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COVER PAGE

Geo-environmental mapping using physiographic analysis: constraints on the evaluation of land instability and groundwater pollution hazards in the Metropolitan District of Campinas, Brazil

[1] Paulo Cesar Fernandes-da-Silva

[1] Ricardo Vedovello vedovello@igeologico.sp.gov.br

[1] Claudio Jose Ferreira cferreira@igeologico.sp.gov.br

[2] John Canning Cripps j.c.cripps@sheffield.ac.uk

[1] Maria Jose Brollo mjbrollo@igeologico.sp.gov.br

[1] Amelia Joao Fernandes amelia@igeologico.sp.gov.br

1 Geological Institute, São Paulo State Secretariat of Environment – Av. Miguel Stefano nr. 3900, CEP 04301-903, São Paulo, Brazil.

2 Department of Civil and Structural Engineering, University of Sheffield, Mappin Street, S1 3JD, Sheffield, United Kingdom.

Corresponding author:

E-mail 1: **paulo.fernandes@igeologico.sp.gov.br**

E-mail 2: **pfernandes_us@yahoo.co.uk**

Phone: (+55 11) 5077 1209

Fax: (+55 11) 5077 2219

Geo-environmental mapping using physiographic analysis: constraints on the evaluation of land instability and groundwater pollution hazards in the Metropolitan District of Campinas, Brazil

ABSTRACT

Geo-environmental terrain assessments and territorial zoning are useful tools for the formulation and implementation of environmental management instruments (including policy-making, planning, and enforcement of statutory regulations). They usually involve a set of procedures and techniques for delimitation, characterisation and classification of terrain units. However, terrain assessments and zoning exercises are often costly and time-consuming, particularly when encompassing large areas, which in many cases prevent local agencies in developing countries from properly benefiting from such assessments. In the present paper, a low-cost technique based on the analysis of texture of satellite imagery was used for delimitation of terrain units. The delimited units were further analysed in two test areas situated in Southeast Brazil to provide estimates of land instability and the vulnerability of groundwater to pollution hazards. The implementation incorporated procedures for inferring the influences and potential implications of tectonic fractures and other discontinuities on ground behaviour and local groundwater flow. Terrain attributes such as degree of fracturing, bedrock lithology and weathered materials were explored as indicators of ground properties. The paper also discusses constraints on- and limitations of- the approaches taken.

Keywords**:** terrain units, satellite imagery, physiographic compartmentalisation, tectonic fracturing, inferential tools.

1. INTRODUCTION

Data about the physical environment (such as rock and soil types, relief, vegetation and natural processes) are essential to formulate and to implement successful strategies for environmental management. Such data underpin all policy-making and planning instruments and enforcement regulations which usually require geo-environmental terrain assessment and territorial zoning in terms of advantages and constraints for development of different types (Culshaw et al. 1990, Zuquete et al. 2004). For regional planning and watershed management purposes, such assessments provide advice about the types of land use that would be acceptable in certain areas but should be precluded in others. Furthermore, ranking of terrain units in terms of the likelihood and consequences of land instability also enable the identification, control and mitigation of hazards as well as provides decision support to contingency actions and/or to engineering solutions (Cripps et al. 2002, Abella and Van Wasten 2008).

According to Cendrero et al. (1979) and Bennett and Doyle (1997) there are two main approaches to geo-environmental terrain assessments and territorial zoning: a) the analytical or parametric approach which deals with environmental features or components individually, and terrain units usually result from the intersection or cartographic summation of several layers of information thus expressing the probability limits of findings without corresponding with ground features; and b) the synthetic approach, also termed integrated, landscape or physiographic approach, in which the form and spatial distribution of ground features are analysed in an integrated manner relating recurrent landscape patterns expressed by an interaction of environmental components thus allowing the partitioning of the land into units or divisions.

Since the advent of airborne and orbital sensors, the integrated analysis is based in the first instance, on the interpretation of images and air-photos. In this case, the content and spatial boundaries of terrain units would directly correspond with ground features. Such correlation and also the recurrence of particular landscape patterns is viewed by some authors to give rise to advantages as follows: 1) it would facilitate understanding by non-specialists and planners (Davidson 1992, Fernandes da Silva et al. 1997); and 2) it provides means of correlating known and unknown areas, thus permitting ground conditions to be reasonably predicted (Finlayson 1984, Moore et al. 1993). Terrain units delineated using the physiographic approach should hold a genetically linked assemblage of components, such as relief, rocks and soils, independent of their sizes. Their definition depends on climatic, tectonic and lithological criteria, as well as those of form (Mitchell, 1991).

