the expected loss avoided from an adverse environmental impact, and for restricting individual cells in the process of selecting landfill sites in a study area. Decisions for the remaining cells can be made on the basis of demographic and cultural screens in conjunction with considerations such as transportation costs.

THE WASHINGTON, D.C., BYPASS ROUTING DEMONSTRATION STUDY

The Regulatory Standards

We consider the development of a new transportation corridor in Loudoun County for a Washington Bypass.[23] According to the Federal Highway Administration, the Washington Bypass is a proposed interstate-type highway that would bypass the Washington, D.C., region, provide additional roadway capacity to the region, improve truck and traffic safety, and provide improved facilities for both through-traffic and local traffic. The action proposed in a published Draft Environmental Impact Statement (DEIS) consists of an Eastern Bypass, a Western Bypass, or both. The jurisdictions affected by the planned bypass are the States of Maryland and Virginia and the cities of Washington, D.C., and Baltimore, Md. Twenty-three counties (or portions of counties) would be affected, including Loudoun County, Virginia. The assumed right-of-way used for the DEIS analysis was located in the center of a corridor 1.3 km wide. The right-of-way assumed for all of the alternatives is 137 m in a new location and 91 m where the facility would be constructed on an existing roadway. The number of lanes and costs will vary by alternative, based on land use and traffic projections and on engineering. All proposed Western Bypass corridors cross the eastern part of Loudoun County. Along the many alternative routes within the bypass corridor in Loudoun County, the length of road varies from 13.2 km to 42.1 km over flat to rolling terrain.

Right-of-way, construction, and maintenance costs for highways are influenced by local variations in near-surface geology and the topography. Engineering practices (the ease of excavating the near-surface geologic materials) along the routes will vary considerably from easy (siltstone) to difficult (diabase and metamorphosed conglomerate). As such, construction costs due to geologic variability are potentially significant. Regardless of the bypass route selected, construction and operation of a Washington Bypass will have short- and long-term impacts on the geology of Loudoun County (U.S. Department of Transportation and others, 1990). Construction activities, which include blasting, land clearing, and soil stockpiling, are short-term effects that include increases in stream siltation and losses of productive soils. Operation of the bypass may cause such potential long-term impacts as slope failure, excessive runoff, and altered drainage patterns.

The specific protocol that we utilized to form the

[23] A Draft Environmental Impact Statement of the Washington Bypass has been prepared by the U.S. Department of Transportation, the Federal Highway Administration (FHWA), the Maryland State Highway Administration, and the Virginia Department of Transportation (U.S. Department of Transportation and others, 1990) as part of an evaluation of a new highway designed to alleviate traffic congestion in the Baltimore-Washington transportation corridor.

basis of a threshold screen is based upon the geologic attribute of rock shear strength.[24] Although slope is also an important consideration, we did not use it to screen cells from further consideration, because slope is independent of the geologic map information. Engineering considerations provide the foundation for the screen. This approach is based on the cut-and-fill requirements for slope stability as described in UBC Chapter 70 (International Conference of Building Officials, 1979) and the construction of retaining walls on both sides of the right-of-way.

Empirical Implementation

We implement the following procedure to estimate the value of the improved geologic map information relative to the existing information in siting a transportation corridor such that expected mitigation costs for slope failures due to construction would be minimized. For this application, we assume that a regulator will be conservative (will have a tendency to overregulate) in his approach to this issue.

With improved geologic map information, better siting decisions can be made (that is, fewer locations along the transportation corridor would be expected to require mitigation for slope failure that has resulted from construction).

> Step 1: For each cell on each geologic map, the value of the geologic attribute, rock shear strength, is compared to the regulatory screen (table II–1) to identify those cells that potentially would require mitigation for slope failures due to construction along a transportation corridor.

The identification of cells potentially requiring mitigation based on geologic attributes is a two-part procedure:

1. For any cell to be considered for mitigation, the value of the average shear strength, $\bar{g}_k$, at the 95-percent confidence level (2σ) must be a finite value (greater than zero). For the cells that meet this condition, the regulatory standard is applied.
2. The regulatory standard consists of one screen: cells that would be expected to require mitigation are those with an average shear strength of less than 0.49 at the 95-percent confidence level (2σ).[25]

A simple example using equation II–1 for the average shear strength attribute, $\bar{g}_k$, illustrates how the model works. Consider the following values: $\bar{g}_k = 0.54$; $R_j = 0.49$; $2\sigma_{v_1} = 0.06$; and $2\sigma_{v_2} = 0.04$. For v_1: $0.54-0.06 = 0.48 < 0.49$, the standard for R_j, so the cell is expected to require mitigation along this section of road. For v_2: $0.54-0.04 = 0.50 > 0.49$, the standard for R_j, so the cell might not require mitigation along this section of road.

Table II–4. Number of cells for each highway construction mitigation outcome

[Outcomes are detailed in the section "The Inclusion of Geologic Map Information in Regulations"]

	1:500,000-scale map (old map)	1:100,000-scale map (new map)	Number of 250-m × 250-m cells
Outcome 1..	Mitigation	Mitigation	3,889
Outcome 2..	No mitigation ..	Mitigation	1,041
Outcome 3..	Mitigation	No mitigation ..	2,237
Outcome 4..	No mitigation ..	No mitigation ..	1,504

The results for the application of step 1 for the two geologic maps are listed in table II–4. Listed in the left column are the possible outcomes of this application. Of particular importance is outcome 3. This is the case where cells would be expected to require mitigation when the earlier geologic map is used but would not be expected to require mitigation when the improved geologic map is used. This outcome represents the situation of overregulation. Note that over 2,000 250-m × 250-m cells are identified in this outcome category, while about 1,000 of these cells are identified in outcome category 2. As such, the case is made for the tendency for overregulation when the earlier (existing) geologic map information is used. Based upon the results in table II–4, figure II–16 is a map of the spatial distribution of the cells that would be expected to require mitigation when using the earlier and the improved geologic map information. By applying improved geologic-map-based information, we can reduce the tendency to overregulate.

> Step 2: For each cell, a probability of loss, $P(L_k)$, is estimated as a function of the geologic attribute for the cell.

The probability of a slope failure as based on equation II–2 is assumed to be a physical process similar to a construction-induced landslide: $P(L_k) = P(H_k \mid \bar{g}_k, V_k)$, where the hazard in this case, H_k, is slope failure due to a roadcut. $P(H_k \mid \bar{g}_k, V_k)$ is estimated as a function of a factor-of-safety variable for failures triggered by new road construction. The probability of a slope failure is based on a binary choice logit regression, wherein the stability of a location changes from a stable to an unstable condition. This equation was estimated for landslides in similar types of terrain in Cincinnati, Ohio (Bernknopf and others, 1988).

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[24] We calculate a shear strength for each specific rock unit on each map. Then for each grid cell, an area-weighted shear strength is calculated from the rock units contained in the cell.

[25] This rule was found to be optimal for a hypothetical evaluation of hillside regulations in Cincinnati, Ohio, to avoid landslides that were construction triggered (see Bernknopf and others, 1988). When geologic map information was added to the hypothetical regulations, there was a significant reduction in the area requiring hillslope mitigation.

