Landslide hazard assessment using remote sensing and GIS techniques

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This thesis is dedicated to the memory of my parents,

Noel Stacey Mason and Meriel Morgan-Nicholas
Abstract

Digital analysis techniques are presented for assessing landslides as a geohazard. A methodology has been developed employing a novel application of multi-scale mineralogical information from a landslide-prone region, enabling creation of a regional assessment for landslide hazard.

The principal study area has been the landslide-prone region of the Langhe, in Piemonte, NW Italy, but also draws on examples from SE Spain and SE England.

Four themes are developed. Firstly, the evaluation and textural analysis of remotely sensed imagery to enhance and identify physical properties of landslides. Secondly, ground-checking using field spectroscopy and XRD to extract soil information likely to be relevant to slope instability. Thirdly, slope stability analysis based on digital topographic data and, finally, the development of a hazard assessment methodology using a GIS database.

The significance of image texture to the analysis of landslide morphology has been investigated using SPOT-Panchromatic and Airborne Thematic Mapper image data for the test sites in NW Italy, SE Spain and SE England. Multi-temporal SPOT-Panchromatic image data has been processed to identify slope instabilities in the Langhe produced by the storm of November 1994. This event caused many fatalities and produced widespread landslides, floods and consequent damage to property. Landsat Thematic Mapper image data of Piemonte has been processed to identify land use patterns and to extract soil property information. Mineralogical field and laboratory analysis (spectroscopy and XRD) have been carried out on locally exposed soil and rock samples. These confirm the presence of mineral groups in soils and rocks believed to be significant to slope instability.

Stability analysis of digital slope data using published geotechnical parameters was carried out to derive a ‘factor of safety’ map. The digital capture of thematic image data, published maps and digital elevation data, managed using GIS, has enabled the computation of hazard assessment maps through the combination and quantitative analysis of physical and chemical attribute data. Critical evaluation of the attributes and techniques has enabled the construction of a hazard assessment methodology.
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Chapter 1 Introduction

1.1 Scope and setting

Landslides are a world-wide problem, threatening and inconveniencing tens of thousands of people and costing billions of dollars every year. Many areas badly affected by landslides have economies driven largely by agriculture or are heavily populated and extremely vulnerable. Disruption to routine and income can be devastating to the communities affected. Some extreme examples include the rock-avalanche at Huascaron, Peru, which in 1970 resulted in 18,000 deaths (Coates, 1977) and in Britain, the failure of the Carsington earth dam in 1984 which cost more than $30,000,000 to make good (Hutchinson, 1992). Surprisingly, landslides are rather insignificant in the British public eye, compared to more 'exciting' natural disasters like volcanoes and earthquakes. In the rest of Europe and other parts of the world, landslides are taken much more seriously. Landslides are complex and varied phenomena, much studied and monitored, yet they are still difficult to predict; and constitute one of many natural process which modify the earth's surface.

A layman could be forgiven for thinking that landslides seem to happen without warning. This cannot be the case since a landslide can only occur when the ratio between shear strength and shear stress decreases to one or less. Since the only instance where this change is very rapid is during an earthquake, there must be some gradual changes and progressive deformation of the slope material (Terzaghi, 1950). Really of course it is a question of not having noticed the warning signs.

This thesis attempts to demonstrate how information useful for predicting the location of future landslides can be derived from remotely sensed imagery (backed up by ground checking) and then compiled and analysed using GIS to derive a regional assessment of landslide hazard.

1.2 Objectives

The general aims of the thesis are:

- to demonstrate the textural expression of landslides in digital imagery
- to investigate methods of textural enhancement and classification to derive information relevant to slope instability using remotely sensed data
- ground-checking remotely sensed data through field and laboratory work
- to demonstrate that soil information can help identify areas susceptible to landsliding.
- to construct a hazard assessment procedure using GIS
• to generate a hazard methodology for the cases studied.

This thesis concerns landslides but it is not intended as a comprehensive study of all forms and varieties, nor does it provide an exhaustive study for a single landslide case. The thesis presents an application of remote sensing techniques relevant to the study of landslides, making reference to selected examples. It then concentrates on one of these, the Langhe in Piemonte, NW Italy (Figure 1.1), an area which has experienced slope instability over a prolonged period, and which suffered a significant landslide event in November 1994. The landslides experienced by the Langhe are in themselves worthy of study, as their setting and timing are complex and their impact is of prime concern to the inhabitants of the region.

1.3 Choice of case studies

Although the main part of this research has been carried out on data collected from the Langhe region of NW Italy, the preliminary stages of the work involved texture analysis of data collected from several areas, including NW Italy, which had experienced landsliding.

1.3.1 Langhe Hills, Piemonte, NW Italy

The research carried out on the data from this region involved processing from preliminary stages through to evolved hazard analysis. This study is a particularly timely one and came about following a storm event in 1994 which caused the landsliding in this area, the details of which are given later. Following discussions and meetings with colleagues at the Politecnico di Torino, it was decided to pursue a collaborative project to study both the flooding and landsliding in the area. This had never before been attempted on a regional scale in this area.

1.3.2 SE Spain and SE England

Data from both Sorbas (SE Spain) and Folkestone Warren (on the southern coast of England) have been used for the purposes of image texture analysis only. This part of the work was intended as a preliminary examination of the morphology of landslides to assess which are the most characteristic features of landslides and which are the features that are applicable to detection by remote sensing and quantifiable using GIS. The examination of landslides in different geologic settings, at different scales and in different image types was undertaken to obtain a better understanding of factors significant to landslide ‘mapping’ and to landslide hazard assessment. The location of the study areas in Sorbas and Folkestone Warren are shown in Figure 1.1.
Figure 1.1 a) Map of Western Europe (and detailed maps) showing locations of the three study areas: b) 1. F okestone Warren, SE Eng and c) 2. Sorbas basin, SE Spain; d) 3. Langhe Hills, NW Italy. B oxes indicate the study areas.
1.4 Methods and Techniques

GIS relies on the availability of at least some hard ground data. Rosenbaum & Popescu (1996) found that using a GIS, landslide hazard assessment in Romania could be based on the factors of slope angle, vegetation and climate combined with regional geological information. They also recognised problems in attempting to apply GIS in the absence of sufficient data. McDonald et al. (1995) developed a rapid-response hazard system for landslides in a large scale study of Papua New Guinea, with limited data. They used a linear combination of hazard attributes which proved to be successful though they found that the relationship between hazard attributes was not in fact linear. Cross (1995) used an objective computer based medium scale system, referred to as the Matrix Assessment Approach (MAP), to derive landslide susceptibility for large areas using a few key parameters, all of which can be relatively easily obtained.

It seems worth remembering that 'classification' is a tool to assist our understanding and should not be rigidly applied to all natural phenomena. The study in Piemonte is characterised by a paucity of geotechnical information, soil and hydrogeological maps; laboratory and field geotechnical data were not available at the time. Limited laboratory analysis has recently been carried out by Bandis et al. (1996) and Forlati et al. (1996). The GIS part of this work is therefore intended to support detailed geotechnical evaluations such as those currently being carried out.

1.4.1 Traditional techniques for landslide investigations

The reasons for investigating landslides are to (a) estimate the stability of an engineering structure in or on a landslide and (b) to design stabilisation measures (including the whole site, not just the landslide itself).

