Lecture Notes: "Land Evaluation"

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Part 2: Geographical Information Systems

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Contents for "Geographical Information Systems"

This unit presents Geographical Information Systems, an indispensable tool for map analysis and presentation for land evaluation. Two related topics are presented in this unit, because of their importance for geographic analysis: Digital Elevation Models and the Global Positioning System.

1. GIS : Introduction and orientation

Almost always a land evaluation presents its results as *maps*. In addition, the *location* and other *spatial characteristics* of evaluation units are often important *land characteristics* in the evaluation itself. In this set of lectures we study GIS and remote sensing *as applied to land evaluation* only. There are many other uses of GIS, e.g., facilities management and network analysis, that we will not study.

1.1 GIS General References

(Burrough, 1986) is the best text on GIS for land evaluation; (Tomlin, 1990) presents a coherent and rational method of spatial analysis with many examples in land use planning. An encyclopedic overview of GIS and its applications is (Maguire, Goodchild & Rhind, 1991). Most GIS programs come with tutorials; the series with IDRISI (Eastman, 1992) and Arc/INFO (Environmental Systems Research Institute, 1993) are both good. The IDRISI project, under contract from UNITAR, has produced a series of workbooks with sample datasets for change and time-series analysis (Eastman & McKendry, 1991), forestry applications (McKendry *et al.*, 1992), coastal-zone management, and decision making under uncertainty (Eastman *et al.*, 1993).

1.2 Sources of information on GIS and digital datasets

The “Frequently Asked Questions” (FAQ) of the ‘comp.infosystems.gis’ Internet news group is indispensable for definitions, addresses of data sources etc. This list is posted to the comp.infosystems.gis and news.answers news groups on a monthly basis; from there you can save it to a file and print it The most current version is available via anonymous FTP on ‘abraxas.adelphi.edu’ in the file ‘/pub/gis/FAQ’

Digital Chart of the World

The Digital Chart of the World is a 1.7 GB digital geographic database that is available on CD-ROM. It was input from 1:1,000,000 Operational Navigation Charts and 1:2,000,000 Joint Navigation Charts of the Defense Mapping Agency. It includes 17 layers, aeronautical information, data quality info, drainage, supplemental drainage, hypsography, hypsography supplemental, land cover, ocean features, physiography, political/ocean, populated places, railroads, transportation structure, utilities, and vegetation. Note the coarse scale of the source maps. Also some areas of the world are much more reliable than others. Mann Library reference has a copy of this data set

Global Resource Information Center (GRID)

This is a system of cooperating centers, organized by the United Nations Environmental Program, that is dedicated to making environmental information more accessible to analysts and decision makers. They collect digital data from a wide variety of sources, and make it available free or for the cost of reproduction.

There is on-line access by ftp to ‘grid2.cr.usgs.gov’, or under Mosaic. There are six offices worldwide; the most accessible from the USA is at the EROS Data Center in South Dakota, e-mail ‘grid@grid1.cr.usgs.gov’.

1.3 Definition

A GIS is an assemblage of computer *equipment* and a set of computer *programs* for the:

1. entry and editing,
2. storage,
3. query and retrieval,
4. transformation,
5. analysis, and
6. display (soft copy) and printing (hard copy)

... of *spatial* data.

Key point: All data in a GIS is *georeferenced*, i.e. located by means of geographical coordinates with respect to some reference system. This is how a GIS differs from computer-aided drafting or graphics program.

1.4 Components of a GIS

Hardware: processor (CPU), often a mathematical co-processor, temporary memory, graphic display and video memory, on-line storage (magnetic or optical disk), off-line storage (tape, removable disks), input devices (keyboard, pointing device, digitizing tablet, scanner), output devices (line plotter, color graphics printer). From quite inexpensive ($1,000) to very expensive ($100,000). May have a *network* of computers sharing their *peripherals*.

Operating system (OS): controls the hardware (and network if any) and executes programs. High-performance GISs almost all work under the UNIX OS or another minicomputer/workstation OS (e.g., VMS). Microcomputer OSs: Microsoft MS-DOS, IBM PC-DOS, Macintosh. Multitasking and network-ready microcomputer OSs: IBM OS/2, Microsoft Windows NT.

Software: modules for map and legend data entry and editing, data transformation (e.g. map projections), data management, data retrieval (queries), map display and output, map analysis. From 'free' (public domain) to inexpensive (<$1,000) to quite expensive ($100,000) for specialized analysis.

As with all other areas of computation, GIS technology is constantly becoming more powerful and less expensive. The trend is towards more power to the individual user on the one hand, and better coordination between users on the others (e.g. shared data bases).

2. Coordinate systems & map projections

Since all data in a GIS must be georeferenced, the question naturally arises, referenced to what? Answer: a *coordinate system*.

A simple explanation of projections, coordinates and datums is in (Eastman, 1993) p 22-27, a bit more complicated in (American Society of Photogrammetry, 1980) p. 413-421. A standard reference is (Snyder, 1987). Strahler’s various physical geography texts also have simple explanations.