Data collection, derivation from secondary data sources, and integration of data into useful databases are time-consuming, costly and difficult tasks to be performed in support of a particular project and/or agency function (Nedovic-Budic 2000). In addition, the complexity of GIS methodology, lack of suitably trained staff, and the scarce organizational resources have been blamed for the under-utilisation of GIS methods (Harris and Weiner 1998, Vernez-Moudon and Hubner 2000). These difficulties and limitations inhibit both local and regional authorities in developing countries (like Brazil) from properly benefiting from geo-environmental terrain assessment outputs in planning and environmental management instruments. From another viewpoint, some authors such as Sahay and Walsham (1996), Barton et al. (2002), Câmara and Fonseca (2007) propose that developing countries should ensure that options for using low-cost technology are properly considered as a way to gain knowledge about the technology itself and also in the creation of products that fit their specific needs.

This paper describes an application of the synthetic (integrated) approach to a geo-environmental terrain assessment and territorial zoning exercise at a semi-regional scale. This is exemplified by a case study that explores a low-cost technique comprising physiographic compartmentalisation based on the use of satellite imagery for the delimitation of terrain units. The resulting map is then interpreted in terms of the potential for land instability and groundwater vulnerability in two test areas situated in the Metropolitan District of Campinas

(São Paulo State, Southeast Brazil, see Figure 2). Key to the success of this approach was the incorporation of procedures for inferring the presence and characteristics of geological structures, such as fractures and other discontinuities and the assessment of these in terms of the potential implications to ground stability and the flow of groundwater. A general description of the physiographic compartmentalisation technique and a discussion of the performance and limitations of the approach are also provided.

2. THE PHYSIOGRAPHIC COMPARTMENTALISATION TECHNIQUE

Geo-environmental terrain assessments and territorial zoning generally involves three main stages, as follows: 1) delimitation of terrain units; 2) characterisation of units (e.g. in bio-geographical, engineering geological or geotechnical terms); and 3) evaluation and classification of units.

The first stage consists of dividing the territory into zones with respect to a set of pre-determined physical and environmental characteristics and properties. Regions, zones or units are regarded as distinguishable entities depending upon their internal homogeneity or the internal interrelationships of their parts. Some authors argue that such homogeneity is subjective and small scale homogeneous units may not exist. For instance, this has lead to the use of fuzzy logic approach (e.g. Zhu et al. 2001; Zhu and Mackay 2001; Shi et al. 2004). Although detailed and spatially continuous terrain information may be attainable through these methods, the required digital data derivation and computing operations tend to be complex thus necessitating specialist hard- and soft-ware that are not always readily available.

The *characterisation of terrain units* consists of ascribing and surveying relevant properties and characteristics of terrain components that are expected to affect the ground conditions relevant to the particular application. Such characterisation can be achieved either directly or indirectly, for instance by means of: (a) ground observations and measurements, including *in-situ* tests (e.g. boring, sampling, infiltration tests etc); (b) laboratory tests (e.g. grain size, strength, porosity, permeability etc); (c) inferences derived from existing correlations between relevant parameters and other data such as those obtained from previous mapping, remote sensing, geophysical and geochemical records.

The final stage consists of *evaluating and classifying the terrain units* in a manner relevant to the purposes of the particular application (e.g. regional planning, transportation, hazard mapping). This is based on the analysis and interpretation of properties and characteristics of terrain - identified as relevant - and their potential effects in terms of ground behaviour, particularly in response to human activities.

In order to reduce the fieldwork effort required for the delimitation of terrain units, consideration was given to an increased reliance on Remote Sensing tools, particularly satellite imagery. The advantages include: a) the generation of new data in areas where existing data are sparse, discontinuous or non-existent and b) the economical coverage of large areas, availability of a variety of spatial resolutions, relatively frequent and periodic updating of images (Schimdt and Glaesser 1998, Lillesand and Kiefer 2000, Latifovic et al. 2005, Akiwumi and Butler 2008)

The physiographic compartmentalisation technique (Vedovello 1993, 2000) utilises the spatial information contained in images and the principles of convergence of evidence (see Sabins 1987) in a systematic deductive process of image interpretation. The technique evolved from engineering applications of the synthetic land classification approach (e.g. Grant, 1968, 1974, 1975; TRRL 1978), by incorporating and advancing the logic and procedures of geological-geomorphological photo-interpretation (see Guy 1966, Howard 1967, Soares and Fiori 1976), which were then converted to monoscopic imagery (as proposed by Beaumont and Beaven (1977), Verstappen (1977) Soares et al. (1981) and others).

Magnitude and variations of light and shade play a key role in the image interpretation, with texture and respective patterns being determined by an interaction between the shapes of surface features and the angle of incidence of light. In this sense, texture expresses the frequency of tonal (grey-level value) change within an image and arises due to the distribution and aggregation of minor components (texture elements) that preserve their own characteristics (e.g. shape, size, tone) at a determined spatial resolution. These unitary elements may be too small to be discerned individually on the image, but define a consistent spatial arrangement that can be described in terms of visual texture features (Tamura et al. 1978). Image interpretation aims at identifying and delineating textural zones on images according to the properties described in Table 1, wherein features such as coarseness, roughness, regularity, and direction are taken into account.