One of the key aspects to such studies includes the identification of the slip surface and there are a variety of different methods for achieving this. A comprehensive account of this subject is presented by Hutchinson (1988). Methods for locating the slip surface fall into two obvious categories: surface and sub-surface observations. The latter includes observations of moving or active landslides and stationary or inactive landslides. In practice it is more effective to use several methods rather than just one (pers. comm. Chandler, 1998).

1.4.1.1 Surface observations

Preliminary reconnaissance of the area under investigation usually involves geomorphological mapping using aerial photographs and a 'walk-over' survey to establish the boundaries of the landslide and to gather as much information as possible about the type and the setting of the
A landslide. Trial pits are often excavated to find the near surface slip surfaces. Another method involves the setting of a series of pegs in the ground, in a line across the landslide, to detect any downslope displacement. Crack gauges and tilt meters can also be used to measure any horizontal displacement. Any movement is recorded as a series of movement vectors from the tops of the pegs, and these vectors mirror the shape of the slip surface (although not the depth).

1.4.1.2 Sub-surface observations

Active landslides - methods involve the use of boreholes and include such simple techniques as shining a torch down the open holes, geo-acoustic methods (the greatest response comes from the shear surface), and slope indicators (inclinometers) which may be purpose built to monitor angular and absolute displacement, or plastic tube indicators where a ‘rod’ and a ‘shoe’ or ‘torpedo’ are lowered into the hole to locate the level of flexure corresponding to the position of the slip surface. Movements of >10 mm are required for an accurate measurement of the slip surface depth. When displacement exceeds ca 0.5 m the torpedo becomes jammed in the hole. It is also advisable to sink more than one borehole for such an exercise.

Stationary landslides - this refers to a site where there has at some time been a landslide. Detection of the slip surface in these cases involves examinations of borehole samples, trial pits and U100 tube samples (BS 5930, Anon 1981). The slip surface may be identified by disruption of bedding through samples, changes in lithology between boreholes, colour changes, fossil zones or changes in water content. Downhole piezometers are commonly used to monitor changes in water table level and behaviour. There is often a marked increase in water content at the shear surface and the slipped material may also have different liquidity properties to the undisturbed ground. Downhole resistivity tests can also be used to identify the shear surface in some marine clays, which contain large quantities of leached sodium chloride relative to undisturbed ground (which does not contain leached salts). Percussion drilling may be preferable to rotary drilling, as the spinning motion often destroys the shear surface (which may be rather delicate), though better results can be achieved using a larger diameter core.

1.4.2 Remote Sensing

1.4.2.1 Role and context for remote sensing

Remote sensing provides a unique perspective in any study of the ground, as it gives the user a metaphorical step back from the target. The flexibility of variable sensor and geometric parameters makes it a powerful tool, regardless of the source of the data.
One seemingly fundamental difficulty is that remote sensing in its view from above, yields information about the surface of the ground within its swath, yet movement of a landslide involves a shear surface which exists at some depth. So how does this information about the surface help in the identification of a sub-surface phenomenon? The answer to this lies in the collection of both direct and indirect evidence of the surface, i.e. the topographic expression of the landslide and from the physical and chemical characteristics of the materials in and above the landslide. Targets for remote sensing in landslide-prone areas include the morphological features of the landslide (arcuate scarp, hummocky ground, tension cracks and disrupted drainage), changes in vegetation as a result of increased water content, soils which contain a lot of water (i.e. are poorly draining), and soils and rocks which have high clay content, or are otherwise known to be susceptible to instability.

The role of aerial photography for landslide reconnaissance mapping is well established, and so is the principle of stereo viewing from such photographs. Images from satellite and aircraft fulfil a similar role but provide information at different wavelengths and/or from a greater height. Other parameters such as the scale of the study, the spatial resolution of the sensor (i.e. the lower limit of what it can actually image), the dimensions of the landslide targets, weather and ground materials must also be considered in the undertaking of such a remote study.

One advantage of satellite remote sensing is that it enables rapid and routine collection of data over a much greater area than that of a typical ground based survey. In cases where landslides are suffered over a sizeable region, an inhospitable region or where information more traditionally associated with landslide studies is not available, remote sensing may be the only source of information about the terrain. Increasingly other digital information is available on a global scale, in the form of Digital Elevation Models (DEMs). The combination of elevation data and remote sensing creates a powerful means of analysing terrain where detailed ground studies are not practical or possible.

1.4.2.2 Tools for remote sensing

In basic terms the tools for remote sensing should include a set of aerial photographs and a stereoscope but for a digital study, rather more sophisticated tools are necessary.

The software used is usually a matter of financial constraint or personal choice. Most image processing systems are capable of the basic enhancement techniques and can import data in a wide variety of formats.

There seems to be an ever increasing choice of data types and sources, as new sensors are designed and previously unavailable military data is released. Once again cost can be an important constraint, as copyright on new data and demand for high resolution data can make remote sensing
a costly technique. The choice of data should be carefully made, taking into consideration for example, the subject of the study, the nature of the terrain and the climatic conditions.

A reasonably powerful computer, with high quality graphic capabilities and with access to a big enough disk to store the large volumes of data integral to remote sensing work, are essential. This study was carried out using a combination of UNIX and PC platforms, running ER Mapper (Earth Resources Mapper), a widely used and flexible image processing system designed for digital analysis of any type of digital image information.

1.4.3 X-Ray Diffraction (XRD) and Reflectance spectroscopy

1.4.3.1 Role for XRD and reflectance spectroscopy

Field spectroscopy can only provide point (local) information but this can be used to calibrate the regional spectral information, provided in this case by Landsat TM (although ideally, this would be provided by an imaging spectrometer e.g. AVIRIS, MIVIS). In theory, this field data can also be used for correction of atmospheric scattering in the satellite image data though this is heavily dependant on the weather conditions at the times of imaging and field data collection and so there is great potential for mis-match between the two.

Generally, the two main targets for reflectance spectroscopy are (a) clays and (b) iron; both of these mineral groups could provide useful information for landslide hazard assessment. A number of authors have reported the significant presence of swelling clays in causing slope instability and have investigated the occurrence of smectite using XRD techniques (e.g. Forlati et al., 1996; El Amrani Pazza & Chacon, 1996; and Al-Homoud et al., 1996; Hossain et al., 1997). Smectite (montmorillonite group) clays are well known for their swelling properties (a feature dealt with in later chapters) and their significant role in slope instability (Bell & Pettinga, 1988). Oxidised iron gives a very distinctive signature and colour to soils and is an indicator of intense leaching and weathering of iron bearing rocks. Intensely weathered and fractured rocks are target areas for the potential initiation of landslides.

1.4.3.2 Tools for XRD and reflectance spectroscopy

The techniques of (XRD) and reflectance spectroscopy are widely used for the analysis of iron-oxide and clay minerals in sediment samples.

XRD is a standard technique for sedimentological analysis, the details of which can be found in many texts such as Hardy & Tucker (1988) and Nuffield (1967). The instrumentation and theory is described in Chapter 6.
Reflectance spectroscopy has been used for a variety of applications. The theory and instrumentation are described in Chapter 6 but can be found in a variety of texts: Hunt (1977 & 1979), Hunt & Salisbury (1970, 1971), Hunt et al. (1971), and Clark (1997). Background and summary information is contained in texts such as Drury (1993).

