Lecture Notes:

Soil Geographic Databases
SOL.SGDB

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Audience

These notes are intended for those who want to build a useful Soil Geographic Database (SGDB). They should also be useful for people who use these databases.

Themes

First, I define SGDB and explain in what contexts they may be useful. This is followed by a somewhat abstract discussion of the basic concepts of the soil cover and how we imagine soils to be distributed in space. One major conceptual model, that of soil bodies as 'topological entities', is developed in detail, both at the conceptual and logical (data) levels. Major emphasis here is on the correct structuring of the attribute database. Another major conceptual model, that of soil as a continuous field, is discussed briefly. Then, practical issues in SGDB construction are discussed, especially the geometric problems caused by diverse source materials. Once a SGDB is constructed, it may be queried; methods for doing this are discussed next. A related practical concern is soil cartography, i.e. how the maps stored in the SGDB are to be presented to the client. Finally, I discuss the very important issue of metadata, i.e. data which describe the database.

Internet resources and background references

Internet links related to soil geographic databases may be found at the 'Digital Soil Survey' topic of my '**Compendium of On-line Soil Survey Information**' at:

> http://www.itc.nl/~rossiter/research/rsrch_ss.html

The literature on SGDB as such is not extensive. Burrough [6] wrote a review article in a GIS encyclopedia. Highly recommended from this same encyclopedia is an article by Taylor [35] on GIS in developing countries. Some important earlier work includes [40]. International workshops were held in the late 1960's and early 1970's, but much of this work is now obsolete because of changing concepts in both soil geography and database theory. Successful operational SGDB's have been developed by several national soil survey agencies (Canada, Netherlands, USA, UK) as well as international groups (EC Soil Map of Europe, SOTER, FAO Soil Map of the World); these are good examples to study, keeping in mind their objectives.

For techniques of modeling the continuous model of spatial variability, a good introduction in a geology context is [11]; a more detailed and very readable treatment is [20]; and a textbook with soil science examples is [38].

Contents

Sections to be added ‘some day’: “Representing uncertainty in SGDB”

1 Conceptual Framework

Key concepts in this Chapter:

- Definition of Soil Geographic Databases (SGDB)
- Purposes of SGDB
- Questions to be answered by a SGDB (1) over an entire study area; (2) at a site; (3) locating areas of interest
- Soil classes vs. soil properties
- Definition of 'soil' as represented in the SGDB
- Levels of abstraction: (1) conceptual, (2) logical (data), (3) physical models of space
- Why are soils variable over space? Deterministic vs. random effects, the Jenny equation
- Long-range vs. short-range variability of soil-forming factors
- Models of soil spatial variability: Discrete (DMSV); Continuous (CMSV); Mixed (MMSV)
- Logical models of space: topologic entity vs. grid.

Soil Geographic Databases (**SGDB**) are structured digital data that contain information about the geographic distribution and properties of the soil cover in a specific area. They are the digital replacement for soil survey maps and reports, but can in principle be much more useful, for all the reasons that digital databases in many fields are more useful than their paper predecessors.

The SGDB has several **purposes**:

1. Data **organization**: to show the logical relation of data, e.g. a profile is made up of a sequence of horizons; a map unit has several component soil types;
2. Data **storage**: to save data for later use;
3. Data **retrieval**: to examine the saved data;
4. Data **manipulation and transformation**: to derive new data from old, e.g. information about an entire map unit derived from information about its constituents;
5. **Data analysis**: to solve problems using data, e.g. land evaluation; environmental risk assessment; and soil management recommendations.

Although we think in the first instance of a database as a means of data storage, this by itself is not sufficient motivation to build a SGDB. Essentially, **databases are built so that questions may be answered**. In order to answer a wide variety of questions, some not anticipated at the time the SGDB is built, a sound structure is necessary. To judge whether a SGDB is well-designed and correctly built, we need only judge if it can supply information as needed by analytical models.

1.1 Questions that a SGDB can answer

Following Beckett & Burrough's work on soil survey [3] we may classify of questions that could be answered by SGDB as follows:

1. **Summarizing over an entire study area**
   (a) What **classes of soil** are present in the area?
   (b) In what **proportion** do these occur?
   (c) What proportion of the area is occupied by soils with **specified properties**?

This first group of questions only require a statistically-sound sampling procedure (point or area), and no map. The only interest in these questions would be for a national inventory. A SGDB usually answers these questions by summarizing geographically-explicit information.

For most decision-making we also need to know the **geographical distribution** of soils, i.e. they must be shown on a **map**, which in the SGDB is represented in digital form. With such a map we can answer the following questions:

2. **At a given site** (a small area of interest)
   (a) What is the **soil class** at a **particular site**?
   (b) What are the **soil properties** at a site? How **variable** are they?
   (c) What is the **spatial pattern** of **soil classes** at or around a site?
   (d) What is the **spatial pattern** of **soil properties** at or around a site?

The above group of questions may be asked by land managers who already own or manage specific areas, and by planners who already have identified specific areas whose use or management must be planned.

Also with a map, we can answer the following questions:

3. **Locating areas of interest**
   (a) **Where** can soil of a particular **class** be found?
   (b) **Where** can soil with **specified properties** be found?
   (c) **Where** can a specific **spatial pattern** of soil properties be found?

The above group of questions may be asked by planners or land users looking for land on which to implement specific land uses.

The last two groups of questions require that we cover the area of interest with **predictions** about the soil cover, so that **at any site** (directly sampled or not) we can answer these questions.

Some points about these questions

1. **Classes vs. properties**:

   'Classes' are **categories of a classification system**, either pre-defined or recognized during the survey as natural landscape elements.

   'Properties' are **measurable Land Characteristics**, e.g. soluble salts, or inferred Land Qualities, e.g. degree of toxicity to a specific plant variety. Soil survey, and also SGDB, often use classes to organize co-varying sets of properties of 'natural' soil bodies.

2. **Implied scale** of these questions: The concepts of 'site' and 'area' imply a scale of interest, and that these questions change their meaning depending on this implied scale.

3. **Spatial patterns**: Some interpretations require a specific spatial pattern of different soil types at a specific ground scale. Sometimes it is not enough to know the proportion of soils at a 'site' or in an area, but also the spatial pattern in which they occur.

Related question

1. How **reliable** are these statements? To what degree can the decision maker rely on them? This requires either a quantitative, usually probabilistic, or qualitative accuracy assessment with respect

to the questions. The SGDB must contain information to allow inferences to be made about reliability of predictions.

Examples of questions that SGDB have helped to answer

1. What is the total Carbon store in the soils of North America (Canada, USA, and Mexico)? What proportion of this is likely to be lost to the atmosphere as the result of changing land use or land 'improvements' such as drainage?

2. Where are areas of 'prime farmland' which should receive highest priority for protection against suburban development?

3. For each field in a farm, what is the maximum permissible load of farmyard manure that can be applied to it per year, meanwhile ensuring that the risk of groundwater contamination is below a certain threshold value?

1.2 What is represented in the SGDB?

The **Soil** Geographic Database primarily represents the **soil** cover, as well as point observations of soil. But what is this, exactly?

1.2.1 What do we mean by 'soil'?

There are three sides of this question: definitional, functional and practical.

Definitional: This topic is covered thoroughly in SOL.27. An acceptable simple definition is by [4, §26.1]

> "Soil is the uppermost layer of the earth's crust, in so far as this layer can support plant roots, or in so far this layer has been altered by the action of physical, chemical or biological processes" (my translation)."

The authors add by way of clarification: "Thus, solid rock and the wet, unripe lower parts of loose sediments are not 'soil' from the point of view of soil science". Other examples of non-soil are permanent water bodies too deep to have rooted plants, mine spoils, dune sands. In this view, soil is a special kind of natural body, studied by pedologists.

Functional: Soil is the uppermost layer of the earth's crust which is the environmental **interface** between atmosphere, biosphere, lithosphere, hydrosphere, and anthrosphere. From a functional point of view, anything that acts as this interface should be considered 'soil', at least for mapping. This includes such earthy 'non-soil' (from a pedologist's viewpoint) such as unripe sediments, mine spoils, dune sands, and fill in urban areas.

All unconsolidated material from the earth's surface downwards, excepting under deep water, is defined as the **regolith**. For understanding some environmental processes, the entire regolith may be important.

Practical: Soil survey works from the surface, which is easily observed over its whole extent, downwards. The further from the surface, the more difficult and expensive the observation. It is impractical to observe below 1.2m (the depth limit of a typical hand auger) except at a few widely-scattered points. So, a 'soil' map is in fact based on observations to this shallow depth. Fortunately, in many landscapes the spatial variability of the regolith is less at greater depths, and many characteristics of the deeper regolith can be inferred from shallower layers.

1.2.2 What is represented?

A SGDB represents a given area of the earth's surface. 'Soil' by any of the definitions of the previous section does not always cover the entire survey area, for the following reasons.

1. There may be **'missing' areas** that are not considered in the map; these are blanks in the map (i.e., unclassified) and have no information in the attribute tables. They are ***terra incognito***. This includes areas outside the survey area or holes within it, that for some reason can not be mapped, or which are deliberately omitted from the survey.

2. **Built-up** or **urban areas** may be also 'missing', either because the soils are not intended to be used for the purposes of the survey, e.g. agriculture, or because the soils are too disturbed to map. In modern soil surveys, urban areas are mapped, and special map units are designed for them, because of the importance of soil to urban applications: civil engineering, pollution, waste disposal, urban gardens, etc. The soil or regolith actually under a building can generally not be directly mapped; it is inferred from the surrounding soil and what is known about the building's construction.

3. Some areas are indeed labeled (classified) by the map, but are **non-soil** by any definition of 'soil'. Examples are water bodies and rock. These receive a class label but usually have no attribute information in the SGDB; they would have attributes in their respective thematic databases (e.g., rock type, water quality…).