The key assumption proposed by Vedovello (1993, 2000) is that zones with relatively homogeneous textural characteristics in satellite images (or air-photos) correspond with specific associations of geo-environmental components (such as bedrock, topography and landforms, soils and covering materials) with a common tectonic history and land surface evolution. Such associations are thought to imply specific ground responses to engineering and other land-use actions.

The interpretation procedure is a top-down process that starts with the whole landscape which is then subdivided into land parcels. It is assumed that there is a correlation between image texture and terrain characteristics that are expressed at different scales and levels of compartmentalisation, generally associated to regions or areal domains of decreasing size. The main outcome of this is a single cartographic product consisting of comprehensive units delimited by fixed spatial boundaries (that correspond with ground features). These are referred to as physiographic compartments or basic compartmentalisation units (BCUs), which according to Vedovello and Mattos (1998), are the smallest units for analysis of geo-environmental components at the chosen cartographic scale. In other words, there is a relationship between the BCUs and the scales of observation and representation, which is governed by the spatial resolution of the satellite image or air-photos being used for the analysis and interpretation.

The tracing of limits of textural zones concentrates on the analysis of the spatial arrangement of natural alignments of image textural elements, particularly groups of contiguous pixels related to the drainage network and relief architecture. Tonal properties are used to help with the identification and interpretation of linear features. Image interpretation may also be supported by external sources such as topographic, geological, and soil maps.

The procedures for the delimitation of units include assessment of spatial characteristics of textural zones to check for internal homogeneity and the degree of similarity between zones, particularly their form (spatial distribution) and directionality of texture elements (degree of isotropy). Usually ground checks are carried out to confirm or adjust the photo-interpreted boundaries of physiographic units (BCUs). Figure 1 shows examples taken from the Campinas study area presented in this paper, in which two BCUs are compared in terms of spatial organisation of textural elements associated with drainage and relief features.

After delimitation, the BCUs are then utilised as a module for storage, processing and analysis of geo-environmental data for further land assessments. The organisation of data and information in relation to the BCU polygons in a geo-referenced databank allows optimised procedures of query and production of derived maps. The analysis and evaluation is undertaken up to the (fixed) spatial boundaries of the BCUs so that different parameters or attributes can be used in the subsequent stages of analysis (characterisation and classification of units) while keeping their cartographic significance and cohesion as unitary entity, i.e. no changes to the boundaries of existing polygons or generation of new ones are required (Tominaga et al. 2004).

3. GEO-ENVIRONMENTAL TERRAIN EVALUATION: A CASE STUDY

The present study was carried out in two test areas, T1 and T2 (Figure 2), located in the Metropolitan District of Campinas (RMC), the State of Sao Paulo, Brazil, which encompasses 19 municipalities and covers approximately 1,800 km2. Area T1 (80 km2) comprises a rugged topography with small and large hills and ridges of significant slope steepness, consisted mainly of Pre-Cambrian crystalline rocks (gneiss and granite). Area T2 (192 km2) consists of Palaeozoic to Tertiary sedimentary and intrusive volcanic rocks that form a flatter topography comprising undulating and rolling hills together with Quaternary age alluvial plain deposits.

3.1. Terrain Compartmentalisation

A Landsat 5 Thematic Mapper (TM) image (path 220, row 076, captured on 12 September 1997, end of dry season) was selected for this study. Factors influencing this choice included temporal, spectral, spatial, and synoptic characteristics as well as good availability and lower cost than other products. The date of image acquisition slightly preceded recent major urban and industrial development in the region. From the full scene two sub-sets of 250 x 313 and 375 x 500 pixels, corresponding to test areas T1 and T2 respectively, were selected. The BCUs were delimited on a geo-referenced composite sub-image - Band 3 (visible wavelength) + Band 4 (near-IR) + Band 5 (Mid-IR) - false RGB colours at 30m pixel resolution using on-screen visual interpretation and vector format manual digitising with Erdas Imaging software.

The delimitation of units was based on image texture characteristics expressed by groups of contiguous pixels related to drainage and relief features. For this a minimum line segment length of 30 metres (one pixel) was used. It should be noted that the dimensions of BCUs directly relate to the spatial resolution of the image and also to the visibility of ground features, such as drainage and relief lineaments. In the present investigation, the smallest BCU in Area T1 was 0.7 km^2 (approx. 820 pixels) and the average area was 3.6 km^2 whereas in Area T2 there areas were respectively 1.24 km^2 (approx. 1,380 pixels) and 6.17 km^2. Visual image interpretation was supported by external ancillary data concerning bedrock lithology, structural geology, topography and geomorphology.

