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Method for Determining Relative Suitability of Existing Geotechnical Data for Regional Planning

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During regional planning studies, the engineering geologists must choose among diverse, competing data sources, each having distinct cost and accuracy characteristics. Recognizing a need for guidelines in this area, the Missouri Division of Geology and Land Survey, Rolla, Missouri, evaluated a sequence of alternative sources of data on the Cape Girardeau quadrangle in southeastern Missouri. Several map sources were compared at three scales: statewide (1:500 000), countywide (1:62 000), and quadrangle (1:24 000). Engineering and geologic considerations were used to establish criteria for 10 land uses associated with residential development. These criteria were used with the appropriate source data to develop a sequence of limitations maps at each scale. Extensive field and laboratory programs were carried out to prepare the best-possible data-reference source with which other map products could be compared. A usefulness index was formulated to measure the degree of agreement between the competing interpreted products and the reference standards. Manual computation of this index proved impractical [a 10-km² (4-mile²) area required 1 person day/comparison]. Thus, computer methods were used that permitted the rapid comparison of approximately 32 000 cells covering the quadrangle and the computation of the resulting usefulness index for about $50.00 (including all salaries and data-processing costs).

The growing interest in and demand for environmental assessment has caused a reappraisal of land-use planning activities and accelerated demands for suitable engineering geology maps. The majority of these demands emphasize the need to display the natural constraints to development of various land uses. These new types of map displays, which range from rather generalized, small-scale displays covering large regions, or even entire states, to more-specific larger-scale ones covering local areas or counties, must be understandable by a variety of people.

Many traditional map forms, however, poorly satisfy these new demands, and considerable experimentation on new mapping formats has been undertaken [some of the new techniques are reviewed elsewhere (1)]. The pressure for the development of new mapping techniques has been felt most intensely by the state geological surveys, and several states have expanded, or even created, agencies to undertake such projects.

In Missouri, a number of environmental geology maps have been developed (2, 3), but a single map, accompanied by tables describing natural conditions and constraints to development, does not always suffice. Planners frequently desire a series of interpretive maps, each showing the degree of constraint for some specified class of use. These maps, reflecting both geologic conditions and estimates of probable hazards to life and property, are used in combination with other planning factors in guiding future development.

In this paper, these interpretative land-use-limitations maps will be called limitations maps. Each such map analyzes for a single land use or for a group of closely associated uses. The development of these maps requires the setting of standards or procedures for their construction in order to maintain quality and consistency.

In the first stages of a program to develop such standards, four steps were undertaken.

1. Limitation categories were defined: Four limitations categories were selected—severe, moderate, slight, and none—to indicate the probable degree of limitation to development.
2. Standard land uses were defined: Ten land uses were chosen—sanitary landfills, road construction, foundations for light structures (i.e., houses), agricultural suitability, septic tank systems, ease of excavation, impoundments, sewage lagoons, soil erosion, and landslide potential—to represent the range of con-

Table 1. Example rating system: sanitary landfill activity.