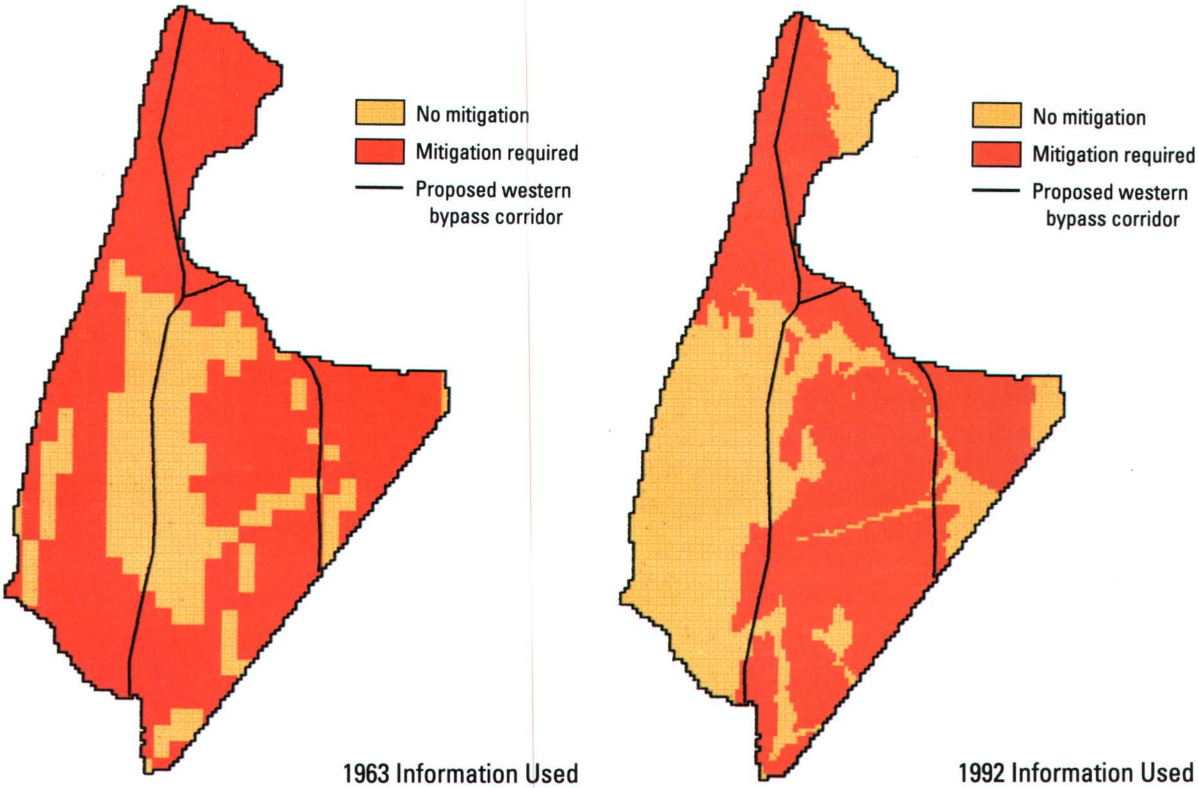

Figure II–16. Spatial distribution of expected slope failures due to road construction, eastern Loudoun County, Virginia, that would require mitigation on the existing and new geologic maps.

The estimate of $P(L_k)$ is:

$$\ln\left(\frac{P(L_k)}{1-P(L_k)}\right)=-0.23-1.45\ln(F_k)+0.72\ln(\tan MS_k)+0.77\ (NR_k) \qquad \text{(II–6)}$$

where $P(L_k)$ comprises landslide incidence H_k ("yes" or "no") given the observed physical characteristics: average slope angle (θ), tan θ, residual of shear strength (tan ϕ') of near-surface materials, $F_k=\left(\frac{\tan\ \phi}{\tan\ \Theta}\right)_k$, maximum slope angle (*MS*), tan (*MS*), and new road corridor excavation (*NR*). The *t*-statistic is 1.21 for the constant, 13.18 for the natural log of F_k, 4.0 for the natural log of MS_k, and 4.28 for *NR*; R^2 = 0.26, and the number of observations (n) = 14,255.

The conditional probability estimate, $P(L_k)$, includes bedrock units and surficial geologic materials. These surficial geologic materials can include transported sediment such as alluvium or landslide debris, as well as weathered, residual bedrock known as saprolite. In equation II–6, the shear strength of the surficial geologic materials is included in places where they are at least 6 m thick. The conditional probability of slope failure (fig. II–17) ranges from 0.013 to 0.838 and has a mean of 0.143 and variance of 0.024 for the new, more detailed geologic map.

Step 3: The cost of the required mitigation in each cell, L_k, for each geologic map is estimated.

For the study area, the expected loss avoided (savings) in road construction costs and repairs (mitigation in the form of retaining walls) is calculated for the cells that require mitigation. The loss avoided is assumed to be a \$1,000 per meter cost of repairing a damaged slope by constructing a retaining wall to prevent further road damage.[26] Because we assume both sides of the road would require mitigation, we used a \$2,000 per-meter cost.

Step 4: For *each cell identified* in step 1, the expected loss avoided (fig. II–18), $E(L_a)_k$, is estimated by using equation II–3 as the product of the probability of a loss (eq. II–6) and the monetary value of the loss (cost of mitigation) in cell k (step 3).

We use \$2,000 per meter per cell, assuming both sides of the road are affected by a slope failure, to estimate the expected damages along a route corridor. The expected

[26] This cost estimate is based on a Consulting Engineering Firm's cost for retaining wall construction along I–66 in northern Virginia (Robert Gladstone, personal commun., 1990).

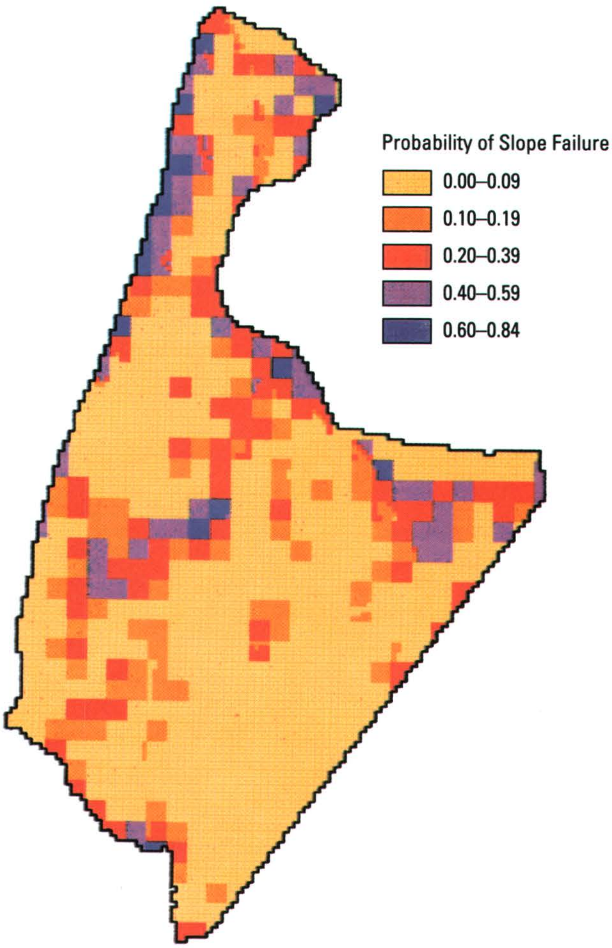

Figure II–17. Conditional probability of slope failure due to road construction, eastern Loudoun County, Virginia. Cell size is 250 m × 250 m.

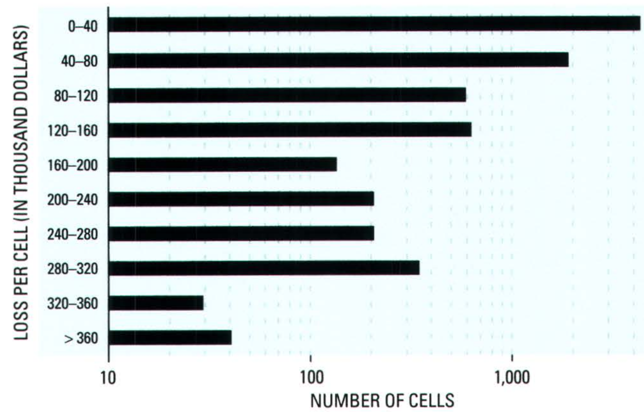

Figure II–18. The expected losses avoided due to highway slope failure for cells in the study area, eastern Loudoun County, Virginia. Cell size is 250 m × 250 m.