2.1 Spherical coordinates

Two coordinates determine the position on the surface of earth’s ellipsoid: *Latitude* (north or south of the equator) and *longitude* (east or west of the standard meridian at Greenwich, England - the last remnant of England’s imperial ‘glory’ - to the International Date Line at 180°E/W in the middle of the Pacific Ocean)

Latitude and longitude are measured in (arc)*degrees* (360° in a circle), (arc)*minutes* (60’ in 1°) and (arc)*seconds* (60” in 1’). The mean minute of latitude defines one nautical mile = 1,852m. Therefore the equator-to-pole distance is (60’ °$^{-1}$ x 90°) x 1.852km ’$^{-1}$ = 10,000 km exactly. An arc-second of latitude, and of longitude at the equator, is thus 1,852/60 = 30.866...m. A degree of latitude, and of longitude at the equator, is 60° * 1.852km °$^{-1}$= 111.12km.

All Lat/Long references must be referred to a standard *datum*, which consists of a reference *ellipsoid* and coordinate *origin*. A datum specifies a coordinate system and the positions of known control points in that system. The origin is at (0°, 0°) as defined by the prime meridian (Greenwich) and the equator. Lat/Long references with different datums may be substantially different (100s of meters between ground points with the same coordinates) between the various ellipsoids.

Advantage: one system for the entire earth, more-or-less conforms to the shape of the earth, so no systematic distortions.

Disadvantage: spherical not planimetric, must use spherical trigonometry to measure areas and distances, must project onto flat maps where the grid lines are curved.

2.2 Planimetric coordinates & the UTM projection

Points on the ellipsoid are *projected* to a flat piece of paper (a 2-dimensional map). Many projections, varying in their properties: can't have all of: (1) equal *areas*, (2) true *directions*, and (3) a single *scale* over the whole map. The most common projection in international land evaluation applications at medium to large scales is the *Universal Transmercator* or *UTM* projection (American Society of Photogrammetry, 1980) p. 419-420, (Davis *et al.*, 1981) p. 571-576. At continental scales, the *Albers Equal-area projection* is often used.

The UTM projection was intended for military purposes over relatively small areas. In the Mercator projection a straight line has constant compass bearing.

Distortion is controlled by orienting the projection to a north-south *central meridians* (so the projection is *Transversal* with respect to the equator), and by dividing the earth in 60 strips (*zones*), each covering 6° of longitude (approx. 667.8km wide at the equator). The scale is exact on two meridians per strip and has a maximum error of 1 part in 1000 at the edges of the strip; the error is 1 in 2500 along the central meridian. Zone 1 is from 180°E/W (the International Date Line) east to 174°W, and so eastward to Zone 60 from 174°E to 180°E/W. There is an overlap of 30' between adjacent zones.

The equator is assigned 0m in the northern hemisphere, 10,000,000m in the southern, so that Y (north-south) coordinates are always positive.

The central meridian is assigned the coordinate 500,000m, so that with the zone being at most 667km wide, there are *no negative coordinates* in X (east-west) either.

Even though areas and distances are not exactly represented on the map, it is more than precise enough for land evaluation and registering remotely-sensed information at project and even regional scales.

2.3 Conversion between projections

All projections are based on exact mathematical formulas, so can be inter-converted. But the datum and reference ellipsoid must be specified. (IDRISI module PROJECT, projections are described in DESCREF, listed in LISTREF, edited with EDIT Option 7.)

2.4 Elevations

Elevations are measured in meters above or below *mean sea level*, a known vertical coordinate defined by the geodetic survey of the country. This is the same whether the X & Y coordinates are spherical or planimetric. In the case of spherical coordinates, the elevations are on the *radius* of the sphere; for planimetric coordinates, they are in the vertical dimension, orthogonal to the two horizontal coordinates X & Y.

3. Digital map representations: grid & vector

The key question is, how do we represent the features of a map (by extension, features on or near the surface of the earth) in the computer? The computer contains a *digital representation* of the map, which it can manipulate and present. There are two *conceptual representations* used in GISs: *grid* (sometimes called 'raster') and *vector*. These are very different ways of thinking about geography, which lead to very different methods of analysis.

3.1 The grid or 'raster' representation of a map

Basic idea: the map area is divided into *cells* (sometimes erroneously called *pixels*, see below), normally square or at least rectangular, on a regular *grid*. Each cell is supposedly homogeneous, in that the map is incapable of providing information at any resolution finer than the individual cell. The map shows exactly one value (land use, elevation, political division...) for each cell.

(Formerly, this representation was referred to as a *raster*. The name 'raster' comes from the original display technology: a scanning CRT, like a television screen, and refers to the left-to-right, top-to-bottom scanning.)

Key point: The *grid cell* is the only unit of spatial information and analysis.

Different *themes* are stored as separate maps (also called *overlays* or *coverages*), which are related by a common coordinate system. For example, there may be one map of population centers, another of political subdivisions, another of geology, another of land cover, etc., all covering the same area.

This is a very simple representation in the computer: conceptually, a 2-D matrix of values which correspond to a grid placed over the paper map.

3	3	3	6	6	6	6	6
3	3	6	6	6	2	2	2
3	3	3	6	6	6	2	2
5	3	5	4	6	4	2	1
5	5	4	4	4	4	1	3

The *resolution* of the map is the lineal dimension of the cell times $\sqrt{2}$ (diagonal). Note there is no *scale* of a grid map, only a *resolution*.