1.4.4 GIS and hazard assessment

1.4.4.1 Role for GIS - a multi-dimensional approach

The structured (layered) digital database of geographically related information is known as a Geographical Information System (GIS). This computer-based tool is widely used for the management, speedy access and analysis of data from a variety of sources. Such data may be in point form (e.g. elevation or borehole data), continuous records (e.g. profiles), raster (e.g. maps or images) or lines (e.g. faults and boundaries). Typical elements of a GIS are shown in Figure 1.2.

The two basic ways in which GIS information is stored are (a) raster and (b) vector. A raster is a regular array of 2D grid cells, of any shape, though square or rectangular are most common. Geographical position within the raster is defined by the sequence of storage within the binary or ASCII file and the precision is controlled by the dimension of the cell (or pixel). Each cell has a unique value or attribute such that every category of attribute requires a separate raster file. This can mean heavy use of computer disk space and processing time, depending on the resolution of the raster data. Vector data is represented as points, lines or areas, together with co-ordinates and feature attributes (for topology); the accuracy of their locations is controlled by the original surveying and by the number of vector points defining them (in the case of polylines). For either storage system many attributes can be stored for any point within an attribute table. The types and elements of GIS are summarised in texts such as Burrough (1998).

Digital analysis, using a GIS, is ideal for assessment of slope instability hazard. GIS provides convenient means of handling large digital datasets. There is an obvious element of uncertainty in the effect of various factors on slope instability. GIS provides a method of combining and analysing such uncertain contributions using decision tools.

The Langhe case study is particularly suited to a regional hazard assessment using a GIS for a number of reasons. Firstly, slope instability in the Langhe is a recurrent problem. The long history of landsliding indicates that a number of geomorphological, anthropogenic and climatic conditions can result in long term slope instability. Secondly, the instabilities are numerous and are spread over a considerable area. To effectively represent the regional hazard, the analysis needs to involve
Figure 1.2 a) Schematic illustration of the component parts of a GIS, from input to results, also indicating the relationship between remote sensing and GIS; b) Elements of hazard assessment using the decision support tools of the GIS, leading to remediation.
large digital datasets. GIS provides an efficient means of handling and analysing large volumes of multivariate data.

1.4.4.2 Tools for hazard assessment

Digital Elevation Models - a digital representation of the continuous variation of relief over space is known as a Digital Elevation Model (DEM) (Burrough, 1998). DEMs can also be used to model the variation of any other attribute over a surface and in this respect they are a convenient method of conveying spatial information. DEMs have many uses, the most important of which are to:

- store elevation data and 3D display of landforms
- analyse cross-country visibility and planning
- tackle road cut and fill engineering problems
- compute slope, aspect maps and profiles
- form a backdrop for draping of other digital information

Data integration - A multi-attribute analysis will usually involve data from a variety of sources and different types, formats, scales and map projections. A good digital mapping system or GIS must be able to integrate these data, and this requires the ability to import, convert, transform, display and finally output the data. All of these processes can be lengthy and time consuming; GIS is one of the best methods for performing these processes routinely.

Decision Tools - once the relevant data has been gathered and standardised, some decisions must be made about how the data should be analysed. To do this, the hazard must be defined in numeric terms on the basis of a number of parameters, i.e. 'factors'. A suitable GIS software system was chosen which contained an appropriate set of tools for this purpose: the raster based Idrisi software, developed at Clarke Laboratories, Clark University, Massachusetts. This operates on a PC platform and has a suite of decision tools which enable data analysis for multi-attribute problems and which can incorporate uncertainty within the decision making process.

Display - the results of the spatial analysis must be displayed, and this is done most efficiently in map or graphic form. Most GIS software contain map composition tools for the preparation of professional quality maps and images.

1.5 Structure of the thesis

This thesis is structured in a modular fashion, dealing with a series of themes. The themes are (a) remote sensing, (b) mineralogical analysis, (c) slope stability analysis and (d) GIS. This has been done so that the thesis can be used as a reference and each theme can be accessed readily.
Each chapter deals with a separate theme of the research. Each is structured so that it begins with a brief explanation of what it is hoped to achieve, followed by methods, results and what has been achieved, and lastly a summary is given of the chapter and how it links with the next.

The present chapter describes the aims and objectives, and the context of the research.

Chapter 2 provides background information about slopes and slope evolution, so making clear the distinction between the problem of landslides (i.e. catastrophic slope movements affecting peoples lives) and other less threatening slope processes.

Chapter 3 describes published work on landslides, landslide morphology and the role of remote sensing and GIS in the study of such phenomena.

Chapter 4 describes the geology, geomorphology, climate and landslides in each study area. Greatest detail is given for the Langhe case as it is this topic which is dealt with in the hazard assessment of Chapter 7.

Chapter 5 describes the processing of satellite image data. Different data types and techniques are described and compared for extraction and enhancement of landslide feature and of information relevant to landslide study using GIS.

Chapter 6 describes the field and laboratory work (spectroscopy and XRD) carried out in situ and on samples collected from the Langhe study area, as a ‘ground-checking’ exercise for the remotely sensed data.

Chapter 7 describes the integration and contents of the GIS and the subsequent hazard assessment. The work describes the decision tools and methods of analysis. The resultant hazard maps for the different techniques and different hazard types are shown, critically compared and summarised to form the basis of the model definition.

Chapter 8 contains the conclusions drawn from the project as a whole and the synthesis of the regional landslide problem, together with the successes and failings of the research. The chapter also deals with recommendations for further work and development of more appropriate techniques/equipment for this type of study.
Chapter 2  Review of Slopes and Slope Evolution

2.1 Introduction

The objective of this chapter is to illustrate the complexity of natural slope forming materials and processes and the longevity of slope evolution, in order to clarify the hazard posed by landslides. The development and evolution of natural slopes is slow and dynamic. Slopes are influenced by weathering and transport processes, climate and rock type. The materials forming those slopes, soils and rocks, are subject to changing forces and processes which affect the overall stability of the slope. Mass movements form one type of the many processes which modify slopes. The most noticeable aspects which identify them as a hazard include the relative velocity at which they work and their damaging nature. This chapter aims to assist in the definition of the problem referred to as landslide hazard in this thesis.

2.1.1 The slope system

A popular approach to the study of slope development is to view it as a complex system involving many interacting processes and forms, none of which should be studied in isolation (Figure 2.1). Slope systems are sustained by various inputs of mass and energy which are balanced by outputs and result in a state of equilibrium. Short term changes in factors, such as climate, may modify the weathering rate, the slope system then adjusts and a steady state is maintained in the long term. For example, a climatic change from a humid to semi-arid environment leads to a reduction in vegetation cover. This increases surface run-off and sediment transport, causing the stripping away of soils. The exposed bare rock is then more rapidly weathered and eroded, which reduces the angle of the slope profile until a steady state is restored. This self-regulation is the principle behind negative feedback, which is common to most natural systems.

