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Measurement-based soil information systems for the Caribbean

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ABSTRACT. **Significant amounts of data are lost in the soil mapping process due to classification and generalization. Although a soil map and a survey report are prepared, the data presented in these documents are soil classes and representative profiles for each soil class. The data collected in the field are not made available to map users. Usually, in the digitization process, the same data presented on soil maps and survey reports are stored in the database. While these data are useful, the raw data are much more valuable for several users. This paper describes a conceptual model for the storage of soil survey observations and their data quality information. This schema is based on an object-oriented data model. This approach allows greater flexibility in the storage, access, modelling and analysis of the soil data that are stored in the database. A more realistic representation of the soil landscape is therefore achievable.**

1. INTRODUCTION

In the last few years, soil information has become increasingly important to many disciplines. This is especially so in the Caribbean where informed decisions are needed to meet conflicting pressures for limited land resources. Sensible use of land is essential if there is to be an adequate distribution for agricultural, housing, tourism purposes, and to cater for loss of coastal lands from sea level rise due to climate change (CPACC, 2001). In addition to farmers, civil engineers and agricultural engineers, applications such as environmental engineering, urban planning, disaster management, and policy-making also need soil information (Purnell, 1993; Zinck, 1993; Winegardner, 1995; K. Kumarsingh, person. commun., 2001). Soil data required by this expanded user community have changed significantly in the last few years (Soil Survey Staff, 1993; Burrough and McDonnell, 1998). Users need these data in different types, amounts, forms, resolutions and reliability levels (Indorante *et al*., 1996; Burrough and McDonnell, 1998). Instead of soil mapping units, high resolution, individual soil property values are needed (Purnell, 1993; Rogowski and Wolf, 1994). These data are now more often needed in digital form (Ibanez *et al*., 1993), and information about the quality of these data is becoming increasingly important (Burrough, 1993a; Burrough and McDonnell, 1998; Ramlal, 1996).

The present systems used for data collection, processing and presentation are inadequate for meeting the increased need for soil data. This paper proposes an alternate approach for the provision of soil information. The first section reviews the present techniques used in the soil surveying and mapping process. Section two discusses the limitations of using these techniques. Emphasis is placed on data quality issues. Section three proposes an alternate approach to providing soil data. Section four presents a conceptual schema for a measurement based soil information system. This section also discusses the inclusion of data quality information with the soil data. The final section provides conclusions.

2. A REVIEW OF THE SOIL SURVEYING AND MAPPING PROCESS

Soil scientists had developed a number of techniques to make soil data more manageable and accessible to users before the advent of computer technology (Heuvelink and Huisman, 2000). Two major problems that they had to address were (i) that humans could not easily remember, process, sort and analyze large amounts of data, and (ii) the available technology did not allow the storage and maintenance of the vast amounts of data acquired daily from the soil mapping process (Burrough, 1991; Ernstrom and Lytle, 1993). Two systems were developed. The first was soil classification methods such as the USDA's soil taxonomy (Soil Survey Staff, 1993). The second method involves the use of soil evaluation models that provide suitability classes for various types of soil for diverse uses.

2.1. Soil Taxonomy

Most Caribbean islands use a similar system to the United States for acquiring and mapping soil data. Soil is usually classified using the Soil Taxonomy as developed by the Soil Survey Staff in the United States (Soil Survey Staff, 1993, 1994). Similar systems are used in most countries in the world. These systems of classifying soil have many limitations (Edmonds *et al*., 1985; Hewitt and Van Wambeke, 1985; Voltz and Webster, 1990). In these schemes, soil is classified on the implicit assumption that there are sharp boundaries between soil units. It is assumed that these soil units are, for the most part, homogeneous (Bouma, 1989; Heuvelink and Huisman, 2000). This assumption is not necessarily a valid one (Burrough and Frank, 1995; Burrough, 1993a; Ernstrom and Lytle, 1993; Voltz and Webster, 1990). The classification scheme categorizes soil property values into classes that lead to a loss of data. The original data are made inaccessible by this classification. Additionally, data for individual units are left out in favour of representative profiles (Burrough, 1991). Classification of soil is based on the use of only a few soil properties. Although the variation of these properties is correlated in most cases, the assumption that changes in these properties are homogeneous over the same area is not valid (Campbell, 1977; McBratney *et al*., 1992). After soil classes are determined, the other soil properties that are associated with soil variation are attached to these classes. This implies that the variation patterns of these properties are the same as those used for the classification. This is normally not the case.