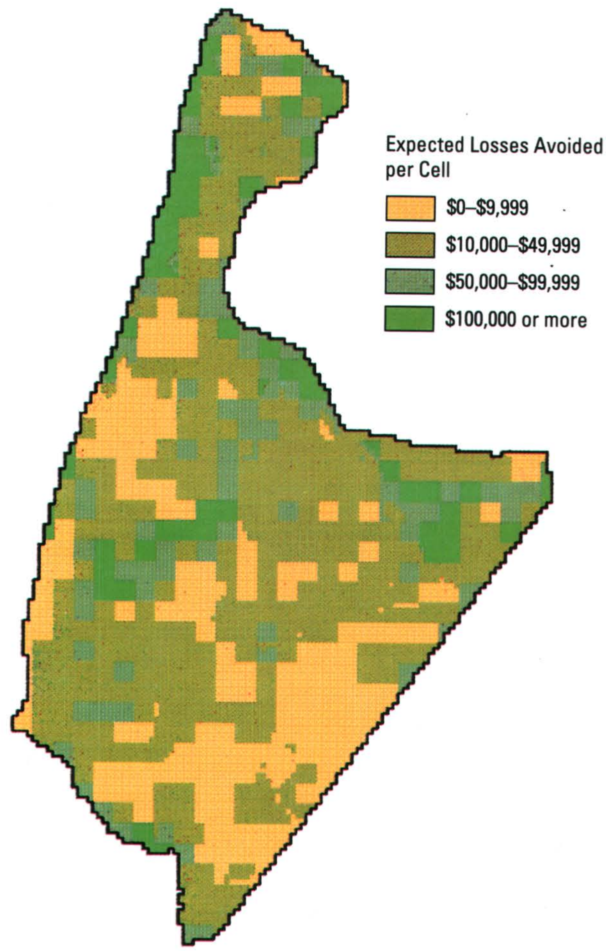

Figure II–19. Spatial distribution of expected losses avoided due to slope failure induced by road construction, eastern Loudoun County, Virginia. Cell size is 250 m × 250 m.

value and standard deviation of the costs are $75,760 per cell and $38,878 per cell, respectively, for the improved geologic map.

Combining the spatial distribution of the $E(L_a)$ (fig. II–19) with those cells identified in step 1 (fig. II–16) yields the expected loss avoided for each geologic map.

> Step 5: Calculation of the benefit of the improved geologic map information is accomplished by taking the difference in expected loss avoided between the two geologic maps.

Depending on the final choice for the location of the three proposed transportation corridors, the difference in expected loss avoided, $E(L_a)_k$, between the two geologic maps for any cell in the study area varies considerably but averages about $11,000 per 250-m × 250-m cell. The cells that would not require mitigation when the improved geologic map is used but would require mitigation when the

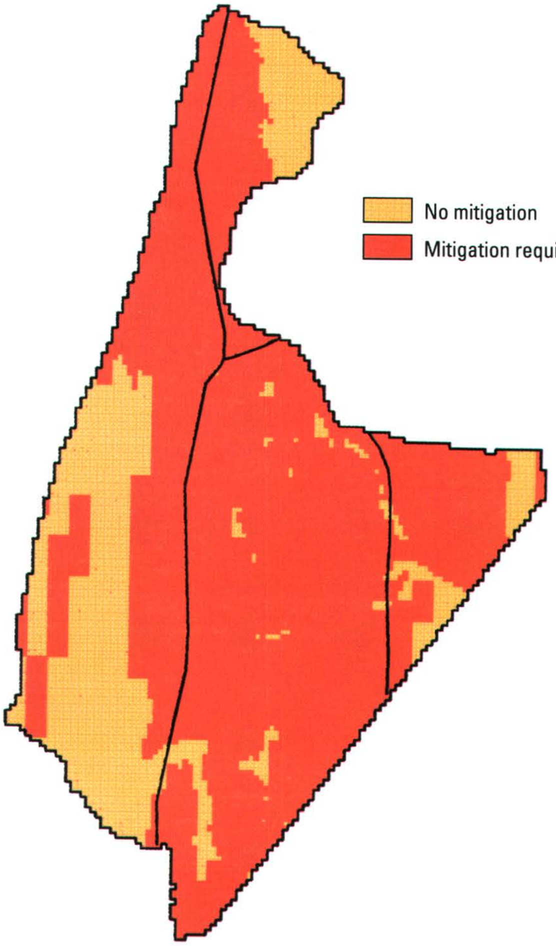

Figure II–20. Areas in eastern Loudoun County, Virginia, that *would not* require mitigation when the improved geologic map information is used but that *would* require mitigation when the existing geologic map information is used.

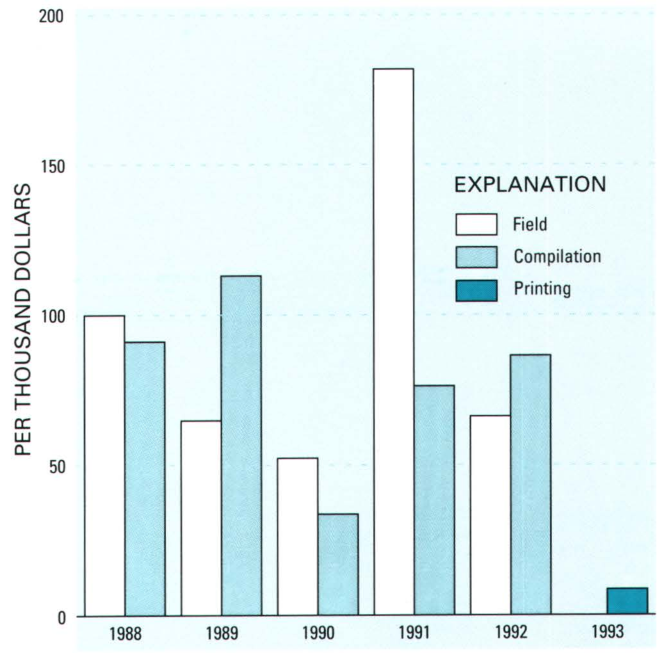

Figure II–21. Cost distribution by year for creating the improved geologic map of Loudoun County, Virginia.

existing geologic map (outcome 3) is used are shown in figure II–20. If it is assumed that any corridor selected will cross a minimum of 85 cells and a maximum of 287 cells (number of cells crossed by the easternmost and westernmost proposed routes in the DEIS), the benefit of the improved geologic map information in locating an interstate-type highway corridor in eastern Loudoun County ranges between $935,000 and $3,157,000.

THE NET BENEFITS OF GEOLOGIC MAP INFORMATION

The purpose of this analysis has been to develop and implement a methodology for estimating the societal value of improved geologic map information. Second, we have derived the benefits of improved geologic map information for two applications. In this section, we apply equation II–4 to estimate the net benefits of the improved geologic map information.

Cost To Produce an Improved Geologic Map for Loudoun County

Loudoun County occupies approximately 1,425 km^2, an area equivalent to about ten 7.5-minute (1:24,000 scale) quadrangles, or about one-third of a 30 × 60 minute (1:100,000-scale) quadrangle. A number of areas within the county have been mapped for other purposes in the past with varying quality and density of observations and have been interpreted and reinterpreted geologically over the last century as different paradigms for geologic understanding were developed, tested, and refined or abandoned. The current USGS geologic mapping project in Loudoun County, therefore, requires both new geologic mapping and compilation and reinterpretation of existing geologic map information. Total costs for the improved geologic map information, the 1:100,000-scale USGS map, are projected to be about $1,160,000 distributed over 6 years, as shown in figure II–21. These costs include an opportunity cost of capital compounded semiannually at 10 percent during the production period. The project cost is about $968,000 and interest is $189,000. The capital and operating costs for the project are $913,000 and $55,000, respectively. Capital costs include utilization of plant and equipment and personnel, while operating costs include daily expenses and supplies.

