CHAPTER 11

TERRAIN DATA FOR A WATER RESOURCES GIS

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Lund, H. G. 1981. Point Sampling -- The Role in In-Place Resource Inventories, in Brann, T. B., L. O House, IV, and H. G. Lund, eds., *Proceedings of a National Workshop on In-Place Resource Inventories: Principles and Practices* (Orono, Maine: Society of American Foresters), 371-374.

Lyle, J. and F. Stutz. 1983. Computerised Land Use Suitability Mapping, *The Cartographic Journal* 20:39-49.

MacDougall, E. B. 1975. The Accuracy of Map Overlays, *Landscape Planning* 2:23-30.

Mader, D. L. 1963. Soil Variability: A Serious Problem in Soil Site Studies in the Northeast, *Proceedings of the Soil Science Society of America* 27:707-709.

Minnesota State Planning Agency. 1979. *Minnesota Cropland Resources* (St. Paul, Minnesota).

Napton, D. and J. Luther. 1980. Procedures for encoding soils data, unpublished report to the Council on Urban and Regional Affairs (Minneapolis: University of Minnesota).

Nichols, J. D. 1975. Characteristics of Computerized Soil Maps, *Proceedings of the Soil Science Society of America* 39:927-932.

Nielsen, D. R. and J. Bouma, eds. 1985. Soil Spatial Variability, *Proceedings of a Workshop of the ISSS and the SSSA* (Pudoc Wageningen)

Pavlik, Hannah F. and Francis D. Hole. 1977. Soilscape Analysis of Slightly Contrasting Terraines in Southeastern Wisconsin, *Journal of the Soil Science Society of America* 41:407-413.

Reimer, D. R. 1981. Some Points to Consider in Determining Mapping and Sampling Intensities, in Brann, T. B., L. O House, IV, and H. G. Lund, eds., *Proceedings of a National Workshop on In-Place Resource Inventories: Principles and Practices* (Orono, Maine: Society of American Foresters), 326-329.

Ruhe, R.V. 1975. *Geomorphology*, (Boston: Houghton Mifflin).

Rust, R. H. and L. D. Hanson. 1975. Crop Equivalent Rating Guide for Soils of Minnesota, *Miscellaneous Report 132*, Agricultural Experiment Station (St. Paul: University of Minnesota).

Soil Conservation Service. 1979. *Engineering Field Manual for Conservation Practices*, Third Printing (Washington, D.C.: Department of Agriculture).

Soil Taxonomy. 1975. Agriculture Handbook No. 436, United States Department of Agriculture (Washington, D. C.: Government Printing Office).

Trudgill, S. T. 1983. Soil Geography: Spatial Techniques and Geo-morphic Relationships, *Progress in Physical Geography* 7:345-360.

Webster, R. 1985. Quantitative Spatial Analysis of Soil in the Field, *Advances in Soil Science* 3:1-70.

Wehde, M.E. 1979. Spatial Quantification of Maps or Images: Cell Size or Pixel Size Implications, in *Joint Proceedings*, 1979 meetings of the American Society of Photogrammetry and the American Congress on Surveying and Mapping (Sioux Falls, South Dakota), 45-64.

Wilding, L. P., N. E. Smeck, and G. F. Hall, eds. 1983. *Pedogenesis and Soil Taxonomy: I. Concepts and Interactions* (Amsterdam: Elsevier).

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SUMMARY: *Terrain Data for a Water Resources GIS*
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Issues

As a basis for predicting crop yields, water use, and runoff potential, a resource manager needs good information about the topography in a watershed. To translate existing information into computer-usable form, and to gather future information in an efficient manner, the designers of a water-resources Geographic Information System must deal with three fundamental issues:

1) The mathematical relationship between slope and elevation. The absolute elevation of a point is usually of little significance in hydrologic simulation, but its position with respect to nearby points is very important. One can compute slope from elevation measurements, but the result may be wildly inaccurate, because the terrain between two sample points may be a uniform slope, a series of steps, a concave chute, a high hill, or any one of an infinite variety of slope forms. Our recommendations must therefore deal with the complexity of real-world topography.

2) Tradeoffs between accuracy of terrain description and cost of data storage. Topographic information can be stored in a GIS in several ways: as digitized contours, spot elevations, Delauney triangles, profiles, or slope measurements at sample points. In each case, closely spaced data can reveal more intricacy of the topography, but halving the sample interval will increase costs of data storage by a factor of four or more. Our recommendations must consider the cost of data storage as well as the accuracy needed for the intended uses of the system.

3) Necessity for relational structure in the GIS. In order to provide data for a predictive simulation (such as the Universal Soil Loss Equation or the Peak Flood Model), a GIS must relate all data to a common coordinate system. When that is done, the simulation can get information on slope, soil, and land cover at exactly the same point and thus reach a valid conclusion about erosion or runoff. Our recommendations must accommodate the data that will be used with the terrain file in solving a resource problem.

Findings

The goal is to build a terrain data base that would describe landforms with reasonable precision, facilitate relational use with other kinds of data, and allow easy addition of better data when they become available. To obtain a basis for recommendations, we examined many different data-handling strategies. Our findings include the following:

Contour digitizing and terrain modeling are costly and provide data in a form that existing hydrologic simulations cannot use.

The USGS Digital Elevation Model is well suited for general maps, but erosion predictions based on it have unacceptably high error.

Tabulating slope classes from soil maps is statistically valid, but most hydrologic simulations also require measurements of slope length.

Intersubjective error in interpolating elevations from contour maps is relatively low; slope angle measurements are likewise fairly reliable, but slope length estimates are more error-prone.

Interpolating elevations at 100-meter intervals from 1:24,000 topographic maps can supply adequate terrain data at reasonable cost.

Recommendations

On the basis of these findings and the results of many other investigations at various scales, we make the following recommendations concerning the file structure for terrain data in a water-resources geographic information system:

1) Avoid attempts to derive slope angle and slope length from the USGS Digital Elevation Model; this data file is suitable only for highly generalized maps.

2) Obtain slope data by direct measurement from 1:24,000 topographic maps, either at 100-meter intervals for local profiles, or at a density of 1-4 samples per square kilometer data cell if only regional averages are needed (e.g. for a soil erosion simulation).

3) Record slope classes while entering data from soil survey maps. The data are inexpensive, reasonably accurate, and can serve as a check on the validity of the terrain data file.

4) Use data from several data files to improve the accuracy of terrain data. For example, the presence of marsh vegetation in a land-cover file, or an area of poor drainage in a soil file, may clarify a potentially ambiguous situation in the topography file.

5) Pay special attention to the methods for making maps from a point-inventory system, in order to avoid misinterpretation. Point sampling allows us to say, with some confidence, that "the average slope in area A is B" or "C percent of area D is in slope class E," but we cannot have the same confidence in trying to describe the slope at a point that did not happen to be one of the sample points. It is difficult to emphasize this too much -- the slope halfway between two sample points may indeed be equal to the arithmetic average of the slopes measured at them, but it also may be much greater or less than either measured slope. For that reason, it is dangerous to interpolate between sample points; the system that produces maps derived from sample data should simply not be permitted to portray data at individual sample points. Rather, it should display only the percentages of larger areas that fall into particular categories. As a rule of thumb, the output map should display data at a resolution that is at least a full order of magnitude less detailed than the sample data. If more detailed information is needed, field surveys are necessary.

TERRAIN DATA FOR A WATER RESOURCES GIS

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INTRODUCTION

To predict crop yields, water use, and runoff potential, a resource manager needs good information about the topography in a watershed. Absolute elevation is not a particularly significant variable in most of Minnesota, but slope (change in elevation over distance) has a number of important hydrologic consequences. All other things being equal, steep slopes will produce more runoff than gentle slopes. South-facing slopes will lose more water by evaporation than north-facing slopes, while east-facing slopes often collect more snow than ones facing the prevailing westerly wind. Floods appear to be less severe but develop faster on convex rather than concave slopes, because the former have the steepest land near the stream channels, where water can get into the river system quickly. Crop production on rough terrain is usually more risky and more costly than on nearly level ground, although artificial drainage is often needed on flat or depressional land. Soil erosion is an obvious hazard for a farmer or a developer on sloping land, especially if slopes are long and uniform. This list of truisms (and qualifications) could be lengthened considerably, but even this short summary can provide a framework for for discussing the kind of data structure required by a geographic information system in order to store topographic information in a form that is usable for hydrologic studies.

Taken individually, the probable hydrologic responses to various slope characteristics seem straightforward and intuitively obvious. Complications arise when several variables operate together; the effects of a particular combination of slope steepness, geometry, length, and so forth are much more difficult to predict. That, in a nutshell, is the reason for a GIS -- to keep track of the interactions among variables in different places. The information system should therefore allow easy comparison of various terrain variables, because the files will probably be used primarily to combine data files into a composite terrain index. At the very least, the terrain file should be able to provide data on five components of topography:

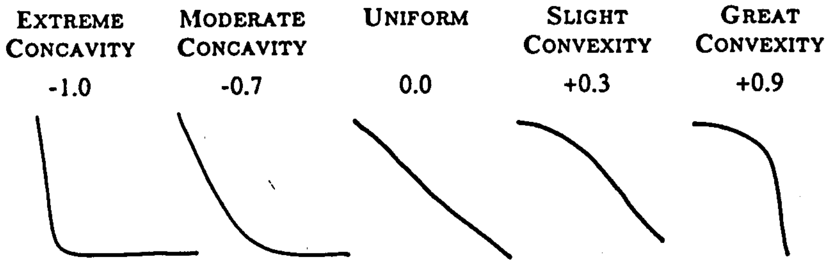
- **elevation** (height above an arbitrary base, usually mean sea level), measured in meters or feet;
- **slope angle** (its inclination from horizontal), usually measured in degrees, percent, or pitch;
- **slope aspect** (the direction it faces), usually represented as a cardinal direction or a number of degrees clockwise from north;
- **slope geometry** (whether straight, convex, concave, or complex), often expressed as an index that ranges from -1 to +1 with zero being a tilted plane (Figure 11-1); and
- **slope length** (the distance one can travel downslope before encountering a major change in slope), usually denoted in meters or feet.