Depiction of natural linear features is dependent upon grey-level values that are influenced by the gradient of land surface and its position in relation to sunlight exposure. Drainage lines were frequently associated with dark pixel patches as follows: a) enriched tonal contrast due to absorption of energy by surface water and strips of riverside vegetation in Band 3; b) dark tonal contrast due to high moisture content emphasised in Near-IR (Band 4) and Mid-IR (Band 5); c) patches of shading or relatively dark tonal contrast as an expression of negative slope breaks (decreasing slope steepness) in valleys and watercourses. Relief lines were usually demarcated by subtle limits between contrasting zones of lighting and shading on the image that were defined by relatively bright ground sloping towards the direction of sunlight. In areas of low vegetation density and soil exposure, lower moisture content tended to enhance these contrasts. In many cases, these features corresponded with ridge tops, crestlines and positive slope breaks (increasing slope steepness), whose identification was also facilitated by association with drainage heads.

The main characteristics considered for the delimitation of BCUs included: (a) density of texture elements related to drainage and relief lines; (b) spatial arrangement of drainage and relief lines in terms of form and degree of organisation (direction, regularity and pattern); (c) length of lines and their angular relationships, (d) linearity of mainstream channel and asymmetry of tributaries, (e) density of interfluves, (f) hillside length, and (g) slope forms. These characteristics were identified mainly on the basis of image interpretation, but external ancillary data were also used to assist image interpretation for the identification of relief-related characteristics, such as slope forms and interfluve dimensions.

Figure 3 shows the basic compartmentalisation units (BCUs) delineated for Test Areas T1 and T2, and the respective drainage networks. As illustrated in Figure 1, units are identified by three letter codes and one numerical character, corresponding respectively to (a) physiographic domain, (b) predominant bedrock lithology and geological structure, (c) geomorphological setting including predominant landforms, and (d) specific characteristics such as soil profile and erosional and aggradational features. Examples of the codification of UBCs are provided in Table 2. A summary of relationships between image texture characteristics, bedrock lithology and relief/ landform system is presented in Table 3.

3.2. Characterisation of units

Based on a minimum areal extent of 3 km^2, accessibility contiguity of units and the planned structural geological analysis, thirteen BCUs in each test area were selected for further geo-environmental assessments in which both spatial image characteristics and external data sources were considered. The areas were verified and complemented with ground checks.

Inferences relating to environmental properties and characteristics of geotechnical interest based on correlations of image properties from remotely sensed data were particularly investigated. The principle postulated was that image texture related to the properties/characteristics of the imaged target enables reasonable deductions about geotechnical-engineering attributes (Beaumont and Beaven 1977, Beaumont 1985).

In view of the aims of the study to estimate susceptibility of land to instability and the vulnerability groundwater to pollution, as well as other factors such as scales of observation and representation, data availability and derivation, the following attributes were primarily considered to be relevant and selected for the characterisation of BCUs: (a) bedrock lithology, (b) tectonic discontinuities (generically referred to as fracturing), (c) soil profile (including thickness, texture and mineralogy), (d) slope steepness (as an expression of local topography), and (e) water table depth.

3.2.1. *BEDROCK LITHOLOGY*

The mineralogy, grain size and fabric of the bedrock and related weathered materials, control properties such as shear strength, pore water suction, infiltration capacity and natural attenuation of contaminants. According to Vrba and Civita (1994), hydraulic accessibility to the saturated zone in sedimentary rocks and unconsolidated sediments, which predominate in Test Area T2, mainly depends on the primary (inter-granular) permeability of the unsaturated zone. Thus this feature directly affects groundwater vulnerability. In metamorphic and igneous rocks, which predominate in Test Area T1, secondary permeability (due to discontinuities) would be more important in terms of groundwater flow and it is also essential to consider the weathered materials originating from such crystalline rocks. In this sense, Fernandes (2003) suggests that two situations should be considered when estimating groundwater vulnerability in crystalline rocks: a) where weathering cover is thick, the composition of the weathered materials will strongly influence vulnerability; and b) where weathering cover is thin or absent, the vulnerability will be conditioned by the occurrence and characteristics of the discontinuities within the rock mass.

Bedrock lithology is also liable to influence land instability processes depending on the mineralogical composition, fabric and inherent structures. The orientations, characteristics and spacings of rock mass discontinuities are particularly important in this regard (Hudec 1998).

In the present study, the bedrock types were grouped according to their fresh (unweathered) state as well as taking account of any saprolitic and other altered materials where present. Crystalline rocks were grouped as follows: Gr - granites (mostly coarse-grained, massive or foliated); Gngr - granitic gneisses (mostly fine-grained, foliated); B-banded gneisses; X - schistose gneisses and shear zone mylonites; Bx - mixed gneisses (including both compositional banding and schistosity); and D – dolerites. Sedimentary rocks were grouped into: Iam - sandstones (medium to coarse grained, mostly massive); Iaf - sandstones (fine grained, mostly stratified); IDR - mudstones with pebbles and laminated rhythmites; FRC - intercalated sandstones, siltstones, claystones, and mudstones of the weakly consolidated Tertiary age Rio Claro formation.