Table II–5. Net benefits of new geologic map information in Loudoun County, Virginia (in millions of dollars)

Benefits for new geologic map information	$2.44–$4.66
Cost of 1:100,000 scale geologic map of Loudoun County	1.16
Net benefits	$1.28–$3.50

Net Benefits of Improved Geologic Map Information

The net benefits from the use of more detailed geologic map information (the USGS 1:100,000-scale map) are the benefits for the new geologic map information ($2.44–$4.66 million) minus the cost of producing that map ($1.16 million). Therefore, the expected net benefit for the 1:100,000-scale Loudoun County geologic map ranges from about $1.28 million to $3.50 million, as shown in table II–5.

Potential Lower-Bound Bias on the Net Benefit Measure

These results should be considered a lower-bound estimate of benefits. Whether the net benefits reflect potential benefits in geologically dissimilar areas is problematic until additional case studies are completed. On the basis of the proportion of the county actually evaluated in this study, this estimate of expected net benefits may be somewhat conservative. Our study area covers about 39 percent of the total area of Loudoun County and represents the benefits of only two applications. The improved geologic map of Loudoun County is anticipated to be used for such activities as airport expansion and siting, land use planning including mountainside and flood-plain development, design and construction of surface water impoundments, and siting of quarrying operations, borrow pits, and municipal well fields.

Implications of the Study Results

The new and more detailed geologic map of Loudoun County, Virginia, will be used in a significant number of additional applications. When used, the newly identified benefits accruable to the improved geologic map information will increase from the results listed in table II–5. The issue of whether *all* applications of improved geologic map information will yield a positive net benefit is unknown. Geologic maps tend to be more important to society in regions that exhibit economic growth. We chose the Loudoun County study area because it is a high growth area and, as such, will need a significant amount of planning in the foreseeable future. This is, of course, speculation on our part. However, the application of spatial information (geologic maps) for planning can be evaluated more completely after a number of case studies have been undertaken.

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Chapter III

Geologic Maps as a Public Good: Provision of Geologic Maps and the Nature of the Demand for Geologic Map Information

INTRODUCTION

This chapter introduces technical issues related to the provision of regional geologic map information as a public good. Two important topics bear on these issues: (1) discussion of testable hypotheses concerning the public or private provision of regional geologic map information and (2) identification of the demand for derivative products based on geologic map products. We pose a variety of questions relative to who should provide geologic map information and discuss how these questions might be answered by use of rigorous economic methods. We present the initial documentation regarding the identification of the demand for regional geologic map information in the remaining sections.

PUBLIC PROVISION OF GEOLOGIC MAPS

In the following sections of the chapter, we identify and summarize a set of economics issues concerned with choosing the public or the private sector to provide regional geologic map information.

In the Organic Act, geologic mapping information is implicitly assumed to be a public good. This is a testable hypothesis. Given the debate about the need to privatize goods and services that now are provided by the government (a reduction in government expenditures), asserting that geologic mapping is a public good is no longer sufficient to resolve the issue. In the privatization debate, determining who should provide geologic map information requires two steps: deriving a conceptual model and conducting an empirical investigation. The unavailability of data at this time limits our investigation to the first of these steps.

What is the appropriate institutional choice for the production of information, the public sector or the private sector? Institutions may best be regarded as systems of constraints on individual behavior. The question becomes, what system of constraints is most likely to result in the lowest cost production of the desired product? This chapter contains an examination of a specific case regarding privatization—the production of regional geologic map information by the USGS and the constraints surrounding such information. Assuming that the USGS is the sole producer of regional geologic maps, we can narrow this analysis to whether production of regional geologic map information should be reassigned to the private sector.[1]

The debate on privatization has focused on two general classes of arguments:

1. The examination of the comparative efficiency of public sector versus private sector enterprise (Sappington and Stiglitz, 1987; Chamberlin and Jackson, 1987). Sappington and Stiglitz note that the recent interest in privatization may reflect the view that previous assignments of responsibility (to the public sector) were incorrect.
2. Whether or not the production constitutes a natural monopoly. In particular, the arguments have focused on whether public sector intervention is necessary, because a natural monopoly may not be sustainable (Baumol and others, 1982).

Apparently overlooked in the privatization debate is the specific role that the nature of the good (product) may play in determining institutional choice.[2] This issue has two aspects: whether the good is a public good that would be underproduced by the private sector and whether the nature of the good that is produced is affected by the institution producing the good. The importance of both of these issues lies in making the choice between relying on public production or on regulation of licensed private producers.

To begin, we summarize whether or not regional geologic map information constitutes a public good. First, do regional geologic maps generate significant positive economic externalities? An affirmative finding suggests that the private sector will underproduce the information and

[1] Several forms of privatization are possible. Vickers and Yarrow (1991) discuss privatization involving competitive firms, privatization of monopolies with accompanying regulation, and contracting out of publicly financed services. Our concerns have mainly to do with the latter two categories.

[2] An exception is Wintrobe (1987), who criticizes the general precept of those studies purporting to show the inefficiencies of public sector production for omitting to recognize that the products produced by private sector firms may not be the same as those produced by public sector firms.

thereby provide justification for government *finance* of the production of geologic information. However, by itself, this answer is not sufficient to justify public sector *production*. Because of the nature of the good that would be produced under different institutional settings, there is a need to further sort out the financing problem associated with the production decision. Second, is the production process subject to economies of scope and scale (that is, a multiproduct natural monopoly)? A finding that there are economies of scope and scale provides an argument for public sector production, although it also offers just as valid an argument for government regulation of a private sector producer. Again, the nature of the good produced under different institutional frameworks is a pivotal argument. Finally, the proposition that choice of institution affects the characteristics of the good could argue for a change in the choice of institution.

HISTORICAL PERSPECTIVE

USGS Responsibility

The existence of the Organic Act supports the view that Congress intended there to be a Federal role in the evaluation of the Nation's lands, environment, and resources. The USGS has the responsibility for classifying the resources on the public lands. The wording of the act suggests that the Congress wanted the role of the USGS to be one of creating and distributing geologic information as a public good. Further, Congress recognized, issues of public goods aside, that the production of the information is best served by a central Federal role. The purpose of this section is to highlight those portions of the Organic Act which support these interpretations.

The USGS is responsible for providing the geologic knowledge base associated with all Federal, State, and private lands. The Director is charged with the "classification of the public lands and examination of the geological structure, mineral resources and products of the national domain." (43 U.S.C. 31(a), p. 6.) The USGS also is responsible for earth science information collection beyond that of the national domain: "The authority . . . to examine the geologic structure . . . is expanded to authorize such examinations outside the national domain where determined by the Secretary to be in the national interest." (43 U.S.C. 31(a), p. 6.)

From these excerpts of the Organic Act, Congress established the USGS as the appropriate institution to produce regional geologic information. Thus, the USGS, under the direction of the Director, was chosen as the primary agent for gathering earth science information. Further, we believe that the intent of Congress was to designate the USGS as the central organization for developing a national geologic information base. Specifically, the types of information that are provided by the USGS "shall consist of geologic and economic maps, illustrating the resources and classification of the lands, and reports upon general and economic geology and paleontology." (43 U.S.C. 31(a), p. 7.) Further, the USGS is directed to provide general (regional) information: ". . . shall execute no surveys or examinations for private parties or corporations." (43 U.S.C. 31(a), p. 6.)

Other Geologic Map Producers

The role of State geological surveys is different:

> State geological surveys have mandates for collecting and compiling geologic information within their States and thus possess detailed knowledge of their regions and resources. This mandate contrasts with the USGS mandate to collect and synthesize geologic data from all parts of the Nation, a task that includes identifying and analyzing regional geologic problems that cross State boundaries. (USGS, 1987, p. 14.)

There is a distinct difference in the mapping responsibilities of the USGS and the State Geological Surveys. The USGS does not systematically produce site-specific earth science information. For instance, when a local authority determines the right-of-way for a highway, it begins the process with a regional geologic map, while the necessity for detailed site-specific geological information arises only after the actual right-of-way has been chosen. A more detailed map or even a site map logically would be provided by another institution. As such, the USGS provides map information that is regional or base information (occasionally the USGS will conduct site-specific analyses). This distinction between Federal and State roles is relevant to our discussion because different types of institutions will generate different types of geologic information. This contrast is addressed in "Conditions for Natural Monopoly."