2.2 Surface processes

The top few metres of material at the ground surface consists of soils, drift and weathered rock which have engineering properties very different from the un-weathered bedrock beneath (see Figure 2.2). Soils are a mixture of weathered mineral debris and plant material, and are usually only a metre or so in thickness. Drift refers to the transported unconsolidated material deposited on bedrock, clay, sand and clastic debris. Colluvium is slope debris transported under gravity, and includes creep and sheetwash. Rockhead is a term referring to the buried rock/drift interface.
Figure 2.1 Interacting endogenetic and exogenetic components of the slope system (after Small & Clark, 1982; and Kirkby, 1995).

Figure 2.2 Weathering grade, profile and lithological description (modified after Anon BS 5930, 1981).
2.2.1 Weathering

This refers to the in-situ disintegration of rocks or the breakdown and alteration of materials near the surface to products more in equilibrium with their surroundings. The main types are, physical, chemical and biological, which act together and often reinforce one another. The former being the mechanical breakdown of rocks and the latter referring to the decomposition of rock minerals by water, oxygen, CO₂, and organic acids. The mechanical break-up and weakening of rocks facilitates the action of water and oxygen and hence chemical breakdown. Weathering is influenced by both endogenetic and exogenetic factors: endogenetic factors relate to structure and composition of the rocks, e.g. highly fractured rocks break down more rapidly than unfractured ones; exogenetic factors include climate, vegetation, temperature changes (diurnal and annual). The complex interplay between these have significance in controlling slope stability.

2.2.1.1 Physical weathering processes

These are four-fold and can be summarised, from descriptions by Brunsden & Prior (1984), Parsons (1988) and Small & Clark (1982) as:

1. Stress release (exhumation) - the reduction in confining stress reduces the strength of rocks which then undergo expansion producing joints, and these allow access of water to the fresh rock causing chemical action and further physical breakdown.
2. Frost shattering (congelification) - freeze-thaw action characteristic of high altitudes and latitudes, present-day periglacial environments and mid-latitude winters.
3. Thermal exfoliation - fracturing on repeated and prolonged exposure to large diurnal changes in temperature (insolation).
4. Salt weathering - growth of crystals causes expansive stresses to grain and joint boundaries. Common to hot deserts.
5. Rain impact - this refers to the act of water droplets on the surface which dislodge individual particles, which then move downslope under gravity.

Processes 1 & 2 have a significant role in the landslide examples cited in this study, processes 3 & 4 are common to desert and high altitude environments.

2.2.1.2 Chemical weathering processes

1. Solution - solution of various materials depending on the pH of the surrounding conditions.
2. Carbonation - converts CaCO₃ to Ca(HCO₃)₂ by rainwater containing dissolved CO₂.
3. Hydration - absorption of water causing volumetric changes and therefore internal stresses.
4. Hydrolysis - decomposition of feldspars to clays.

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5. Oxidation & reduction - combining with O₂ or the dissociation from O₂ (especially in iron minerals) in the presence of water.

6. Chelation - the formation of organic acids from decaying vegetation which then affects the solubility of elements especially iron.

2.2.1.3 Biological weathering processes

Biological weathering and erosion was pioneered in the last century, e.g. Sollas (1880), and is currently a field of active research. Biological weathering refers to the action of lower plants and micro-organisms on rock substrates (they do not require soil as a growth medium). This was at initially quite a controversial issue but now is accepted as reality. Organisms responsible include bacteria, fungi, algae and lichens, which may be autotrophic or heterotrophic, and terrestrial or freshwater in habitat, Viles (1995). Their activity includes micro-fracturing and etching of rock surfaces, though lichens have been implicated in both physical and chemical weathering.

Factors influencing their initiation and development include:

- air and water-borne arrival, in some cases growth is faster on wet surfaces than on dry ones.
- the roughness of the rock surface - increased roughness encourages growth.
- pores, grain and crystal size.
- light availability - for photosynthetic organisms.

Biological weathering agents should also include the contribution of macro-vegetation via the action of root growth, widening fissures and fractures and therefore increasing water infiltration. This organic form of weathering operates in one form or another in all weathering zones (Chorley et al., 1984).

2.2.1.4 Weathering of rock

The thickness of the weathered mantle is thickest on transport restricted natural slopes but varies considerably (Chorley et al., 1984). Its thickness depends on the balance between the depth of equilibrium (as dictated by permeability, fracturing and climate) and the degree of transport restriction (as controlled by the angle of slope, creep and water content), Chorley et al. (1984). The thickest weathering mantles are observed on gentle slope angles with good drainage and rapidly weathering rock, e.g. in tropical and periglacial environments. Simplified weathering profiles of igneous and sedimentary rocks and their properties are shown in Figure 2.2. Sedimentary rocks which are highly structured and porous may weather as deeply as granites and metamorphic rocks which are less in chemical equilibrium with their surroundings. The weathering and breakdown of rocks at or near the surface requires contact with air and water, and so is influenced by climate.
Many chemical processes are accelerated in hot, wet climates and by organic acids produced by dense plant cover.

A major chemical process is the production of clays from silicate minerals. There are three main locations where clay mineral formation occurs: weathering environment, depositional environment, and during diagenesis (Hardy & Tucker, 1988). In sediments or sedimentary rocks, clay minerals originate from inheritance (detrital), neoformation (formed in situ) or transportation (when inherited clays are modified). Clays are altered very little during transportation by wind or water and when deposited, clay rich muds have chemistry which is a reflection of both the climate and weathering and composition of the source areas. Non-marine sediments are dominated by inherited clays.

The presence of temperature and moisture is significant in controlling the behaviour and breakdown of minerals under weathering (Chorley, et al., 1984; Velde, 1985):

- poor drainage (low percolation) and warm, wet climates - feldspars (e.g. albite) are broken down, Mg and Na are not flushed away and react with Al and Si, to give smectites (montmorillonite).
- better drainage - Mg and Na are flushed out and albite is broken down to form kaolinite.
- rapid drainage and warm, wet climates - Mg, Na and Si are lost and bauxites (gibbsite) are formed.
- rapid drainage and temperate climates - feldspars breakdown to form illite, and then kaolinite on further weathering.

Diagenetic changes result in progressive alteration of clays with rising temperature. One of the first changes is that of smectite to mixed-layer smectite-illite, and then to illite. Chlorite develops at depth and kaolinite is converted to chlorite and illite under incipient metamorphism. Samples taken vertically through a sedimentary sequence of mudrocks may show variations in clay assemblage which reflect climate or source area change through time. These changes are discussed in a number of texts, e.g. Hardy & Tucker (1988), Perry & Hower (1970) and Jennings & Thompson (1986).

2.2.2 Material transport

2.2.2.1 Creep and solifluction

Creep refers to the slow downslope movement of regolith as a result of the individual movement of soil particles. The process is dependent on inter-particle stresses and is driven by gravity. Creep is caused when regolith particles are disturbed by some agent and affected by gravity, producing a downslope movement of the particle. Volume changes are caused as particles...
fill voids, slope form varies and the result is expansion and contraction of the soil. The main agents of disturbance are temperature changes, wetting and drying, freeze-thaw action of soil moisture, plant root activity, soil fauna, volume changes due to chemical weathering, and precipitation.