4. Some areas are labeled and are considered 'soil' by the layman, if not by all pedologists. They are earthy materials (not water or hard rock) which are not easily classified as soils. Examples are gravel pits, mine spoils, and landfills. These receive a class label and perhaps some attributes. They are important as environmental interfaces. In some surveys they are called **miscellaneous land types**, but are increasingly thought of as soils to be described and classified.

1.2.3 What is special about a SGDB?

A SGDB has some special characteristics that make it more than a generic geographical database:

1. Soils are **three-dimensional** bodies; thus the database not only describes surface extent (two dimensions), but also depth (third dimension), usually considered as **horizons** but sometimes just as sampling layers.

2. Soil bodies as represented on a map are **heterogeneous**, i.e. not everywhere identical within a delineation or even a grid cell. Yet, this heterogeneity can often be described by geomorphic analysis, classical sampling, or geostatistical techniques.

3. Soil is difficult to map, because it can't easily be observed. Some soil landscapes are easier to map than others. The resulting maps vary widely in geometric and thematic **quality**.

4. The type of **queries** asked of a SGDB are complex and often involve information at several conceptual levels.

1.3 Representing space in the SGDB

We can distinguish **three levels of abstraction** when discussing space:

1. **Conceptual**: how we conceive of space; how we think that the phenomena we are trying to map are organized. This is our mental model, but not yet specific enough to work with.

Example: space as discrete entities; space as a continuous field; Discrete Model of Spatial Variation; Continuous Model of Spatial Variation (see below)

2. **Logical**: how the conceptual model of space is realized in mathematical and logical form, so that we can reason and calculate with it. This is a logical model which can later be realized in the computer. This is sometimes called the **data model**.

   Example: topological entities; grids

3. **Physical**: how logical spatial entities are actually stored in the digital form, where they may be manipulated.

   Example: raster, vector, quadtrees.

Physical models are only important to the computer scientists who implement GIS, DBMS and similar tools which are used to build a SGDB. The remaining two levels, conceptual and logical, must be harmonized for SGDB design.

1.3.1 Soil spatial variability

Conceptual models of the spatial distribution of soils should correspond to the reality of soil geography that they intend to conceptualize. Thus, we first discuss how it happens that soils are not everywhere identical, and how we might expect this variability to occur. We distinguish between spatial variability due to natural causes and due to human activity, since these have different causes and resulting patterns of variability.

Of course, many ‘natural’ soils have some human influence, and vice-versa.

Natural soils

Spatial variability of **natural** soils results mainly from the **interaction of** (spatially-variable) **soil-forming factors**, and in theory could be explained by them. The principal evidence for this statement is that not all possible combinations of soil properties occur in nature; instead, properties co-vary according to the pedogenetic environment, so that it is possible to recognize ‘typical’ soils or ‘central concepts’ for various environments, as well as intergrades that correspond to transitions between these. Mapping and explaining soil spatial variability on the basis of a pedogenetic model has been a major activity of soil scientists since the beginning of soil geography in the days of Doukachaev. Buol *et al.*[5] present a historical review of soil geography; Burrough [8] reviews most of the relevant literature. Wilding & Drees [39] review methods for studying spatial variability and summarize results, i.e., how variable are soil properties in nature.

Soil spatial variability can in theory be explained by soil-forming processes, summarized in the well-known Jenny equation [21-23, 39]:

$$s = f(cl, o, r, p, t)$$

i.e. soil results from the action of *cl*imate (precipitation, temperature…) and the *o*rganisms (plants, animals, microbes) on an initial *p*arent material in a specific *r*elief position, over *t*ime. These factors, and the resulting soil, can be considered partly *deterministic* and partly *stochastic*. In addition, when our understanding of the deterministic processes is incomplete, we may use statistical methods to characterize the results, without assuming that the processes is in fact stochastic. Many experiments (e.g. [24, 27]) and geostatistical studies (e.g. [36]) have shown that some soil properties may be highly variable even within very small areas, where the soil-forming factors presumably are close to uniform. There has also been some suggestion that the soil-forming processes may be chaotic at field scales [30]. Fractal analysis may be a useful tool to characterise this sort of variability [7].

The soil-forming factors can vary from **gradually** to **abruptly** in space; the range at which a factor is independent is its **range**. The same factor can have different ranges, depending on the context. For example, the amount and type of annual precipitation generally varies gradually, on the order of 10's to 100's of kilometers; on the other hand, in a region with strong orographic rainfall and directional winds, the range may be much less.

Human-affected soils

Spatial variability of **human-affected** soils results from disturbances and inputs by human activity, usually on a natural soil. In the extreme, soils are created from earthy materials by human activity (e.g., mine spoils). The disturbances can be minor (e.g., shallow tillage, light fertilization) to extreme. Humans choose where and how to manage soils, so the variability can be in theory reconstructed from historical records. In practice, it may be inferred from the observed spatial pattern.

1.3.2 Conceptual models of space

Heuvelink [17] proposes two fundamental ways to view the spatial distribution of soils: the **Discrete Model of Spatial Variation** (DMSV) and the **Continuous Model of Spatial Variation** (CMSV); these may be combined in a **Mixed Model of Spatial Variation** (MMSV).

Discrete Model of Spatial Variation: DMSV

In the DMSV, all mapped changes in soil properties are considered to occur at the **boundaries** of polygons, and the internal variation within a polygon is not mapped but only characterized with non-spatial statistics and descriptive terms, e.g. the *consociation*, *association* or *complex* of the Soil Survey Manual [32]. The DMSV conforms to the 'entity-class' model of a polygon GIS: each point on the map is in exactly one polygon, each polygon is in exactly one legend category (class), and each class is described in the database by its attributes.

This model conceptualizes the situation in which soil-forming factors also change at fairly **well-defined boundaries**. We recognize **transition zones**, but they are thin with respect to the polygons they enclose, and in the pure DMSV are insignificant at realistic map scales. This model is consistent with soil mapping using geomorphological airphoto interpretations as the primary means of spatial stratification.

An example of a well-defined boundary, from the factor ***p*** (parent material), is where thick, tilted, beds of two contrasting rock types, e.g. limestone and shale, have a contact.

Continuous Model of Spatial Variation: CMSV

In the CMSV, spatial variability is assumed to be continuous, and mapping is carried out by sampling and interpolation, using the techniques of spatial statistics. In the past 25 years, much effort has gone into characterizing the soil cover as a continuum. The techniques of geostatistics, first developed for the mining industry, have been widely applied to soil science. A good introduction to these techniques in a geology context is by Davis [11]; a more detailed and very readable treatment is [20]; a simple explanation in the context of soil science is [28]; a textbook with soil science examples is [38]; software for geostatistical analysis and mapping includes the EPA's *GEOEAS*, Deutsch's *GSLIB* [14], and the University of Utrecht's *GSTAT* [29] as well as fully commercial packages such as VarioWin and Surfer.

This model conceptualizes the situation in which soil-forming factors change gradually, or are apparently random. These are the two extremes of the scale of **spatial dependence**, i.e., to what degree knowledge of soil properties at one location helps us predict soil properties at 'nearby' locations. In its pure form, this model does not conceptualize the situation in which soil-forming factors change at more-or-less abrupt natural boundaries.

An example of a **gradual effect**, with **long-range** spatial dependence, for the factor ***p*** (parent material) is the thickness of a loess layer downwind from its source.

An example of an apparently **random effect**, with **short-range** spatial dependence, for the factor ***p*** (parent material) is a horizontal limestone layer has differential solution, so that the overlying soil has pockets of deep solution holes within a generally shallow layer over the limestone bedrock.

The CMSV usually applies to **individual soil properties**, i.e., a separate map is produced for each property. In addition, samples represent **specific depths or horizons**, so a separate map is produced for each depth or horizon, even of the same property. However, constraints can be placed on the model to recover known correlations of several variables.

Mixed Models of Spatial Variation: MMSV

Soil geographers and pedologists recognise that both the DMSV and CMSV are valid to some extent: the DMSV where soil-forming factors change relatively abruptly at natural boundaries, and the CMSV where boundaries are diffuse or non-existent and even within 'discrete' soil bodies where there is spatial dependence. This leads to a hybrid model of spatial variability in which an initial stratification into map units based on the DMSV is used to improve interpolation based on the CMSV. One method is universal kriging, using a step function instead of a smooth trend; a related technique is ordinary kriging with an external drift. Another synthesis of the two models is *pattern analysis*, whereby the shape and size of polypedons is analyzed.

De Gruijter *et al.* [13] argue for another mixed model, and are able to produce continuous soil maps of soil classes defined by fuzzy *k*-means. They state:

> "[S]oil distribution modelling should be based on a new classification paradigm: that of fuzzy set theory. In geographic space, this enables representation of gradual as well as abrupt transitions, i.e. soil distribution models that can predict variables at pedon level. … For interpolation of the class memberships we developed a new method, Compositional Kriging, which takes into account that the memberships have the structure of compositional data: they must be positive and add up to a constant (1) for each individual. "

1.3.3 Logical models of space

The DMSV and CMSV correspond fairly well to the well-known '**topologic entity**' and '**grid**' models.

> Note: These are sometimes called 'vector' and 'raster' models; but these terms more properly refer to physical models, see below.

Topological entity:

In this logical model, geometric **entities**, including points, polylines, and polygons, are formed with **topological consistency**, i. e. constraints on their arrangement and connection. These entities correspond to conceptual objects, e.g.. soil bodies.

In a SGDB, this model is tied to the DMSV's concept of **soil bodies** ('polypedons'). Soil is represented mainly as polygons, but also lines and points may be used for soil bodies that are too thin or small to be mapped as polygons.

Points also represent **field observations**.

Grid:

In this logical model, the only spatial entity is the **grid cell**, i.e. a fixed small area. The set of grid cells fill the area of interest. Grid cells have only one topological relation, namely adjacency, which is implied by their position on the grid. This is a good fit to the CMSV data models of satellite remote sensing, geostatistical interpolation, and grid DEM. The ‘continuous’ field is represented as a more-or-less fine grid.