The Distribution and Pricing of the Information

The distribution of geologic information also is dictated by the Organic Act as follows:

> The Director . . . is authorized . . . to dispose of the . . . geologic maps . . . at such prices and under such regulations as may from time to time be fixed by him . . . and a number of copies of each map . . . shall be distributed gratuitously among foreign governments and departments of our own Government to literary and scientific associations, and to . . . educational institutions and libraries . . . (43 U.S.C. 31(a), p. 8.)

Further, the maps are to be distributed at a price that is below the average cost of production and distribution: "Three thousand copies of each shall be published for scientific exchanges and for sale at the *price of publication* . . ." (43 U.S.C. 31(a), p. 7, emphasis added.) Through the

Organic Act, Congress dictated that earth science information should be widely available and clearly recognized that there was no social benefit to restricting access to geologic information. Thus, Congress reaffirmed its position that geologic information is a public good.

As part of the privatization debate, Chamberlin and Jackson (1987) provide an interesting perspective that suggests the debate could end at this point. They posit several conditions that, if fulfilled, would lead to the conclusion that privatization is warranted.

> Where purchases are frequent, information is abundant, costs of a bad decision are small, externalities are minimal, and competition is the norm, privatization ought to be pursued. At the other extreme, in situations where externalities and collective interests abound, natural monopolies are dominant, distributional goals are important . . . public provision should continue. (abstract)

Clearly, all of the conditions for a private good are *not* fulfilled in the case of regional geologic map information. Purchases are infrequent, information is limited, and potential external costs are high. Thus, there is support for the argument that the production of geologic information should be carried out in the public sector.

Recently, a revision of OMB Circular No. A–130 was published in the Federal Register that stated that information products should be sold at a price no greater than their marginal cost of production and distribution (Federal Register, April 29, 1992). Draft legislation has been introduced into Congress that effectively stipulates the same requirement (H.R. 3459, 1991).

GEOLOGIC INFORMATION AS A PUBLIC GOOD

Types of Information

Discussion of the public-good attributes of information begins with the distinction between general and specific information. A frequently made argument (see Musgrave, 1959; Becker, 1975; Cohn, 1979) is that general information is a public good, while specific information is a private good. There is the presumption that general information possesses more of the characteristics of a public good, having a lack of exclusion possibilities (anyone can use the information) and a lack of congestion costs (there is no cost of competition in the use of the information).

As applied to geologic maps, general information is collected at a scale that would be valuable for a variety of regional planning decisions encompassing a set of choices for land uses such as highway route selection, waste repository siting, energy exploration, and development impacts.[3] Such information also would be available for a long period of time, given the slow rate of decay of its usefulness.

Specific information, on the other hand, is much more localized (for example, specific siting characteristics of interchanges along a single road right-of-way) and of much less use for further application. In essence, the collection of site-specific geologic information for determining the economic and environmental feasibility of siting a waste repository would be of little use in road planning unless the road is to be constructed in the same location as the proposed waste facility. As the information becomes more specific, the number of users becomes smaller. Thus, geologic information can be both general and specific information. Our concern is with geologic maps in the general information category. We note, however, that in compiling specific information, general information is often necessary to provide background data. In what follows, we discuss the economic concepts associated with the production of a public good in order to gain insight into the nature of regional geologic information. From this discussion we propose a series of testable hypotheses that can be examined empirically.

Public Goods

Pure public goods have two key characteristics. First, it is impossible, or inefficient, to exclude anyone (nonrival in consumption) from consuming the good once it is produced.[4] The availability to other users is not diminished. Second, the production of the good is characterized by jointness of supply (Musgrave, 1959).[5] The extreme case of jointness of supply arises when the cost of the good is made up entirely of fixed costs. The key characteristics of a public good are discussed in more detail in this section, including a brief introduction to the "free-rider" problem.

Nonrival in Consumption

Public goods are nonrival in consumption; that is, any one individual's consumption of the output does not reduce the consumption by others. Maps are available free to certain groups, readily available in certain repositories, and reproducible, so there is little reason to believe that any

[3] We are aware that a map cannot be all things to all users. We generalize, despite Varnes' (1974) caution, because it is highly likely that a regional geologic map will have at least two users.

[4] For many types of public goods it may be technically impossible to exclude individuals from consumption of the good once it is produced. National defense is one such good, and, at a local level, police and fire protection also have this characteristic.

[5] Economic efficiency is achieved when the cost of production is equal to the market valuation of the good for the last unit produced. If the marginal cost is zero (all costs are fixed and would be incurred whether one unit or one hundred units were produced), economic efficiency requires that the good be "sold" at zero price—be made freely available.

individual could be restricted from use. There is an *obvious* case of nonrival consumption for regional geologic maps.

A second aspect of the nonrival consumption argument is the ability to legally exclude others from making full use of information through the use of patents and copyrights. Such rules for exclusion are necessary for the private sector to have the appropriate incentive to produce map information that would be otherwise publicly provided information. Since individuals are able to obtain map information by not paying (a "free ride"), a private sector producer would not be able to recover the cost of production and would not provide the good.

Implementation of an exclusion scheme is difficult in the case of regional geologic map information because the range of potential users is large and dispersed. Effectively there is no way to implement a payment scheme. As a general rule, as information becomes more general, there is a larger group of potential beneficiaries and there is less likelihood that exclusion is feasible. This point can be seen by comparing the possibilities of exclusion from use of a general theoretical development in seismology and earthquake prediction in California, relative to an engineering rehabilitation job on a building in Berkeley, Calif., which is used in a particular application. In the case of the general information, there may be a role for the government to produce such information.

Jointness of Supply

The jointness of supply condition is fulfilled; that is, the per-unit production and distribution costs of regional geologic map information are near zero, while the per-unit costs of the information collection make up almost 100 percent of total per-unit cost. Regional geologic maps possess this characteristic, because the bulk of the costs of producing such maps are borne "up front,"[6] while the actual printing and distribution costs are relatively small. Because the printing costs are relatively low, the cost of serving an additional consumer also is small.[7] For example, the expected per-unit cost of information collection and synthesis for a 1:100,000-scale map covering Loudoun County, Virginia, is about $1.16 million, while the cost of production and distribution are about $8.44 per unit.[8] Therefore, excluding consumers once the good has been produced is inefficient.

[6] These costs comprise the data collection, organization, interpretation, coding, and other functions that precede the actual publication of the USGS geologic maps.

[7] See Matti and others (1988) for a presentation of relative cost figures.

[8] See Matti and others (1988, table 1) for the costs of producing a regional geologic map. Total costs of map compilation and publication are $21,100. The normal production run is 2,500 copies.

Table III–1. Payoffs to the provision of a public good
[C, contribution; NC, no contribution]

		Person B	
		C	NC
Person A	C	4, 4	1, 5
	NC	5, 1	2, 2

"Free-Rider" Problem

When the above two characteristics for a public good occur, in most cases, the private supply of this type of good such as a regional geologic map will yield inefficient **market** outcomes. Too little geologic information is produced, and a market failure ensues. This type of market failure is known as the "free-rider" problem. Free riders are individuals or groups who attempt to enjoy a good while not paying for it; it is impossible or inefficient to exclude them from the activity. The nature of the free-rider problem may be illustrated as an application of the prisoner's dilemma (see Mueller, 1989, p. 8–17), summarized as follows:

> Consider a simple economy with two persons. Each person begins with an endowment of two dollars and each has two choices (strategies): to contribute to the provision of a public good or not to contribute. The public good is generated by summing the total contributions and multiplying this by 1.5 to reflect the consumer surplus (total area under the demand curve or total willingness to pay for a commodity) generated by the public good. The public good is enjoyed equally by both persons, and their payoffs are given by the value of the public good minus their contributions. The payoffs to these strategies are shown in table III–1. For example, if both choose C (contribution), the total contribution is 4, the value of the public good is 6, and each person receives 4 as his net payoff. If both choose NC (no contribution), then they keep their endowment, so the payoff is $2 to each. If one contributes and the other does not, then the contributor receives $1 (his share of the public good is $3, and his contribution is $2), while the noncontributor receives $5 (share of the public good is 3 and he keeps his endowment). The equilibrium outcome in this game is (NC, NC) with no public good being produced. This result is unfortunate, since the total payoff is clearly greater in the (C, C) outcome. The (NC, NC) outcome arises because NC is a dominant strategy for both of the persons in this economy. That is to say, it is not in either individual's interest to separately contribute to the public good since the payoff from this strategy is lower than from the strategy of not contributing.