Graphic representation: on the computer screen or printer with one or more *pixels* ('picture elements') which are the smallest areas of the display device that can receive a separate graphic treatment (color or intensity).

The *graphic scale* depends on the actual size of the image on the output device compared with the feature being represented.

$$Scale = \frac{Lineal\ size\ of\ pixel}{Lineal\ size\ of\ cell} \cdot pixels\ cell^{-1}$$

For example, a printed page of 216mm width, divided into 80 printer positions, gives 2.7mm pixel^{-1}. Suppose 2 cells must be represented by each pixel (contraction by a factor of two), gives 0.5 pixels cell^{-1}. Suppose each cell represents 30m x 30m on the ground, i.e., the lineal size of the cell is 30,000mm. Graphic scale: (2.7/30,000) x 0.5 = 0.000045 = 1:22,222.

3.2 Advantages of the grid representation

1. Simple concept
2. Easy management within the computer; many computer languages deal effectively with matrices (including special-purpose matrix languages like MATLAB and APL).
3. Map overlay and algebra is simple: cell-by-cell
4. Native format for satellite imagery
5. Suitable for scanned images
6. Modeling and interpolation is simple, because the grid of data is dense and complete
7. Cheap technology

3.3 Disadvantages of the grid representation

1. *Fixed resolution*, can't be improved. So when combining maps of various resolutions, must accept the coarsest resolution
2. *Information loss* at any resolution, increasingly expensive storage and processing requirements to increase resolution
3. *Large amount of data* especially at high resolution
4. Not appropriate for high-quality cartography (line drawing)

5. Slow transformations of projections (must transform each cell)

6. Some kinds of map analysis (e.g. networks) is difficult or at least not ‘natural’.

Note: there are more advanced data types based on a variable-size grid (finer where more detail is needed) that do away disadvantages (1), (2), and (3), but the advantages (2), (3) and (6) become less applicable. Commercial system based on ‘quadtrees’: SPANS.

3.4 The vector representation of a map

Basic idea: *points* on a map are stored in the computer with their ‘exact’ (to the precision of the original map and the storage capacity of the computer) coordinates.

-— Points can be connected to form *lines* (straight or described by some other parametric function) or *chains*;

—- Chains can be connected back to the starting point to enclose *polygons* or *areas*.

Each of these *spatial entities* may have an *identifier* which is a *key* to an attached *database* containing the *attributes* (tabular data) about the entity. All the information about a set of spatial entities can be kept together, i.e., multi-thematic maps.

> Example: a point which represents a population center may have a database entry for its name, population, mean income etc. A line which represents a road may have a database entry for its route number, number of lanes, traffic capacity etc. A polygon which represents a soil map unit may have a database entry for the various soil characteristics (depth, parent material, field texture...).

(The name ‘vector’ comes from the connection between points by means of a line with specified *magnitude* and *direction*, and from the original display technology: CRT with controllable electron beam.)

3.5 Topology

In the vector representation, the various geographic entities (points, chains, polygons) have a definite spatial relation called *topology*. Although as humans we perceive these spatial relations without even thinking about them, they must be explicit for the computer. Some examples:

(1) *Connectedness*: lines are connected at *nodes*.

(2) *Adjacency*: polygons are adjacent if they share a common boundary line.

(3) *Containment*: one polygon can contain another as an 'island'.

Topology can be stored as part of the map representation (in the database tables) or built as needed from the coordinates of each entity.

In the grid representation, the only topology is cell *adjacency*, and this is *implicit* in the representation (i.e., defined by the grid addresses), not explicit as in vector topology.

3.6 Advantages of the vector representation

1. Precision is only limited by the quality of the original data (very rarely by the computer representation);

2. Very space-efficient, since only points about which there is information or which form parts of boundaries are stored, information for the areas between such points are inferred from the topology;

3. Explicit topology makes some kinds of spatial analysis easy;

4. High-quality output.

3.7 Disadvantages of the vector representation

1. Not suitable for continuous surfaces such as scanned or remotely-sensed images and models based on these;

2. More expensive hardware and (especially) software.

3.8 Converting from vector to grid

A common operation is converting *vectors* (points, lines or polygons) to a *grid* map; this processes is often referred to as *rasterizing* a vector map. The basic idea is simple: (1) set up a grid, (2) scan the vectors, placing the vector identifier in each grid cell where it occurs (points or lines) or which is bounded by the vector (polygons). In IDRISI, these steps are accomplished with modules INITIAL (step 1) and POINTRAS, LINERAS or POLYRAS, depending on the type of entity to be converted (step 2).

A major question is: To what grid *resolution* should a *vector* map be converted? This depends on the *scale* of the paper map from which the vector map was created. The basic idea is to retain the *minimum legible delineation* (MLD), which is a concept that depends on map scale (Forbes, Rossiter & Van Wambeke, 1982), in the grid map. The MLD is conventionally defined as 0.4cm^2 to 0.25cm^2 on the map; we will use the higher-resolution definition, i.e., 0.25cm^2, which represents a square of 0.5cm on each side.