The grid cell has a label, which may be a soil **class** or a value of a **soil property**. In the second case, it is common for the SGDB to be made up of many geographically-identical grids, each with a separate property, implicitly related by their fixed position on the grid.

1.3.4 Physical models

The implementation of GIS is well explained by Burrough [9], and of attribute databases by Date [10]. For each logical model, several physical models may be used. Some may have conceptual or practical advantages.

2 Structure of an entity-oriented SGDB

Key concepts in this Chapter:

- The SGDB consists of both spatial and attribute information
- Spatial: polygons (soil bodies), lines (boundaries and soil bodies), points (observations and soil bodies)
- Attributes may be stored on all objects individually or grouped
- Map scale; Minimum Legible Area; Minimum Legible Delineation
- Map Units (legend categories) related one-to-many with soil bodies
- Relational data bases; tables; rows (= records, tuples), columns (= fields), keys, cells
- Attribute tables: (1) spatial-entity, (2) primary-class, (3) secondary
- Entity-relationship diagram

A entity-oriented SGDB consists of two kinds of information on the entities, **spatial** and **attributes**. In addition, there are a set of **relationships** that define the links between these.

1. **Spatial** (the map). Geographic objects in a entity-oriented are of three kinds:
    1. **Polygons**, representing **delineations** of **map units**;
    2. **Lines**, representing **boundaries** between delineations as well as **linear features** at the map scale;
    3. **Points**, representing **point observations** (sample sites) and **point features**.
2. **Attributes** (information about the mapped entities)
    1. Attributes of **individual polygons**, including their area and shape;
    2. Attributes of **polygon classes** (map units), including the soil(s) found in polygons of the class and their spatial arrangement within the polygons;
    3. Attributes of **individual polygon boundary lines**, including their length, accuracy and precision (implicit width);
    4. Attributes of **individual polylines**, including their length and width;
    5. Attributes of **line classes**, including the soil(s) or special feature(s) found along lines of the class;
    6. Attributes of **individual points**, including the details of an observation;
    7. Attributes of **point classes**, including the soil(s) or special feature(s) found at points of the class and the radius of their associated area.
3. **Relationships** (links), for example:
    1. Spatially, map units are made up of delineations;
    2. Thematically, map units are made up of components that can’t be mapped separately;

The link between these is the **name of the geographic object**. The label on the map corresponds to an entry in the attribute tables.

2.1 Polygons

Polygons on a map represent areas of the earth's surface.

We consider polygons of an **area-class polygon** soil map. In this model, the survey area is **divided into polygons** by **boundary lines**, each polygon being labeled with a **map unit** (class) **name**, and each map unit in turn being described in a **legend**. A map unit is also known as a **legend class**; thus the set of legend classes makes up the legend.

Almost all familiar paper soil survey maps are of this type, and can easily be represented by the **entity-oriented GIS model**. Conceptually, these maps conform to the **discrete model of spatial variation** (DMSV) [17]: the variation across the landscape can be partitioned by sharp boundaries in to relatively 'homogeneous' areas.

Both individual delineations and map units may have non-spatial **attributes**.

The **polygon** is the **basic unit of spatial analysis**, because it has a definite location. Its basic attributes are stored in a **polygon attribute table (PAT)**, whose **table key** is a unique **polygon ID** The most important item in the PAT is the **map unit** (class) **ID**, which is the link to attributes which apply to the entire map unit.

2.1.1 Minimum Legible Polygons

The minimum size of a polygon entity is controlled by the source document. We start with the cartographic concept of **Minimum Legible Delineation** (MLD) and then convert this to the real-world **Minimum Legible Area** (MLA).

Minimum Legible Delineation (MLD)

This is the smallest area (cm^2_m) **on the map** that be legibly delineated. It is a somewhat arbitrary **cartographic** concept.

According to the Cornell University group on Adequacy of Soil Resource Inventories [16], the MLD is defined as = **0.4 cm^2_m** = 40mm^2_m. This definition is based on the observation that in most published soil surveys there are rarely any delineations smaller than 0.4cm^2. Actually, somewhat smaller delineations *are* marginally legible, and therefore some authors, such as Vink [37], use a smaller area, MLD = **0.25 cm^2_m** = 25mm^2_m; this is also followed in some countries' soil survey programs, e.g. Netherlands [18, §29.2.2] and is sometimes cited in GIS work, because of the improved precision of automated methods.

(Cornell) MLD: 0.4cm^2 = 40mm^2 ≈ 6.325x6.325mm; r ≈ 3.6mm
(Vink) MLD: 0.25cm^2 = 25mm^2 = 5x5mm; r ≈ 2.8mm

Vink adds **a restriction on delineation width**: that **the smaller dimension ('width') of an elongated delineation** (e.g., a map unit following a river, or a seep at the base of a hill) **should be at least 2mm**; other authors, e.g. [18, §29.2.2], give 2mm as the absolute minimum width but recommend a 3mm minimum width. So, according to Vink, the smallest narrow delineation must have dimensions of at least 2mm x 12.5mm, to attain his MLD of 25mm; using the more conservative 0.4 cm^2 MLD and 3mm width, the smallest narrow delineation must have dimensions of at least 3mm x $13.\underline{3}$mm.

> In smaller delineations, the **actual line width on the printed map occupies a significant part of the delineation**; e.g. #00 pen (line width 0.30mm) to delineate a 0.4 cm^2 circle occupies 8.2% of the circle's area (assuming that half of the boundary line, i.e. 0.15mm, falls

inside the circle); to delineate a 0.25cm^2 circle it occupies 10.3% of the area. The area actually covered by the line represent an ‘arbitrarily classified’ area, so should be minimized. Also, in smaller delineations there is **no room for a symbol**.

Minimum Legible Area (MLA)

The MLA is defined as **the minimum ground area that is legible on the map**, defined as the MLD converted to ground scale using the square of the **Scale Number** (SN). The SN is the denominator of the scale ratio, e.g. for 1:50 000 scale ration, the SN is 50 000.

(Cornell) MLA, ha = $(\text{Scale Number} / 1\,000)^2 / 250$.
(Vink) MLA, ha = $(\text{Scale Number} / 1\,000)^2 / 400$.

Example for a 1:50 000 map:
(Cornell): MLA = $(50\,000 / 1\,000)^2 / 250 = 2500 / 250 = 10$ha
Example (Vink): MLA = $(50\,000 / 1\,000)^2 / 400 = 2500 / 400 = 6.25$ha

There are two useful relations for up- or down-scaling, both derived easily from the fact that the **area varies as the square of the linear scale**.

(1) **Halving** the scale quadruples the MLA;
Doubling the scale divides the MLA by 4.

Examples, using the fact that the MLA at 1:50 000 scale is 10ha by the Cornell definition:

MLA at 1:100 000 = ½ x1:50 000 ⇒ 4 x 10ha = 40ha
MLA at 1:25 000 = 2 x 1:50 000 ⇒ ¼ x 10ha = 2.5ha.

(2) **Dividing the scale by 10** multiples the MLA by 100;
Multiplying the scale by 10 divides the MLA by 100.

Examples, using the fact that the MLA at 1:50 000 scale is 10ha by the Cornell definition:

MLA at 1:500 000 = 1/10 x1:50 000 ⇒ 100 x 10ha = 1 000ha
MLA at 1:5 000 = 10 x 1:50 000 ⇒ 1/100 x 10ha = 0.1ha = $1\,000\text{m}^2$.

2.2 Map units

A **map unit** of an area-class map is a **set of delineations**, all supposed to have the ‘same’ properties except for their geographic position.

One Map Unit ⇔ many delineations

A map unit is also called a **legend category**. The list of the map units is the **map legend**.

Thus there is a **hierarchical division** of the mapped area into m map units, and then each map unit is divided into n_j individual delineations. Each delineation belongs to exactly one map unit. This is a many-to-one relation between map units and delineations.

<u>**Total survey area**</u>
  Map Unit 1
    Delineation 1.1
    Delineation 1.2
    …
    Delineation $1.n_1$
  Map Unit 2
    Delineation 2.1
    Delineation 2.2
    …
    Delineation $2.n_2$
  …
  Map Unit *m*
    Delineation m.1
    Delineation m.2
    …
    Delineation $m.n_m$

Map units are the **information carriers** for **non-spatial** land evaluation & management at the map scale, i.e. all statements about land suitability that are *not* dependent on location can be answered by analysis of the map units.

2.3 Lines

Lines on a map represent either:

1. **Conceptual lines**, e.g. political boundaries; these do not occur in soil survey; *or*

2. **Boundaries** between polygons; *or*

3. **Areas** of the earth's surface that are **cartographically too narrow** to show as polygons

2.3.1 Boundary lines

These are not usually considered as separate features, only as lines to separate delineations, but their characteristics may be important, in particular, the nature of the transition across the boundary, sharp to gradual, or, the width of the transition area.

Leung [25] divides a mapped polygon into a core region (matches the class concept), an edge region (transition between class concepts), and a boundary (equally in either class), and uses fuzzy-set methods to define these, although statistical methods would be equally applicable. Mark & Csillag [26] developed a typology of boundaries. It seems these techniques could be used to categorize boundaries in the SGDB, and could be useful for spatial interpretations.

2.3.2 Linear features

At any map scale, some polygonal features are **too narrow** to be represented as a polygon. Generally, these are **features that would be <3mm at map scale**. E.g. on a 1:50 000 soil map, a soil body narrower than 150m can not be shown as a polygon. Yet distinct soil or other bodies can exist on the landscape. The classic example are **small streams and drainageways** with their associated wet and flooded soils. These can be shown on the map as the **center line** of the narrow feature, and the properties of their soils considered as a legend category, associated with a linear feature.