Clay content and its variation through the weathering profile have a particularly significant effect on groundwater vulnerability and erosional processes (Aller et al. 1987, Hill and Rosenbaum 1998). In this regard, lithological groups B, X, and Bx give rise to predominantly clayey weathered materials that are likely to provide greater attenuation capacity and reduced hydraulic accessibility to the saturated zone. On the other hand, groups Gr and Gngr would produce sandy materials and greater hydraulic accessibility to the saturated zone. The presence of schistosity and foliation discontinuities within the rock and saprolitic materials would tend to cause slope failure and landsliding hazards, depending on the orientation of those features with respect to the direction of slopes and also on the groundwater conditions.

Data on bedrock lithology were derived from existing geological maps which were cross-referenced with image textural characteristics including density of aligned textural elements related to drainage and relief in particular (see Table 3).

3.2.2. *TECTONIC DISCONTINUITIES*

Geological structures such as faults and joints in the rock mass, together with their relict structures in saprolitic soils, exert significant influences on shear strength and hydraulic properties of geomaterials (Aydin 2002, Pine and Harrison 2003). In the present study, analysis of lineaments extracted from satellite images and knowledge about the regional tectonic evolution of the area (Table 4) underpinned inferences about major and small-scale structures, including joints and schistosity.

As demonstrated by Fernandes and Rudolph (2001) and Fernandes da Silva et al. (2005), lineament analysis can be integrated with empirical models of tectonic history based on outcrop scale palaeostress regime determinations to identify areas of greater density and interconnectivity of fractures as well as greater probability of open fractures. In addition, it is possible to deduce angular relationships between rock structures (strike and dip) and between these and hill slope directions.

The following assumptions were made in order to characterise fracturing in the rock or saprolitic soil mass:

a) Variations of density and connectivity of fractures could be mapped through lineament analysis by direct correlation respectively with density and intersection of lineaments on images, because in the study area most of the fractures were vertical or sub-vertical so they appeared as rectilinear traces at the surface.

b) Late tectonic events (Cenozoic) control the aperture of fractures and according to Fernandes and Amaral (2002), in most cases, a particular tectonic event gives rise to a generally pervading stress field which controls the orientation and character of fractures in a localised area. Those generated by extensional tectonic stress are of particular interest as usually display greater apertures. For instance, water flow tends to be much faster in with the wider aperture fractures as gravity forces would prevail over capillarity forces and soil-matrix hydraulic conductivity in rainy episodes and nearly-saturated conditions (Wang and Narasimhan 1993).

Lineaments extracted from images were cross-referenced with field (structural-geological) measurements gathered in the present study and also available from Fernandes (1997). Density of lineament (km/km2) and lineament intersections (number/km2) were computed automatically using a computer script written in MapBasic ® in a MapInfo package, and then cross-referenced with visual inspection and manual counting to check the accuracy of the automated method.

Non-parametric statistical tests (see Fernandes da Silva et al. 2005, Fernandes da Silva and Cripps 2008) were performed in combination with visual analysis of trends of lineaments on rose diagrams (see Fernandes and Rudolph 2001, Fernandes and Amaral 2002) to identify the tectonic structures associated with specific tectonic events in each basic compartmentalisation unit (BCU). Greater probability of occurrence (and frequency) of open fractures was deduced from BCUs where extensional stress regimes were considered to prevail due to the effect of tectonic event E3-NW (see Table 4).

Estimates of the potential magnitude of fracturing were derived from qualitative scores given according to the following attributes (Table 5): (a) lineament density (per km^2); (b) lineament intersections (per km^2); (c) predominant tectonic event in each BCU. Such scores were assigned in relation to statistical mean values determined for each attribute excepted for the relevant predominant tectonic event. In this case, maximum score (A) was assigned to tectonic event E3-NW and minimum score (B) to any other event including E4-NS (also extensional). Classes of fracturing were derived from the relative proportion of these qualitative scores as follows: Class 1: three scores “B”; Class 2: one score “A”; Class 3: two or three scores “A”. These classes were designed to express increasing magnitude of fracturing and therefore greater potential influence on ground behaviour.

3.2.3. *SOIL PROFILE, SLOPE STEEPNESS AND WATER TABLE DEPTH*

The development of a particular thickness and type of tropical soil profile depends not only upon the parental materials present but also upon local topography and drainage conditions. In this regard slope steepness is a meaningful and measurable indicator. Similarly, water table depth is also controlled by the local topography. Hence, the assessment of potential for land instability and enhanced groundwater vulnerability were based upon soil profile, slope steepness and water table depth, either solely or in combination.

For instance, infiltration capacity is a function of slope steepness and inter-granular (primary) permeability of the uppermost layer of the unsaturated zone (Rubin and Steinhardt 1963, quoted by Fernandes 2003). As observed by Thornton et al. (2001) contaminants are mostly attenuated by processes of biodegradation and adsorption that depend on the mineralogical composition, texture and thickness of the unsaturated zone materials.