Creep is a very gradual process and as such is very difficult to measure in the field (Brunsden & Prior, 1984). Continuous creep, as defined by Terzaghi (1950), is that produced by gravity, unaided by other agents. It can affect both rock and regolith and is caused by the weight of overburden. It is considered a minor surface process but is can be a precursor to rapid mass-movements (Schumm & Chorley, 1964).

Solifluction can be described as the slow flowing from higher to lower ground of masses of waste saturated with water. It is typical of periglacial environments and leads to a distinctive micro-relief, composed of stone banked steps and lobes with flatter, finer grained material between the steps, generally on slope surfaces of between 10-25°. Solifluction is caused by seasonal freezing (drawing up of water into the frozen layer) and thawing (release of water producing subsidence). It comprises components of both frost creep (movement by freeze-thaw action) and gelifluction (flow). Displacement decreases linearly with depth, from ca 0.16 m (at the surface) to 0.02 m at a depth of 0.50 m and down to zero below 0.50 m depth. Rates of movement may be 0.06-0.60 m³/m/yr. There seems to be little relation between rate and slope angle (Parsons, 1988). Greater correlation exists with moist areas which show more movement, than with well-drained areas. Materials with high silt contents also display large movements.

2.2.2.2 Slope wash

Slope wash is the downslope transport of regolith across the surface by moving water. There are two distinct processes involved: raindrop impact and surface flow. Surface flow maybe in the form of sheetwash (via a moving layer of water) and rillwash (in channel flow). The effects of these processes are two-fold: soil detachment, the removal of soil particles from their original positions; and soil transport, the carrying of material downslope.

Rapid surface wash occurs under conditions which are normally characteristic only of arid and semi-arid environments, i.e. sparse vegetation, bare ground and a weakened soils structure, but occurs in cooler climates too. Such conditions are often produced by human activity, bad agricultural practices, or prolonged drought, which then lead to stripped and poor soils and therefore increased run-off.
2.2.2.3 Raindrop impact

Raindrop impact refers to the action of individual droplets of water on soil particles and is more or less independent of slope angle. The impact disrupts the surface and facilitates erosion. It is an important erosive agent when the surface is only partially covered by vegetation, and especially when the surface is dry. Raindrop erosion on a an already wet surface results in intermediate value of erosion whereas moving water on the surface alone produces insignificant erosion (Chorley et al., 1984).

2.3 Slope evolution and classification

The study and classification of slope form is usually approached from the profile view. It involves the description of present form but also infers the probable development of the slope through time. It is difficult to observe slope evolution directly, as investigations can rarely go on long enough and soft materials and rapid erosion are required. More often, two indirect approaches are adopted which make a compromise between observation and speculation. One method involves the reconstruction of slope form, from a series of direct observation, made over a period of time (for shorter total time periods), or about the state of a slope taken at several times in the past (for longer time periods). These are placed in correct order and used to reconstruct the form of the slope as it evolves. Another method involves the observation of several slopes in different localities, under similar geological and climatic conditions, in the hope that they will represent different stages of a single type of development.

Several models have been formulated to describe the form and evolution of slopes. The first and simplest of these is the Four unit model, proposed by Wood (1942), which involves the development of two sections, a rectilinear talus slope and retreating cliffs. Each of these sections comprises 2 further parts, a convex upper part, and a concave lower part produced by weathering and sediment transport (Figure 2.3). The four sections or ‘units’ are termed (i) convex waxing slope, (ii) free face, (iii) constant slope, and (iv) concave waning slope. This model requires a resistant rock type, a high initial slope angle and an absence of basal undercutting, all of which are typical of semi-arid environments.

This model was modified into the Five unit model of Caine (1974) which is common of mountainous areas. This has the same basic four units but Caine included a ‘talus foot’ between the rectilinear and waning slope units, which represents the operation of periglacial processes (Figure 2.4). Another variation is the Nine unit model, by Dalrymple (1968), which is again based on the four unit model but three other units have been added in the valley floor section (Figure
Figure 2.3 The Four unit slope model, a) to d) developing phases, e) summary block diagram (modified after Wood, 1942).

Figure 2.4 The Five-unit (Alpine) slope model (after Caine, 1974).
2.5). It is most applicable to humid-temperate regions but this model also relies heavily on the presence of a free face.

Slope evolution theories were pioneered by three geomorphologists, W. M. Davis (1899), W. Penck (1924) and L. C. King (1957). The three broad theories are referred to as *slope decline*, *slope replacement* and *parallel retreat* which are summarised as follows and illustrated in Figure 2.6:

1. **Slope decline** (Davis) - the steepest part of the slope progressively decreases in angle and the slope acquires convexity (over *ca* 20% of the profile) and concavity (over *ca* 10% of the profile). Erosion is rapid on the upper parts, and less so on the lower slopes. Davis also suggested the concept of graded valley sides where coarser material is found on the upper parts of the slope profile and finer material on the lower portion. Davis’s view of slope decline suggests that slope retreat is accompanied by a decrease in steepness such that the concavity and convexity progressively acquire a larger radius of curvature (Figure 2.6a).

2. **Slope replacement** (Penck) - the maximum slope angle decreases through replacement by gentler slopes, from below, causing concavity over the greater part of the slope (*ca* 60%). e.g. the cliff (free face) is replaced by shallower angle debris slope, this debris slope is then replaced by a still gentler slope and so on (see Figure 2.6b).

3. **Parallel retreat** (King) - the maximum angle and the absolute lengths of all parts of the slope are constant, and the concavity increases in length. The angle at any point decreases with time. The free face seems to occupy the same portion of the slope profile at each stage. The rate of cliff retreat controls the development of the slope as a whole (see Figure 2.6c).

Davis developed a model of the cycle of erosion in which landforms passed through an irreversible sequence of changes associated with his so called stages of youth, maturity and old-age. These three approaches encompass descriptive properties and evolutionary aspects. It is also probable that all these slope evolution theories are correct under certain circumstances and that combinations may operate together in some situations. Other more recent studies have suggested that these theories are useful but are considered too general (Chorley *et al.*, 1984).

In terms of processes, two broad categories of slopes are generally recognised (Selby, 1982):

1. weathering-controlled slopes, where the rate of regolith removal exceeds the rate of weathering, and the slopes are usually bare of soil.
2. transport-controlled slopes, where transport processes cannot keep up with weathering and regolith production.
Figure 2.5 The Nine unit slope model (modified after Dalrymple, 1968).

Figure 2.6 Cartoons summarising the theories of a) slope decline, b) slope replacement and c) parallel retreat (after Small & Clark, 1982).
Transportational slopes are intermediate forms where there is an equilibrium between weathering and removal. Landslides have a significant role in landform development in transport-controlled slopes (Cendrero & Dramis, 1996).

2.4 Slope Morphology

2.4.1 Slope angle, aspect and curvature

True slope is defined as the angle of surface slope of the ground in the direction of maximum slope, i.e. perpendicular to the contour. Apparent slope is the angle of surface slope in any other direction. True and apparent slope are therefore equivalent to the relationship between true and apparent bed dip in geology. Slope aspect or azimuth is defined as the direction, measured in degrees from north that the slope faces. Beaty (1956) asked the question "do slides tend to be more numerous on any particular slope exposure, or do they occur more or less randomly, without any regard for slope aspect?"; a possibility that had previously been discounted by many authors but which now is considered as significant in many cases. Profile curvature is defined as the rate of change of angle with distance down true slope, expressed as degrees per 100m. Convex slopes have positive curvature and concave slopes negative curvature.