2.2. Interpretative Systems for Land Evaluation

Once soil surveying and mapping are completed, the soil data may be used to provide land suitability classification or land evaluations for particular purposes. These classes are normally derived using soil interpretation models. Suitability classes for a particular use are assigned to the soil class but not to individual mapping units. The validity of some of these models has been verified from empirical evidence. However, sensitivity analysis of how individual factors affect the outcome of these models has not been carried out (Burrough, 1993a). Cartographic representation of these interpretations is not normally included in the soil survey report. The major limitations of using an interpretation system for land evaluation are: the quality of the model used is unknown; the quality of the data used in the model is also unknown; crisp logic is used. However, a few researchers have proposed the use of fuzzy classification and mathematical methods for improving land evaluation modeling (Burrough *et al*., 1992; Burrough, 1989; Odeh *et al*., 1990). Soil that may be suitable for a particular use may be omitted because of the use of crisp logic (Burrough, 1991, 1993a; Bouma, 1989). Finally, the correlation or lack of correlation between soil properties is not considered in these qualitative models (Bouma, 1989).

2.3. Limitations in the Provision of Soil Data and Data Quality Information

The providers of soil information have been unable to meet the specific needs of users, both in terms of the soil data provided and the lack of information about data quality for assessing the fitness for use of these data. Their failure may be attributed to many problems including inadequate presentation of soil survey results; loss of information due to the mapping process and inadequate classification systems; the provision of information that is of questionable or unknown quality (Ibanez *et al*., 1993; Brown, 1988); and the inadequate provision of information about data quality (Burrough, 1993a). A number of the above problems are directly attributable to the models used to represent the soil landscape (Burrough, 1986, 1989, 1991, 1993a; Hole and Campbell, 1985; Ernstrom and Lytle, 1993; Indorante *et al*., 1996).

Maps have been traditionally used for the storage and presentation of soil data. The amount of data that can be placed on a map is limited (Dent, 1985). Attribute data not placed on the soil map are usually included in the soil survey report. However, not all data that are collected are made accessible to users (N. Kalloch, person. commun., 2000). Soil data are normally represented on maps as soil mapping units.

With recent advances in computer technology, the ability for storing, manipulating, analyzing, and presenting spatial data has been greatly enhanced. It is now possible to handle vast amounts of spatial data in digital form. Digital soil data are stored in the form of soil mapping units with attached attributes (Dumanski *et al*., 1975; Fernandez and Rusinkiewicz, 1993; Reybold and TeSelle, 1989; H. Ramlal, person. commun., 2001). Soil data are converted to digital form by first digitizing soil map units then attaching attributes to them. GIS software may allow the user to view soil maps in new and innovative ways. The problems associated with paper map display may be reduced to some extent, but the limitations introduced into the data by the modeling process still remain.

Both analog and digital soil maps use the object model (see Couclelis, 1992; Heuvelink and Huisman, 2000), which significantly influences the way data are collected, processed and presented. Attribute data stored for each soil unit are limited because much of the data observed in the field and obtained from laboratory analysis are left out of the database (McBratney, 1992). In fact, soil surveyors frequently do not record all the data that may be collected. Instead they rely on expert knowledge to classify soil mapping units in the field rather than taking quantitative measures (Soil Survey Staff, 1993). As a consequence, there is a loss of data, which results in a database of limited use and a reduction in the type of analysis that may be carried out (Burrough, 1989; Voltz and Webster, 1990).

The object model also influences the way data quality is determined for the data collected. For well-defined mapping units, the applicable components of quality include positional accuracy of boundaries, purity of soil units with respect to soil classes, and resolution in terms of the smallest area that may be mapped at a given scale (Marsman and de Gruijter, 1986). While these measures may be useful to some extent, there are many inherent limitations. Positional accuracy of soil class boundaries has little meaning (Heuvelink and Huisman, 2000). The purity measure of a soil unit is determined by assessing how closely the class for a mapped unit conforms to what is found in the field. Classes are based on a few key properties and if these properties match with values found in the field, high purity values are assigned to these units (Burrough, 1993b). This purity measure does not always reflect the variation of other properties that were not used in the classification process. Another significant limitation is the assumption that the entire unit is homogeneous (Hole and Campbell, 1985). This assumption does not normally hold. The minimum mapping unit measure of resolution is typically not reflective of how the data were collected but how they were graphically compiled.