Step 1: Determine the *scale factor* of the original map. Example: 1:1'000,000 has a scale factor of 1'000.000 or 10^6. The units of the scale factor are (ground distance) ÷ (map distance), e.g. (ground cm) ÷ (map cm).

Step 2: Convert the 0.5cm side of the MLD square to map scale, by multiplying by the scale factor. This tells us how much ground distance is represented by the side of the MLD. Example: $(0.5\times10^{-2}\ \text{m}) \times (10^6\ \text{m m}^{-1}) = 5\times10^3\ \text{m}$ = 5km.

Step 3: To preserve cartographic accuracy, divide the ground distance by 2. This ensures a more pleasing grid map without excessive and false precision or excessive storage requirement. Example: 5km÷2 = 2.5km = 2,500m. This is the *lineal resolution* to be used when creating the grid image, e.g., using IDIRISI's 'INITIAL' command.

4. Data types and basic operations on maps

For a thorough treatment see (Burrough, 1986) Chapter 5.

4.1 Data types

It is crucial to know, for each map, the *type* of data it represents. Although the computer may represent all data types by numbers, this is only for convenience; conceptually the data type is derived from the kind of information being represented. *Operations must be consistent with data types* or the result will be meaningless.

(Example: what is the meaning of (political subdivision code) / (soil textural class)??)

1. '*Continuous'* values are represented by integer or floating-point (computer approximation to real) numbers (e.g., elevation, reflectance, vegetation index). Two kinds of scales:

1a. A *ratio* scale has a natural zero, so ratios of two numbers on this scale have meaning. Example: population. It makes sense to say 'New York City has 1,000 times the population of Ithaca'.

1b. The *interval* (also called *ordinal*) scale has no natural zero. The origin ('zero') of the scale is assigned for convenience, therefore ratios have no meaning. Example: temperature in °C. It makes no sense to say 'today's maximum temperature of 30°C is twice yesterday's of 15°c'; although mathematically this is true it has no meaning.

Note: the only difference between continuous integers and continuous floating-point is the fineness of the measurement scale, neither is truly 'continuous' mathematically.

2. *Classes*, with a natural order , are represented by integer codes(e.g., increasingly-steep slope classes); these are called *ordinal classes*.

3. *Classes*, no natural order, are represented by integer codes (e.g., political subdivisions or land cover classes, here alphabetic order might be considered 'natural' but really it is just an accident). Also called a *nominal classes*.

4. *Logical*, Boolean, 0/1, true/false, yes/no, included/excluded are usually represented by the numerical values 0 and 1. But they can't be added etc.

in the same sense as the integers 0 and 1, their arithmetic follows Boolean logic.

5. *Continuous* classification values (sometimes called ‘fuzzy’ values) are real numbers on the interval [0,1], which represent varying degrees of membership in the class. These are a generalization of Boolean or logical values.

4.2 Commensurate variables

A set of variables are said to be *commensurate* if they have the same scale of measurement. This is independent of whether they have the same data type.

Example: hydraulic conductivity can be measured in any units of (length time^{-1}); these are not commensurate unless a conversion factor is applied.

Example: a continuous variable ‘soil depth’ measured in cm, and a classified variable ‘soil depth classes’, each class defined by a range of depth also measured in cm, *are* commensurate.

4.3 Updating a map

Non-zero areas of the first map overwrite any values of the second. So the non-zero points, lines or areas contain corrected values. Example of new points: new climate stations. Example of new lines: new roads. Example of new areas: new suburban subdivisions.

IDRISI command OVERLAY option 7

4.4 Querying a map

Given the map, we will want to extract information from it.

4.4.1 What is the value at a point?

IDRISI command COLOR (display), subcommand ‘x’ or ‘c’, shows the coordinates and value. In the case of classified maps, shows the class (legend category).

4.4.2 What is the value over a region?

Uses two maps: the map containing the values (the *image*) and the map which defines the region(s) for which the values should be determined (the *geographic* *definition*). The geographic definition is used to divide up the image, and the values corresponding to each geographic entity are aggregated in various ways: minimum, maximum, sum, mean, range, standard deviation.

> Example: if each cell of the image contains a vegetation index, and the geographic definitions are forestry management units, EXTRACT/average would produce a map of the average vegetation density of each forest unit.
>
> Caution! the operation must make sense given the data type. For example, averages only makes sense with continuous values. None of these make sense with unordered classes.

IDRISI command EXTRACT

4.5 Transforming one map

4.5.1 Grouping or transforming classes

Class-to-class function. E.g. from a map of 12 soil textural classes (sand, sandy loam, loamy sand, ..., silty clay loam, clay loam, clay) to one of three general classes ('coarse', 'medium', 'fine'). Can never increase the number of classes (information content). This is sometimes referred to as *re-classifying* a map, because the existing classification is being replaced with a new classification.

IDRISI command ASSIGN (RECLASS can also be used here).

4.5.2 Classifying continuous values

Continuous-to-class function. Used to group a continuous variable, e.g. slope % to slope classes.

IDRISI command RECLASS.

4.5.3 Transforming continuous values

Logarithm, exponential, power, reciprocal... any univariate function of the data values, which must be continuous.