Limiting angles are those which describe the range of angles within which given forms or processes occur and are often described as upper (maximum) and lower (minimum) limiting angles. Characteristic angles are those which occur most frequently and may form as a result of the following:

- random variations.
- particular structures - different lithologies and dip attitudes often give rise to characteristic slope angles because of differing resistances to weathering and erosion.
- features of slope evolution irrespective of rock type or climate.
- local morphological conditions.

Generally, gentler slopes are more frequent than steep ones. This may reflect the relative survival time of slope angles, i.e. steep slopes are more rapidly destroyed. One explanation of frequency patterns is that they reflect morphological history, in that predominant gentle slopes represent extensive survival of late-stage landforms and the low-frequency steep slopes correspond to recent rejuvenation and down-cutting. This becomes more complex when valley asymmetry in involved.
2.4.2 Valley asymmetry

The effect of aspect on slope form can be considered in terms of asymmetry and the two main causes are recognised as structure and process, with structure being the most common.

In general, in the northern hemisphere, north-west to north-east facing slopes are cooler than south-west and south-east facing slopes due to greater exposure to solar irradiance. These slopes also have a higher regolith moisture content, retain snow and ice longer and often favour different vegetation. In a study by Beaty (1956) 70% of landslides occurred in slopes facing north and east (northern hemisphere). Where weathering processes are the dominant agents in producing asymmetry, these northerly facing slopes are usually the steepest slopes, by the assumption that denudation processes are more rapid on these slopes. The reverse situation can occur when there is a strong influence of structure on valley asymmetry (Figure 2.7). The steep scarp slopes experience rapid slope wash and retreat more rapidly than the gentle dip slopes where drainage is restricted and the soil profile is thicker. It is likely that in such cases, different processes of slope evolution can be attributed to the asymmetry.

There are a variety of causes of asymmetry and topics which require consideration include whether the asymmetry is contemporaneous with or subsequent to valley formation, or whether it results from steepening of one side or the flattening of the other. Another possibility is that asymmetry is produced by differential lateral erosion, where one slope is undercut by fluvial action and the other is protected by a footslope (Cendrero & Dramis, 1996), or as a result of differing resistances of rock types for example. Interruptions in basal undercutting of slopes results in a rapid decrease in mean gradient and free face scarp size (Hutchinson, 1967).

Hack & Goodlett (1960) noted that ground moisture varies considerably for a variety of reasons which include the form and aspect of the terrain. These variations are controlled by exposure and geologic structure so that the down-dip slopes tend to be steepest and wettest. Water seeps downslope between bedding planes and in fractures, and is protected from the drying effects of the sun and wind.

Slope orientation statistics may be of interest when channel pattern reflects local geological structure, tectonic history and geomorphology. Lambert (1961) divided slopes into conformable and inverse categories, depending on their relationship to bed dip. He found that inverse slopes tended to be steeper and to retreat more rapidly than conformable ones. This is true of slopes in the Langhe, dip slopes ranging from 4 - 20° and scarp slopes from 20 - 53° (see Figure 2.7).
Figure 2.7 Cartoon illustrating the influence of geology on valley asymmetry in the Langhe.

Figure 2.8 Hydrologic system and its complex interactions with slopes (after Small & Clark, 1982).
2.5 The influence of tectonics

In the long term, tectonic activity is a significant modifier of slope form and especially so in active mountain belts and plate margins.

Earthquakes produce shaking and cause faulting. One side of the fault is moved (up, down or laterally) relative to the other and if the fault is near or intersects the surface, the landform is changed. Tectonic uplift also causes tilting and rotating so that scarps are moved and changed, irregular and asymmetric landforms are produced, rivers are re-directed and the pattern of erosion modified. Tectonic activity represents a massive source of potential energy for landform change (Chorley et al., 1984). Tectonics can suddenly and episodically upset the state of equilibrium that exists and the slope system then re-adjusts to restore equilibrium. Earthquakes are also a frequent trigger of landslides (Murphy, 1995, Murphy & Vita-Finzi, 1991).

2.6 Biogeomorphology - vegetation, climate and slope sensitivity

There is increasing interest in the relationships between vegetation, climate and landform change in a field of research termed biogeomorphology. Biogeomorphology encompasses a variety of issues including:

- the effect of vegetation, and different types of vegetation, on sediment transport and hydro-geomorphological processes (e.g. Gurnell et al., 1995; and Prosser et al., 1995).
- the responses of vegetation, which tend to be continuous (Phillips et al., 1995), to episodic changes in landform (such as those produced by landslides and floods).
- the effects of bioturbation on soil development and erosion (e.g. Yair, 1995).
- the influence of animals as agents of geomorphology (e.g. Butler, 1995; and Trimble, 1995).

The influence of livestock animals, such as cattle, as geomorphic agents has also been investigated, e.g. Trimble (1995). The long-term heavy grazing of cattle causes soil compaction, reduced infiltration and increased run-off and results in erosion, increased sediment yield and formation of terracettes.

Hack & Goodlett (1960) were some of the first researchers to approach the combined subject of geomorphology and plant ecology. Their themes of study included convergent surface and groundwater flow (moist conditions) and plant distribution, divergent water flow (indicating drier conditions) and the effects of parallel flow paths to plant tolerances (intermediate moisture conditions). Their findings have been supported and reinforced by Osterkamp et al. (1995) who
state that the distribution of plant species can be a physiographic response to localised environmental conditions, i.e. the distribution of established vegetation is not random. Species distribution is controlled by slope angle, aspect and curvature, landform, rock type, soil moisture and temperature conditions. Hack & Goodlett (1960) also suggested that vegetation plays an important role in geomorphological processes in the years following a catastrophic change, such as a landslide.

Resistance to weathering and erosion is afforded by a dense root system which increases soil cohesion. Up to 90% resistance to surface flow is given by a the plant stems of a densely grassed surface (Prosser et al., 1995). Kirkby (1995) suggests that vegetation is an intermediate through which climate and landuse modify geomorphologic processes.

Variations in climate and soils cause changes in the sensitivity of slopes to failure, particularly in humid-temperature regions since the last glaciation (Brooks et al., 1993). Seasonal increases in groundwater levels form a major contribution to slope failure. The recharge period of the water table occurs during the winter months and so slopes are vulnerable to pore pressure increases, depending on storm frequency, evaporation rates and soil drainage (which itself is controlled by chemistry, structure and attitude). Soil drainage is most rapid immediately after rain ceases, and slows markedly with time (Brooks et al., 1993). Immediately after a storm, soil moisture content is almost at saturation point so that any further rainfall may be critical. The interval time between rainfall events is considered significant in the initiation of failure (Ng & Shi, 1998 and Polloni et al., 1996). The complex interactions of the slope-hydrological system are summarised in Figure 2.8.

2.7 Mass movements and slope stability

2.7.1 Terminology

'Mass movements' collectively refer to a host of different phenomena and these will be described in Chapter 3, this section is concerned with a brief description of mass movements within the context of slopes.