These five slope components are not completely independent. On the contrary, they have mathematical links that make it possible to calculate one of them if two

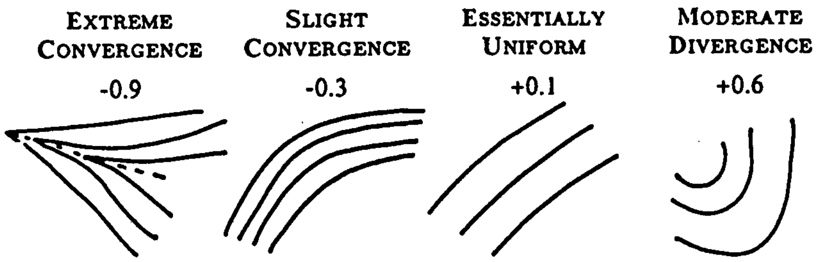
NUMERICAL EXPRESSIONS OF SLOPE GEOMETRY

The geometry of a slope has a profound influence on the behavior of water. Slopes that are uniform will produce runoff simultaneously all along their length, if the soil texture is fine enough to prevent lateral movement of water through the pores. Coarser soils allow percolating water to move downslope, which saturates the soil near the bottom of the slope and causes runoff to commence there first. In time (if rain continues) the zone of runoff will enlarge upslope in a predictable manner.

An concave slope will tend to saturate the soil near the "toe" first By contrast, some water from a very convex slope will get to the stream quickly, whereas runoff from near the crest will be delayed. Obviously, a valid index of slope shape would be very useful in hydrologic simulation. One simple index is based on a side profile through the slope, as illustrated in these examples:



The major problem with a profile index is the fact that a slope in the real world is a three dimensional surface -- it has curvature when viewed from above as well as from the side. A slope that is convex on a contour map (a "nose," "shoulder," or "spur") will tend to spread water and thus remain drier than a concave slope (a "draw" or "hollow"). This principle forms the basis for some new physical-based runoff simulations. As in the case of profile analysis, a numerical index can communicate the horizontal "divergence" and "convergence" of a slope:



A combination of these two indices, together with a measure of average slope angle and total slope length, can do a reasonable job of describing geometrically simple slopes, those that form on uniform surficial materials. Unfortunately, the real world has rocks and soils with different degrees of mechanical stability, resistance to weathering, and moisture-transmitting ability, and these can have some very significant hydrologic implications at a field scale.

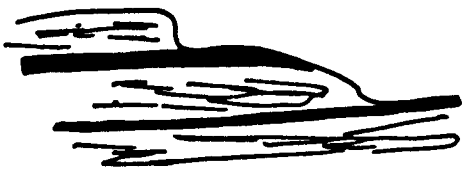


Figure 11-1

or three of the others are known. This fact may allow the designer of a GIS to reduce costs by putting only a few kinds of terrain information in the data files and deriving the others when they are needed. Our task in trying to formulate a recommendation, therefore, is to evaluate the relative costs and advantages of storing terrain information in different ways. To do this, we will first examine several theoretical issues that affect the efficiency of data gathering and storage. Then, we will report the results of a number of tests of the error associated with different data file structures, especially when used as sources of data for standard hydrologic simulations (e.g. models that predict flood peak or soil erosion; see Nieber and Lopez Bakovic, chapters 8 in this volume, T. Beach, chapter 9, and Anderson et al. 1987).

ALTERNATIVE WAYS OF ENCODING ELEVATION AND SLOPE DATA

The absolute elevation of a point is usually of little significance in hydrologic modeling, but its altitudinal relationship with nearby points is very important. For example, a big difference in elevation over a short distance will generate more runoff and erosion than a gentle slope with similar soil and surface cover. Closed drainage basins (low areas surrounded by ground that is high enough to prevent water flow into regional river systems) can be important as recharge areas for groundwater. Knolls and other convex slopes tend to spread water and thus dry out faster than hollows, which concentrate moisture where it is sheltered from the drying effects of sun and wind. Finally, the direction of drainage will dictate which areas are likely to have impacts on other areas -- flowing water can carry sediment and pollutants from higher to lower ground, but not vice versa.

For a small area, all of this terrain information is readily available in the detailed topographic maps published by the United States Geological Survey. Unfortunately, a collection of printed topographic maps is simply too unwieldy to be useful as a source of data for a hydrologic study of a county-sized watershed. Complete coverage of the state of Minnesota involves more than 1700 topographic maps at a scale of 1:24,000; most counties spread across more than twenty maps. Scanning these detailed maps at a resolution of 300 dots per inch (the resolution of this printed page) would give us more than 30 million bits of information per map, or a total of more than *half a billion* for a typical county (fifty billion for the state).

In one sense, this is a straw-person calculation, because the USGS uses vector (line) rather than raster (grid-cell) logic to encode its elevation information in a computer file. Converting the topographic data for the state to vector form might reduce its bulk by more than 99 percent (i.e. to a mere 500 million bits!). However, the purpose of the digital line graph (DLG) file is only to display the topography, not to combine terrain data with soil and land-cover information in a hydrologic model (Allder and Elassal 1985). For our purposes, it is important to remember that vector encoding makes data harder to use in hydrologic modeling.

We thus have a real need to find some way of sampling terrain in raster mode, in order to store its essential features in a geographic information system that a regional planner can use with a microcomputer. There are at least eight alternative strategies that might be used for this task (each capable of being used at a variety of spatial resolutions):

1) **sampling elevation.** With this strategy, someone records the elevation of the land at regular intervals across the landscape. This could be done either in the field (an outrageously expensive

operation), from aerial photographs (still quite expensive), or from printed or digital topographic maps (time-consuming but feasible). We measured elevations from 1:24,000 topographic maps at intervals of 100, 200, 500, and 1000 meters for various phases of this project. The US Geological Survey also publishes computer files of elevation samples (Digital Elevation Models, or DEMs) at several different resolutions, which we examined in order to test their validity in hydrologic simulation (Elassal and Caruso 1983; see also Ackermann 1978).

2) **profiling the terrain.** This approach involves tracing the elevation at intervals across the landscape. The result looks like a side view of the land surface along a straight line, usually due east-west or north-south for simplicity. The profile approach can produce graphs and diagrams that are easy to read; we used it for several figures in this chapter. However, the method is not easy to use in hydrologic modeling, because the steepest slope of the land goes in different directions in different places and therefore is seldom aligned with the profile. It is possible to calculate slope from a parallel set of profiles, but the procedure is cumbersome and costly.

3) **analyzing ridgelines and streamlines.** A third approach is to store the lengths and orientations of ridgelines (high points) and streamlines (valley bottoms) in a data file. A computer program then links a segment of the ridgeline with a point in the valley (or vice versa) to produce a triangular plane whose orientation, size, and shape can be described quite easily (Figure 11-2). If sampling is done at a sufficiently fine interval, the result can be a reasonably accurate description of the terrain (often called a Delaunay Net, Triangulated Irregular Network (TIN), or Digital Terrain Model (DTM); see Peuker et al. 1978). Combining a DTM with a file of soil or land-cover data, however, is quite awkward. Doing so in the glacial landscapes of Minnesota, with their undulating topography and disconnected drainage, is all but impossible on a microcomputer.

4) **identifying information-rich lines along profiles.** This method is basically a combination of the profiling and triangulation approaches, because it involves programming a computer to recognize places where a profile shows a significant change in slope (Douglas 1987). The method produces excellent depictions of coarsely mountainous terrain, but its utility in describing a complex rolling landscape like Minnesota is questionable.

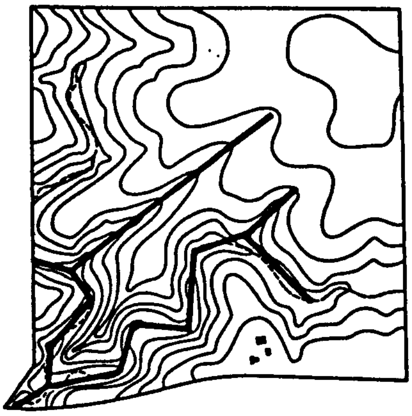
5) **outlining areas of reasonably homogeneous slope.** To help identify areas of high soil erosion potential in Canada, an investigator is trained to examine a large-scale topographic map and to draw lines around zones with "uniform" slope angle and length. The method is time-consuming (about forty minutes per square mile (Snell 1984)), subjective (different investigators may recognize different regions), and logically incompatible with the point-sampling procedures we are recommending for other data files. After trying the method in two small areas in Minnesota, we decided that a procedure of direct measurement at sample points would be preferable for a water resources GIS.

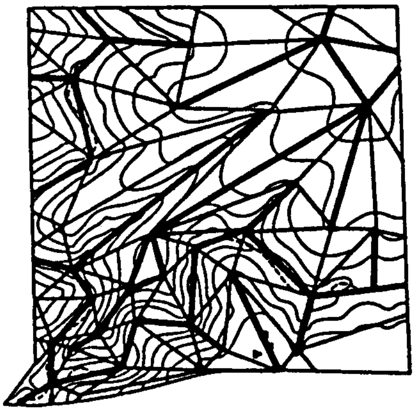
DESCRIBING A LANDSCAPE AS A TRIANGULATED IRREGULAR NETWORK

Translating a contour map into a form that can be displayed on a computer screen can require an enormous amount of data storage. One way to minimize the storage requirement is to record only the major changes in slope and to assume that all surfaces between those slope "breaks" are simple geometric planes. Mathematical definition of a triangular plane requires only three sets of coordinates, one at each vertex. Definition of an adjacent plane could "re-use" two of those and thus would add only one set of coordinates. A landscape that can be described as a set of nearly plane surfaces would not require much computer storage space.

This is the principle behind the construction of a "Delaunay net," a set of connected triangles that mathematically define a landscape. The first diagram on the left is a topographic map of a typical quarter-section "homestead" (actually 166 acres) with a few heavy lines that mark, in a general way, the major changes in slope at the bottoms of stream valleys. The cartographer has added some ridgelines and a few connecting lines in the second diagram. The complete system of linked triangles appears on the third, and the last diagram shows the Triangulated Irregular Network (TIN) all by itself. The three-dimensional coordinates of the vertices of these lines could replace the contour lines in the computer memory.

This particular example is from a mature stream-dissected landscape along the Mississippi River, about 60 miles southeast of the Twin Cities. A TIN at this resolution is obviously not easy to read, and the pattern would be even more complicated in the irregular terrain of a recently glaciated area.