For the present investigation, data on thickness and texture of soil profiles were assembled to express the mineralogy, grain-size, structure, strength and density/degree of compaction of generic soil types. Soil horizons were characterised using a geotechnical approach as saprolite, residual, superficial, and gravity-transported horizons. Primary data were derived from existing soil maps supplemented with field observations for representative soil profiles in each BCU. Soil profile data were stored as a BCU attribute table using the MapInfo package.

Thirteen representative soil weathering profiles, from sandy to clayey, were identified and three classes of soil thickness were defined as follows: (a) < 2 metres, (b) 2 - 5 metres; (c) > 5 metres. These classes were designed to account for the different impacts of soil thickness on hydraulic accessibility to the saturated zone as well as to the potential impacts of construction work.

Average slope steepnesses were derived both manually and semi-automatically for each BCU. The manual procedure involved measurements from existing printed topographic 1:50,000 scale maps. The freeware GIS and image processing package SPRING (Câmara et al. 1996, INPE 2009) was used for the semi-automated methods. The procedure included: a) digitising of sub-sets of 20-metre contour lines from the existing paper record 1:50,000 topographic maps (as no digital maps were available); b) derivation of heights from a 50x50-metre square numerical grids obtained by interpolation from 20-metre contour lines. Generation of numerical grids was performed using a built-in weighted mean interpolator based on quadrants and restriction of repeated elevation values. Overlaying operations and use of a computer routine written in LEGAL® (Spatial Language for Geo-processing Algebra) to perform neighbourhood operations over the numerical grids provided average slope steepness values for each polygon. The following slope steepness classes were used: Low – less than 5°; Medium – between 5 and 10°; High – between 10 and 15°; Very high – greater than 15°.

Tonal contrast in Near-IR (Band 4) and Mid-IR (Band 5) was used to indicate the presence of water in the sub-surface, particularly in the unsaturated zone. However, such proxy information was insufficient for use in engineering land assessments. Therefore data on water table depth from existing borehole and well records were also used and cross-referenced with image interpretation. Data on hydrostatic depth from borehole and well records were plotted on the digitised topographic maps to allow derivation by interpolation and extrapolation where water table depth contours were assumed to be approximately parallel to the topographic contours. However, such derivation approach led to inaccuracies such as major variations of hydrostatic level in similar topographic situations, and in order to reduce them, image interpretation and statistical parameters (median and standard deviation) were combined to determine the trends in hydrostatic depth in top, hillside, and valley situations. By this means contour lines for 5m, 10m, and 20m depth were traced with approximately 80% of confidence, where the confidence level was determined by validation against the original data. For convenience, the 10m contour line was then adopted as a criterion in further evaluation and classification of units as this was consistent with relatively coarse scale of the cartographic maps (1:50,000), and the amount of data available.

3.3. Evaluation and classification of units

Three steps were required for the evaluation and classification of units: a) definition of classes to express the estimated magnitude of the parameter being analysed; b) definition of classification rules depending on the purposes of the study; and c) evaluation and final cartography, including the application of classification rules and analysis of units for presentation on maps or other forms of output.

Firstly, four classes each of groundwater vulnerability and of susceptibility to land instability were designated as: very high, high, moderate, and low. Attribute or “synthesis” tables were constructed (in GIS MapInfo package) specifically for these purposes. These contained data on the selected attributes for each BCU, which were allocated in fields or columns as follows (see Tables 6A and 6B): a) BCU: unit code; b) G_LITO: grouped bedrock lithology; c) CLAS_FRAT: classes of fracturing; d) TYPE_SOIL: predominant soil type considering the whole weathered profile; e) THICK_SOIL: average thickness of the whole profile; f) NA: average water table depth; g) CLAS_DECLIV: class of slope steepness (declivity).

Qualitative and semi-quantitative rules of classification were devised from a mixture of empirical knowledge and statistical approaches and then applied to each BCU. The classification tool was a spreadsheet-based model that used nominal, interval and numerical average values as assigned in the synthesis attribute tables, in a two-step procedure to produce the required estimates. In the first step, each selected attribute was analysed and grouped into three categories shown in Tables 7A and 7B, as follows: high (A), moderate (M), and low (B) depending upon their potential influence on groundwater vulnerability and land instability processes. In the second step, all attributes were considered to having the same relative influence and final classification for each BCU was the sum: A +, M, + B. The possible combinations of these are illustrated in Table 7c.

As discussed later in the paper, limitations for deriving information on soil thickness and water table depth as well as to make such information compatible to BCUs prevented the incorporation of all selected attributes into the classification scheme. Therefore the evaluation/classification of units was based upon: bedrock lithology, tectonic discontinuities (fracturing), soil type and slope steepness (declivity).

The classification of units was performed either manually or semi-automatically through GIS-based operations. The latter involved logical spatial operations to set attributes into categories high (A), moderate (M), and low (B) with mathematical (summation) to produce the final estimates.

The outcomes presented here were achieved manually using GIS to display and manipulate results. Tables 8 and 9 show the estimated susceptibility to land instability processes and groundwater vulnerability in the two test areas with each attribute considered individually and summed for all the attributes. Figures 4 and 5 show overall classifications in spatial map format.