The causes of mass movements under natural conditions have been documented by a number of authors, but generally can be grouped into two categories, passive conditions which increase the susceptibility of the slope to mass movements; and active conditions, which trigger movement. Broadly speaking, the passive conditions are lithological, structural, topographic, hydrological and climatic. The main active conditions include seismic activity, slope steepening by basal erosion (toe
removal) and exceptionally heavy rainfall, especially when accompanied by a prolonged wet period where the water table is raised considerably.

The infiltration of water into regolith and soil acts as a trigger for mass movements more than any other activity (Carson, 1976). This happens for a number of reasons. The increased bulk weight causes an increase in shear stress; the formation of perched water bodies and increase in the pore water pressure reduces shear strength and reduces friction on potential shear planes; and periodic wetting and drying of regolith and soil particles also reduces stability. Such situations are characteristic of humid-temperate regions, slopes are gentle and are often termed semi-frictional slopes.

So what constitutes a mass movement? The downslope movement of rock and soil under the influence of gravity seems a reasonable first definition. Creep and solifluction involve the movement of masses of material downslope under gravity and yet they are usually referred to as processes of mass transport. The difference between mass movements and mass transport is perhaps then related to the speed at which they occur (see Figure 2.9 and Table 2.1). Mass movements are also often damaging and dangerous, especially in extremely rapid examples.

Table 2.1 Classes of mass movement and transport

<table>
<thead>
<tr>
<th>Movement type</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valley rebound</td>
<td>Minor elastic movements - erosion related stress relief</td>
</tr>
<tr>
<td>Cambering and bulging</td>
<td>Large plastic deformations - resulting from periglacial conditions</td>
</tr>
<tr>
<td>Creep</td>
<td>True creep - continuous displacement under constant shear stress</td>
</tr>
<tr>
<td>Landslides</td>
<td>Occur on slopes where ( s \geq \tau ) (description and classification in Chapter 3)</td>
</tr>
<tr>
<td>Block falls, toppling</td>
<td>Ice wedging</td>
</tr>
<tr>
<td>Subsidence</td>
<td>Natural (limestone karst, ice thaw, sub-surface erosion) or man-made (mining, pumping)</td>
</tr>
</tbody>
</table>

The definition of mass movements is therefore not a simple one, though it is an important one. If mass movements are to be termed ‘hazards’ within the context of this and other studies, we must be quite sure what they are and why they constitute a hazard. Chapter 3 provides more detailed definitions, descriptions and classifications of mass movements so that the nature of the hazard is understood in the context of slope processes and of mass movements collectively.

Some well documented examples, which demonstrate adequately that mass movements are indeed hazardous, include the following:

- Mount Conto, Switzerland, 1618 - the slope failed above the town of Pleurs and killed 2430 people (Coates, 1977);
Figure 2.9 Classification of slope modifying processes based on velocity and water content.
- Vaiont Dam, Piave valley Italy 1963 - a major rock-slide at the side of the dam caused a flood which killed 1900 people in the valley below (Sorriso-Valvo & Gulla, 1996);
- Merthyr valley, South Wales, 1966 - the failure of a spoil-tip (flow-slide) from the hill above Aberfan, resulted in the death of 146 school children (Bishop et al., 1969; Hutchinson, 1986);
- Huascaran, Peru, 1971 - a rock avalanche-debris flow, estimated at $10^6$ m$^3$ in volume, travelling at 400 km/h over 14.5 km, killed 18,000 people on market day (Coates, 1977).

2.7.2 The relative significance of mass movements as a surface process

This refers to the proportion and rate of material transported from the slopes by the different processes. Important considerations include the distinction between catastrophic modifications and continuous denudation (and the relative significance of each) although the two should not be considered as completely separate issues. The catastrophic type includes mass movements and in any single event, the occurrence is usually localised and temporally irregular. Continuous denudation involves processes acting on the whole or large portions of the slope simultaneously and the frequency interval for substantial denudation is short i.e. it acts more or less uniformly in time and space.

Cendrero & Dramis (1996) have developed a quantitative expression of the role of landslides in landform evolution which they have termed the Relative Landslide Rate (RLR). The RLR is defined as the ratio between the landslide mobilisation rate and the denudation rate. The greater the value of RLR, the more significant is the role of landslides. On transport-limited slopes, this ratio should be greater than 1, less than 1 on weathering-controlled slopes, and about 1 on transportational slopes.

Differing energy requirements and forces in terms of debris transport depend on the type of process. Table 2.2 illustrates the differing energy involved and the efficiency of various slope processes.

Table 2.2 Energy expenditure for different modes of material transport

<table>
<thead>
<tr>
<th>Force</th>
<th>Total work ($J/m^3 \text{ pa}$)</th>
<th>Total work of downward debris transport ($J/m^3 \text{ pa}$)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity: (slides and falls)</td>
<td>1-100</td>
<td>1-100</td>
<td>100</td>
</tr>
<tr>
<td>Water flow: (dissolved &amp; suspended load in rivers, and)</td>
<td>$10^5 - 10^6$</td>
<td>10 - 100</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>0.02 (grass)</td>
<td>0.002</td>
</tr>
</tbody>
</table>
The Second Law of Thermodynamics states that entropy increases irreversibly in a closed system. Entropy is a measure of the freedom of energy in a system, to perform work. A low-entropy, closed system is one where there are spatial variations of energy enabling the flow from high to low energy to occur. Through time the energy in the system becomes evenly distributed and entropy increases until there is no flow of energy and no work is done. Landforms and most natural systems are not closed but are open to input and output of energy in a variety of forms:

- potential energy - input uplift and tectonics; weight of rock and soil in an unstable mass under influence of gravity.
- kinetic energy - input from rainfall; output via stream flow and sediment load.
- thermal energy - input from solar radiation and released from chemical breakdown of rocks; output from evaporation and stream discharge.
- chemical energy - output from dissolved stream load.

Interruptions of the flow of energy and the cycle of erosion are generally of two types (Chorley et al., 1984): climatic and base-level changes. Climatic changes cause local accelerations of erosion or deposition through alteration of the balance between vegetation, surface run-off and debris supply; base-level changes cause accelerated erosion and deposition. Positive changes in base-level cause flooding of the lower parts of valleys. Negative changes in base-level cause rejuvenation of landforms and increased incision, causing terraces, breaks in slope nick-points in river courses. These changes are commonly discontinuous and cyclic. One drainage anomaly produced by this cyclic erosion is river capture. Capture may occur when a accelerated downcutting of one river has an erosional advantage over another (softer rock or steeper gradient) and causes diversion. Capture may also occur as a result of tectonic activity and re-orientation of topography and structure. The result is renewed and accelerated erosion and landform changes.

### 2.8 Summary

This chapter has described the main natural processes which operate on, modify and influence the stability of slopes, and this demonstrates the differences between the gradual, continuous processes of slope evolution, and the localised catastrophic and sporadic occurrence of
mass movements. Slope processes act on the landscape, caused by natural exogenic factors and controlled in some way by the structure of the rocks and tectonic history of the region, and they modify the landscape on a time scale measured in years and decades. The mass movements which have occurred in the Langhe, Rio de Aguas area and Folkestone Warren drastically modify the slopes in a spatially and temporally localised way. Movements are relatively rapid, especially so in the case of debris flows on the inverse (scarp) slopes in the Langhe. Variation in the speed of processes is an important factor to consider in the definition of the problem, i.e. in defining the objectives of the research. Since mass movements are a form of slope modifying process, a clear differentiation between the hazard and the gradual process must be made.