Rating	Constraint
No limitations	The bottom and sides of the landfill must be of a material such that leachates (a) travel less than 30.5 m horizontally in 1000 days and (b) never reach the groundwater table (unless the leachate will cause no decrease in quality of the highest-quality groundwater body that has historically existed within a 16-km radius)
	There must be sufficient soil at the site for a 15.2-cm daily cover
	There must be sufficient soil at the site for a final cover 0.9 m deep
	The final cover should be equal to or less permeable than the bottom and sides of the landfill
	The landfill site must never be subject to flooding
	The site must not be susceptible to collapse, for example, collapse induced by saturation, inundation, or high transmission rates of leachates
	The landfill must be located at least 1.5 km from the nearest water well or spring that produces 378 L/min and at least 0.75 km from all other water wells or springs
	There must be a minimum of 3 m of material between the bottom of the landfill and the normal wet-season piezometric surface
Slight limitations	The bottom and sides of the landfill must be of a material such that leachates (a) travel less than 30.5 m horizontally in 1000 days and (b) never reach the groundwater table (unless the leachate will cause no decrease in quality of the highest-quality groundwater body that has historically existed within a 16-km radius)
	There must be sufficient soil at the side for a 15.2-cm daily cover
	There must be a sufficient supply of soil located less than 1.6 road-km from the landfill to provide a final cover 0.9 m deep
	The final cover should be equal to or less permeable than the bottom and sides of the landfill
	The landfill site may be subject to flooding by a 100-year flood (U.S. Water Resources Council, 1967)
	The site must not be susceptible to collapse, for example, collapse induced by saturation, inundation, or high transmission rates of leachates
	The landfill must be located at least 1.5 km from the nearest water well or spring that produces 378 L/min and at least 0.75 km from all other water wells or springs
	There must be a minimum of 3 m of material between the bottom of the landfill and the normal wet-season piezometric surface
Moderate limitations	The bottom and sides of the landfill must be of a material such that leachates (a) travel less than 61 m horizontally in 1000 days and (b) will not reach the groundwater table in less than 1000 days (unless the leachate will cause no decrease in the quality of the highest-quality groundwater body that has historically existed within a 16-km radius[a]
	There must be sufficient soil at the site for a 15.2-cm daily cover
	There must be a sufficient supply of soil located less than 4.8 road-km from the landfill to provide a final cover 0.9 m deep
	The final cover should be equal to or less permeable than the bottom and sides of the landfill[a]
	The landfill site may be subject to flooding by a 25-year flood (U.S. Water Resources Council, 1967)
	The site must not be susceptible to collapse, for example, collapse induced by saturation, inundation, or high transmission rates of leachates
	The landfill must be located at least 1.5 km from the nearest water well or spring producing 378 L/min and at least 0.75 km from all other water wells or springs
	There must be a minimum of 0.9 m of material between the bottom of the landfill and the normal wet-season piezometric surface[a]
Severe limitations	All other areas

Notes: 1 m = 3.28 ft; 1 km = 0.62 mile; 1 L = 0.264 gal.
Landfills are rated primarily on surface material and susceptibility to surface and/or groundwater pollution unless corrective measures are taken.
[a] If a site in this area is to be used, this condition must be upgraded by appropriate engineering, to the value(s) given for "no limitations".

cerns related to residential developments.

3. An objective rating system was developed: A standard, objective rating system was developed for each land use to allow the translation of geologic conditions into constraints; an example rating system is shown in Table 1.

4. Data sources and scales were identified: A variety of data sources—federal, state, local, and private—and scales were identified for many types of data, and three distinct mapping scales were identified—statewide at a 1:500 000 scale, countywide at a scale of about 1:62 500, and local and quadrangle at scales of 1:24 000 or larger.

The engineering geologists were thus faced with the problem of reconciling and recompiling existing information available at a variety of scales and accuracies. Each data source had some distinctive, but generally unknown, cost and accuracy characteristics. Obviously the more-expensive data sources are generally more detailed and hence more precise and therefore should yield more-accurate interpretive limitations maps. On the other hand, in the face of budgetary constraints, use of the most expensive data is not always the best solution. For example, if two competing data sources are such that the cost of one is only 25 percent of the cost of the other, but the interpretive results of the first are at least 80 percent as accurate as those of the second, should the cheaper source be used?

In an attempt to answer such questions, a few interpretive limitations maps were produced by using competing data sources. These maps showed similar, but not identical, patterns of limitations. A more-precise method of evaluating the quality of competing data sources was needed and, accordingly, a research task was de-

fined to establish such a method. This paper describes the results of that task.

THEORETICAL BASIS AND METHODOLOGY

The comparison of two or more maps is a common geological and geographical problem. Although quantitative comparisons seem potentially useful to geologists, only a few attempts have been made to produce such values. Fortunately, geographers have studied this problem for several years and have developed a number of techniques (4, 5). None of the existing methods could precisely solve the needs of this study, however, and a modified procedure was developed based on cross-correlation concepts (4).