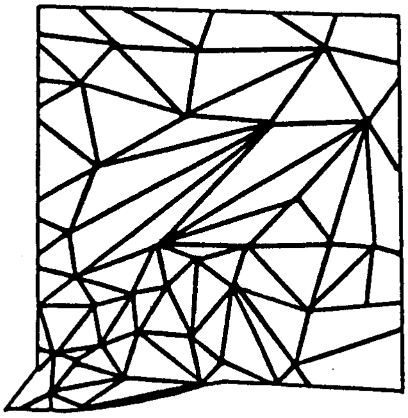


Figure 11-2

6) **determining slope angle and length at sample points.** Rather than record elevation, the user of this approach measures the angle and length of slope at sample points. The procedure goes faster if one makes a transparent overlay with a bar scale and a set of lines to translate contour spacing into slope angle (Figure 11-3). With this kind of template, it is possible to code slope data for an erosion study covering sixty square miles in a single evening (Gersmehl 1987). On the minus side, it is much harder to reconstruct a stream network from slope data than from elevation data (Mark 1984; see also Jensen 1985).

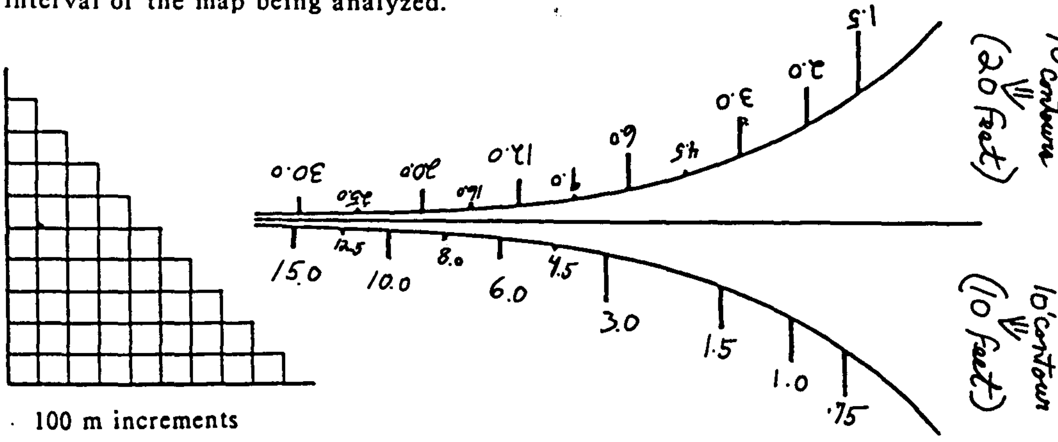
7) **recording slope categories from soil survey maps.** The mapping units in a county soil survey consist of a three-part code: a pair of letters or group of numbers that represent the soil series, a single capital letter that denotes a range of slope, and a number indicating degree of erosion. The soil maps are *tag maps* (area-descriptive rather than inventory), with all of the drawbacks of that approach (see Gersmehl et al., chapter 2 in this volume). Nevertheless, the map areas may be small enough to keep error to an acceptable level. Advantages of coding slope from soil maps include efficiency and relational accuracy gained by recording two kinds of data in a single step. One huge disadvantage is inconsistency; the "B" slope in one county may extend from 2 to 6 percent, whereas adjacent counties may use the same letter to designate 2-5, 3-7, 2-4, or some other percentage range.

8) **using surrogate measures to extend sample data.** This procedure is used in the AGNPS simulation, which divides the state into four broad geomorphic regions and assigns a single slope-length value to each region (Young et al., 1986). When done on such a grand scale, the procedure has serious drawbacks. Potential deviation from the designated slope length for each region is so great that the error in the slope-length factor alone could bias the results of a simulation by 25 (which certainly should raise questions about the six-significant-figure accuracy displayed in the AGNPS output). On the other hand, if a medium-scale map of landform regions (e.g. Hobbs et al. 1982 or the PIC file of geomorphic regions) were coupled with elevation data and a program of field sampling, the result might be an acceptable estimate of average slope angle and length within a set of designated regions.

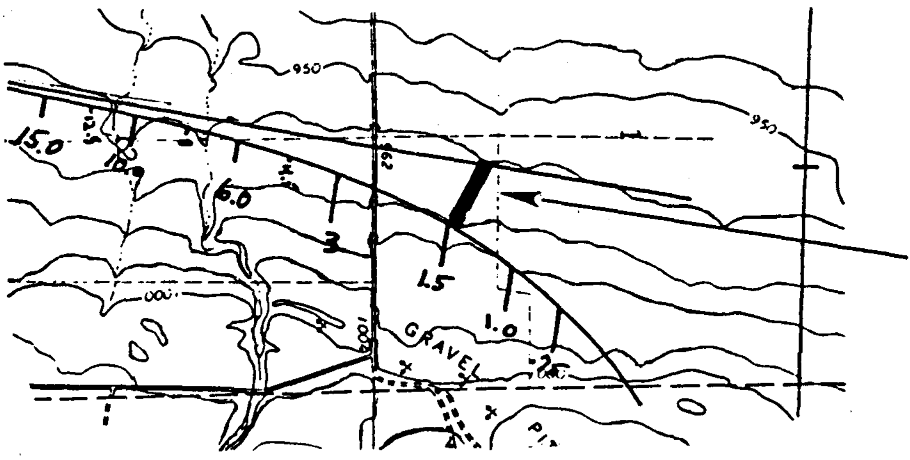
After a literature search and a preliminary examination of the advantages and disadvantages of each of these approaches, we concluded that profiling, area delimitation, richline identification, and building a digital terrain model were currently not feasible at a regional scale in Minnesota. The viable options include using the existing digital elevation model or designing an efficient method of point sampling that will work for elevation, slope angle, and/or slope class. To evaluate these options, we selected three dissimilar watersheds and performed a number of studies of the costs and errors associated with different sampling methods. The baseline for most of these investigations is a detailed sample, at 100-meters intervals, of elevation, slope, and terrain class from 1:24,000 topographic maps. We tested the validity of this sample against actual field measurements in a few selected areas. The sample is not perfect, but the average elevational error is well under the threshold ("one-half contour interval") for maps that meet the National Map Accuracy Standards (see Thompson 1982).

TEMPLATES FOR MEASUREMENT OF SLOPE ANGLE AND SLOPE LENGTH ON TOPOGRAPHIC MAPS

This diagram is just a copy of the templates we made in order to record data on slope angle and slope length from standard 1:24,000 topographic maps. The angle template indicates the gradient depicted by different amounts of space between adjacent contour lines. The length template is little more than a ruler with gradations that represent distances on a map with a scale of 1:24,000. Use of these templates is straightforward, provided that they are keyed to the scale and contour interval of the map being analyzed.



The measurement of slope angle appears, at first glance, to be mechanically more complex than estimation of slope length, but in practice the latter proved to be much more difficult and less reliable. Two people independently measured the angle and length of slope at the same 100 sample points in a landscape that included some hilly glacial moraine and somewhat more level outwash plain. One interpreter obtained an average slope angle of 4.9 percent, while the other, in two separate trials, delivered averages of 4.8 and 4.7 (an interesting situation, in which the same map interpreter is no more consistent in two trials than two different interpreters). Their estimates of the average length of slope, by contrast, differed by much more widely (118 versus 85 meters). The biggest problem, as reported by both interpreters, was the difficulty in defining the probable start of "concentrated flow," which marks the end of a hydrologic slope and the beginning of a channel.



The slope estimate measured between these two contours equals 1.5 percent.

Figure 11-3

PIC-DEM (THE PLANNING INFORMATION CENTER DIGITAL ELEVATION MODEL)

In this section, we explore the validity of an existing computer file o elevation data as a source of slope information for water-resource simulation The angle of a uniform slope is easy to compute from measurements of elevatio (percent slope is equal to 100 times the vertical distance divided by the horizonta distance between two points). In the real world, however, that kind of mechanica slope calculation from elevation data is seldom accurate, because the terrai between two sample points may be a uniform slope, a series of steps, a depressio a hill that rises above either point, or any one of an infinite variety of slope form (O'Neill and Mark 1985). Moreover, it is possible to calculate twelve differen slope angles for each data cell in a square grid (Jensen 1985). Our purpose was determine the extent to which these potential inaccuracies would interfere with th use of elevation data as an input for hydrologic simulation.

The United States Geological Survey has produced a Digital Elevatio Model (DEM) by encoding the elevation at sample points from topographic maps a scale of 1:250,000. The USGS DEM is a "three arc-second" grid. Since an ar second is one-sixtieth of a minute (or 1/3600 of a degree), this data file contai 1200 sample points per degree of latitude or longitude. The spacing of data poin in Minnesota is therefore about 300 feet in a north-south direction; the east-we spacing decreases (due to convergence of the meridians) from about 215 feet ne the southern border of the state to just less than 200 feet in the north.

The unequal spacing of data points in different parts of the state poses problem in trying to calculate slope from this elevation file. For that reason (a others), the Planning Information Center (PIC) of the Minnesota State Planni Agency translated the USGS DEM into a modified DEM, with metric measureme units and a uniform spacing of 100 meters between data points. (At least, we thi that is what happened; unfortunately, the data file does not have a header reco or other documentation that describes its origin. It may have been derived fro an alternative source, a Defense Mapping Agency DTT (Digital Terrain Tape). T DMA file also starts with the 1:250,000 series of topographic maps, but it uses "one-hundredth of a map inch" grid, which results in a sample spacing of about 2 feet in the real world. In the DMA file, the convergence of the meridians wou pose a problem primarily at the edges of the map sheets. The PIC-DEM is thus clear illustration of the problems that arise when the sources and algorithms us to derive a data file are separated from the contents of the file itself; see Gersm et al., chapter 2 of this volume).

The PIC file, on paper, looks like a very useful source of elevation data a water-resources GIS. The location of data points is unambiguous; their spacin uniform. The data are related directly to the Universal Transverse Mercator g the metric system of coordinates that appears to be the most flexible base for GIS (Hardy and Senykoff 1981; see also chapter 2 in this volume). Linkage of file with other UTM-based systems is reasonably straightforward. Reconstruct of a printed contour map for a county-sized area is also quite simple. Fina calculation of apparent slopes in percentages is easy, given the precise 100-me baseline between elevation figures.