Despite the many limitations of the object model approach, many examples of its use are available. Presently soil information systems, based on an object model are used by the Natural Resources Conservation Service (NRCS) (Ernstrom and Lytle, 1993), the Dutch Soil Survey, and many other organizations in the Caribbean, North America and Europe (Rosenthal *et al*., 1986; Ibanez *et al*., 1993; D. Lytle person. commun., 2000). The proliferation of soil information systems using the object model may be attributed to the traditional route taken to automate existing processes rather than trying to find new approaches for storing and manipulating data.

In the last few years, the continuous field model (see Couclelis, 1992) has been increasingly used to represent soil data. This normally takes the form of storing point samples from which continuous surface maps are generated using various interpolation techniques (Burrough, 1993a; Peluso *et al*., 1993). While this representation is closer to what may be found in nature (Bregt and Beemster, 1989), it does not include sharp changes that may exist in soil properties. Omission of these data leads to a loss of important structural information. Additionally, data obtained from other sources are often excluded in the continuous field model.

From the above limitations, it may be concluded that these models are not the most appropriate ones for representing soil variation. In fact, Burrough (1993a, p. 19) argues "*that no amount of data storage and retrieval technology can compensate for an inappropriate conceptual model of soil variation*." Several soil scientists have questioned the validity of the object model (Webster and De La Cuanalo, 1975; Hole and Campbell, 1985; Nortcliff, 1978; Campbell *et al*., 1989; Nettleton *et al*., 1991). However, it seemed a reasonable compromise given the absence of enabling technology until very recently (Ernstrom and Lytle, 1993). The need for more accurate and individual soil property information coupled with the high cost of soil data acquisition dictates the re-examination of present methods used to represent the soil landscape and data quality information (Burrough, 1991; Ibanez *et al*., 1993).

3. AN ALTERNATIVE APPROACH

A new direction for soil data provision is to represent the soil landscape using a mixed variation model. This model views the landscape as consisting of both continuous and discrete spatial variations (Burgess and Webster, 1984; Hole and Campbell, 1985; Campbell, 1977; Ramlal, 1996; Heuvelink and Huisman, 2000). In the object model, soil spatial variations are represented by major jumps in attribute values at the boundaries of the mapping units. "*The continuous field model assumes that the spatial variation of a soil attribute is second-order stationary. That is, it has a constant mean and the attribute's spatial autocovariance is a function only of the distance between the locations*" (Heuvelink and Huisman, 2000, p. 112). The mixed variation model is therefore a combination of the object and continuous field models.

In the mixed variation model, measurements are stored as primary entities instead of continuous fields or soil mapping units. These measurements can be assumed to be observations on an underlying continuous distribution. Lines of abrupt change in soil properties are stored as discrete entities (see Ramlal, 1996). The strategy is similar to capturing spot heights for elevation and capturing ridge and valley lines for very sharp changes on the landscape. The resulting data therefore more effectively captures the spatial variations that are present on the landscape.

There are two major advantages that may be gained by using the mixed variation model. The first advantage of this approach is that it incorporates a more representative picture of the structural characteristics of the soil landscape than other models and thus more closely explains the variations present in the soil landscape. Hole and Campbell (1985, p. 103) conclude: "*if one must accept a single model for soil variation, this one of mixed variation seems to be the one most nearly consistent with our experience, at least at the level of detail usually applied in modern soil survey. However, such a model is realistic only if we recognize the great variation in the degree of abruptness at boundaries to the point that in some instances a boundary may be difficult to observe, whereas others are easily observed*."

The second advantage is the possibility to improve the provision of data quality information for soil data (Ernstrom and Lytle, 1993). Goodchild (1988) argues: "*it is much easier to assign indices of accuracy to raw data than to abstractions and interpretations.*" Since original measurements are used in this approach, it is easier to determine their quality and track it through various processing steps. Data quality is related to the accuracy and reliability of data. The information provided with data that allows the assessment of the level of trust that may be placed on the data is known as data quality information. This includes information about accuracy, resolution, completeness, consistency and lineage with respect to time, theme and location (Guptill and Morrison, 1995). Data quality information improves our ability to assess fitness for use of a particular data set for a given application.