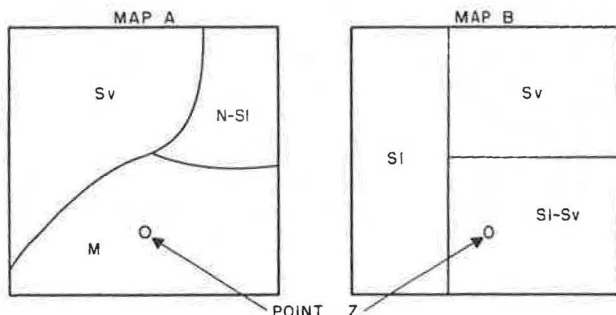### Limitations Categories and Limitations Units

As shown in Figure 1, by combining any two of the four standard limitations categories, a new distinctive limitations unit can be produced. By using all possible combinations, 10 distinctive limitations units can be shown on each map. The range of each limitation unit is defined by an upper (or ceiling) limitation that reflects the most-restrictive category and a lower (or floor) limitation that reflects the least-restrictive category.

In cases of perfect agreement between the limitations units on two maps, it is easy to see that the two maps are in perfect agreement. Similarly, in those cases where two map units totally disagree (a severe limitations unit on map A corresponding to a moderate limitations unit on map B, for example), it is easy to recognize perfect disagreement. Such situations are rare,

Figure 1. Derivation of 10 distinctive limitations units from four main limitations categories.

Figure 2. Two maps that have overlapping limitation units: example.

however; most commonly, the limitations units on one map (map A) will partially, but not completely, correspond with the limitations units on the second map (map B). Because the limitations units are defined in terms of the four original limitations categories, the possibility of partial overlaps in their ranges is high. The number of possible partial overlaps ranges from one to four.

Figure 2 shows two theoretical limitations maps. At Point Z, map B has the limitation unit "slight-to-severe" and map A has the limitation unit "moderate". Because moderate is not identical to slight-to-severe, it can be argued that the two maps do not correlate. On the other hand, one could argue that, because moderate is included within the range slight-to-severe, the correlation is perfect! Neither of these arguments gives a true representation of the relative similarity of the two maps.

What is required is a method of computing a quantitative degree of correlation between the two maps that takes into account the degree of similarity (or overlay) and the ranges of the two map units. This can be done by the following procedure:

1. Define the concept of an agreement number (a),
2. Compute a usefulness number (U_a) based on the agreement number, and
3. Compute a usefulness index (UI) by summing the usefulness numbers, weighted according to subareas, over the entire area of interest (which may be the entire map).

Thus, the usefulness index is a single value for the entire area of interest, while the other values are essentially point values associated with unit areas.

Agreement Number

The agreement number measures the degree of commonality between two limitations units. It is defined as one more than the number of nonoverlapping limitations categories (n) occurring in the two limitations units being compared (i.e., a = n + 1).

Thus, if two limitations units match perfectly, there are no nonoverlapping limitations categories; therefore, n = 0 and a = 1. Where no commonality exists, the agreement number is defined as zero (a = 0). By referring to Figure 1, it can be seen that, provided some commonality exists, n is between 1 and 3 and, thus, the agreement number is between 0 and 4.

Usefulness Number

The usefulness number converts the agreement number to a measure of usefulness of the two data sources. Where there is perfect agreement between the limitations units on the two maps (a = 1), both maps are totally useful predictors of the limitations. Where there is total disagreement between the two maps (a = 0), the maps are useless as predictors.

The usefulness number should range from 0 (useless) to 1 (totally useful); the distribution between these limits may be linear, geometric, or logarithmic. A geometric distribution was chosen, and usefulness number was calculated by using Equation 1.

$$U_a = 0 \qquad (a = 0)$$
$$U_a = [1/2^{(a-1)}] \qquad (a \geqslant 1) \tag{1}$$

The relationships among the degree of overlap (commonality), number of nonagreeing limitations (n), agreement number (a), and usefulness number (U_a) are summarized below.

Degree of Overlap	n	a	U_a
None	Not applicable	0	0.0
Perfect	0	1	1.000
Some	1	2	0.500
Some	2	3	0.250
Some	3	4	0.125

Usefulness Index

The usefulness number can be used to compute a single usefulness index that expresses the degree of commonality of one area, region, or map with another. The usefulness index (UI) is the weighted sum of the areas belonging to each level of agreement and can be calculated by using Equation 2.

$$UI = 10 \sum_{a=0}^{l} A_a U_a / A_t \tag{2}$$

where

A_a = map area(s) belonging to agreement number a,
A_t = total mapped area, and
l = maximum agreement number = number of limitation categories.