On the other side of the ledger, some problems can arise as a result of process of translation from a latitude-based (or map-based) system to the U grid. One probable side effect is a noticeable "smoothing" of the data. Some of "data points" in the PIC file represent a single measurement in the USGS (or D DEM, whereas others are mathematical averages of two, four, or (rarely) t USGS (or DMA) numbers (Figure 11-4). This averaging procedure can red

PIC-DEM (THE PLANNING INFORMATION CENTER DIGITAL ELEVATION MODEL)

In this section, we explore the validity of an existing computer file of elevation data as a source of slope information for water-resource simulations. The angle of a uniform slope is easy to compute from measurements of elevation (percent slope is equal to 100 times the vertical distance divided by the horizontal distance between two points). In the real world, however, that kind of mechanical slope calculation from elevation data is seldom accurate, because the terrain between two sample points may be a uniform slope, a series of steps, a depression, a hill that rises above either point, or any one of an infinite variety of slope forms (O'Neill and Mark 1985). Moreover, it is possible to calculate twelve different slope angles for each data cell in a square grid (Jensen 1985). Our purpose was to determine the extent to which these potential inaccuracies would interfere with the use of elevation data as an input for hydrologic simulation.

The United States Geological Survey has produced a Digital Elevation Model (DEM) by encoding the elevation at sample points from topographic maps at a scale of 1:250,000. The USGS DEM is a "three arc-second" grid. Since an arc-second is one-sixtieth of a minute (or 1/3600 of a degree), this data file contains 1200 sample points per degree of latitude or longitude. The spacing of data points in Minnesota is therefore about 300 feet in a north-south direction; the east-west spacing decreases (due to convergence of the meridians) from about 215 feet near the southern border of the state to just less than 200 feet in the north.

The unequal spacing of data points in different parts of the state poses a problem in trying to calculate slope from this elevation file. For that reason (and others), the Planning Information Center (PIC) of the Minnesota State Planning Agency translated the USGS DEM into a modified DEM, with metric measurement units and a uniform spacing of 100 meters between data points. (At least, we think that is what happened; unfortunately, the data file does not have a header record or other documentation that describes its origin. It may have been derived from an alternative source, a Defense Mapping Agency DTT (Digital Terrain Tape). The DMA file also starts with the 1:250,000 series of topographic maps, but it uses a "one-hundredth of a map inch" grid, which results in a sample spacing of about 208 feet in the real world. In the DMA file, the convergence of the meridians would pose a problem primarily at the edges of the map sheets. The PIC-DEM is thus a clear illustration of the problems that arise when the sources and algorithms used to derive a data file are separated from the contents of the file itself; see Gersmehl et al., chapter 2 of this volume).

The PIC file, on paper, looks like a very useful source of elevation data for a water-resources GIS. The location of data points is unambiguous; their spacing is uniform. The data are related directly to the Universal Transverse Mercator grid, the metric system of coordinates that appears to be the most flexible base for the GIS (Hardy and Senykoff 1981; see also chapter 2 in this volume). Linkage of the file with other UTM-based systems is reasonably straightforward. Reconstruction of a printed contour map for a county-sized area is also quite simple. Finally, calculation of apparent slopes in percentages is easy, given the precise 100-meter baseline between elevation figures.

On the other side of the ledger, some problems can arise as a result of the process of translation from a latitude-based (or map-based) system to the UTM grid. One probable side effect is a noticeable "smoothing" of the data. Some of the "data points" in the PIC file represent a single measurement in the USGS (or DMA) DEM, whereas others are mathematical averages of two, four, or (rarely) three USGS (or DMA) numbers (Figure 11-4). This averaging procedure can reduce

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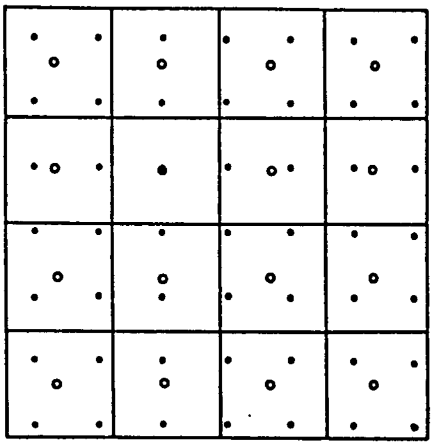
PROBLEMS WITH THE TRANSFORMATION OF AN ALTITUDE MATRIX TO A 100-METER GRID

A computerized Digital Elevation Model (DEM) is available from the Planning Information Center in the Minnesota State Planning Agency. This file of elevation "measurements" at 100-meter intervals is actually a tranformed version of a more cumbersome file of elevation data produced by the United States Geological Survey (or the Defense Mapping Agency, see text). The 100-meter spacing of data points in the PIC-DEM is substantially wider than the 208-foot interval between sample points in the DMA file (or even the 300-feet-by-200-plus-feet in the USGS file).

The black dots on this diagram represent locations of DMA data points in a small tract of land. The lines show a matrix of grid cells that are 100 meters on a side. The small circles depict the locations of the "measurement points" in the PIC-DEM grid.



Clearly, only one of the 16 PIC-DEM points in this example corresponds exactly to any of the DMA data points. Many of figures derived at the other data points in the PIC-DEM are really some kind of average of two or four (or, in rare cases with the USGS file, three) measurements from the original file. Each of these averages might be a simple arithmetic mean, a linear interpolation, or some other kind of distance-weighted calculation; we do not know (see text).

In any case, the process of averaging has "smoothed" the topography considerably. The broken lines on the two profiles below represent the "actual" landscape, as depicted by interpolating elevation data at 100-meter intervals from a topographic map. The solid lines show the landscape as recorded, also at 100-meter intervals, in the PIC-DEM.

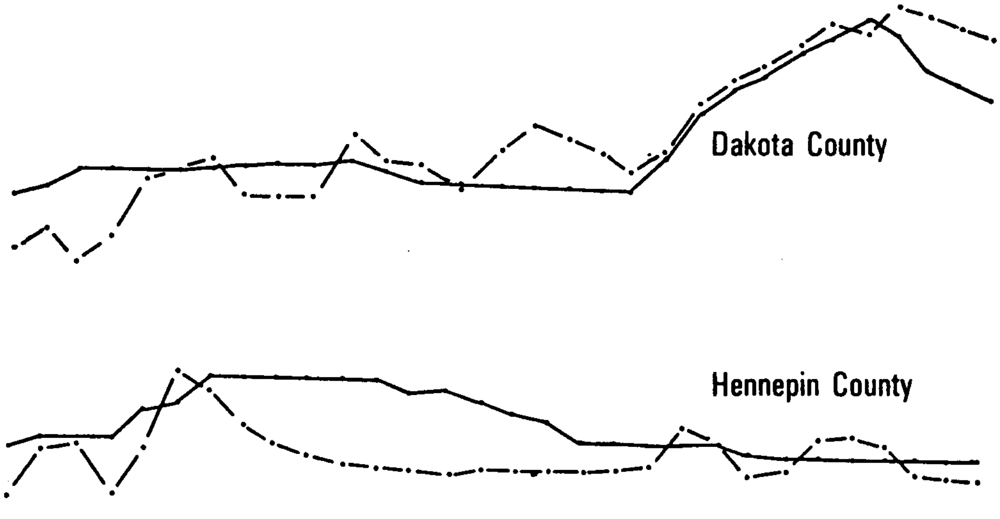


Figure 11-4

apparent slopes in intricate terrain. In effect, averaging will substitute a middle number (and an effective internal slope of zero) for what might have been a group of high and low points that had a great deal of slope associated with them. To evaluate the effect of this smoothing on the usefulness of the file, we examined a recent application of the elevation data in an erosion-hazard study.

Use of the PIC-DEM to map areas of high erosion hazard

The Minnesota State Soil and Water Conservation Board (SWCB) used the PIC-DEM (the Digital Elevation Model from the Planning Information Center) in a pilot program to target areas for conservation assistance (Meussig et al. 1983). Under pressure to comply with a Federal mandate to define target areas of high erosion hazard, the agencies cooperated to devise a modified Universal Soil Loss Equation. This procedure combined soil data from the Minnesota Soil Atlas files with elevation data from the PIC-DEM in order to determine the probable worst-case erosion rate from each forty-acre tract of land in Dakota County. According to an unpublished report entitled *Guidelines for Implementation of the Pilot Planning Program*, they derived a

> "slope steepness factor (from) digital terrain data determined for 2.5 acre cells and applying it to the steepest slope occurring in a 40 acre parcel."

The procedure appears to be a reasonable one, because the Board was trying to produce a "worst-case" map. The use of the modified USGS (or DMA) digital elevation model, however, may have compromised the validity of the simulation. To test this possibility, we selected a number of small parcels of land and replicated the procedures of the SWCB study, in order to study the results obtained by using three different sources of slope data. With the nicknames we will give them in this discussion, these are:

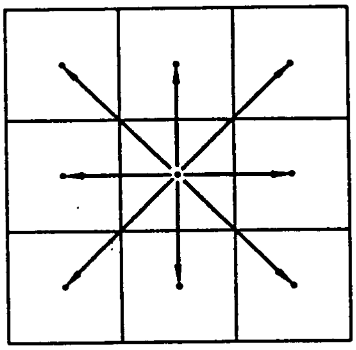
- "PIC-DEM," consisting of slope angles that were computed, in the manner described by the Soil and Water Conservation Board, from data in the digital elevation model provided by the Planning Information Center;
- "TOPO-DEM," consisting of slope angles computed with the same mathematical procedures but using elevation figures that were interpolated at 100-meter intervals from detailed (1:24,000) topographic maps; and
- "SLOPE SAMPLE," consisting of slope angles that were measured directly (from contour spacing) at data points spaced at 100-meter intervals on 1:24,000 topographic maps and checked, in a few instances, against field measurements.

Performing the calculations with these three different sources of slope data provided strikingly different estimates of erosion. In order to concentrate on the effects of slope, we held all other factors in the Universal Soil Loss Equation constant. For our demonstration, we used factors derived in the manner described by the SWCB ($R = 135$, $K = 0.32$, $L = 100$, $C = 0.39$, and $P = 1.0$). In general, estimates based on our SLOPE SAMPLE and on the TOPO-DEM were fairly close (within five tons per acre per year in more than half of the comparison sites). Estimates based on the PIC-DEM, by contrast, were highly variable, ranging from less than 10 percent to more than 150 percent of the erosion rates derived from direct slope measurements (Figure 11-5).

THE EFFECT OF DIFFERENT SOURCES OF SLOPE DATA ON THE AMOUNT OF SOIL EROSION "PREDICTED" BY THE USLE

An accurate estimate of the steepness and length of slope is important in trying to predict the rate of soil erosion from a field. To test the effect of different sources of slope data, we used the standard Universal Soil Loss Equation and held all factors constant except for the slope angle factor (S). Data on slope angle came from three different sources, as described in the text:

- slope angle measured directly from 1:24,000 topographic maps, using the template reproduced as Figure 11-3.
- slope angle calculated from elevation figures obtained by direct interpolation from 1:24,000 topographic maps, and
- slope angle calculated from the modified USGS-DMA-PIC Digital Elevation Model described in the text.