A possible shortcoming of the mixed spatial variation model compared with the object model is the increase in the cost of data acquisition. However, there are several benefits that offset this initial expense: the soil mapping process is removed from the mixed spatial variation model, the need for many expert soil scientists and surveyors for data acquisition is reduced but not removed, and much more raw data is available for multiple uses.

4. A CONCEPTUAL SCHEMA FOR A MEASUREMENT-BASED SOIL DATABASE

A list of entities that may be recorded for soil is given in Table 1 (Soil Survey Staff, 1993). This is not meant to be an exhaustive list. The data presented in Table 1 were analyzed to determine the relationships between the different sets of entities. These were used to develop the conceptual schema for the database for the soil information system.

The conceptual schema was developed using the entity-relationship modeling technique. The schema is shown in Figures 1 to 4. Several diagrams are used to accommodate the complexity of the data and to avoid an unnecessarily cluttered presentation. From these diagrams, a hierarchical structure is identifiable. This schema captures the continuous variation and the discrete changes of soil data both in the spatial and temporal domain. It also accommodates the resulting fields from the interpolation of these measurements.

Figure 1 provides an overview of the entities needed to represent the soil landscape. At the highest level of the hierarchy, there are four entities: metadata, point samples, lines of abrupt change, and fields. Metadata consist of data quality information and reference data for the entire data set. In general, data quality information includes resolution or level of detail, completeness or the extent of coverage of the data set, lineage or the history of the data set, consistency and accuracy information. See Veregin (1989) or Guptill and Morrison (1996) for an in-depth discussion of data quality components. Point samples consist of many individual point samples. Each sample contains data on horizons, general profile properties, a photograph of the profile, and a description of the sample site. Lines of abrupt change contain individual lines. Each of these lines consists of locational data and a list of properties.

At the highest level of the hierarchy, denoted as 1 in Figure 1, data quality information is stored for the entire data set. This information is stored as part of the metadata. Overall data quality information is needed for all point samples and fields. The data quality information stored at this level for point samples and for fields includes completeness, resolution, and consistency.

The third level consists of individual point samples, lines of abrupt change and fields. Data quality information is recorded for each of these features. An attribute completeness measure may be stored for each point sample. The data quality information attached to each line of abrupt change

Table 1. A sample list of soil entities and attributes that need to be accommodated by the conceptual scheme

Abrupt Changes
Boundary ID
Coordinates for abrupt change
Source of data
Method of delineation
Soil properties for which changes are relevant
Depth , width to which change applies

Photograph of profiles
Photograph ID
Date of acquisition
Profile ID

General Profile Data
Profile ID
Soil depth
Rooting depth
Soil parent material
Rock outcrops
Soil drainage status
Available water content

Horizons
Profile ID
Horizon ID
Thickness
Depth of Horizon

Site Description
Profile ID
Grid reference/Coordinates
Latitude/ Longitude
Locality
Relief: elevation, slope, aspect, regional relief, micro-relief
Climate and weather
Cultural activities
Geomorphology
Soil erosion and deposition
Drainage of site
Land use
Vegetation
Surface stoniness
Surface form and condition
Presence of salt and alkali

Chemical Properties
Horizon ID
pH,
Salinity
Sodium absorption ratio,
Cation exchange capacity
Base saturation

Biological Properties
Horizon ID,
Fauna - type, abundance

Pans
Horizon ID, kind,continuity structure, thickness

Physical Properties
Horizon ID
Structure- type, grade, size
Kind of organic matter
Content of organic matter
Mottles - type, size, contrast, abundance, sharpness
Colour - hue, value, chroma
Pores - form, orientation, continuity, distribution, size, quantity
Cementation
Texture
Consistence
Porosity
Plasticity index
Bulk Density
Roots - size, quantity
Rocks - size, quantity
Weathering,
Erodability factor
Clay content,
Liquid limit
Calcium carbonate content
Gypsum content,
Permeability rate
Shrink - swell potential

Cutans
Horizon ID
kind
continuity
thickness

consists of accuracy, resolution, and lineage. Data quality information stored for each field includes resolution and lineage.

Figure 2 provides a more detailed schema for horizons of soil profiles. Each horizon may consist of a pan, a cutan, and a set of properties. These properties are placed into three categories: chemical, physical and biological properties. Several attributes are attached to each of these categories. Attached to each point sample are data that apply to the entire profile rather than to individual horizons. This is illustrated in Figure 3. Several attributes are included. Some of these may be categorized as properties while others are general attributes. Similar to properties for individual horizons, properties are categorized into physical, chemical and biological properties. Data quality information is recorded for each attribute. At this level, attribute accuracy and lineage information such as date and method of measurement are expected to be stored for each of these attributes. For each category, additional components of quality may be included. For example, the completeness of attributes recorded for chemical properties may be recorded at this level.