2.4 Points

Points on a map represent either:

1. **Conceptual points**, e.g. observations (even though these have some small extent, e.g. 1m^2, they are conceptualized as points); *or*

2. **Areas** of the earth’s surface that are **cartographically too small** to show as polygons (see Minimum Legible Area, above).

2.4.1 Observation points

The sites of actual observations by the soil surveyor, noted on the GPS (direct entry of coordinates to SGDB) or airphoto (digitized from rectified airphoto).

2.4.2 Small soil bodies (‘spot symbols’)

At any map scale, some polygonal features are **too small** to be represented as a polygon. Generally, these are **features that would be smaller than the Minimum Legible Delineation** (40 or 25mm^2) **at map scale**. E.g. on a 1:50 000 soil map, a soil body smaller than 10ha (Cornell) or 6.25ha (Vink) can not be shown as a polygon. The classic example are small wet spots in an otherwise well-drained area. These can be shown on the map as the **center point** (‘centroid’) of the small feature, and the properties of their soils considered as a legend category, associated with a point feature.

2.5 Attribute databases

Feature classes and individual features are both linked to **attribute databases**, which give thematic information about the object. The map only shows geographic location and an identification.

> For the terminology and principles of database design, a standard text such as Date [10] may be used. Many simpler, practical texts are more accessible, for example that of Howe [19].

Attribute databases are conventionally organized as a set of **relational tables**. A table is defined by several **columns**, one per **attribute**, and several **rows**, one per item. Each cell in the table (row-column intersection) contains an **attribute occurrence**, i.e. the value of the attribute for the individual which is stored in that row.

The following **standard terms** are used in the description of entity-oriented SGDB logical structures.

Table	A set of **rows** each containing the same **columns**; contains information of a determined kind about a set of individuals.
Column	A **set of values** of a single **attribute**. Also known as a ‘**field**’.
Row	A set of values of all attributes, exactly one value for each column in the table. Also known as a ‘**tuple**’ (from ‘multiple’?) or ‘**record**’.
Cell	A single attribute value for a single row; intersection of row & column; the smallest unit of data storage.
Key	**A set** (one or more) **of columns** that together **uniquely identify a row** within a table. No two rows may have the same key; this is enforced by the DBMS.

Foreign Key	A column which is a key in another table

The database designer must decide where to store each kind of information in this set of tables. Formally, the set should be **normalized** into **third-normal form**, which eliminates redundancy; i.e., a piece of information is never repeated, and all relations between tables must be many-to-one. The advantage is that the DBMS enforces data consistency and integrity. Intuitively, each piece of information is entered at the most general level possible. In practice, some redundancy may be tolerated for efficiency, but this can lead to inconsistencies.

We store information at the **individual** level ('primary-individual') when it only applies to a single instance, and the **class** level ('primary-class') when it refers to all objects in a class.

Example: observation points (all different, so must be described individually) vs. spot symbol points (all represent the same type of small area, e.g. stones or wetness, so can be described as a class).

Attribute tables are of three types: **spatial-entity**, **primary-classes** and **secondary**.

2.5.1 Spatial-entity tables

These refer directly to geographic objects, i.e. individual polygons, lines, or points.

The **key** is simply the **internal GIS identifier** of the object, sometimes called the **'internal IDs'**.

In the simplest case, there is no explicit **data**, but the GIS maintains information on the object's geometric attributes, i.e. area and perimeter (for polygons), or length (for lines). The objects may be given external identifiers, i.e. keys into the primary-class tables. These are sometimes called **'user IDs'**.

In the more general case, **data** includes observations on individual objects. For example, a table of point observations may include information on the observation date, type, author, etc.

2.5.2 Primary-class tables

These refer to **legend categories**, i.e. groups of objects of the same class (point, line, or polygon).

The **key** is the external identifier from the primary-individual tables, given to the **class**. Thus the primary-class table refers to a **set** of geographic objects.

The **data** include facts about the legend category, including references to **secondary tables**

Polygons: phase; name; composition

2.5.3 Secondary tables

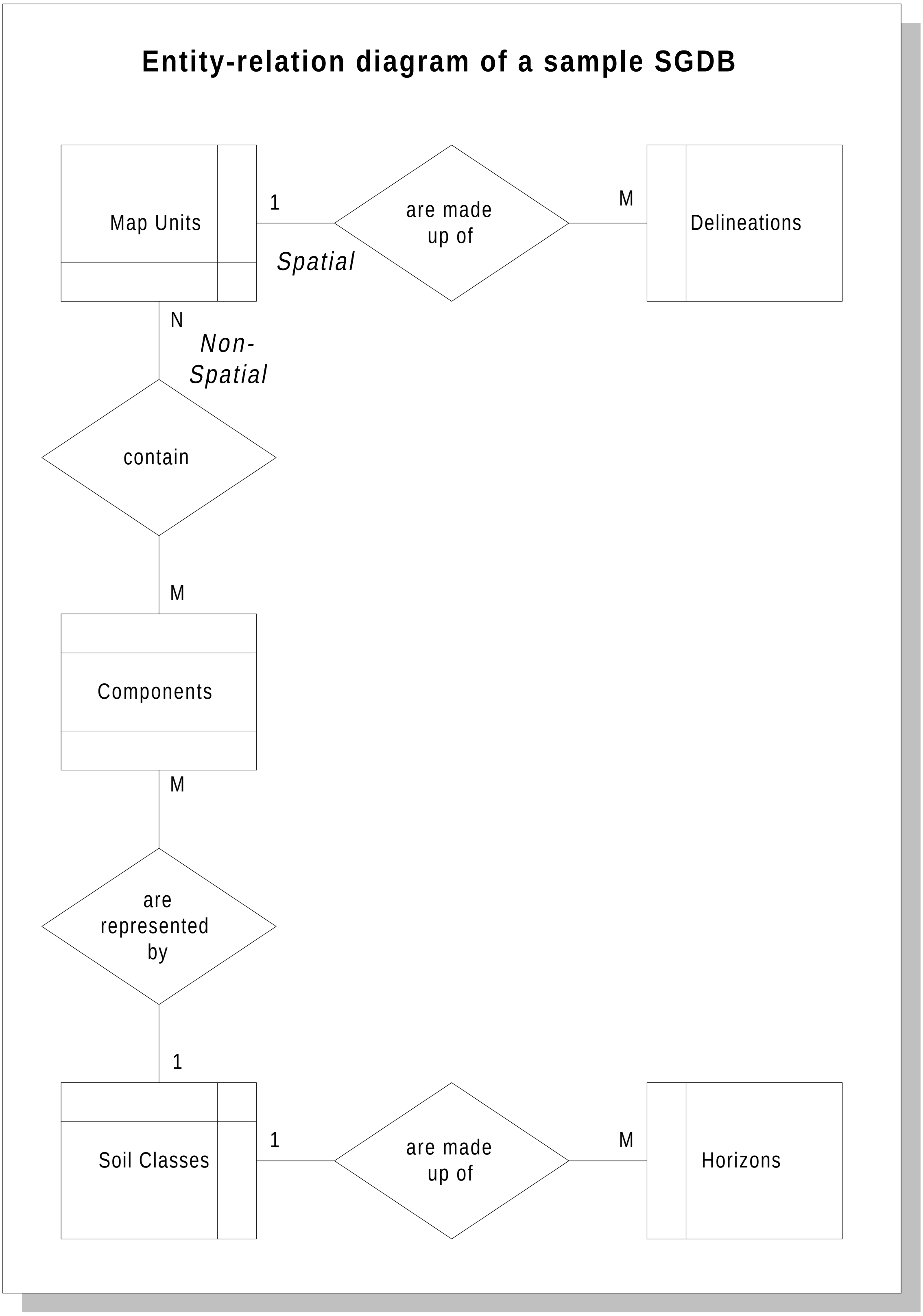
There can be many more tables, referred to by one of the primary tables, or by another secondary table.

Example: components of map units; **key** component name.

2.5.4 Support tables

Also called 'lookup tables'. These contain codes and their translations for various attributes in the primary-class and secondary tables. They are used to maintain **data integrity**. For example, a column in a secondary table might store the taxonomic class of the dominant soil in a map unit as a code; a support table would contain the list of legal codes and their translations.

2.6 Entity-relationship diagram



3 Example of an entity-oriented SGDB

Key concepts in this Chapter:

- Tables for the soil map: Map units, Map unit composition, Components, Soil classes, Soil horizons, Codes
- Tables for the observations: Observations, Observation horizons
- Logical consistency: within-column, between-column, between rows

This is a set of database **schemas**. All tables are normalized and have unique **primary keys**, indicated by **bold type**. The key can include one or more columns. Columns in one table which are used to join with other tables (i.e., keys from the 2nd table, so-called **foreign keys**, are written in *italics*, with the table they are defined in written after '>>' and in (parentheses):

Primary keys: **Like this**
Foreign keys: *Like this* >> (primary key of this TABLE)
Combined keys: ***Like this*** >> (also is primary key of this TABLE)
Implicit attributes: (Like this)
Explicit attributes: Like this

We divide the database into (1) **polygons, lines** or **points** of **map units**; and (2) **observation points**.

3.1 Polygons, lines, and points of map units

3.1.1 Spatial-entity tables

Table: Polygon Attribute (PAT): implicit: polygon boundaries
.... **Poly_ID**
.... (area, perimeter)
.... *MU_ID* >>(MU)
.... [other attributes of individual polygons]

Notes: The PAT has two functions: (1) It links mapped polygons to a legend category ('map unit'), and (2) It allows individual delineations to have attributes beyond those in the map unit to which the delineation belongs.

In addition to **polygons**, we can associate soil information with **lines** and **points**; these point directly to the component table (below) because their area is so small that it is hard to imagine such features having more than one component. We use lines and points for the cases where entities are too **thin** or too **small** in all dimensions to show as polygons.