The outcome for the general case of the pure public good is that private (voluntary) production will lead to suboptimal levels of production.[9] As a result of this type of individual behavior, economics research has argued that the government should intervene to ensure proper provision of the good.[10]

CONDITIONS FOR NATURAL MONOPOLY

The Natural Monopoly Framework

A natural monopoly is said to exist when the least cost means of producing a given quantity of a good (or group of goods) is achieved only when the production is carried out by a single firm. The technical condition for an industry to be a natural monopoly is that the cost function be *subadditive* (see Sharkey, 1982; Baumol and others, 1982). For a single-product firm, the cost function (C) is subadditive if:

$$C(q) < C(aq) + C[(1-a)q] \qquad \text{(III–1)}$$

where $0<a<1$ and aq represents the fraction of the total quantity (q) produced by each firm. Equation III–1 states that production costs are lower if the entire output is produced by one firm rather than two (or more) firms.

Geographic regions of the United States are unique; therefore, the production of regional geologic map information is a multiproduct industry. In the case of multiproduct industries, subadditivity of the cost function requires that

$$C(q_1) + C(q_2) > C(q_1, q_2) \qquad \text{(III–2)}$$

To argue that the production of regional geologic information is a natural monopoly, the cost function must be subadditive over different geographic regions. The sources of such cost subadditivity are a useful starting point for an investigation. Specifically, we begin by determining whether the production of regional geologic information is characterized by the following:

1. Substantial "up front," or setup, costs associated with the production of regional geologic information for a particular region.
2. A decrease in per-unit cost for a given map of a region (this is a corollary of 1).
3. Cost complementarities across map types within a given region (the cost function is subadditive within a region).
4. Cost complementarities across regions (the cost function is subadditive across regions).

If all of these conditions are found to exist, there is support for a natural monopoly.[11]

The Cost Function

For a given region, the cost function can be characterized in equation III–3 (adapted from Alchian, 1959) as:

$$C = f(V, x, T, m) \qquad \text{(III–3)}$$

where C is total cost;
V is the planned volume of maps (of all types) of a region to be produced over a foreseeable time frame;
x is the rate of output (total number of all types of maps of a region to be produced over a given time span);
T is the time at which the production is to start; and
m is the length of time the production is expected to last (production will end at $T + m$).

If any three of the terms in this cost function are fixed, the other is determined. For multiple geographic regions, this function is redefined as follows: the planned volume, V, refers to the planned total volume of maps produced across all regions, and x refers to the total rate of output across all regions.

A number of propositions arise when this cost function is used. The empirical question of whether the production of regional geologic map information satisfies the conditions of a natural monopoly can be investigated with data from the USGS production of regional geologic map information.

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[9] When we see some voluntary contributions in the "real world" it is usually the case that the good generates some private benefits (including the utility from donating) or that the good is not a pure public good. Some classes of public goods may be provided via the private sector, although not necessarily at efficient quantities. Cornes and Sandler (1986) and Bergstrom and others (1986) demonstrate these findings. In their setting, some individual is willing to privately provide an initial quantity of the public good because his marginal utility exceeds the cost of the good. For other individuals in the economy, the public good is viewed as an income transfer, and, where the public good is normal, the result is an increase in the willingness to pay for the good by these persons. The resulting response is analogous to a Cournot reaction and can be shown to lead to positive provision. The key initial assumption of this analysis is that at least one person's demand exceeds the cost of providing the first unit of the good. For most public goods this is not the case, and the outcome is that private provision will be at zero levels.

Where the cost of the public good is such that no one person is willing to supply *any* amount on his own, there is some debate as to whether the private market will supply a positive amount. Where use of the good may be prevented after it is made available (a club good), Bagnoli and McKee (1991a) have shown that a "focal equilibrium" exists in which the good is supplied at efficient levels. Where the good is subject to ex post consumption by noncontributors, Isaac and others (1985) have shown that the good is generally undersupplied.

[10] The free rider problem must be overcome by compelling payments for public goods through a tax system with penalties for noncompliance.

[11] Additionally, there is the question of whether the industry is vulnerable to a class of "cream-skimming," in which other producers enter to produce a subset of the regional information bases. The result is higher total costs overall.

Proposition 1:

$$\partial C/\partial T \mid_{x=x_0,\ V=V_0} < 0 \qquad \text{(III–4)}$$

In equation III–4, the cost declines (in constant dollars) as the production start time, *T*, is moved back. This proposition allows the producer some lead time to acquire inputs and to plan the production process more carefully. If proposition 1 is true for regional geologic map production, the implication is that there is an optimal program for the production of maps which matches willingness to pay for timely information to the cost of production. Each geographic region represents a different map, and the demand for these maps is not uniform. Where the demand is low (willingness to pay is low), delaying production to achieve cost savings may be appropriate policy. This point will be elaborated in connection with proposition 3.

When proposition 1 is coupled with subadditivity of costs over regions, there is a clear case for natural monopoly. The cost savings arise from an optimal schedule of production over regions.

Proposition 2:

$$\partial C/\partial V \mid_{x=x_0,\ T=T_0} > 0,\ \partial^2 C/\partial V^2 \mid_{x=x_0,\ T=T_0} < 0 \qquad \text{(III–5)}$$

In equation III–5, the marginal cost declines as the planned volume (number of different types of maps produced within a region) increases. With higher planned volume, the producer can take advantage of production technologies that may have higher setup (basic information gathering) costs but have reduced per-unit production costs sufficiently enough to recover the setup costs. In the multiple region setting, proposition 2 introduces the possibility of significant cost savings as the number of areas to be mapped increases.

Proposition 3:

1. The cost of production of future map types declines as more types are produced within a given region or at a given time.
2. The cost of production of maps in new regions is lower, on average, than that in the current region.

This proposition states that the production process is subject to considerable learning effects. If the production of regional geologic maps obeys the above conditions, then production should be carried out by a single "firm" in order to capture the gains from learning. Further, the production of maps should be ordered in such a way that the maps demonstrating the highest willingness to pay should be produced first.

To demonstrate the existence of a natural monopoly in the single product case, it is sufficient to demonstrate the existence of decreasing costs of production and distribution of the output for the single product. More generally, one must test whether the cost function is subadditive over a relevant range of the quantity produced (Baumol, 1977). This is fairly simple to demonstrate by determining whether average and marginal cost decrease with increase in output. However, as the discussion indicates, the problem is slightly more complicated when dealing with a good that is complex and that is subject to a high fixed cost of production.

For the multiple task or multiple product case, the situation is more complicated. We must determine whether the cost function is subadditive over several products.[12] If subadditivity exists, then there are "economies of scope": the costs of producing the component parts of the regional geologic information may be greater than the costs of producing the whole. Such a situation may arise from cost complementarities, shared fixed assets, or learning on the part of workers.

Subadditive cost functions are a necessary condition for the efficient industry structure to be a monopoly. However, such a structure may not be sustainable through only private market forces. In a multiproduct setting there is the potential for firm entry to occur in which the new firm produces only a subset of the entire product line. While production costs will be higher, the entrant could earn a profit. However, society will lose because the total cost of the entire line of products will be greater with the two producers (the economies of scope will be foregone). This condition for sustainability may be discussed with the aid of figures III–1 and III–2, which demonstrate the situation for a two-product operation. The axes denote the prices of goods 1 and 2.