The data attached to each site description are location data, data on the relief of the area surrounding the point sample, and other attributes that describe the soil landscape around the point (Fig. 4). Data quality information is required for each of these entities. The information required for site description includes accuracy, lineage, and completeness. Information on the completeness of the horizon data stored for each profile is also required.

5. CONCLUSIONS

As GIS technology develops, it is much easier to store, manage, process and analyze large databases in a digital environment. Network technology makes the sharing of these databases simple. The

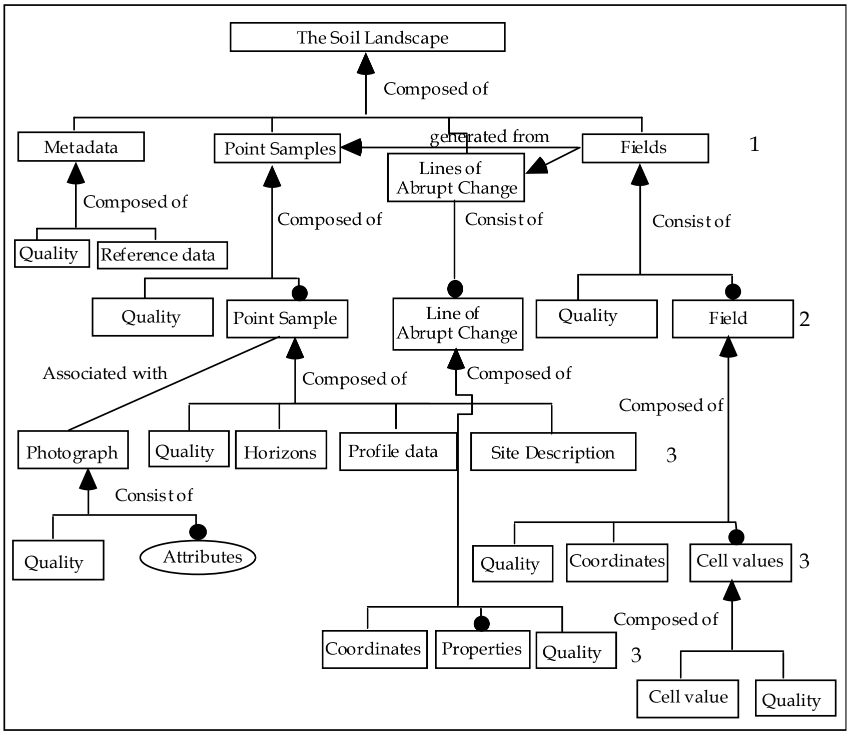

Figure 1. Conceptual schema for soil data including data quality information

use of a measurement-based approach for storing and managing observation data and data quality information offers many advantages; especially if the conceptual schema is implemented using an object-oriented database model. This method stores all components of soil data and their data quality information at the most applicable level. Because quality is stored together with each of the entities to which it pertains, the possibility of inconsistencies between the soil data and data quality due to