IDRISI commands SCALAR, TRANSFORM.

4.5.4 Identifying individual polygons

Finds and numbers individual polygons (*connected* areas with the *same value*).

IDRISI command GROUP.

4.6 Working with more than one map

To work with more than one map at a time, the coverages must:

(1) be *registered* to the *same coordinate system*;

(2) cover the *same land area*;

(3) in a *grid* representation, have the *same resolution* and *origin*.

The following sections outline the procedures to ensure that points (1) - (3) are satisfied.

4.6.1 Register to the same coordinate system

Some maps (already georeferenced) may have to be *transformed* to another projection. Basic procedure:

1. establish the mathematical relation between points in the two projections

2. create a blank map in the new projection at the desired resolution

3. fill in the cells by projecting values from the original map

Problem: cells in new image (projected) rarely correspond to cells in the original image.

IDRISI command: PROJECT

4.6.2 Cover the same land area

Use a windowing operation to make a sub-image of the larger image; we can only analyze the area for which we have complete coverage.

IDRISI commands: WINDOW, SUBSET

4.6.3 Make the resolutions identical (grid images)

If the two images do not have the *same cell size*, one or both must be adjusted, because grid overlays are cell-by-cell.

Simple case: the cell sizes are *even multiples*.

> E.g., Land cover classification from SPOT panchromatic imagery at 10mx10m resolution, to be compared with a land cover classification from Landsat TM image at 30mx30m resolution. One Landsat TM cell covers exactly the same area as 3x3 = 9 SPOT cells.

We have two possible solutions: increase the apparent resolution of the coarser image or decrease the actual resolution of the finer image.

Solution 1: *expand* the image with the coarser (larger) cell size by an even multiple. The value in the original cell will be entered in each of the new, smaller cells covering its original area.

IDRISI command: EXPAND

Major problem with Solution 1: the expanded image promises more information than it actually has. It was not sampled at the resolution at which it is presented. Still, this may be justifiable if it is known that the theme is quite homogeneous across large areas (low-frequency features), so that the only errors are at the borders between themes, which may appear wider than they really are and are not accurate to within the apparent resolution of the new map. Example: map of political units.

Solution 2: *contract* the image with the finer (smaller) cell size by an even multiple. We are *losing information* in the contracted image, but at least we are not misrepresenting the sampling density, as in Solution 1. The value in one new cell must somehow represent the values in several original cells. Several possibilities:

IDRISI command: CONTRACT

(1) *Pixel thinning*: simply use the value in the upper-leftmost (or, any arbitrarily-chosen) original cell of the window to be contracted. This corresponds to coarser sampling. This is the best choice for maps of nominal classes. Example: land cover classes.

(2) *Pixel aggregation*: some function of the original set of values is used to obtain the new value. This has several possibilities:

(2.1) Average: appropriate for continuous variables, such as reflectances (remote-sensing images)

(2.2) Maximum or minimum value: appropriate for ordinal classes. The analyst chooses to minimize or maximize according to the purpose.

(2.3) Mode: most usual value. A good choice for nominal classes when 9 or more cells are being aggregated, not enough samples to be feasible for smaller windows.

Harder case: the cell sizes are *not* even multiples.

E.g., a Digital Elevation Model is available with 90m horizontal resolution, and a soils map has been prepared with 50m resolution.

Solution 1: if one of the maps was prepared from a vector map, *re*-rast*erize* to the resolution of the other map., always supposing that the new resolution is justified by the scale of the original map.

IDIRISI commands: POLYRAS, LINERAS, POINTRAS, following INITIAL

Solution 2: *Resample* one of the maps to the other's resolution. Basic procedure:

IDRISI command: RESAMPLE

(1) Set up an output map on the grid of the map that won't be resampled (the project standard)

(2) Fill in the cells of the new grid with values from the original map. How to fill?

(2.1) Center value: use value from the original map at the *center* of the new grid.

(2.2) *Aggregate* the values from the original map that are included in the new cell. Possibilities: *weighted average* (by area of the cell to be filled): only appropriate for maps of continuous values; *most likely value* (like a mode), picking the one single value that covers the most area of the cell to be filled. Can aggregate only in the new cell or based on a *window*.

4.7 Combining two or more maps

4.7.1 Arithmetically combining continuous values

Purpose: derive a map from a set of source maps, all of which represent continuous values, based on some multivariate function.

Add, subtract, multiply, divide, normalized ratio. In general. any multivariate function, with the 'variables' being the map values.

IDRISI command: OVERLAY, options 1-6. Division only makes sense with ratio-scale data. None make sense with classed values.

4.7.2 Combining Boolean values

Purpose: combine a set of source maps, all of which represent Boolean values, based on some truth function.

AND, OR etc.: binary logical operators. Common use: to combine partial suitability maps into final suitability. Examples: 'Areas that are zoned for the use AND are physically suited to it'. 'Areas that are suitable for cotton OR for maize but are NOT suitable for housing developments'.

IDRISI command: OVERLAY, multiply or minimum (for AND) or maximum (for OR). Works on '0/1 maps', 0 = false, 1 = true.