Table: Line Attribute (AAT): implicit: ordered vector nodes & vertices
.... **Arc_ID**
.... (length)
.... *COMP_ID* >>(COMP)
.... Arc_Width: width of the soil body associated with the arc
.... [other attributes of individual arcs]

Table: Point Attribute (TAT): implicit: point location
.... **Point_ID**
.... *COMP_ID* >>(COMP)
.... Point_Radius: radius of the soil body associated with the point
.... [other attributes of individual points]

3.1.2 Primary-class tables

3.1.2.1 Map Units (MU)

This table gives the attributes of the map unit considered as a whole, i.e. attributes shared by all delineations and the entire delineation.

Table: Map Units (MU)
.... **MU_ID**
.... MU_Name
.... MU_Type = {Consociation, Association, compleX, ?}
.... MU_Pattern
.... MU_Phase_Slope
.... MU_Phase_Surface
.... MU_Phase_Erosion
.... MU_Phase_Substratum
.... [map unit interpretations]

Phase information could also apply to only some component; e.g. if within an association there is only one eroded soil. Then the component's table is used instead.

In this model, interpretations are derived at the component level (see below), and the interpretation for a map unit is derived by rules from the components' interpretations, depending on the application. However, it may be convenient to store derived interpretations in this table.

3.1.2.2 Map Unit Component List (MUCOMP)

This table links the map unit with its several components, and also records what is the proportion of each within the map unit. It breaks up the many-to-many relation between map units and components into two one-to-many relations (MU:MUCOMP and MUCOMP:COMP). It contains some information of its own, however: the proportion and landscape position of each component.

Table: Map Unit Component List (MUCOMP2)
.... ***MU_ID*** >>(MU)
.... ***COMP_ID*** >>(COMP)
.... COMP_Proportion: proportion of component in MU, [0…1]
.... COMP_Position: landscape position of component within a delineation

3.1.3 Secondary tables

3.1.3.1 Components (COMP)

This table gives the attributes of map unit components. A component may be found in several map units, but it has the same attributes regardless of map unit in which it occurs. Components consist of a soil type (or miscellaneous land type), whose attributes are found in the linked table SOL, using the linking column SOL_ID, and may include surface or substrata phases. Internal soil phases are not recorded here, rather in the SOL table.

Table: Components (COMP)
.... **COMP_ID**
.... COMP_Name
.... *SOL_ID* >> (SOL)
.... COMP_Phase_Slope
.... COMP_Phase_Surface_Stoniness
.... COMP_Phase_Erosion
.... COMP_Phase_Substratum
.... [component interpretations; can be in another table for convenience]

3.1.3.2 Soil Classes (SOL)

This table gives the attributes of ‘natural’ soil bodies, not including surface phases, but indeed including internal phases that are not reflected in the classification. For example, ‘Tarboro loamy sands, lamellic phase’.

Table: Soil Classes (SOL)
.... **SOL_ID**
.... SOL_Name
.... SOL_TaxClass: coded name in a standard classification system
.... SOL_Phase_Internal
.... [whole-soil attributes, e.g. profile water-holding capacity]

The SOL table and corresponding HOR table (next) usually refer to **synthetic** or **modal** soil individuals, meant to represent the class.

> **Modal** individual: An actual individual observation, thought to best represent the class. This is also called a **representative profile**. Advantage: a real data point.
>
> **Synthetic** individual: Not a real observation, but a synthesis by the correlator of a ‘typical’ or ‘central concept’ individual for a class. Advantage: can synthesize many observations.

In both cases, a correlator may introduce bias, either by selecting a modal individual that is not in fact representative, or by synthesizing an individual that does not represent the group.

3.1.3.3 Soil Horizons (HOR)

This table gives the attributes of individual horizons within a SOL.

Table: Soil Horizons (HOR)
.... ***SOL_ID*** >> (SOL)
.... **HOR_NUM**: sequential horizon number, from the surface
.... HOR_Symbol: standard soil description symbol, e.g. 2B2tx3
.... HOR_Top: depth to top of horizon
.... HOR_Thick: horizon thickness
.... HOR_Boundary: type of lower boundary
.... [horizon physical and chemical properties; can be in other tables
.... for convenience]

3.1.4 Support Tables

3.1.4.1 Codes (CODE)

Table: Codes (CODE)
.... **CODE_TYPE**: a column name from another table
.... **CODE_Code**: code
.... CODE_Name: translation

This is the support table, giving legal codes and their translations for all columns.

3.1.5 Simplifications of this structure

The structure can be simplified by including the MUCOMP table in the MU table, as long as we are willing to accept a maximum number of components.

Table: Map Units (MU)
.... **MU_ID**
.... MU_Name
.... MU_Type = {Consociation, Association, compleX, ?}
.... [other attributes of the map unit]
.... *COMP_ID_1* (>> COMP)
.... COMP_Proportion_1: proportion of component 1 in MU, [0…1]
.... *COMP_ID_2* (>> COMP)
.... COMP_Proportion_2: proportion of component 2 in MU, [0…1]
.... [map unit interpretations]

This is the structure used in the SSURGO SGDB. It makes some queries more difficult, for example, looking for all map units where a certain component occurs.

The structure can be further simplified by combining the **component** (COMP) and **soil classes** (SOL) tables. This has the disadvantage that there is only one phase of each soil class.

Table: Components (COMP)
.... **COMP_ID**
.... COMP_Name
.... COMP_TaxClass: name in a standard classification system
.... COMP_Phase_Slope
.... COMP_Phase_Surface
.... COMP_Phase_Erosion
.... COMP_Phase_Substratum
.... COMP_Phase_Internal
.... [whole-soil attributes, e.g. profile water-holding capacity]
.... [component interpretations; can be in another table for convenience]

Then the **horizons** table (HOR) is keyed by component:

Table: Soil Horizons (HOR)
.... ***COMP_ID*** (>> COMP)
.... **HOR_NUM**: sequential horizon number, from the surface
.... HOR_Symbol: standard soil description symbol, e.g. 2B2tx3
.... HOR_Top: depth to top of horizon
.... HOR_Thick: horizon thickness
.... HOR_Boundary: type of lower boundary
.... [horizon physical and chemical properties; can be in other tables
.... for convenience]

3.2 Observations

Actual **observations** are in a separate set of tables, related to map units by their **location** (geometry) and by a **correlation** to a named soil type. Note that an observation does *not* have to be located within a map unit to which it is best correlated.

Table: Observations (OBS): implicit: point location
.... **OBS_ID**
.... OBS_Type: { pit, trench, minipit, auger… }
.... *SOL_ID* >> (SOL): correlation of this observation to a named soil type
.... [site attributes, e.g. current land use, topographic position…]
.... [whole-soil attributes]

Observations typically have information in layers:

Table: Observation Horizons (OBS_HOR)
.... ***OBS_ID*** >> (OBS)
.... **HOR_NUM**: sequential horizon number, from the surface
.... HOR_Symbol: standard soil description symbol, e.g. 2B2tx3
.... HOR_Top: depth to top of horizon
.... HOR_Thick: horizon thickness
.... HOR_Boundary: type of lower boundary
.... [horizon physical and chemical properties; can be in other tables
.... for convenience]

In some type of observations there may be incomplete information; e.g. in an augering it is often difficult to assign a horizon symbol, but the depth is known.

3.3 Logical consistency

The above structure ensures only that entities are unique and correctly related in the database. In addition, we would like to ensure that the entities are logically consistent.

3.3.1 Within-columns

The simplest check on data integrity is to make sure that all data in a single column are logically possible.

For **coded** values, they should be checked against a **data dictionary** to make sure they really exist. The data dictionary is implemented as a **support table** which is referenced during data entry. For example, horizon boundaries must be from the set {a, c, g, d} meaning {abrupt, clear, gradual, diffuse}; soil colours are described by the Munsell notation from a fixed set of hues, values, and chromas. The code set should be from standard documents, e.g. the FAO Guidelines for Soil Profile Description or the USDA Soil Survey Manual [32].

For **numerical** values, they should be checked against an **allowed range**, which can also be stored in a support table. For example, pH must be between 1 and 14. Also, the **precision** of stored data should match that of the measurement in the field or laboratory. The relevant laboratory manuals can provide guidance here, e.g. [2, 33].

A special case is whether **missing values** are allowed. Some must not be allowed, e.g. depth of a horizon boundary. Others may be allowed, because they are only used for some analyses, e.g. pH.

A blank data item is ambiguous. Does it mean 'not present' or 'not measured'? In some cases the meaning is clear: for pH a blank would mean 'not measured'; the soil *has* a pH for sure, even if we didn't measure it. For surface stoniness, however, it could mean 'not recorded' or 'no stones'. The database designer must specify which is intended. In general, a blank should be used for 'not measured', and the absence of a feature should be explicitly coded.

3.3.2 Between columns

Columns in the same record often have logical relations. For example, a layer with sandy texture can not have a water content at pF2 higher than, say, 20%. A simpler example is that the sand% + silt% + clay% = 100% in the fine earth fraction.

These relations must be coded in **rules** in the data entry or validation program. They require expert knowledge about the object being represented in the database.

3.3.3 Between rows

Some constraints apply to several rows taken together. For example, in the MUCOMP table, we expect that the proportions of components of the map unit sum to 100%, otherwise there are areas that are unaccounted for.

These constraints can’t be checked during table editing, since the table is edited row-by-row. They are checked either as the table is closed, or with a special ‘consistency-checker’ routine.

4 Structure of a field-oriented SGDB

Key concepts in this Chapter:

- Filling a spatial field: Direct measurement vs. Interpolation

In this section we consider a field-oriented SGDB that corresponds to the Continuous Model of Spatial Variation (CMSV). In this model, **individual soil properties** are represented on the same grid. This fits the other CMSV data models such as satellite remote sensing, geostatistical interpolation, and grid DEM.

Case 1: **Direct measurement**: Properties are measured at **each grid point**, e.g. by remote sensing; either the raw values are stored directly, or calibrated values (e.g., estimates of surface salt content from a combination of TM bands).