For the elevation-based slope estimates, we programmed a microcomputer to use a moving 3-by-3 "window" (like the one shown here), compute all eight possible slope angles from the center of each 100-meter grid cell, and report the one that was numerically the greatest. Then, following the procedure used by the Soil and Water Conservation Board, we took the largest of the 16 individual slope estimates for each 40-acre tract of land.

The diagrams below show the results of the analysis for four 40-acre test sites in each of three different kinds of terrain in Dakota County. The leftmost bar in each set depicts the erosion estimated on the basis of direct slope measurements. The central bar shows the results of the simulation with slopes calculated from the elevations derived directly from topographic maps. The dark bar in each trio represents the erosion estimated by using slope data calculated from the PIC-DEM. We conclude that estimates of erosion based on data from either Digital Elevation Model are not accurate enough for planning.

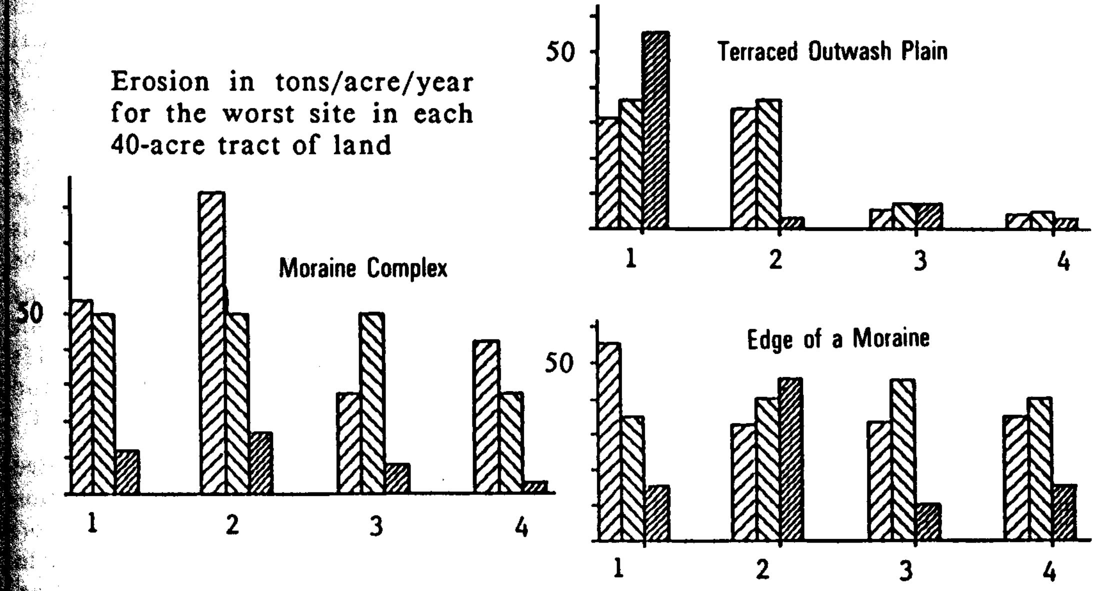


Figure 11-5

We conclude, therefore, that it is risky to use slope data calculated from a 100-meter DEM as a source of data for this kind of simulation. Others have also shows that data from a 30-meter DEM requires a lot of pre-processing and still produces questionable estimates of erosion (Gesch and Naugle 1984). We found that a TOPO-DEM (one made directly from topographic maps) might be acceptable for research, but not for applications such as zoning or targeting policy. The modified USGS-DEM, by contrast, had apparent errors that were both large and inconsistent. As a result, it is a shaky foundation for either research or planning.

The problem with this digital elevation model originates in the attempt to derive detailed slope data from general elevation measurements. The 1:250,000 topographic map series is already highly generalized, with a contour interval of (typically) fifty or one hundred feet in Minnesota. Interpolating elevation measurements at regular intervals from those contour lines will generalize that pattern even further; translating the DEM into metric coordinates will add even more "smoothing" to the data pattern (recall Figure 11-4).

The resulting data file can provide a useful general map of terrain for an area the size of half a dozen counties, but it simply does not contain the right kind of data for a calculation of slope at the scale of individual fields (Figure 11-6). Attempts to compensate for data limitations by selecting the largest estimate for each 40-acre area and calling the result a worst-case scenario are also doomed to failure, because the smoothing process used to make the PIC-DEM has left it with a wildly inconsistent pattern of error. As a result, the actual erosion for one data cell may be reasonably close to the estimate provided by the study, while in an adjacent cell it might be half, twice, or even ten times as much as "predicted" by the study. We conclude, then that the PIC-DEM is not adequate as a source of slope data for erosion studies. By implication, its utility is questionable for other hydrologic simulations at a similar scale.

THE ISSUE OF SAMPLE DENSITY

One alternative to using an existing digital elevation model is to wait until the next-generation USGS DEM is available for Minnesota. This data file will contain elevations that are determined (by photogrammetry) directly from aerial photographs. The spacing of the data points in experimental versions of the DEM is about 30 meters. This level of elevational detail is too minute for most kinds of regional hydrologic analysis with a microcomputer. Moreover, that file would have a serious theoretical barrier that could affect slope calculations. With a one-meter vertical resolution and a 30-meter horizontal spacing of sample points, it would be impossible to represent a slope between zero and 3.3 percent, a difference that is considered quite large for soil erosion studies. For other purposes, it would be relatively easy to use the DEM to derive a smaller file with estimates of slope angle and length made by trend-surface analysis at sample points. For this subsampling procedure to be successful, we must know the nature of the tradeoffs between sample density, arrangement, accuracy, and cost of data storage and processing (see Ayeni 1982 for a theoretical analysis of DEM considerations).

Another option is to interpolate elevation data at sample points on printed topographic maps and enter them into a computer file for use by the simulation studies. This way of gathering data will almost certainly be necessary in the short term, before detailed digital elevation models are available for the entire state. Training people to interpolate elevations from contour maps does not take long, and the process of digitizing locations at 100-meter intervals and entering elevation

TERRAIN REPRESENTATION BY TWO DIFFERENT SOURCES OF ELEVATION DATA AT 100-METER INTERVALS

The Digital Elevation Model in the Planning Information Center (PIC-DEM) appears to provide elevation data at 100-meter intervals in a regular X-Y grid. To evaluate the accuracy of these data, we selected three study areas of one square kilometer in Dakota County and recorded the elevation at 100-meter intervals, as interpolated from 1:24,000 topographic maps. Then, we obtained the PIC-DEM data for the same square kilometers. Finally, we entered both elevation matrices into a standard computer program (Golden Graphics) to draw a perspective view of the terrain. Clearly, the PIC-DEM can provide a general impression of topography but is an inadequate source of terrain data at the scale of a farm field.

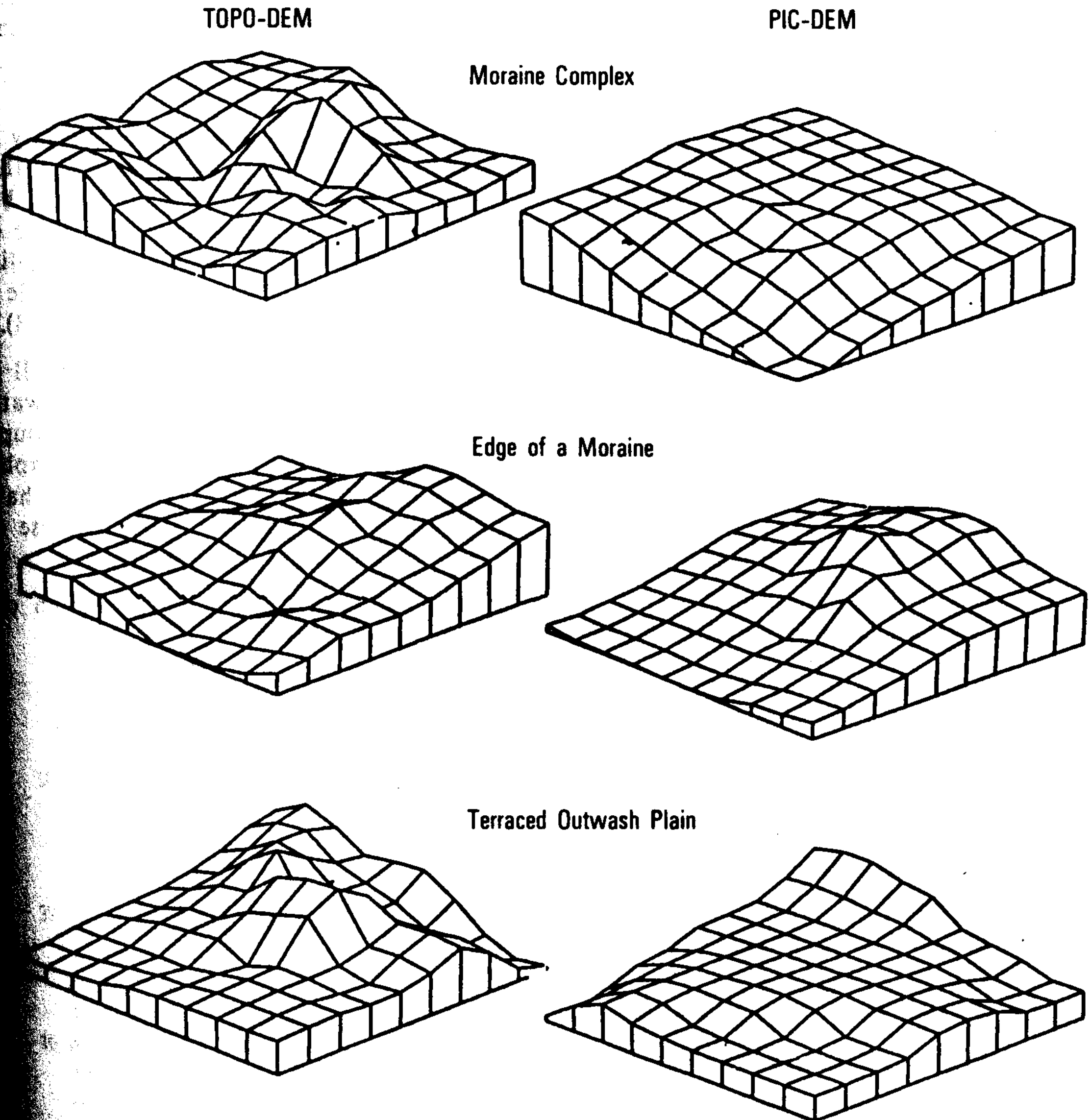


Figure 11-6

data seems to require only about twenty minutes per square kilometer. Obviously, the time required for data entry would decline if a coarser resolution (with fewer data points per cell) is acceptable.