In figure III–1, the locus through A and B denotes the set of zero profit price vectors. Inside this locus the profits are positive, while outside the locus profits are negative. Only the portion of the locus from A to B is relevant, because all other points require higher prices of at least one of the goods. Sustainability requires that prices on AB be such as to *not* permit profitable entry into one of the two product markets.

Figure III–2 depicts the case for which the demand for the products is independent (neither substitutes nor complements). This case appears to be the most relevant to the issue, because, for example, a regional geologic map produced for Nebraska is not a substitute for a map of New Jersey. The shaded areas denote ranges for the prices of goods 1 and 2 for which profits are positive, and the locus AB is the same as in figure III–1. The crosshatched area shows the region in which two single-product firms could simultaneously operate. The locus CD denotes prices that will yield zero profit and not attract entry, because there are no lower prices for good 1 or 2 that will yield a positive

[12] For a detailed discussion of subadditivity of cost functions and their implications for the natural monopoly argument, see Baumol and others (1982).

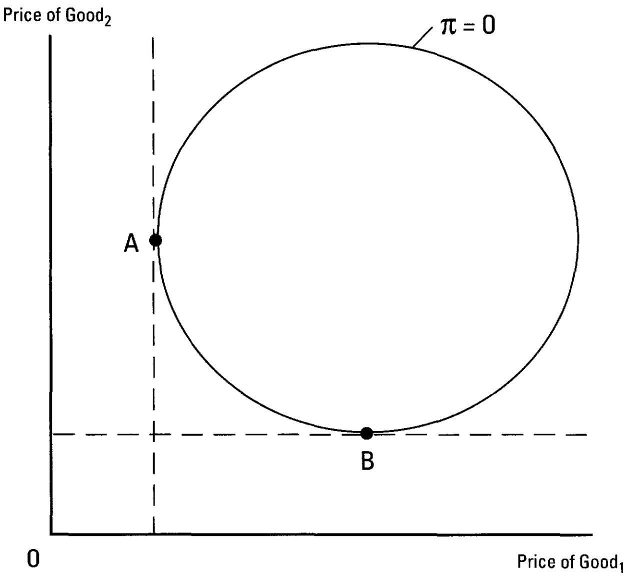

Figure III–1. Total profit of a multiproduct firm that produces information. The locus through A and B represents the isoprofit locus for $\pi = 0$; inside this locus $\pi > 0$; outside, $\pi < 0$; relevant range of $\pi = 0$ is AB, since all other points require higher price of goods 1 and 2.

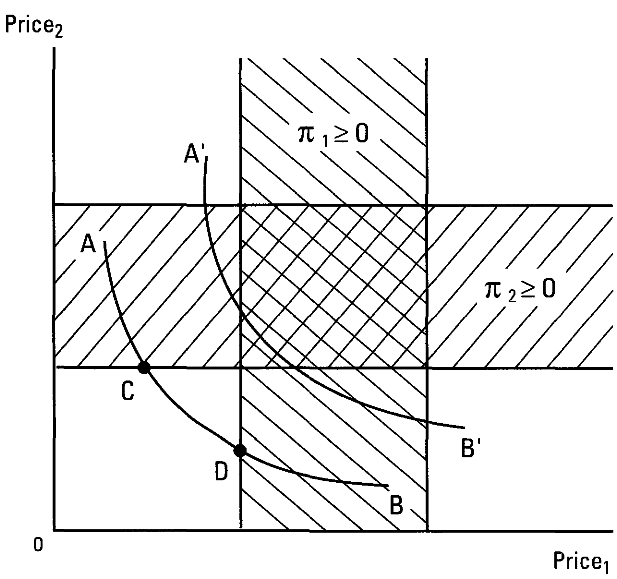

Figure III–2. Isoquants of a multiproduct firm showing the requirements for industry entry. Goods 1 and 2 are independent. The crosshatched area denotes price ranges where two single-product firms could simultaneously operate. CD denotes prices on AB (zero profit locus) for which the natural monopoly A′B′ denotes a two-product analog to the nonsustainable case.

profit. The natural monopoly here is sustainable without government intervention; the firm can prevent entry through its own pricing strategy. This demonstrates that in a natural monopoly in which the products have independent demands, sustainable prices always exist. The locus CD is not empty.

THE NATURE OF THE GOOD IS DETERMINED BY THE INSTITUTION

Other Governments and Agencies

A clear case for natural monopoly is not sufficient for public sector production to be the institutional choice. In fact, it is not strictly necessary. We consider the impact of the choice of institution on the characteristics of the good that is produced and argue that the institution will make a difference in the good.

First, a great deal of USGS information is used by Federal, State, and local governments (as well as users in the private sector). If the USGS did not produce this information, would these agencies receive the types of information necessary for land use planning (zoning) and economic development from a private sector firm? Second, there is the question of who should pay for and regulate the quality of this information, given that the Federal Government frequently mandates its use (as under EPA regulations, for example) by State and local governments. For instance, contracting out the information is not costless.

Monitoring the Producer of Information

The production of information cannot be monitored costlessly by the party that will be using the information. The key point is that the production of regional geologic map information is a science. The design of the sampling procedure (how dense, how deep, how repeated, and how it should be done) and the interpretation of the data are essentially the tasks of the geologist. In such situations there is the potential to produce biased output. It may be that a public sector agency would not always have the resources to produce the most reliable data, but it is likely not to have an incentive to produce biased results. The same result may not be true of private sector firms. Given the consequences of incorrect information (impact on such things as waste site location, oil exploration, zoning, and construction) and the irreversible nature of many of the decisions made with this information, the information must be unbiased and as close to correct as possible.

Vertical Integration

Another argument that may be made is that it will be costly to specify all the important attributes of the regional geologic information. In the case of private sector production, the response to this problem is vertical integration (Klein and others, 1978; Grossman and Hart, 1986). This response implies increasing concentration in the energy exploration industry, for example. In this case, the small exploration firms will not be in a position to provide information for themselves and consequently will be required to rely on the larger firms to provide timely data.

Network Externalities

Finally, there are many goods for which the utility derived from use increases as the number of others using them increases. Good examples are word processing software, fax machines, and telephone answering machines. The greater the number of people using a particular word processor program, the easier it is to exchange information. The same is true of fax machines and answering machines. Katz and Shapiro (1986) discuss some general conditions for such network externalities to be relevant.

Regional geologic information satisfies these conditions. Consider the siting of hazardous waste dumps. The greater the number of parties using the same regional geologic information, the more likely there will be some agreement on the choice of sites. Using maps with the same information will significantly reduce administrative procedural costs associated with siting such facilities.

TESTABLE HYPOTHESES

The issue of privatization of government activities is multifaceted. We have explored the issue of privatization in the case of the production of regional geologic map information: Should the production of regional geologic map information be undertaken by the federal (public) sector, contracted out to the private sector, or should all responsibility be assigned to the private sector? The Congress has mandated through the National Geologic Mapping Act (P.L. 102–285) that regional geologic information is a public good, and it follows that socially efficient production should be carried out by the Federal Government.

Moving beyond just accepting the Congressional mandate, we have explored the technical requirements that must be met for the Federal Government to be the appropriate institution for the production of regional geologic information. In doing so, we distinguished between two broad classes of geologic information: specific (larger than 1:24,000 scale) and general (1:24,000 scale or smaller). It is the latter that is of specific interest in our discussion.

We considered three different technical requirements. First, does the good—regional geologic map information—fulfill the conditions for being a public good? The second technical requirement for public sector production is that the least cost means of production is a single producer. We explored the conditions for a natural monopoly. Finally, the choice of institutions is shown to depend on the interaction between institutional setting and the characteristics of the good that is produced. We considered the role of the institutional setting for the characteristics of the good. It appears that the characteristics of the good will vary under alternative institutional settings. We argue that this is a critical consideration for determining the appropriate institutional framework for the production of regional geologic information.