Case 2: **Interpolation**: Properties are measured at **sampling points** and **interpolated** over the grid with geostatistical techniques. Two maps must be maintained: (1) values and (2) error.

5 Constructing a SGDB

Key concepts in this Chapter:

- Needs assessment: building the system to satisfy client need
- Accuracy vs. precision
- Point location: GPS, topographic maps, airphotos; maximum location accuracy
- How to obtain geometrically-correct boundaries from airphotos
- Satellite images as base maps; maximum scale
- How to obtain geometrically-correct boundaries from published soil maps; determining how soil maps were compiled
- Consistency with other coverages
- Thematic consistency

This chapter discusses the issues that arise when a SGDB is built from primary materials and observations, according to client needs. Often multiple sources must be integrated, which requires much judgement. In any case, the decisions made must be recorded for the database user; this is covered in the next chapter 'Metadata'.

We consider the two main aspects of SGDB design separately: spatial (geometric) and attribute (thematic).

5.1 Needs assessment & system design

The first step in any system design is to decide what it should do once it is built. This is called 'needs assessment'. This is the only way to ensure that a system, once built, will be used, and will answer the purpose for which it was built.

In the context of SGDB design, the following questions must be answered, in consultation with the clients:

Conceptual issues

1. **Who will use the SGDB?** This includes **primary** users, i.e. those who manage and use the system directly, and **secondary** users, i.e. those who will use its results but who will not directly manipulate it. How user-friendly must the system be? How much computer or soil survey knowledge must system users have?

2. **What questions will the SGDB be asked to answer?** In particular, what is the spatial **scale** and thematic **detail** of these decisions? For example, consider the difference between having to model carbon fluxes at field and regional scales.

3. **What data must the SGDB store?** The usual answer is 'all of it!', but a trade-off must be considered between the expense of organising, coding, verifying, and storing large amounts of data and its utility.

4. **Is there already a well-developed conceptual model** that must be made into a logical model, or must a conceptual model also be developed?

System issues

1. Are there any limitations or constraints on **hardware** or **software** that must be used?

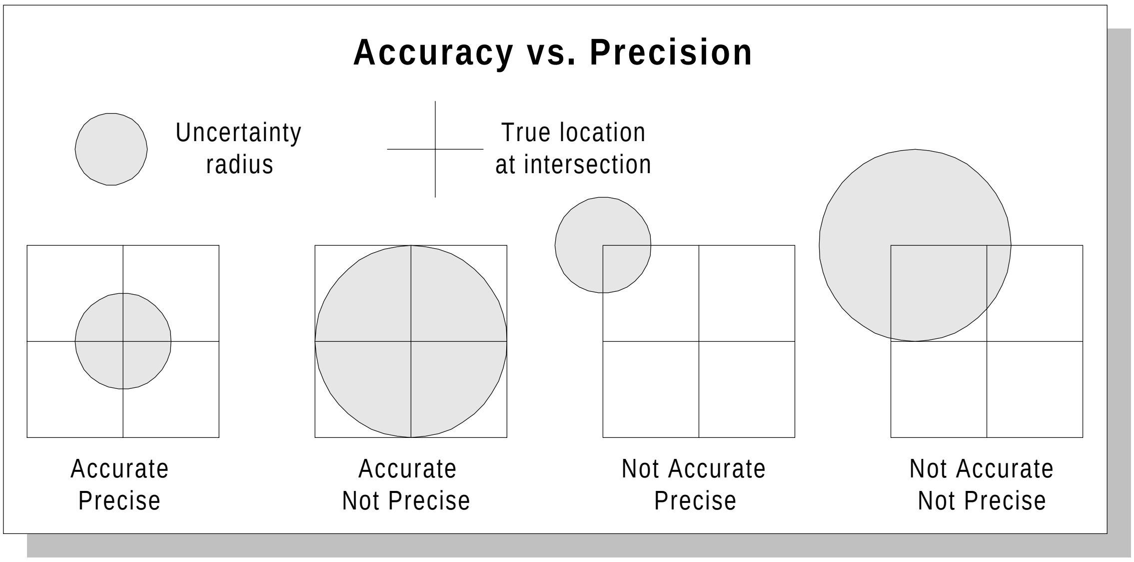
2. Is a **multi-user** or **networked** system required?

3. How much **time** is available to build the system? How much **expertise**? An imperfect, off-the-shelf, solution that is available quickly might be preferable to a ‘perfect’, custom solution that is never completed.

5.2 Geometric issues

5.2.1 Accuracy vs. Precision

These two concepts are sometimes confused. Map **accuracy** is how **close** a feature on a map is to its true location; Map **precision** is how small is the area of **uncertainty** of a feature’s location. Obviously we want both.



5.2.2 Point location

The accuracy and precision of a point in a SGDB depends on how it was obtained and how it is transferred to the SGDB.

Exact points: e.g. geodetic survey benchmarks; these have published co-ordinates which can be entered from the keyboard. Their accuracy is essentially perfect and their precision extremely high, and thus they are the standard for all other points.

High-precision measured points: e.g. differential GPS, land survey; co-ordinates can be entered from the keyboard or downloaded directly from a GPS or total survey station; precision is known from the device’s characteristics (e.g., GPS ‘GDOP’); accuracy depends on absolute references. Expected values of GPS readings are in any case highly accurate, since bias is corrected for by receiving signals from several satellites at the same time.

For each method of measurement, the accuracy and precision can be determined by **field experiments** with the method, against known points.

Low-precision measured points, e.g. by pacing and compass from a known point.

Points on airphotos: e.g. observations visually located on airphoto. Three issues:

1. how close is marked point to the real point; this depends on the density of features on the airphoto and how close the point is to observable features;

2. scale of photo = inherent error in marking the point on the photo (0.25mm)

3. precision of georeferencing the airphoto for digitizing (see below)

Points on topographic maps: Same three issues as with airphotos, except (3) is almost always much easier.

Inherent error of plotting points on a map: A **well-defined point** on a map is defined by typical **map accuracy standards** as 0.25mm (¼ mm) on a **paper** map [12]; i.e. the point must be within ¼ mm of its true position 90% of the time. This includes both location and plotting errors. With **automated cartography** the point can be *plotted* more accurately, but still there is paper shrinkage & expansion, uncertainty in the mechanical positioning of the plotting pen, and the location of the point in the field, so that the precision is not much better, perhaps 0.1mm in the best case.

<u>Computing maximum location accuracy</u> [16, Table 1.2]

Multiply the SN by 0.25mm (0.1mm for GIS products) and then convert to ground meters.

> Example: 1:50 000: 50 000 mm_g mm_m^{-1} × 0.25 mm_m = 12 500 mm_g = 12.5 m_g
> (5 m_g for a GIS-produced map on stable paper with a high-precision plotter).

Interpretation: it is inherently impossible to plot a point closer than 5m even on a GIS-produced 1:50 000 map. Also, any line can not possibly have a width <5m, since any point on the line could not be located more precisely.

5.2.3 Geometrically-correct boundaries from airphotos

A very effective method of boundary delineation is stereoscopic photo-interpretation, with lines being drawn on one photo of a stereopair. Unfortunately, stereopairs of air-photo are not geometrically correct, so neither are photo-interpretation or field lines drawn on them. For a correct map, especially one that will be included in a GIS, the boundaries must be geometrically accurate and geo-referenced.

Recall that the **geometric errors** in airphotos are of three kinds: **tilt**, **radial**, and **relief**. In addition, airphotos are usually not at the same nominal **scale** as the desired map. See a standard photogrammetry text, e.g. [1], for detailed information.

<u>Solution 1: manual transfer to orthophotos</u>

An **orthophoto** is a photograph which looks like an aerial photograph but which is as geometrically correct as a topographic map, and which has been georeferenced. It is produced from aerial photos and an elevation model. A set of orthophotos may be combined to make a base map of a study area.

Lines on unrectified airphotos can be **manually transferred** to orthophotos which cover the same area as the unrectified photos used for mapping. No special device is needed; with the subtle details of the photos, boundary lines can be re-drawn by hand extremely accurately. Since the orthophoto is geometrically-correct, lines drawn on the photo or a mylar overlay may be digitized or scanned and geo-referenced by four control points.

The problem is obtaining the orthophoto.

Solution 2: manual transfer to a correct base

Lines on unrectified airphotos can be **manually transferred** to a geometrically-correct **base map** (typically, a topographic map) with a mirrored light table or a zoom transfer scope. Continuously adjust by eye, work on small pieces only between adjustments. Accuracy can be high if there are dense features for interpolation. Accuracy is very high if a feature shown on the base map is followed exactly, e.g. a river or a sharp contour line. The zoom transfer scope is more precise, the mirrored light table does not require stereo vision. In both cases, the tilt and scale displacements can be removed. Radial and relief displacement can not, hence the need to work in pieces.

Problem 1: The base map may not show enough features. E.g. large arid plain, with low relief (no contour lines), no permanent drainage ways, very sparse infrastructure, but important soil differences that are clear on the photo (salt spots, blowouts, different playas & fans) but not on the map.

Problem 2: The base map may be poor-quality: old cultural features, shifted natural features e.g. rivers, incorrectly-drawn contours (poor quality control)

Solution 3: register & georeference a photo overlay

Individual airphotos may be register & georeferenced with 10 to 20 identifiable, sharp points that can be seen on the photo & on the base map. Typically, the mylar overlay with the soil lines is geo-referenced on a digitizer, first marking the points themselves on this same overlay.

Examples of ground control points (GCP): road intersections, building corners.

Caution! Buildings are sometimes schematic, not geometrically correct (although their center should be correct)

Caution! Natural features may shift (especially river junctions, sand bars, land points in lakes). If possible, choose rock-controlled features, as they will not move so fast.

Problem: The so-called ‘correct’ base map may be incorrect!

Solution 4: pre-mapping with geometrically-correct maps

The basic idea is to find some soil or landscape boundary lines on geometrically-correct maps, then join other lines to these.