The usefulness index will be between 0 and 10; the higher the index number, the better the agreement between the two maps.

As defined, the usefulness index can be used to compare two maps only. Where it is necessary to compare three or more maps, one map should be chosen as a

Table 2. Computer-calculated usefulness indices: comparison of reference standard maps and data source maps.

Data Source Map	Map Scale	Usefulness Index									
		Landfills	Roads	Foundations	Agriculture	Septic Tanks	Excavations	Impound-ments	Lagoons	Erosion	Land-slides
Rock	1:500 000	5	1	1	6	4	3	4	6	0	2
	1:62 500	4	1	2	5	6	2	4	5	0	1
Soils	1:750 000	4	3	5	1	5	3	2	3	1	1
	1:63 300	5	3	5	2	5	3	3	3	1	1
Engineering bedrock	1:24 000	2				1		5	2		
Surficial geology	1:24 000	2	10	10	7	9	7	8	2	10	10
Groundwater	1:24 000	4					6		4		
Flooding potential	1:24 000	1							2		
Surficial unit per-meability	1:24 000	2			5	9		8	2		
Time of travel	1:24 000	7				3			9		
Strength	1:24 000		5	10							
Slope	1:24 000				3						

Table 3. Comparison of usefulness indices for landfills and roads computed manually and by computer.

Data Source Map	Map Scale	Manually Computed Value				Computer Value (entire map)
		Area 1	Area 2	Area 3	Average (areas 1-3)	
Landfills						
Bedrock	1:500 000	3	6	2	3.7	5
Bedrock	1:62 500	5	4	4	4.3	4
Soils	1:750 000	4	5	3	4.0	4
Soils	1:63 360	5	5	5	5.0	4
Roads						
Bedrock	1:500 000	1	1	1	1	1
Bedrock	1:62 500	1	1	1	1	1
Soils	1:750 000	2	3	5	3.3	3
Soils	1:63 360	2	2	3	2.3	3

Figure 5. Landfill limitations map for entire Cape Girardeau quadrangle: computer generated from all 1:24 000 data.
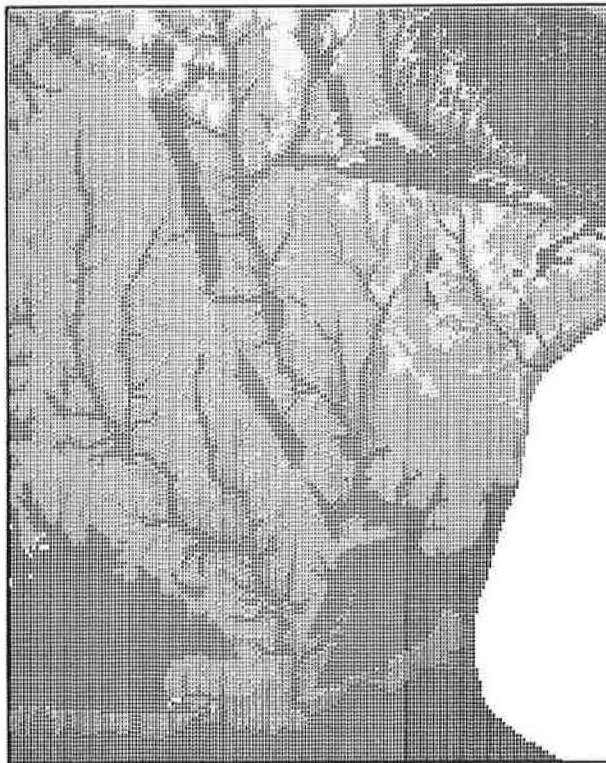
tainty remained with such small areal samples.

Computer techniques were used to solve this problem. A computer-assisted component-cellular mapping system called GMAPS (6, 7) was used to provide for the arithmetic and logical overlaying of maps to form new maps. In the program, all maps are stored in a computer in a matrix format of small cells. These can be repeatedly modified so that a single source map can produce a very large number of permutations. In this step, the source map documents for the Cape Girardeau quadrangle were converted to about 32 000 cells, each covering 2.5 hm² (1.1 acres) and having ground dimensions of 61x76 m (200x250 ft).