A third option is to measure slope angle and length directly, rather than compute them from elevation samples. This procedure demands a higher level of sophistication on the part of the investigator, who must be able to interpret patterns of contour lines as well as interpolate elevations from them. At the same time, direct measurement may provide a more accurate estimate of slope traits than can be derived indirectly from elevation data. A hydrologic simulation may therefore be able to achieve an acceptable level of accuracy with a smaller number of measurements, which would reduce the encoding time and storage space needed by the terrain data file. The tradeoff between accuracy and sample spacing is not the same for direct slope measurements and elevation-based calculations.

Yet another alternative is to get slope data from printed soil survey maps, as described above. The question of sample density reappears, in a slightly different guise, when the samples come from an area-classified (*tag*) soil map. This kind of map substitutes a uniform slope code for the continuous variation in slope that characterizes most topography in the real world.

Finally, a fifth option is to sample slope length and angle, either directly in the field or indirectly on topographic maps, and then extend the results of that sampling to the intervening areas. This can be done by simple interpolation, but results are likely to be much more reliable if we use a good medium-scale map of landform regions as a guide (e.g. Hobbs and Goebel 1982). Statistical reliability would be enhanced even further by *clustered sampling*, which could provide a larger number of data points for the same amount of effort (Peterson et al. 1983).

Obviously, the question of sample density lies near the foundation of all of these methods of gathering terrain data. To help answer that question for a water resources GIS, we conducted a number of investigations into the effect of sample spacing on accuracy of terrain depiction. Figures 11-7 through 11-11 are graphic summaries of some of these studies; as in other chapters in this volume, we have chosen to report the results in this manner in order to facilitate their use in training programs and demonstrations.

We have drawn four general conclusions about sample density from our analyses of terrain measurement in many Minnesota landscapes:

- Using point measurements of elevation to describe topography does work, but it requires a relatively large number of sample points. Twenty-five samples per square kilometer (spaced 200 meters apart) are good enough to paint a general picture of typical Minnesota terrain. Calculating slope with reasonable accuracy in typical Minnesota terrain appears to require a measurement of elevation every 100 meters. A sample spacing of 20 meters (2500 data points per square kilometer) is barely adequate for calculations of slope lengths in many Minnesota landscapes.
- Direct measurement of slope angles and lengths at sample points is an efficient way to get data for current hydrologic simulations, but only if the data on slope, soil, and land cover all come from exactly the same sample locations. Four point samples of slope angle and slope length per square kilometer are adequate for simulating runoff and erosion in a typical mid-sized watershed (100 to 1000 square kilometers).

FREQUENCY DISTRIBUTION OF ELEVATION MEASUREMENTS FROM TWO DIFFERENT SOURCES OF DATA AT 100-METER INTERVALS

The Digital Elevation Model in the Planning Information Center (PIC-DEM) appears to provide elevation data at 100-meter intervals. To test the accuracy of this data file as a source of elevation data, we prepared graphs that show the frequency distribution of particular elevations in three different kinds of terrain in Dakota County. The solid bars show the number of times the PIC-DEM reported a given elevation; the hollow bars represent elevation figures interpolated from the corresponding 1:24,000 topographic map. The "smoothing" effect in the PIC-DEM is apparent in its tendency to report the same elevation for a relatively large proportion of the sample points in each square kilometer.

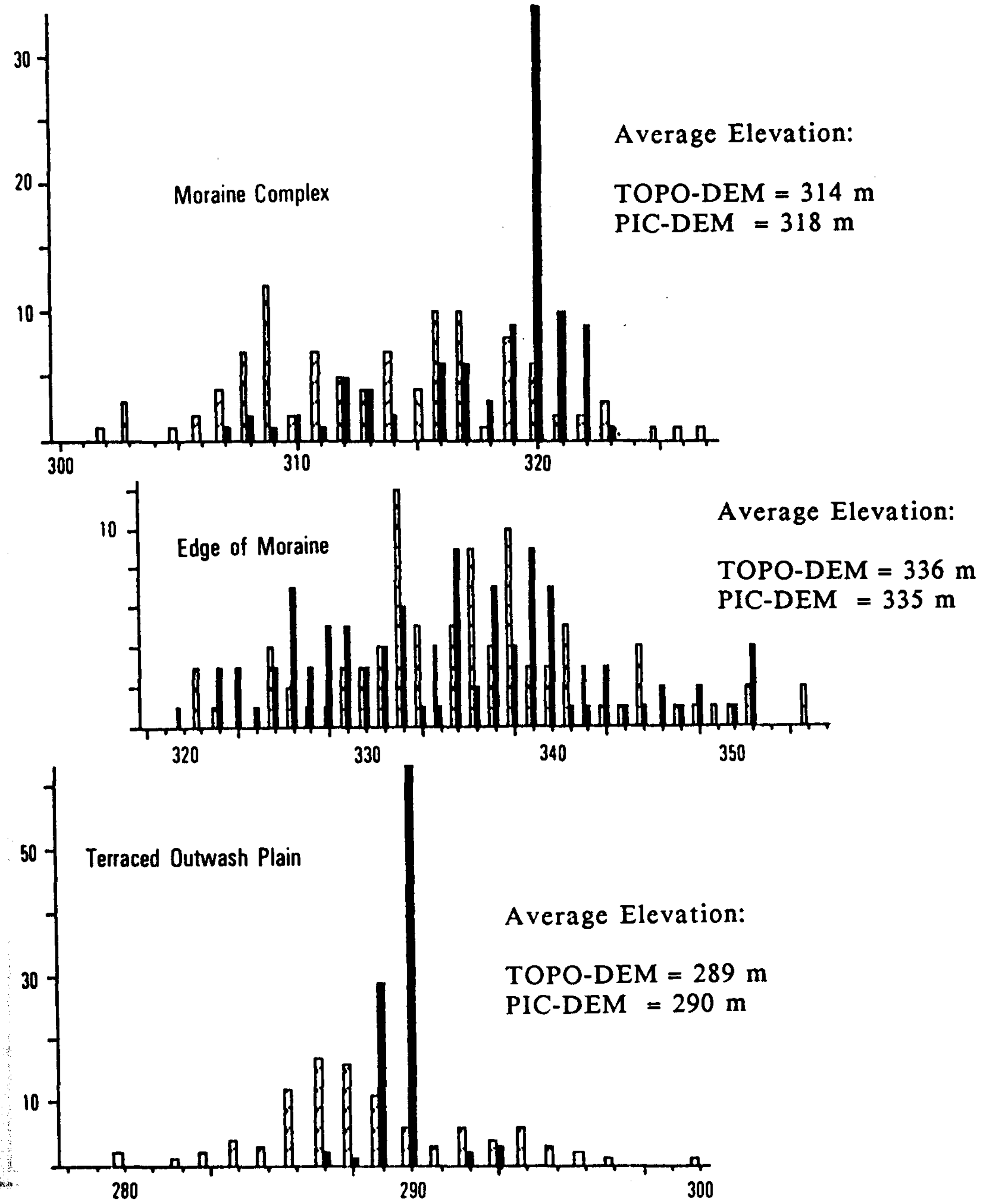


Figure 11-7

SAMPLE DENSITY NEEDED TO REPRESENT LANDFORM COMPLEXITY WITH A DIGITAL TERRAIN MODEL (DEM)

To investigate the ability of an elevation matrix (Digital Elevation Model) to represent typical Minnesota landscapes, we chose three transects, each four kilometers long, from near the centers of randomly selected topographic maps in Douglas, Olmsted, and Redwood Counties. The top line in each set is a profile of the terrain as depicted on the contour map. The other three lines are profiles drawn from point samples of elevation at intervals of 100, 200, and 400 meters.

The top set is from the Alexandria Moraine, a complex landform. Clearly, elevation samples at intervals of 100 meters can capture most of the complexity depicted on the topographic map. A "smoothing" effect is evident on the 200-meter profile, and most of the elevation changes are gone from the 400-meter profile. We then calculated the average slope angle and average slope length for each segment of the profiles. These figures show that enlarging the sample interval causes estimates of slope angle to decrease and estimates of slope length to increase.

For less complex landforms, a 200-meter interval between elevation data provides an adequate profile. Unfortunately, changing the sample density in order to accommodate landform complexity requires prior knowledge of the landform. Moreover, changing the sample interval results in an awkward data structure for a GIS.

Douglas County

	Calculated Data	
Sample Interval (meters)	Slope Length (meters)	Slope Angle (percent)
100	166	3.0
200	333	1.8
400	444	1.2

Redwood County

	Calculated Data	
Sample Interval (meters)	Slope Length (meters)	Slope Angle (percent)
100	222	0.9
200	364	0.7
400	571	0.3

Olmsted County

	Calculated Data	
Sample Interval (meters)	Slope Length (meters)	Slope Angle (percent)
100	260	6.4
200	475	5.5
400	720	4.5

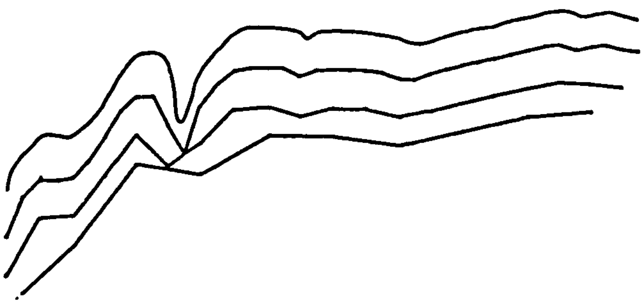


Figure 11-8

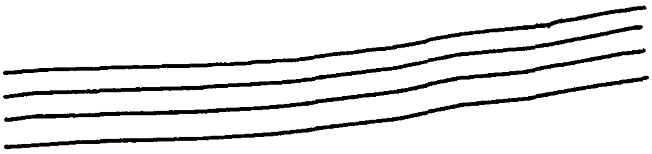
PROBLEMS OF CALCULATING EFFECTIVE HYDROLOGIC SLOPE LENGTH FROM A DIGITAL ELEVATION MODEL (DEM)

The X-Y coordinate structure of a digital elevation model allows a computer to determine elevation differences between adjacent cells and thus to calculate slope angles and lengths. Unfortunately, "slope length," as defined by an erosion analyst, is not equivalent to the intuitive idea of "continuously declining elevation." For example, the Universal Soil Loss Equation needs "field slope length," measured from the high point to where water flow changes from sheet and rill flow to some kind of defined channel. A good topographic map will have enough clues for the interpreter to locate channels, but a computer supplied only with elevation data at 100-meter intervals may not be able to identify the end of slopes for the USLE.