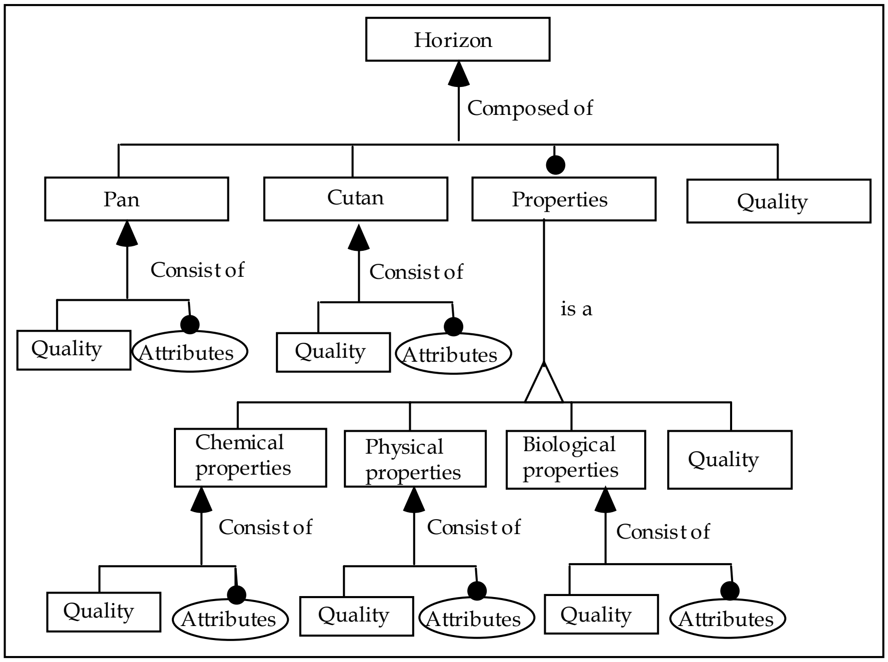

Figure 2. Details for soil profile with data quality information

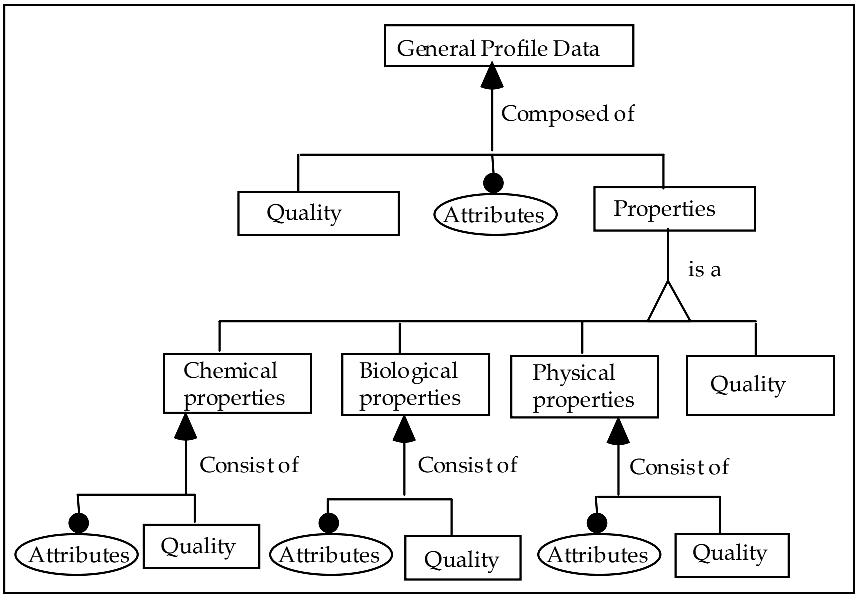

Figure 3. Details for general point profile data including data quality information

updates are minimized. All data including the data quality information may be retrieved using the same query language. Additionally, propagation and inheritance properties of the database model make it easier to determine the quality of single measurements as well as groups of measurements. Major disadvantages in using this method are the increased costs of data acquisition and the large increase in the storage requirements additional spatial data and data quality information. However, it may be argued that this is a small price to pay for the benefits gained by the inclusion of data quality information together with the data. It may be concluded that a measurement-based soil information system that is based on the mixed variation model of the soil landscape provides access to data that may be used to generate a more realistic representation of the soil landscape.

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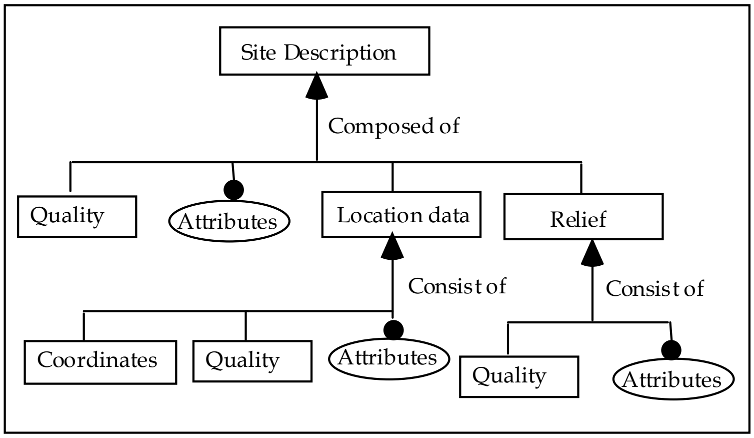

Figure 4. Details for the soil sample site description with data quality information

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