4.7.3 Choosing the minimum or maximum value

Purpose: determine the extreme value, for commensurate continuous variables or ordinal classes.

IDRISI command: OVERLAY, options 8 & 9. OK for ordinal classes (e.g., maximum suitability class).

4.7.4 Identifying which map has the maximum value

Typical use: identifying the 'best' use: the source maps represent the predicted 'value' of each land use, and must be measured on the same scale.

IDRISI command: MDCHOICE.

4.7.5 Cross-tabulating

Purpose: Identify all combinations of two classified maps (maximum number of result classes *n x m*, in practice most maps have some correlation so that not all classes actually occur). Example: soil groups x climate zones = soil-climate homogeneous regions.

This is a very common operation for defining 'homogeneous' map units for land evaluation.

IDRISI command: CROSSTAB.

4.7.6 Cutting out areas

Purpose: Limit the area of one map to a defined area on a second map. Also called 'masking'. Example: map 1 = soils of NY state, map 2 = Tompkins County (as 0/1 map), result map = soils of Tompkins County (blanks outside the county boundary).

IDRISI command: OVERLAY, multiply, the mask image must contain only 0's (in the area to be eliminated) and 1's (in the areas to be retained).

4.8 Analyzing single maps

Map analysis does not alter a map or create new maps, instead, it extracts facts about existing maps.

4.8.1 Descriptive statistics

For continuous variables, a histogram and descriptive statistics. Can be used to identify breakpoints for classification. For classified variables, a frequency distribution of classes.

IDRISI command: HISTO.

4.8.2 Area, perimeter

Almost always we want to know how much land is in each suitability class. The perimeter is less commonly measured but can be useful for estimating how much fence is needed etc. Good-bye planimeter!

IDRISI commands: AREA, PERIM, compactness ratio CRATIO

4.8.3 Spatial autocorrelation

How similar are nearby cells? (later lecture on spatial variability) Only makes sense for continuous variables.

IDRISI command: AUTOCORR, correlates adjacent cells. For larger 'lags', CONTRACT the map first.

4.9 Analyzing two maps together

4.9.1 Correlation and regression

To what degree can one map be used to predict the values on another? and what is the mathematical expression of that relation? Example: temperature vs. elevation in the tropics.

For continuous variables, linear regression etc. (IDRISI command: REGRESS)

For classified variables, chi-square & related statistics based on cross-tabulation (IDRISI commands: CONFUSE, CROSSTAB)

5. Spatial analysis of geographically-based land characteristics

In this lecture we talk about geographically-based land characteristics important for land evaluation and how they can be determined the *spatial analysis* in a GIS.

There are some land characteristics that have a geographic expression and can be mapped with a GIS but which do not require spatial analysis. Example: current land use, political entity, land tenure.

5.1 Distance

The distance of a land area to a feature (point, line or area) is important for many uses. Examples: by law a certain use may be prohibited within 1km of a national park; irrigation by small pumps may only be practical within 100m of a permanent stream. These are examples of *buffer zones*.

For polygonal map units, the distances of its interior points must be aggregated in some way. Possibilities: minimum distance (closest point), maximum distance (furthest point), average distance, distance to the *centroid* ('center of gravity' of the polygon).

IDRISI command: DISTANCE

5.2 Transportation cost

A more general form of 'distance'. The 'cost' (difficulty) of moving from one point to another is determined both by distance and by the 'resistance' of the path between the points. More expensive (in terms of time, money or both) to travel on a paved highway vs. a dirt road, to walk over a mountain than across a plain, to walk through dense vegetation than sparse etc.

Two maps: target (as in distance) and *cost surface*: each cell has a relative cost (1.0 = standard).

IDRISI command COST.

5.3 Allocation to 'nearest' feature

Assign each cell of the map to its 'nearest' of a set of target features (e.g., school, market, well). Distance can be true distance or a cost. Then the land characteristic is the identifier of the 'nearest' feature.

IDRISI command ALLOCATE, follow-on to DISTANCE or COST

5.4 Land area

A land use may require a certain *minimum* (or, less commonly, *maximum*) contiguous area. For example, forest plantations less than 20ha may not be worth the effort to build an access road. The GIS can compute the area of each polygon of a suitability map, and discard those that are too small.

IDRISI command: GROUP the polygons of the suitability map, calculate their AREA, RECLASS those that are too small to 'unsuited - too small' and those that are large enough to 0 (background), COVER the original suitability map with the 0/1 map of too-small areas.

5.5 Adjacency

Some land uses may be prohibited *adjacent to* other uses (e.g. no agriculture adjacent to a national park).

Some land uses may *require* adjacency, e.g., a rule that suburban development must be located adjacent to existing urban or suburban areas. Or a LUT may require two kinds of land together: e.g., dairy farms with both pasture and grain.

This is different from a buffer zone, because in the present case we visualize the planning units as already being specified.

In a vector system with polygon topology, a query such as 'show all polygons adjacent to polygons with land use A' are trivial. In a grid system this is more difficult; IDRISI provides no primitive command to do this.