By using the GMAPS program, it was possible to compute usefulness indices for 70 map pairs (see Table 2). It was also possible to produce limitations maps for each use; Figure 5 shows the landfill limitations map generated by the computer.

The computer calculations produced usefulness indices for the entire quadrangle. The earlier manual calculations had been for only three small areas. Comparison of the manual and computer-derived indices (see Table 3) shows that local variations do change the rankings of some data sources. The computer calculations do agree fairly closely with the average of the usefulness indices for the three areas; perfect agreement could not occur unless there were only three landform types, represented by the three areas, and each covered one-third of the quadrangle.

CONCLUSIONS

A new method for quantitatively comparing two maps has been developed and tested. The method produces a single value, the usefulness index, that defines the degree of commonality between the two map units in a range of 0 to 10. Limitations for a specified land use that are predicted by using a single data source can be compared with those predicted by using a more-complete standard reference map. Such comparison permits ranking of data sources. The use of the method for the Cape Girardeau area showed that surficial materials are, by far, the most critical factor for the majority of land uses in that area. However, for two land uses (landfills and lagoons), the percolation rates data are the most

important. Such information should prove useful in planning future field studies.

Except for very limited test areas, manual calculation of the usefulness index is impractical. Computer-based techniques are feasible, however. These can compute a single usefulness index for a quadrangle for about $50.00 (including data entry, processing, and display costs, for both salaries and computer time). Most of the data entry and checking can be carried out by technicians. Although, in this study, the computation of the indices was performed by senior staff, this is not necessary because the process can be documented and followed in a routine manner by technicians.

ACKNOWLEDGMENT

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Computerized Information System for Indiana Soils

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A comprehensive information storage system for Indiana soils is being operated on a computer at Purdue University, West Lafayette, Indiana, and at the Division of Materials and Tests of the Indiana State Highway Commission. Information is being collected that includes geotechnical, pedological, and geological data from records of subsurface investigations obtained during the period 1950-1978. Test data from more than 2500 soil samples have been stored and, within the year (1978), it is anticipated that data for an additional 6000 soil samples will be recorded. The data have been evaluated by various statistical methods. Results indicate that the range in values to be expected for a given soil parameter depends on the particular physical property and on the population from which the soil has been sampled. Some soil properties appear to be inherently more variable than others. To illustrate applicability, correlations have been made by using the information relative to physiographic unit and parent material. The grouping of soils by physiographic regions or origin of parent material (or both) suggests that the predictability of some parameters can be improved for certain combinations of parameters and soil groups. Specifically, prediction equations were generated for compression index, compression ratio, and unconfined compressive strength for certain soil populations. It is also possible to predict compaction test values, standard American Association of State Highway and Transportation Officials maximum dry and wet densities, and optimum moisture contents for selected physiographic and parent-material groupings.

The accumulation of laboratory and field-test data for characterizing the engineering properties of Indiana soils is extensive. An enormous amount of data, collected and stored from highway projects during the period 1950-1978, have been retained in the form of subsurface investigation reports. These reports were prepared by private consulting firms and governmental agencies from routine soil investigations. In their bulky, voluminous form, the majority of these data are not particularly useful for planning and engineering studies.

The need exists to make this information more accessible to both the engineer interested in detailed information about a site and the engineer interested in general soil characteristics over a large area. A computerized geotechnical data bank was judged to be the most efficient, expedient, and economical way to reduce the accumulated data to a form that could readily be made available to interested individuals.

This paper describes the development of a comprehensive information-storage system for soils data. Geological, pedological, and geotechnical engineering information are being collected and stored in a computerized system. Test data from 2508 soil samples have been stored in conjunction with developing and testing the computer system and, in addition, approximately 5500 other data sets have been stored (for a total of more than 8000 soil test samples).

Various statistical methods have been applied to some of the data. Results indicate that the range in values to be expected for a given soil parameter depends on the particular physical property and on the population from which the soil was sampled. The grouping of