To investigate the severity of slope-length misrepresentation, we chose three transects, each four kilometers long, from near the centers of randomly selected topographic maps in Clay, Dakota, and Hennepin Counties. The top line in each set is a profile of the terrain as depicted on the contour map. The other three profiles come from point samples at intervals of 100, 200, and 400 meters. In each county, the topographic profile has obvious channels that interrupt the slope but do not appear on the DEM profiles (which explains why all of the DEM estimates of slope length, here and on Figure 11-8, are much longer than the ones we got by direct measurement; see Figure 11-3). This inability to show slope lengths with sufficient accuracy for hydrologic modeling will plague even the forthcoming 30-meter DEM, obtained directly from aerial photography (O'Neil and Mark 1985).

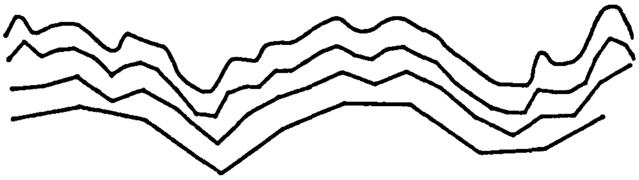
Clay County

	Calculated Data	
Sample Interval (meters)	Slope Length (meters)	Slope Angle (percent)
100	4000	0.16
200	4000	0.16
400	4000	0.16



Dakota County

	Calculated Data	
Sample Interval (meters)	Slope Length (meters)	Slope Angle (percent)
100	229	7.9
200	317	6.1
400	720	4.6



Hennepin County

	Calculated Data	
Sample Interval (meters)	Slope Length (meters)	Slope Angle (percent)
100	244	5.9
200	271	5.1
400	600	2.3

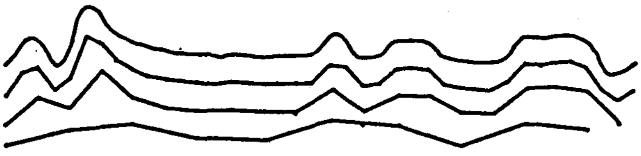


Figure 11-9

EFFECT OF SAMPLE DENSITY ON THE ACCURACY OF ESTIMATES OF AVERAGE SLOPE ANGLE AND SLOPE LENGTH

The terrain data file in a water resource GIS must provide accurate estimates of slope angle and slope length. We have concluded that direct measurement of slope at sample points on topographic maps is an efficient method of entering slope information into a data base. In this study, we are trying to determine how many sample points are necessary to hold error to an acceptable minimum. The study area consists of four square kilometers that span the edge of a subdued glacial moraine and an outwash plain in Dakota County. Using the template reproduced in Figure 11-3, we measured the slope angle and slope length at the centers of 100 data cells arranged in a regular 10-by-10 grid within each square-kilometer.

The first step in this process was to determine the direction a drop of water would take if it flowed away from the center of the cell. Then, we measured the spacing between contour lines in that direction. Finally, we measured the apparent length of flow down that slope, starting at the top of the hill or ridge and ending where the flow is likely to enter a channel. Figure 11-3 reported the degree of variation among two people doing this kind of task -- their measures of slope angle are usually very close to each other, but the estimates of slope length can vary by as much as 35 percent.

Our next step was to extract subsamples from this set of 400 measurements. We took ten sets of samples at each of three densities. The graphs on this page show the error associated with determining average slope angle and length with different numbers of measurements per square kilometer. We conclude that measuring slope angle at eight or nine sample points would adequately describe the anerage slope angle of a square-kilometer UTM data cell [see chapter 2]. Slope length is a bit more of a problem; 25 samples per square kilometer still have a probable error of more than 10 percent in describing the average slope length in that data cell. For describing average slope lengths in a larger area, however, a smaller number of samples per square kilometer would be adequate (as long as the output maps do not attempt to display data at a one-kilometer resolution; see chapter 2]. Finally, we should note that the number of sample points needed in different landscapes will vary -- we deliberately chose a rather complex landform in order to run these tests [see Figures 10-4 and 10-11 for related studies].

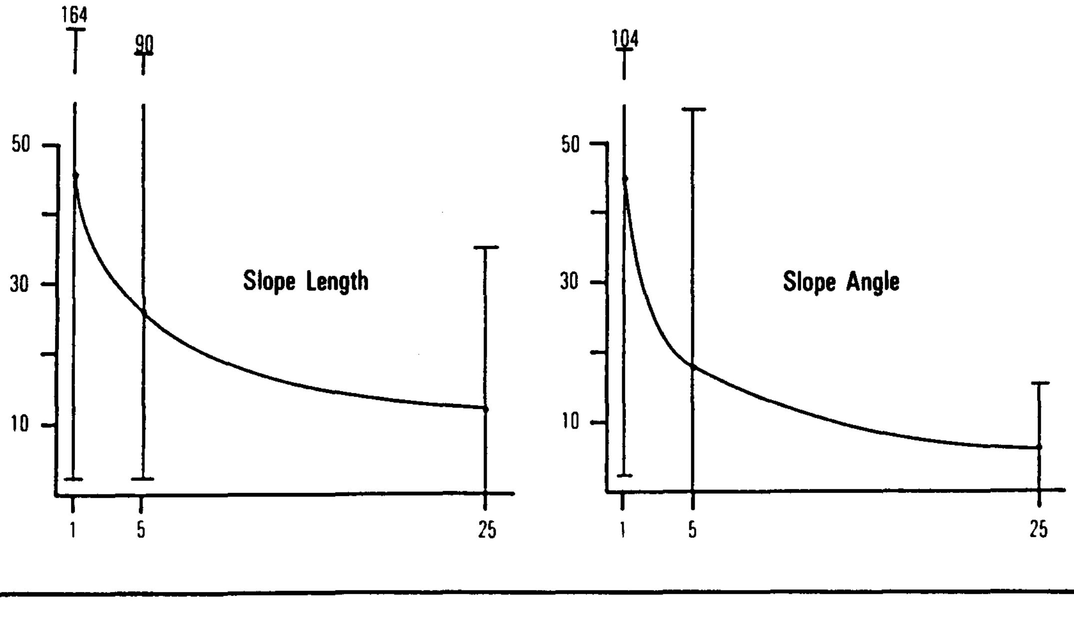


Figure 11-10

VALIDITY OF COUNTY SOIL SURVEYS AS A SOURCE OF TERRAIN DATA FOR A WATER RESOURCES GEOGRAPHIC INFORMATION SYSTEM

The mapping units on the detailed maps in a county soil survey include a single-letter code that indicates the general slope class for the soils in that mapping unit. If they are accurate enough, these codes could serve as a source of terrain data for a water resources GIS. We tested their accuracy in depicting the average slope for nearly a hundred 40-acre tracts of land in Olmsted County, Minnesota. The study area, part of Marion Township, included part of a gently rolling plateau and several incised creek valleys.

We used a random-dot template with 160 dots per square mile and recorded the slope class from the county soil survey and the calculated slope angle at the same locations from 1:24,000 topographic maps. The coding was straightforward and fairly fast from the soil survey -- the correlations between records by two different map interpreters were well above 0.9. By contrast, determination of slope angle from topographic maps took about three times longer and involved some judgment calls, and the correlation between two analysts was only about 0.8. Interpretation of the results, however, was more difficult with the soil survey data, because a slope class in the soil survey actually spans range of slope angles (e.g. the slope angles in the "B" class extend from 2 to 6 percent).

Using a median value for the slope classes resulted in a relatively high correlation of 0.74 between the soil survey groups and the slope angles measured on topographic maps. In other words, the soil survey interpreter got about as close to one topographic map interpreter's estimate of average slope in a 40-acre cell as the other topographic map interpreter did. The pattern of deviation was consistent, with the soil survey showing slightly steeper slopes than the measurements from the topographic map. Substituting the minimum end of the range for each slope phase gave smaller estimates of slope and lower correlations with topographic map measurements ($r = 0.64$). It might be possible to improve the correlation slightly by searching for an optimum interpolated value within slope classes, but examination of the six square miles in the study area suggests that the optimum might vary in different kinds of terrain. We conclude, then, that the detailed maps in a county soil survey are a reasonably accurate source of slope information for a GIS.

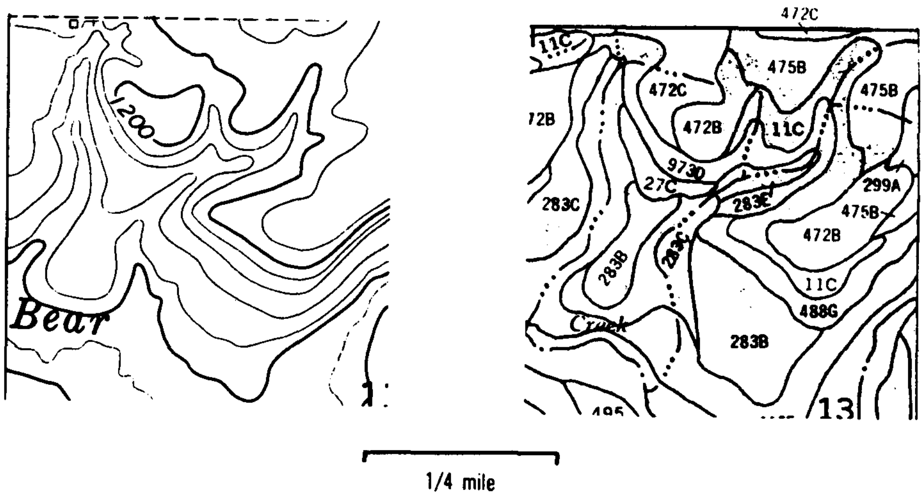


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Figure 11-11

- Recording slope information from soil maps is a viable alternative to using topographic maps, but only if there is no need for data on slope length. Most runoff and erosion simulations require both kinds of slope data, and therefore we do not recommend the use of soil maps as a sole source of terrain data. Recording slope information while collecting soil data, however, can provide a valuable check on the accuracy of terrain measurements from topographic maps or other sources.
- A two-stage design (using a medium-scale landform map as a guide in extrapolating from data taken at sample points) could make a big improvement in present files of slope data at relatively low cost. Sources of map data might include the PIC files derived from the Minnesota Soil Atlas (described in chapter 10 of this volume) and the map by Hobbs and Goebel (1982). The result, however, is best be viewed as no more than an interim solution, because it could not provide the strict relationality required for hydrologic simulation (see chapter 2 in this volume).