Relatively greater slope steepness and fracturing as well as predominant sandy soils in Test Area T1 were associated with a greater number of BCUs classified as to high and very high susceptibility to land instability processes (12 out of 13) in comparison with Test Area T2 (just 1 out of 13). On the other hand, by reducing rates of infiltration greater slope steepness may lower the impact of fracturing on groundwater vulnerability, particularly in crystalline and less weathered rocks, which predominate in Area T1.

In Test Area T2, high and moderate groundwater vulnerability (6 out of 13 BCUs) was associated with sandstone dominated bedrock lithology, sandy soils, and low slope steepness. In addition, BCUs with greater frequency and connectivity of fractures were classified as having high and moderate groundwater vulnerability despite consisting of clayey bedrock lithologies such as mudstones and rhythmites in which inter-granular primary permeability is less than in the coarse and medium grained sandstones.

4. DISCUSSION

As described in previous sections, a physiographic approach provided basic compartmentalisation units (BCUs) which were experimentally used for terrain assessments.

The opportunity is taken here to discuss the advantages and limitations of the approach taken, particularly how these have affected the outcomes, and what can be done to enhance the results or to overcome difficulties.

The analysis of fracturing proved that there is good association between physiographic compartments and homogeneous tectonic domains for which the density and directional trends were relatively uniform, as proposed by Fernandes and Amaral (2002). In most BCUs it was possible to determine particularly significant tectonic events, for example those of an extensional nature (see E3 and E4 in Table 4). In addition, non-parametric statistical tests and visual inspection of rose diagrams provided similar reassuringly consistent inferences. This association between tectonic domains and physiographic compartments would probably express the influence of the Cenozoic tectonics over the arrangement and structuring of drainage and relief textural elements on images. Although some variability did exist, the results demonstrated considerable regularity and persistence of spatial relations held by tectonic structures across the test areas. These aspects were fully corroborated by good matching between predominant orientations of inferred structures and palaeostress regimes as indicated by a regional empirical tectonic model and field observations.

Density and interconnectivity of fractures were the key attributes in the characterisation and evaluation of BCUs in terms of engineering geological and hydrogeological applications. This empirical tectonic modelling enabled both major structures and also small-scale fractures to be considered in the analysis where the latter were incorporated in the interpretation and evaluation procedures. Additionally, it is suggested that further interpretations supported by the use of empirical tectonic models would allow derivation of 3D relationships. The main aspects to be considered include: a) angular and cut-crossing relationships between different types and sets of structures (planes of fractures and other discontinuities); b) spatial relationships between structures and natural slopes (taking steepness into consideration. Consideration of these relationships should enhance the evaluation of BCUs and convey key information to local scale analysis.

A general issue of relevance is that monoscopic satellite images are bi-dimensional representations of land surface whilst the intended geo-environmental assessments relate to both surface and sub-surface aspects. Thus spatial information rather than spectral information needs to be analysed. On the other hand, data on determined attributes had to be derived from external sources using imagery as a subsidiary tool. Accordingly, textural zones with relatively high internal homogeneity and fixed spatial boundaries which were observed on images may require practical adaptations to be translated into conceptual classes such as comprehensive physiographic units. In this experimental study such adjustments were incorporated in the later stages of characterisation and evaluation/classification of units but as explained below, this was not universal.

For the sake of the present implementation, some terrain attributes such as bedrock lithology and related weathered materials, degree of fracturing, and slope steepness were selected and taken as proxies for properties and processes including shear strength, permeability, natural attenuation capacity, infiltration rates, and hydraulic accessibility to saturated zone. It was assumed that the selected terrain attributes would exert some control over the properties and processes. Data on such attributes were derived qualitatively and semi-quantitatively by a combination of means that included image interpretation, input from existing data, and field observations. Shortcomings and inaccuracies may stem from this process of derivation.

For instance, in a number of cases, BCUs comprised considerable portions of two or more bedrock lithologies in which case priority was given to the lithology liable to result in greater likelihood of hazard. However, adoption of such criterion may be biased and lead to a greater number of BCUs being classified as having higher vulnerability or susceptibility.

Major difficulties found during the characterisation of units included the estimation of water table depth and soil profile (thickness), which precluded proper incorporation of these attributes in the evaluation/classification of units.

Data on water table depth were derived through an experimental approach that combined hydrostatic depth obtained from borehole and well records with interpolation and extrapolation of values following topographic contour lines. This was manually implemented as semi-automated procedures based only on spatial data analysis would not allow direct correlation between interpolated values of water table depth and surface contour lines. However, it was found that the manual derivation of data led to unreliable estimates of water table depth, thus resulting in considerable variations at similar topographic conditions. These variations may have arisen because the primary borehole data were affected by: (a) groundwater exploitation in different media and at varied piezometric depths in a same well (e.g. weathered materials at shallow sub-surface and fractures in fresh rock at depth); (b) heterogeneous hydraulic conductivity of the aquifer and of the unsaturated zone. These shortcomings suggest that derivation of data on water table depth from external sources may require more specific data, particularly on shallow sub-surface layers. Such data could possibly be derived from open pit well measurements, which appears to be more compatible with the characterisation of the unsaturated zone in the shallow sub-surface and with the physiographic approach itself (based on land surface features on images). Data from open pit well measurements could be then cross-referenced with remotely sensed data and topographic maps before extrapolation of values following topographic contour lines.