6. Digital Elevation Models (DEM) for land evaluation

(Burrough, 1986) Chapter 3

The digital elevation model, abbreviation 'DEM', is an extremely useful product of a GIS for land evaluation. Basic question: how do we represent the three-dimensional structure of the earth's surface in the computer, and what can we infer from this representation?

Definition of a DEM: "digital representation of the *continuous variation* of *relief* over *space*". 'Relief' can be any continuous variable that depends on geographic coordinates. The most common is elevation above mean sea level. The exact same representations and techniques can be applied to *continuous* soil characteristics (pH, depth, ...), climate characteristics (rainfall, evaporation,...), vegetation characteristics (biomass, greenness...).

Note: some people reserve the term 'DEM' for what we call 'grid DEM', 'altitude matrix', or 'gridded DEM'. Then the more general term is 'Digital Terrain Model' (DTM).

There is no ideal DEM, because the full complexity of a surface can not be captured by the computer; there is always a *sampling* problem and a *representation* problem. Various sampling schemes and representations may lead to very different results both in the DEM itself and especially in its derivatives. Caution is advised in this highly-technical specialty that is still somewhat of a black art). The accuracy of the individual *elevations* does not necessary ensure the accuracy of derivatives such as slope maps.

There are two general ways to represent a surface: by a *mathematical function* that expresses elevation as a function of the horizontal coordinates, and by an *image* of the surface, explicitly giving the elevation at some set of points, with no functional dependence with horizontal coordinates.

6.1 Representing a surface: mathematical methods

Basic idea: Fit a continuous three-dimensional function to sample points ('elevations'), and then the elevation at any point can be determined by evaluating the function at that point.

Advantages: very compact representation, smooths noisy data from observational and sampling errors.

Disadvantages: smooths abrupt changes and extreme points even if they are real. The smoother the surface to be represented, the more appropriate this method.

6.1.1 Global trend surfaces

One function for the entire map.

Polynomials of various orders with the geographic coordinates as independent variables (higher-order polynomials allow interactions between the coordinates). Fourier series for periodic surfaces (dunes).

Common in geology (e.g. elevation or thickness of a formation)

Example: $z = b_0 + b_1 \cdot x + b_2 \cdot y + b_3 \cdot x^2 + b_4 \cdot xy + b_5 \cdot y^2$

Here the elevation 'z' is a 2nd-degree (quadratic) polynomial function of the two coordinates 'x' and 'y' with a reference level b_0 and an interaction term with parameter b_4.

The polynomial is fitted by least-squares estimation.

IDRISI command: TREND.

6.1.2 Local patches

Piecewise functions, each applicable over some area of the map, must have equal values at the edge of the patches although the derivatives may not be continuous. Various orders of continuity are possible with *thin-plate splines* (Wahba, 1990).

Regular or irregular patches.

Not visually pleasing, not common in cartography.

Commonly used in Computer-Aided Design (CAD).

6.2 Representing a surface: image methods

6.2.1 Regular grid or altitude matrix: grid DEM

The surface is represented by a matrix of elevations on a regular grid. Exactly a grid data structure.

Problems are as with any grid structure: tradeoff of resolution and storage requirement; over and under-sampling (matching grid to terrain complexity)

Advantages: simple data structure, simple data entry. Widely used for hydrologic modeling, e.g. (Abbott *et al.*, 1986a, 1986b, Bork & Rhodenburg, 1986, Rhodenburg, Diekkruger & Bork, 1986)

6.2.2 Irregular grid: Triangulated Irregular Network (TIN)

The surface is represented as a sheet of edge-connected of triangular facets based on Delaunay triangulation of irregularly-spaced control points. Advantages: can explicitly follow stream and ridge lines; sampling can be intensified in areas of high slope complexity and made sparse in other areas. Some computations (e.g., slope) are very efficient.

6.2.3 Lines

The surface is represented by isolines ('contours'). This is the method used on most topographic maps.

Rarely used for digital models, except for data entry (see below).

6.3 Sampling strategies for a DEM

Basic question: what sort of sampling strategy do we use to create DEM? and what processing will the computer have to do on the samples? The sampling may be well-matched with a particular representation method or not.

6.3.1 Regularly-spaced point observations

Record the elevation at regular-spaced grid points. Field survey or by overlaying the grid on a topographic map.

Advantage: already a grid DEM with no further processing. Suitable for trend surfaces.

Disadvantage: inefficient sampling, although *progressive* sampling on increasingly-finer grids according to relief complexity is possible (still must store all the redundant points)

Disadvantage: the highest/lowest points on the landscape are rarely sampled, since they aren't likely to fall directly on the sample grid.

6.3.2 Irregularly-spaced point observations

Record the elevation at selected points.

Advantage: can include the highest/lowest points; can increase sampling in zones of high relief. Suitable for trend surfaces.

Advantage: can be directly represented as a TIN

Must interpolate to unsampled points for a grid DEM. IDRISI command INTERPOL. Sophisticated interpolation procedures and terrain-specific sampling schemes give better results, e.g. (Hutchinson, 1989).

6.3.3 Contours (isolines)

Follow the same elevation and draw a line representing it. Typically by stereoplotters from stereo pairs of aerial photos.

Advantage: 'infinitely dense' information along the contours, inter-contour spacing is closest in zones of high relief.