In summary, we have a variety of options for providing terrain data for a water-resources GIS. Selection of one or two of these options should be a high-priority task, because terrain information is currently a very weak link in the data chain for most hydrologic simulations. The validity of the Universal Soil Loss Equation (and other simulations based on it) is seriously compromised by the lack of good estimates of slope length in different regions. We would recommend a rigorous program of direct measurement of slope angle and slope length at sample points throughout the state. In the meantime, we could partially fill the gap by a modest program of sampling from topographic maps and extrapolation with the assistance of data from existing landform maps.

THE NEXT GENERATION OF HYDROLOGIC SIMULATIONS

Measurement of slope angle and length at sample points, even at a relatively coarse resolution (four data points per square kilometer) is more than adequate for existing hydrologic simulations. As described in chapters 2, 6, and 9 of this volume, current methods of predicting runoff, erosion, and flooding are primarily *fitted models* that require precise measurements at a few sample points in order to describe relatively large areas. Nieber and Lopez Bakovic, however, included some descriptions of an emerging set of *physical-based models* that require detailed information for small areas in order to run (see chapter 8 in this volume).

Many of these new hydrologic simulations begin by calculating the amount of surface area that can potentially contribute runoff to each segment of a contour line on a topographic map (Moore and Burch 1986; Moore, personal communication, May 1987). This procedure is repeated for each contour line from the crest of a hill down to the receiving stream. The contour maps needed for contributing-area analysis to work are substantially more detailed than those currently being produced by the USGS, but the procedure is capable of defining areas of flow convergence and divergence better than any other method.

Analysis of contributing areas is labor-intensive, given the current state of topographic mapping, and therefore it has not yet been applied to catchments larger than a few square kilometers. Nevertheless, if the method can overcome some serious theoretical problems with runoff routing, it does have potential as a substitute for the watershed models currently in use. Among other things, area-analysis can do a much better job of defining zones of soil saturation, a key element in trying to simulate the process by which overland flow is generated from soils that have substantial amounts of internal lateral seepage.

In summary, there is little question that a sound physical-based simulation will eventually replace the hybrid models currently used to predict runoff. We believe, however, that a new generation of contour maps, probably in digital form, will be available by the time the next generation of simulation algorithms have been developed. In other words, we see no reason to begin widespread vector-encoding of existing contour data for a Minnesota GIS at this time. The structure of the water resources GIS should be keyed to the demonstrated data needs of those hydrologic simulations that are likely to be used here in the near future. We should not design our GIS on the basis of speculation about the possible data requirements of emerging theoretical models whose traits are not yet known.

SUMMARY AND CONCLUSIONS

In this chapter, we have examined the roles that information about terrain might play in a geographic information system designed to provide data for water resources managers and planners. Specifically, we have investigated the costs and accuracies of six ways of handling terrain data: vector encoding of contour lines, storage of altitude measurements in a Digital Elevation Model, construction of side profiles, Delaunay triangulation, recording slope classes from soil survey maps, and calculating slope angles and lengths directly from topographic maps. Our major conclusions include the following:

1) The digital elevation files produced by the United States Geologic Survey are good sources of data to depict generalized topography in an area. However, in many Minnesota landscapes (e.g. glacial moraines, pitted outwash plains, drumlin fields, beach ridges, or stream terraces), the USGS data files simply do not capture the essential complexity of the terrain.

2) Calculating slope from an existing computerized digital elevation model (DEM) does not produce results that are acceptable for hydrologic simulation. As an illustration, we examined a study of "High Priority Water Erosion Areas in Dakota County," based partly on elevation data derived from the USGS DEM; we found that it produced estimates of soil erosion that ranged from less than one tenth to more than twice the amount calculated on the basis of direct slope measurements.

3) Good terrain depictions can be made on the basis of interpolated elevations taken from 1:24,000 topographic maps at densities of about 100 samples per square kilometer, but this procedure is costly in terms of labor for data entry and error correction.

4) A system of direct measurements of slope angle and slope length at sample points can produce data for hydrologic simulations that is more accurate and less expensive than any other method we investigated. Indeed, our studies appear to support the counter-intuitive idea that a single direct slope measurement per square kilometer may be more useful than a hundred elevation samples per square kilometer in assessing total runoff or soil erosion in a township-sized watershed.

5) Sampling of slope classes from soil survey maps is quicker and almost as accurate as direct slope measurements from 1:24,000 topographic maps. Unfortunately, many parts of Minnesota have no up-to-date soil survey. Moreover, even in those areas with modern surveys, some analysis of topographic maps is still necessary in order to obtain data on slope lengths, a vital component of many hydrologic simulations.

6) The next generation of simulation studies of runoff or erosion on a field scale will work better if detailed contour lines are digitized in vector form. No water-resource simulation at a regional scale, however, is currently able to make use of that kind of data.

7) A combination of several data files may help improve the accuracy of terrain data. For example, the presence of marsh vegetation in the land-cover file, or an area of poor drainage in the soil file, may help to clarify a potentially ambiguous situation in the topography file. This cross-examination is especially useful in trying to derive a drainage network from terrain data (see Brown et al., chapter 12 of this volume).

8) Output maps from a point-inventory system must be carefully made to avoid misinterpretation. A point-sampling procedure allows us to say, with some confidence, that "the average slope in area A is B" or that "C percent of area D is in slope class E," but we cannot have the same confidence in trying to describe the slope at a point that did not happen to be one of the sample points. It is difficult to emphasize this fact too much -- the slope midway between two sample points may indeed be the arithmetic average of the slopes measured there, but it also may be greater or less than either measured slope. For that reason, it is dangerous to interpolate between sample points; the printing system that produces maps derived from sample data should simply not be permitted to portray data at individual sample points. Rather, it should display only the percentages of larger areas that fall into particular categories. As a rule of thumb, the output map should display data at a resolution that is at least a full order of magnitude less detailed than the sample data. If more detailed information is needed, field surveys are necessary.

REFERENCES

Ackermann, F. 1978. Experimental Investigation into the Accuracy of Contouring from DTM, *Photogrammetric Engineering and Remote Sensing* 44:1537-1548.

Allder, W. R. and A. A. Elassal. 1985. Digital Line Graphs from 1:24,000-scale Maps, *Circular Number 895-C* (Washington, D.C.: United States Geological Survey).

Anderson, K. L. et al. 1987. Twin Cities Surface Water Simulation Modeling Demonstration, *Special Report Number 12* (St. Paul, Minnesota: Water Resources Research Center)

Ayeni, O. O. 1982. Optimal Sampling for Digital Terrain Models: A Trend Towards Automation, *Photogrammetric Engineering and Remote Sensing* 48:1687-1694.

Douglas, D. H. 1987. Experiments to Locate Ridges and Channels to Create a New Type of Digital Elevation Model, *Cartographica* 23:29-61.

Elassal, A. A. and V. M. Caruso. 1983. *Digital Elevation Models*, Circular Number 895-B (Washington, D. C.: United States Geological Survey)

Gersmehl, P. 1987. Use of a Cellular Geographic Information System in Assessing Soil Erosion and Sediment Deposition in Two Medium-sized Watersheds, *Proceedings*, Urban and Regional Information Systems Association, Fort Lauderdale: in press.

Gesch, D. B. and B. I. Naugle. 1984. An Analysis of the Utility of Landsat Thematic Mapper Data and Digital Elevation Model Data for Predicting Soil Erosion, in M. M. Klepfer and D. B. Morrison, eds., *Machine Processing of Remotely Sensed Data* (West Lafayette, Indiana: Purdue University Laboratory for Applications of Remote Sensing), 260-265.

Hardy, Ernest E. and Ronald S. Senykoff. 1981. Design Concepts for Natural Resource Inventories, in Brann, T. B., L. O House, IV, and H. G. Lund, eds., *Proceedings of a National Workshop on In-Place Resource Inventories: Principles and Practices* (Orono, Maine: Society of American Foresters), 101-107.

Hobbs, H. C. and J. E. Goebel. 1982. *Geologic Map of Minnesota: Quaternary Geology*, State Map Series S-1, scale 1:500,000 (Minneapolis: Minnesota Geological Survey).

Jensen, S. K. 1985. Automated Derivation of Hydrologic Basin Characteristics from Digital Elevation Model Data, *Proceedings*, Auto-Carto 7:301-310.

Mark, D. M. 1984. Automated Detection of Drainage Networks from Digital Elevation Models, *Cartographica 21:168-178.*

Meussig, L. F., A. Robinette, and T. Rowekamp. 1983. *Application of the USLE to Define Critical Erosion and Sedimentation in Minnesota* (St. Paul: Minnesota State Soil and Water Conservation Board).

Moore, I. D. and G. J. Burch. 1986. Physical Basis of the Length-Slope Factor in the Universal Soil Loss Equation, *Journal of the Soil Science Society of America* 50:1294-1298.

O'Neill, M. P. and D. M. and Mark. 1985. "The Use of Digital Elevation Models in Slope Frequency Analysis," paper presented at the Pittsburg Conference on Modeling and Simulation, April 25-26.

Peterson, D. L., D. Noren, and G. Gnauck. Methods and Results of Three Unequal Probability Multistage Sampling Designs for Timber Volume in the Pacific Northwest, in J. F. Bell and T. Atterbury, eds., *Renewable Resource Inventories for Monitoring Changes and Trends* (Corvallis: Oregon State University), 326-329.

Peuker, T. K., R. J. Fowler, J. J. Little, and D. M. Mark. 1978. The Triangulated Irregular Network, *Proceedings of the DTM Symposium*, American Society of Photogrammetry - American Congress on Surveying and Mapping (St. Louis), 24-31.

Snell, E. A. 1984. *A Manual for Regional Targeting of Agricultural Soil Erosion and Sediment Loading to Streams*, Working Paper No. 36, Lands Directorate, Environment Canada.

Thompson, M. M. 1982. *Maps for America*, 2nd Edition (Washington, D.C.: United States Geological Survey)

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1986. *Agricultural Nonpoint Source Pollution Model: A Watershed Analysis Tool* (St. Paul: Minnesota Pollution Control Agency).