Another issue to be considered is data on soil profile thickness. In the study these were based on field observations and they were considered to be insufficient for the intended analysis. In general, difficulties with the characterisation of soil profiles in terms of thickness and texture stem from limited knowledge about the processes that control landscape evolution and soil formation and the ways by which these processes influence image texture. Improved understanding of these issues would allow superior correlations and extrapolation of values to be achieved. Therefore, future work should investigate the distribution and the characteristics of soil profiles and potential correlations of these with image texture due to relief features, with particular reference to morphometric aspects such as density and amplitude of interfluves (or ridges) and length of natural slopes.

The manual procedure for derivation of data on slope steepness (see Section 3.2.3) appeared to produce more accurate results, which were then used in the classification process. Inaccuracies observed in the semi-automatic procedure possibly stemmed from the averaging process with respect to polygons. The calculated mean value was meant to be representative of slope steepness for the whole BCU. However, slope steepness was observed to range considerably in some BCUs, which would affect the interpolated numerical grids. For instance, in 80 % of the area of a BCU slope steepness ranged between 8° and 10° whilst in 15 % of area ranged from 15° to 18°, and in 5 % of area it ranged between 24° and 27°. The expected representative value would be the 8-10° range. Nonetheless, since the semi-automatic calculation took a much greater number of interpolated values than the manual procedure, the resulting mean value may be unnecessarily influenced by outlying values. Further investigations into semi-automatic derivation of slope steepness data would need to look into ways of restricting the range of variation that would be acceptable and considered for calculation of a BCU mean value. For instance, the calculation procedure could incorporate a priori probabilities by taking into account the proportion of area within a BCU that determined slope steepness intervals would attain thus using such proportion to weight the resulting mean value.

In the stage of evaluation/classification of units, all attributes were given equal weight, although the relative influence of each attribute is not known. The main areas of uncertainly were the influence of degree of fracturing (Class 3) on permeability, or the effect on aquifer recharge on of a low-slope angle area with sandy superficial soil horizon, For instance, in Test Area T1 (see Figure 4), the high number of units (12 out of 13) classified as high to very high potential for land instability appears to be strongly influenced by steeper slope gradients. Further investigations are to consider different weights for each attribute with checks on the influence of these on the final classification results.

5. CONCLUSIONS

In the present study remote sensing techniques were used to delimit terrain units and to derive geo-environmental data. Data from external sources, including water well logs and records, existing thematic maps and field studies were also used. The delimited units were further interpreted in terms of potential to land instability and vulnerability to groundwater contamination at a semi-regional scale of 1:50,000

The successful use of low-cost techniques based on satellite image interpretation, non-commercial software package (SPRING) and manual data processing procedures justified this approach and a wide range of difficulties and limitations liable to be experienced by local and regional agencies in developing countries were addressed. Particular limitations such the need for time-consuming and costly field mapping and data integration into appropriate databases were circumvented and potential problems arising from a lack of hardware and software capabilities, shortages of trained staff, and scarce organizational resources would also be liable to compromise the viability of other approaches. The main advantages of utilizing satellite imagery are low-cost coverage of large areas and the large amount data that may be obtained in areas of sparse, discontinuous or non-existent data. An integrated top-down (regional to site scale) approach was adopted for data analysis and interpretation which facilitated a predictive capacity concerning terrain characteristics including tectonic fracturing, geotechnical properties, and ground conditions.

Lineament analysis combined with the use of an empirical tectonic model allowed areas with greater density and connectivity of fractures, including small-scale ones, to be delimited and areas of greater probability of occurrence of open fractures were also identified. These aspects were considered in the evaluation/classification of terrain units as they would exert significant influences over land instability and groundwater vulnerability to pollution hazards. Further research work should focus on the derivation 3D relationships and enable interpretations the angular relationships between rock structures (strike and dip) and hill slopes to be made. This would greatly enhance the potential of the method for engineering applications at a local scale. There is also potential for the development of automated procedures. For example, for the delimitation of terrain units based on image classification of spatial properties such as detection of groups of contiguous pixels and recognition of line patterns based on length, direction and angular relations between groups of contiguous pixels

Future and specific investigations should include revision of procedures of data derivation from external sources other than imagery, such as water table depth. Further implementation of the physiographic compartmentalisation approach for engineering and geo-environmental terrain assessments are required to evaluate its application in other geological and geomorphological settings and different scales of observation, analysis and graphic representation.

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