Source 1: topographic base map: rivers, sharp contours

Source 2: satellite images (see next §). Advantage: very little relief distortion; system errors are understood and can be controlled by standard procedures. Usually can geo-reference and resample to within one to three pixel error (30 - 90m). This may be good enough for maps at 1:100 000 or smaller scales (here, MLA = 25m).

5.2.4 Using satellite images as a base map

A satellite image may be a good choice for a geometrically-correct base map. These **cover large areas** and so provide a **synoptic view** with fairly good **geometric accuracy** at medium to small scales.

What map scales can be reasonably supported by a geo-referenced satellite image? We can calculate this from the image resolution, with the principal that the base map should provide the same precision as a paper map at a given scale.

First, we need the concept of **inherent position error** (IPE). This is the maximum distance, in ground meters, that a well-defined point may be displaced in the image.

The first limitation on scale is the **image resolution**. Satellite images have an inherent per-pixel ground resolution, e.g. nominally 30x30m for a Landsat TM image, 10x10m for a SPOT panchromatic image. The true position of a point represented by a pixel (implicitly at the pixel's center point) may be anywhere in the pixel, as far away as a half-diagonal, so that

$$\text{IPE} = (\text{pixel side}) \times [(\sqrt{2})/2]$$

For Landsat TM, this is ≈21.2m; for SPOT panchromatic this is ≈7.1m. We must now find the maximum map scale for this position error. Since Maximum Location Accuracy (MLA) in ground meters = SN/1000 × 0.25 (manual) or 0.1 (automated), we can compute maximum SN as:

$$\text{Maximum SN} = \text{IPE, m} \times 4\,000 \text{ (manual)}$$
$$\text{Maximum SN} = \text{IPE, m} \times 10\,000 \text{ (automatic)}$$

For example, if IPE = 21.1m, for manual maps, the Maximum SN = 84 400 ≈ 1:85 000, meaning that a satellite image with 30m pixel sides should never be used for a base map at scales larger than 1:85 000. In other words, such an image is equivalent to a paper map produced by conventional methods at 1: 85 000.

Continuing this example, a GIS map produced by fully-automated techniques, in which case this satellite image would be equivalent to a map at 1:211 000. This means that, with fully-automated techniques, the satellite image would be the weak link in the precision chain.

For SPOT panchromatic images, the corresponding scales are 1:28 400 ≈ 1:30 000 and 1:70 700, respectively.

Another limitation on scale is the precision of the image **geo-referencing**. The image processing system reports this precision as a so-called 'sigma' or error value, in pixels. If this sigma is greater than [(√2)/2] ≈ 0.707 pixels, the geo-referencing is less precise that the resolution, and the previous calculation is repeated with an inherent position error = sigma x (pixel size).

We can not expect a sigma below one pixel if we use maps at scales smaller than the Maximum SN (manual) to identify ground control points (GCP). In practice, this means that maps at a somewhat larger scale should be used. To geo-reference a Landsat TM image, the minimum scale should be 1:50 000; for a SPOT panchromatic image it should be 1:25 000.

If GPS survey is used to find GCP's in the field, we must use a GPS system with a precision higher than the IPE.

5.2.5 Geometrically-correct boundaries from published soil maps

A large number of soil maps have been published over the years, and it seems much more practical to store these in the SGDB than to re-survey. The first step is to determine how geometrically-accurate is the paper map; this comes from knowing how it was compiled and from some tests with the digitizer.

Case 1: Topographic base map

If the soil lines are drawn on a topographic base map, they can be digitized directly. We can't improve the drafting of the original soil lines. All we need are four ground control points, which may be the four map corners, to register the map on a digitizer.

Once the lines are digitized, we may see discrepancies with other features on the corresponding topographic map, e.g. rivers, swamps, rocky areas and contours. The lines may be adjusted accordingly.

Case 2: Photo-mosaics

Many soil maps are drawn on photo-mosaics with various degrees of control. The photos may be visible as background (as in the USA) or not. Here it is very much trial-and-error. It is quite unlikely that the entire map can be registered at the same time. Ground control points are typically well-defined cultural features such as road junctions which were drawn as locational aids on the soil map. In extreme cases, a ‘pure’ soil map has been produced with no cultural features! The only hope here is to find soil lines that correspond to identifiable topographic features, e.g. river banks.

5.2.6 Geometric consistency

When a soil map is to be used as part of a GIS, it will be combined with other maps. Many of these represent features that are **correlated to the soil pattern**.

We must ensure that **common boundaries are represented only once**; therefore we must establish a **hierarchy** of boundaries, based on their reliability and logical relation, as well as the primary data provider.

Example: All soil maps delineate water bodies (non-soil), which are not further characterized in the soils theme. If a standard topographic map exists, the water bodies should be digitized once, preferably by the agency responsible for the topographic map, and used by the soils map. The water boundaries would *not* be re-digitized. This may not work for shallow waters, seasonal waters, or flood plains, if the topographic map was made to represent high waters, when in fact the soil is often not under water.

Example: A geological map may show lithology and structure (e.g. terrace levels) that correspond to differences in soil type. Especially where these are sharp lines, also seen by the soils photo-interpreter, they should be digitized once and used by both thematic maps.

5.3 Thematic issues

See also the section on ‘Logical Consistency’ in Chapter ‘Example of an entity-oriented SGDB’, above.

5.3.1 Enterprise rules

The database consists of logically-related information. The **conceptual model** is partly determined by the **nature of the object** we are trying to describe (soil cover, soil observations, soil classes…) and partly by **constraints** on the data . These are sometimes called **enterprise rules**, i.e. rules set by the organization.

Examples: ‘Map units must be described with a dominant and up to two sub-dominant soil types’; ‘Surface phases apply to entire map units, not to components’; ‘All horizons with water pH<6 also have pH measured in KCl’.

These rules are incorporated into the metadata, and they help the database designer structure the database.

5.3.2 Coded columns

Any column that can only contain a limited set of values should be **coded**, with the codes and their plain-language translations held in a reference table. The ‘unknown’ class is a special value.

Codes should be chosen from standard sources, e.g. the FAO Guidelines for Soil Profile Description or the USDA Soil Survey Manual [32]. Soil Classification codes can be taken from the key codes in the Keys to Soil Taxonomy [34] or the World Reference Base [15]. National and international standard codes exist for political divisions; see the International Standards Organization web site, http://www.iso.ch. ISO has some soil-related codes, in standard ISO 13.080.

Soil colours are described by the Munsell notation from a fixed set of hues, values, and chromas; see http://munsell.com/munsell1.htm for details of these codes.

It is preferable to use a short list of classes for each coded attribute. More detailed lists are harder to apply because they are ambiguous. Consider, for example, the classification of horizon boundaries of the FAO from the set {a, c, g, d} meaning {abrupt, clear, gradual, diffuse} and being defined by the FAO to represent transition zones {<2cm, 2-5cm, 5-10cm, >10cm}. Why not allow more classes, e.g. code 'ac' meaning 'abrupt-to-clear', or 'x' meaning 'exact, <1cm'? The first answer is that field scientists will not be able to consistently apply finer divisions. The second answer is that the differences are not significant for interpretation.

Extra information from the observant field scientists can be stored as text notes.

5.3.3 Numeric columns

Any column that can only contain a **limited range** of numeric values must be controlled by a **validation rule** to ensure that the column only contains legal values. The 'unknown' value should be represented by a blank column or special 'unknown' marker, **not** by a reserved numeric value.

Numeric columns must store values with the appropriate **precision**, also controlled by a validation rule. This precision is determined by the data-gathering and analysis technique.

5.3.4 Non-coded text columns

Free (non-coded) text is only useful to store and print. Text is difficult or impossible to retrieve with a query, mainly because of **inconsistent terminology**. The only free text columns that should be present are comments. These can then be read one-by-one when records selected by other queries are retrieved.

5.3.5 Other non-structured columns

Other information can be put in digital form and stored in the database. A good example are **photos** at any level: map unit, component, soil, or horizon. They can't be queried, but can be printed in a report or displayed along with structured data that was retrieved by a query.

6 Querying a SGDB

Key concepts in this Chapter:

- Queries: spatial, non-spatial, mixed
- SQL and QBE

A SGDB is built in order to be used. In this section we discuss how information is extracted from the SGDB. We refer back to the list of questions that a SGDB can answer from the first section.

6.1 Spatial queries

These require a GIS.

At a given site:

These include the questions about a given site: 'What is the **soil class**?' The site is identified either interactively (on-screen) or by its coordinates obtained from some other source (map or field measurement). This question is easily answered because of the link between spatial and attribute data.

In a topological-entity GIS, a point-in-polygon search identifies the delineation containing the point. In a grid GIS, the coordinates refer to a specific grid cell. The delineation or grid cell refer to the soil class primary attribute tables.

Finding a given site:

These include the questions about a given site: 'What is the **soil class**?' at a site. The site is identified either interactively (on-screen) or by its coordinates obtained from some other source (map or field measurement). This question is easily answered because of the link between spatial and attribute data.

Locating areas of interest:

These include the question: '**Where** can soil of a particular **class** be found?' The class in question is identified in the attribute tables, and the GIS is asked to select all delineations of the class. Summary statistics can be calculated on this set of delineations, e.g. total area, histogram of areas.

6.2 Non-spatial queries

These do not require a GIS, only the attribute databases. Modern DBMS allow queries to be formulated with Structured Query Language (SQL) [10] and a more visual Query By Example (QBE).

Sample queries: 'Which observations are correlated to a specified class?'; 'Which observations have specified properties?'

6.3 Mixed queries

These require both the GIS and the attribute database. They use the link between the legend and the attributes database. Queries: 'What are the **soil properties** at a site?'; '**Where** can soil with **specified properties** be found?'; 'What proportion of the area is occupied by soils with **specified properties**?'