Disadvantage: highest/lowest contours are never the highest or lowest points. Can supplement a derived grid or TIN DEM with these points. Interpolation methods may not give satisfactory results if the contour interval is too sparse.

Must interpolate to unsampled points for a grid DEM. IDRISI command INTERCON.

Must create *tie-lines* for a TIN.

6.4 Products derived from a DEM, useful in land evaluation

6.4.1 Slope, Aspect, Form

See (Burrough, 1986) p. 49-52, also (Evans, 1980)

Slope is a critical land characteristic for all land uses that I can think of. It affects land qualities such as runoff, erosion hazard, moisture balance, landslide or slump hazard (catastrophic erosion). Sometimes called *gradient*. It is defined as the maximum derivative in any direction of a plane tangent to the surface as modeled by the DEM.

Aspect or orientation is an important land characteristic for land qualities having to do with insolation and winds. It is the normal to the plane, projected onto the X-Y plane.

Form (concavity, convexity in various directions) is important in determining direction and velocity of surface water flow. These are defined as the various partial derivatives of the DEM.

Global trend surface: each point has a first total derivative, maximize this to find the normal (aspect) and gradient (slope).

TIN: each triangular facet has a slope (angle of inclination of the triangle) and the normal to the facet gives the aspect.

Altitude matrix (grid DEM): the local neighborhood of nine cells is considered as a small patch of nine sample points; the maximum difference in Z (corrected for diagonal) is the slope and the direction of this slope is the aspect. IDRISI command SURFACE.

The slope (gradient) *G* for the central cell of a 9-cell (3x3) neighborhood is:

$$\tan G = \sqrt{\left(\frac{\delta Z}{\delta X}\right)^2 + \left(\frac{\delta Z}{\delta Y}\right)^2}$$

i.e., the sum by quadrature of the gradients in the X and Y directions, where δX is the distance across the 9x9 grid and δZ is the elevation difference. There are various ways to estimate these quotients from the actual elevations.

The aspect from a 9-cell neighborhood is:

$$\tan A = \frac{-\delta Z / \delta Y}{\delta Z / \delta X}, \quad -\pi < A < \pi$$

6.4.2 Contour maps (isolines)

The DEM can be used to create maps of *isolines* (i.e., lines of equal value, in this case, equal elevation) for visualization or to separate land units on the basis of elevation. There are good commercial (e.g. SURFER) and public-domain (e.g. GEO-EAS) programs to draw the contours. There is no single 'correct' way to interpolate contours; see (Davis, 1986) pp. 353-377 for a good introduction to the various techniques.

6.4.3 Drainage basin

Given the slope and aspect, and a *target* drainage system (e.g. its outlet or the main stream), the computer can follow the terrain to the inter-basin divides, and divide the landscape into watersheds. (Mark, 1984, Marks, Dozier & Frew, 1984)

These are useful for automatically generating map units in watershed analysis.

IDRISI command: WATRSHED. Problems with spurious *pits* (low points with no apparent outlet, usually caused by sampling error) can be avoided by previous FILTER, but then the divides may become diffuse. The procedure of (Hutchinson, 1989) overcomes these difficulties.

6.4.4 Drainage network

The drainage *network* can be inferred by following the presumed surface water flow through the DEM and noting when it is concentrated enough to form an intermittent stream, then a permanent stream, then a river.

6.4.5 Analytical shading

Projective geometry can be used to simulate the illumination of a landscape from a given point. Often used to created shaded relief maps. This is a nice presentation tool. It can also be used to determine hours of insolation for each site in mountainous terrain: simulate the direct illumination at various intervals and sum the hours of sunlight.

6.5 Ready-made DEMs

The obvious utility of DEMs has lead to demand from many users, so that some national mapping agencies are creating DEMs for sale or by network access (US Government)

1. *USA*: Based on USGS 7.5” topographic sheets (1:24,000), sampling is 30m horizontal resolution. Vertical sampling was 10’ or 20’ contours, unclear if the DEM was interpolated from the contours or from the original stereomodel (this would be more accurate).

2. *World*: Digital Chart of the World (DCW): The contour lines can be used to create a DEM. Also there is a ready-made DEM at a resolution 3” of arc (about 90m N-S and E-W at the equator).

7. Global Positioning System (GPS) for land evaluation

Reference: (Leick, 1990), trade publication ‘GPS World’

The Global Positioning System or ‘GPS’ is a set of satellites collectively called the NAVSTAR series developed by the US Department of Defense for military navigation. It has revolutionized location determination, especially in remote areas with few identifiable landmarks, and in areas with poorly-developed survey.

In land evaluation, the principal uses are:

(1) the rapid construction of base maps with acceptable accuracy; in fact with appropriate techniques it is even possible to substitute for traditional land survey (Leick, 1990);

(2) the determination of the location of ground-truth sites for remote sensing;

(3) the determination of the location of control points to rectify existing maps that did not have adequate ground control, so that these may be used in a GIS.

Problems: a very demanding technology fraught with pitfalls for the unwary, all the way from field work to data reduction. But these are rapidly being simplified for the ‘lay’ (non-GPS or surveying specialist) user.

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