The following hypotheses can be tested to suggest answers to the economic issues that have been posed. For the section "Geologic Information as a Public Good," the question is whether it is socially optimal to exclude individuals from using general information such as regional geologic map information. Do we want the patent or copyright system to cover truly general knowledge about our environment? A great deal of the information produced by the USGS may be classified as general knowledge, as opposed to specific knowledge. In light of Federally imposed requirements for the use of regional geologic map information, Federal regulatory requirements would be difficult to satisfy if regional geologic map information were copyrighted. Further, the public good argument is a necessary condition in supporting continued public sector provision (and possibly production) of the information product.

> H_1 (Nonrival in Consumption): The marginal cost of an additional user of regional geologic information is zero.

Once regional geologic map information has been produced, it is essentially costless to provide to additional users. In addition, the valuation of the previous users is not affected when additional users are added.

> H_2 (Jointness in Supply): A priori, there is effectively zero private provision of general regional geologic map information.[13]

The approach that would need to be taken to test the hypothesis could be in two parts. First, we could attempt to observe the provision of regional geologic information by the private sector. Second, we could utilize survey techniques to attempt to observe the marginal willingness to pay for regional geologic information relative to the cost.

> H_3 (Free Rider): Ex post, if the good is being provided, then exclusion is problematic.

The essential point is that regional geologic map information is different from road maps, books, tapes, and other physical manifestations of information. Behind each of these examples are the ideas embodied in the product,

[13] We should be clear that we are not hypothesizing that no private maps exist. However, those that do exist will consist of more specific information than would be produced by the public sector. Private-sector-produced maps will be considered proprietary information. The energy industry is a good example of a private organization that produces such maps.

and these ideas are protected by patent or copyright laws. An important characteristic of the private production of such ideas is that the cost of the road map or tape is small, and the good is priced to reduce the incentives to illegally reproduce the good. Such goods depend on a *large market* if they are to be produced efficiently. The question here is whether regional geologic map information shares the characteristics of road maps, musical tapes, and such. Initial observation suggests there may be important differences.

In order to test hypothesis H_3, we would have to turn to the development of an availability index. This would involve ascertaining the general availability of the good and demonstrating that, unlike the situation with private goods, exclusion is difficult.

There are several additional testable hypotheses from the section "Conditions for Natural Monopoly" that concern different aspects of the costs of producing regional geologic maps. Propositions 1, 2, and 3 represent testable hypotheses concerning the cost behavior of the production of regional geologic maps. Proposition 1 implies that cost will be lower for the production of maps that have longer lead times. Specifically:

> H_4: The per-unit cost of regional geologic information is a decreasing function of the length of the planning horizon for the production of the information.

Proposition 2 implies that per-unit costs will be a decreasing function of the planned volume of the particular map output. If the USGS is assumed to be able to forecast the demand for the product (the actual output is the planned output), then:

> H_5: The *average* per-unit costs of the actual maps produced will be inversely related to the level of output.

Proposition 3 states that the production of maps is subject to the effects of learning by doing. Thus:

> H_6: The cost per set of map information falls as the variety of maps produced increases.

This hypothesis would be supported when there are cost advantages to having a centralized group of geologists producing information for the entire Nation rather than state-level production. Such cost savings may arise from sharing of information or from the accumulation of human capital in the production of a specialized task (Becker, 1975).

Each of these hypotheses has a corresponding multiregion version. As noted above, the production of maps within the USGS is a multiproduct operation. Economies may be realized through the production of a single map, as suggested by the preceding discussion. Economies also may be realized through joint production—sometimes referred to as economies of scope. Where these economies exist, the cost function will be subadditive.

> H_7: The cost function for the production of regional geologic information is subadditive.

Subadditivity may arise from several sources. The learning effects referred to in proposition 3 will provide economies of scope where the skills required in the production of one product are used in the production of other products. There may be common costs associated with the production process. The cost function may be of the form:

$$C(q) = C_0 + C_1(q_1) + C_2(q_2) \qquad \text{(III–6)}$$

and

$$C(q_i) = C_0 + C_i(q_i)$$

where i is an output.

A further empirical question is whether the USGS is a sustainable natural monopoly or whether there is some potential for the private sector to enter part of the market for regional geologic maps (and information) with the result that the total cost of the information is increased.

The cost function for the production of the various regional geologic map information products produced by the USGS is written as equation III–7:

$$C(q) = F(S) + \Sigma_{i = 1, n}\, c_i(q_i) \qquad \text{(III–7)}$$

where S is the set of outputs with positive output, F(S) is the fixed cost associated with the set S, and c_i is the constant marginal cost of producing the output, i. An output (i) may be regional geologic mapping information for a given region or it may be mapping information produced at different scales.

Sharkey (1982) has shown that a sufficient condition for the existence of sustainable prices is that costs satisfy weak complementarity and demands are independent. Thus:

> H_8: Costs of producing regional geologic mapping information for different regions (and scales) are (weakly) complementary.

> H_9: The demands for the various regional geologic information outputs are independent (neither substitutes nor complements).

The section "Conditions for Natural Monopoly" yields testable hypotheses less readily than the other sections. However, we can investigate and compare the type of specific geologic information produced by private sector firms and public sector agencies. We would hypothesize that the information produced will be different:

> H_{10}: Private sector production of geologic information will focus on less general types of information (that is, be more specific), smaller geographic areas, and will be in less accessible forms of information provision.

Table III–2. Federal users of USGS geologic map information

USER	APPLICATION
Department of Interior (DOI): Bureau of Land Management (BLM) Bureau of Mines (BOM) Bureau of Reclamation (BOR) Office of Surface Mining (OSM) Minerals Management Service (MMS) National Parks Service (NPS) Fish and Wildlife Service (FWS)	Energy and mineral resource assessments; resource management plans; multiple-use plans; dam and reservoir development; wilderness assessments; ground-failure stability analysis.
Department of Defense (DOD): Army Corps of Engineers	Development planning; waste repositories; geologic-hazards analysis; siting of water works.
Department of Energy (DOE)	Energy resource assessments; waste repository developments and cleanup; seismic evaluations; siting of nuclear tests.
Environmental Protection Agency (EPA)	Assessment of naturally occurring toxins; ground-water assessments, multiple-use plans, waste site evaluations.
Nuclear Regulatory Commission (NRC)	Nuclear plant and waste site evaluations.
U.S. Department of Agriculture (USDA): Agricultural Research Service (ARS) Forest Service (FS) Soil Conservation Service (SCS)	Toxic substance evaluation; ground-water resource evaluation; wilderness assessment; Resource Management Plans.
Department of Transportation (DOT)	Transportation and utility corridor evaluations; airport and facilities siting; geologic-hazards evaluation.
Housing and Urban Development (HUD)	Transportation and utility corridor evaluations; geologic-hazards evaluation; urban area zoning.
Federal Emergency Management Agency (FEMA)	Geologic-hazards evaluation.
Tennessee Valley Authority (TVA)	Geologic-hazards and ground-water evaluations.

It would seem likely that the regional geologic information available will differ across regions according to the relative shares produced by public and private sector firms:

> H_{11}: Where there is greater private production of geologic information, there will be less information in total, the information will be more specific, and it will be more costly to use.

In order to test these hypotheses, we possibly will have to assemble a survey. This survey will investigate the nature of the information produced by the private sector.

BACKGROUND ON NATIONAL GEOLOGIC MAPPING PROGRAM

Beginning in 1988, the National Geologic Mapping (NGM) Program of the U.S. Geological Survey began an outreach to selected Bureaus in the Department of Interior and other Federal agencies to identify their priorities for geologic mapping. This was undertaken to help the program in its long-term planning and to begin closer coordination between the USGS and other Federal agencies in the area of geologic mapping.

NEEDS FOR GEOLOGIC MAP INFORMATION

In addition to prioritized requirements for geologic map information already submitted to the USGS National Geologic Mapping Program, a derived demand can be identified by looking at past cooperative projects with a variety of Federal agencies. Table III–2 lists the past and present Federal users of USGS geologic map information and the societal application.

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