7 Cartography

Key concepts in this Chapter:

- Use of colour to group a legend
- Reducing a polygon map to a smaller scale: cartographic & thematic issues
- Enlarging a polygon map to a larger scale is rarely justified
- Reducing and enlarging grid maps

One of the purposes of the SGDB is to produce printed maps. For this purpose, the well-established principles of cartography, as explained in standard texts, e.g. [31] should be followed. There are some special considerations for **soils** maps, which we cover here.

7.1 Colours

Colour is very attractive, but if it is used, it must mean something! It should reflect some **meaningful grouping of the map legend**. Traditional colours such as purple for peat, blue for poorly-drained mineral soils, green for well-drained mineral soils, and yellow for excessively-drained soils seem psychologically satisfying, but their use should be verified with clients. A standard cartography text such as that of Robinson *et al.* [31, Chapter 21] should be consulted for psychological, symbolic and practical issues of colour use. These may well vary by culture or user group. Colour use is dangerous in this sense, as it may lead to mis-interpretation.

The worst possible use of colour is if extremely different colours are used for similar soils. This happens if desktop mapping software, e.g. ArcView, is used uncritically, since such software often assigns contrasting colours to adjacent legend categories.

Cartographic rules of thumb: more than six to ten major hues are confusing; dark colours obscure topographic reference features.

Some soil survey organizations, e.g. in the USA, do not use colour; so that the map is just an information carrier. Space is divided by boundary lines and labeled by symbols. There is no visual bias, and the client makes no unwarranted inferences.

7.2 Polygon maps

7.2.1 Reducing a polygon map to a smaller scale

The GIS allows a map to be printed at any scale. Here we consider the case where a map is printed at a smaller scale than the source documents.

The cartographic result of a **mechanical** reduction in map size (i.e., a decrease in scale) is to each delineation smaller, in accordance to the square of the ratio of scales. The Minimum Legible Area is increased correspondingly, i.e. proportionally to the reduction in *area* scale. For convenience, we define the **reduction ratio** (RR) as the ratio of the two linear scale numbers:

Reduction ratio $\equiv SN_{new} / SN_{original}$

> For example, if a map is originally compiled on a 1:50 000 base and then reduced to 1:100 000, the linear scale is reduced by 2x, and RR = 100 000 / 50 000 = 2. Therefore, the **area** scale is reduced by $2^2 = 4$x. The MLA increases from 10ha to 40ha.

This presents **two cartographic problems**:

1. **Some delineations become illegible**, i.e. those where the MLA of the larger-scale map is illegible on the smaller-scale map. In the above example, any delineation between 10ha and 40ha (legible at 1:50 000) is now illegible at the reduced scale (1:100 000.)

2. **The Index of Maximum Reduction (IMR) is smaller**, and may indicate **overall illegibility** of the map, even if individual delineations are large enough. An IMR =2 is considered optimal; thus unless the original IMR was $\geq 2\times(RR)$, the IMR will be <2 after reduction.

In the case of soil maps, **there is no purely cartographic solution**. We must, of course, mechanically throw out illegible polygons and assign their area to a surrounding or adjacent polygon. In the case of 'islands', they must be absorbed by their surrounding polygons. But what about a small polygon that borders on several larger polygons? Or a group of small polygons that together would be >MLD at the new scale? The **landscape pattern** at the new, smaller, scale must be analyzed.

Even in the case of 'islands', the remaining large polygon has a different composition, i.e. different proportion of soils. The remaining map units must be re-examined, re-described and **possibly re-named** in light of their new composition. See the next § for rules on naming map units. A common situation would be several consociations now described as associations, with known landscape patterns of the components.

Note that the GIS *can* perform a mechanical generalization, e.g. by eliminating polygons that are too small and merging them with their largest neighbor. But that is purely cartographic, and we must consider the categorical implications.

> For example, think of a pitted glacial outwash plain, with two components: deep, well-drained gravelly loams on the higher positions, and poorly-drained, organic matter-rich, fine textured soils in the 'potholes' in the depressions. These can easily be delineated on an airphoto. Supposing that the potholes occupy approximately 1ha each, they can be legibly delineated at 1:16 000 or larger, e.g. 1:12 500 (MLA = 0.625ha). We have a map that looks like Swiss cheese, where the potholes are clearly shown. Suppose that the potholes occupy 20% of the total area, and the gravelly loams the other 80%. There are two map units, both consociations.
>
> Now, suppose we reduce the 1:12 500 map to 1:25 000 (RR = 2). The MLA is 0.625×4 = 2.5ha, much larger than the potholes. They become illegible, and must be deleted. Their area is now included in the surrounding polygons.
>
> If we omit them from the map, suddenly we don't have Swiss cheese, we have one large map unit, consisting of 80% gravelly loams and 20% potholes. Thus we **must** change the legend! Since the potholes are strongly contrasting and limiting, even though there are only 20%, they must be included in the map unit name; since these two landscape components can obviously be mapped separately at a larger scale (i.e., the original scale), the new map unit is an association. The smaller-scale map is still categorically-detailed, but cartographically-general.

7.2.2 Enlarging a polygon map to a larger scale

Here we consider the case where a map is printed at a larger scale than the source documents. Since we can never add information, the larger-scale map is **misleading**, because the MLD at this larger scale were in fact not mapped. We can not assume that there are no areas larger than the MLA of contrasting soils. Also, boundary lines look smooth; they may in fact be more detailed at the larger scale, but they were not mapped. It is very rarely justified to print a map at a larger scale than its original source.

At a larger scale, line and point entities that represent soil bodies should be represented as polygons, assuming that the line width or point radius was controlled by the original map scale.

7.3 Grid maps

Reducing and enlarging polygon maps corresponds to decreasing and increasing the resolution of a grid map.

7.3.1 Decreasing the resolution of a grid map

It may be necessary to decrease the resolution, i.e. increase the grid cell size, of a grid map, usually in order to match another grid map made with coarser resolution. There are two general methods: **filtering** and **resampling**, and a method that only applies to continuous-value maps, **averaging**. All methods are applied when the grid cell resolution is decreased by any square, i.e. four, nine, sixteen… grid cells are combined into one; of course, this operation can be repeated.

Filtering:

A **majority filter** assigns to the one new grid cell the majority value from the group. A priority rule is used to break ties. Values that occur only as isolated pixels will not be represented in the coarser map.

Re-sampling:

The value of the **central grid cell** of the group is applied to the new grid cell.

Averaging:

The values of the cells in the group are **averaged** and this value is then is applied to the new grid cell. This makes sense for a continuous variable where the average value is meaningful, e.g. salt content.

8 Metadata

Key concepts in this Chapter:

- Without metadata, a SGDB is next to useless
- Useful metadata standards and tools are freely available
- Metadata is essentially about careful procedure and documentation

Metadata are 'data about the data'. They describe the dataset to all users. Even a simple description may be considered metadata, but nowadays the term is reserved for a detailed, formal description.

Metadata standards have been developed by the Federal Geographic Data Commission (FGDC) of the USA. This contains the following principal sections:

1. **Identification_Information**: identifies the dataset and gives its geographic limits
2. **Data_Quality_Information**: how reliable is the data? This explains how the data were collected, sampling designs, analytical techniques etc. For interpolated maps, the interpolation method must be specified.
3. **Spatial_Data_Organization_Information**: explains which spatial model was used to represent the data
4. **Spatial_Reference_Information**: explains the co-ordinate system used for georeference
5. **Entity_and_Attribute_Information**: explains the attributes (variables) in the database, for example, the meaning of codes, and the structure of attribute tables
6. **Distribution_Information**: explains how to obtain the data, including on-line access, and any restrictions on the use of the dataset.
7. **Metadata_Reference_Information**: explains who is responsible for the metadata, and which standard it follows

8.1 Metadata sources

Principal reference: Federal Geographic Data Committee. 1994. Content standards for digital spatial metadata (June 8, 1994 version). Federal Geographic Data Committee. Washington, D.C..

Available in HTML format from the FGDC at URL: http://www.fgdc.gov/metadata/contstan.html. This page also allows you to download the standard in Adobe PDF; also in Word Perfect 6.1, ASCII, and PostScript printer-ready. Their home page is http://www.fgdc.gov/ .

It is also available at the USGS site, http://geology.usgs.gov/tools/metadata/standard/metadata.html, along with much other information on formal metadata from the USGS at URL http://geology.usgs.gov/tools/metadata/

A very useful site for everything to do with metadata is http://www.blm.gov/gis/nsdi.html , maintained by Sol Katz of the Bureau of Land Management (BLM). Metadata creation can be supported by various tools; a page reviewing these is http://badger.state.wi.us/agencies/wlib/sco/metatool/mtools.htm

8.2 Soils metadata

The FGDC’s **Soil Data Subcommittee** has a page at http://www.statlab.iastate.edu/soils/fgdc-sds/

The Soils Map of Mexico, 1:1’000 000, has metadata at http://www.cep.unep.org/data/north/soils/mexsoils.html

9 Abbreviations

AAT	Arc Attribute Table
CMSV	Continuous Model of Spatial Variation
DBMS	Database Management System
DEM	Digital Elevation Model
DMSV	Discrete Model of Spatial Variation
DTM	Digital Terrain Model
FAO	Food & Agriculture Organization of the United Nations
FGDC	Federal Geographic Data Commission (USA)
GCP	Ground Control Points
GIS	Geographic Information System
GPS	Global Positioning System
IMR	Index of Maximum Reduction
IPE	Inherent Position Error
MLA	Minimum Legible Area; Maximum Location Accuracy
MLD	Minimum Legible Delineation
MMSV	Mixed Model of Spatial Variation
PAT	Polygon Attribute Table
QBE	Query By Example
RR	Reduction Ratio
SGDB	Soil Geographic Data Base
SN	Scale Number (inverse of the scale ratio of a map)
SQL	Structured Query Language
SSURGO	Soil Survey Geographic Database (USA)
URL	Universal Resource Locator (Internet)

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