Two key points to be noted are firstly, that most elements of slope evolution are slow and gradual, involve imperceptible change, and are continuous and generally non-dangerous natural processes. Secondly, the slope movements referred to in this research are relatively rapid, spatially localised, catastrophic, irregular in time, dangerous to human life and very costly for communities affected. These factors justify the study and analysis of the slope movements as hazards in all three study areas.
Chapter 3 Review of Landslides

3.1 Introduction

In the previous chapter landslides were considered one of several natural processes that modify slopes, there are also many types of landslide. This chapter provides an overview of landslides types, classification and morphology, in order to better understand what constitutes a hazard. The chapter also describes landslides in the context of remote detection, using digital imagery.

3.2 Landslide Classification

The term "landslide" is often used to refer to all types of slope movement whether they involve true sliding or not. The issue of landslide classification has been dealt with in the past, in an attempt to include all types of slope movement, but perhaps there will never be an all inclusive term which is satisfactory to all viewpoints. There have been several important and comprehensive publications of landslide descriptions and classification schemes, including Hutchinson (1968), Nemcok et al., (1972), Varnes (1978 and 1984), Hutchinson (1988), International Association of Engineering Geologists (1990), Working Party/World Landslide Inventory - International Geotechnical Society (1990, 1991 & 1993), Cruden (1991) and Dikau & Brunsden (1996). In addition to many definitive works on specific landslide cases, causes of landslides and stability and engineering e.g. Skempton & Hutchinson (1969), Chandler (1970 & 1984), Hoek & Bray (1977), Bromhead (1992) and Brunsden & Prior (1984).

Classification of natural phenomena should always be made with caution as rigid boundaries do not generally exist in nature. Classification of landslides, slope processes, or of any natural phenomenon, all involve the imposition of artificial divisions between classes which do not really exist. Natural phenomena are usually evolutionary products of many continuously interacting processes, and hence governed by laws of chaos (Percival, 1992). Nevertheless classification assists our recognition, which in turn, is a step towards prediction and remediation, and is therefore essential.

3.2.1 Definitions

Every mass of soil (or rock) on sloping ground is subject to gravity and has a tendency to move downward. If this tendency is counteracted by shear resistance then the slope remains stable, if not then a movement occurs. If a failure occurs without external provocation on a stable slope
then it is caused by either an increase in pore water pressure or by a progressive decrease in shear strength (Terzaghi & Peck, 1967). Many definitions of landslides have been put forward. Sharpe (1960) defined a landslide as “the perceptible downward sliding or falling of a relatively dry mass of earth, rock or a mixture of the two”. In 1978, Varnes modified his earlier definition of a landslide to that of “a downward and outward movement of slope forming materials under the influence of gravity” in order to incorporate movements which did not involve true sliding. Brunsden (1984) prefers the definition under the heading ‘mass movement’ to distinguish it from phenomena which involve a transporting medium e.g. water and air. Cruden (1991) described a landslide as ‘a movement of rock, earth or debris down a slope’. Most definitions give some hint about the mechanism as well as simply the type of material involved. The following list of points, compiled by Coates (1977) in agreement with many other authors (e.g. Brunsden & Prior, 1984), encompasses the components of a slide:

1. landslides are one category of phenomena which concern mass movement.
2. gravity is the main force involved.
3. movement is moderately rapid (to distinguish it from creep), excludes frozen ground phenomena (i.e. solifluction) and can include falling, sliding and flowing.
4. the plane or zone of movement is not that of a fault.
5. movement is down and outward, with a free face (so that subsidence is excluded).
6. the displaced material has well defined boundaries and can include soils and/or rock.

These criteria help identify a phenomenon as a landslide. The next problem is of classification, i.e. what is the type of mass movement and what is its mechanism. Classification of slope movements can be approached in two ways, geotechnical and morphological. Both approaches are valid and instructive but have different uses and yield different information. The geotechnical approach is quantitative and seeks information about the mechanism and the subsurface morphology. The morphological approach is descriptive and divisions are made using surface characteristics, materials involved and the mechanism.

3.2.2 Geotechnical classification

The two main aspects to geotechnical classification, involve consideration of strength properties (and forces resisting movement), and the development of pore pressures (forces encouraging movement).

3.2.2.1 Strength properties

Two groups are identified by the strength properties of the materials involved:
• First time movements - in soil, rock or both, where at least some of the failure occurs at peak strength. In more plastic materials, progressive failure occurs so that the average strength is somewhere between peak and residual (Figure 3.1).

• Reactivated movements - involving failure surfaces at residual strength, such as existing landslides, tectonic shear planes and shearing due to stress relief.

3.2.2.2 Pore pressure regime

Five classes are identified by their varying stability under differing drainage conditions:

• Short term (undrained) - failures in low permeability materials where pore pressures are variable. Total stress ($\phi_u = 0$) analysis is usually appropriate (rather than effective stress).

• Intermediate term (partially drained) - pore pressures are increasing, the slope is swelling and strength decreases as a result. Many slopes fail in this condition. Total stress analysis is not appropriate as the original pore pressure has reduced. Analysis must be in terms of effective stress, i.e. pore pressures must be measured or predicted. As pore pressure increases, shear strength decreases.

• Long term (fully drained) - pore pressure is controlled by drainage boundary conditions and eventually reach equilibrium with the new ground level (the drained state) when steady state seepage conditions have been reached and there are no excess pore pressures. Long term shear strength is less than the original pore pressure. Stability analysis is usually in terms of $c'$, $\phi'$ and pore pressures are required.

• Rapid drawdown - undrained removal of external water load. Total stress ($\phi_u = 0$) analysis is usually appropriate;

• Critical pool level - under drained conditions but changing external water levels. Stability analysis is in terms of $c'$, $\phi'$ and pore pressures are required.

3.2.3 Geomorphological classification

3.2.3.1 Morphology and classification

Notable classification schemes include Varnes (1978), Hutchinson (1988), and Zaruba & Mendl (1982) on the basis of morphology. More recently the need for internationally recognisable landslide nomenclature has resulted in the compilation of unambiguous, descriptive terms and references which apply to all forms of mass movement (WP/WLI-IGS, 1990, 1991 & 1993).
Figure 3.1 Relationship between shear strength (τ) and effective stress (σ').

Figure 3.2 Landslide dimensions, as defined by WP/WLI-IGS (1993). Dimensions include: - Displaced mass: width (1), length (4) and depth (6); - Rupture surface: width (2), length (5), and depth (7); and Total length (3).
Descriptive terms of the representative features and dimensions of an idealised landslide, as described in WP/WLI-IGS (1990, 1991 & 1993), are illustrated in Figure 3.2 and Figure 3.3.

Hutchinson’s classification involved eight categories based on the movement mechanism, which are outlined in Table 3.1. Hutchinson includes the processes of creep and rebound in his classification of landslides, terms which are excluded from WP/WLI-IGS (1990 & 1993) on the grounds that they are forms of mass transport.

Table 3.1 Landslide classification scheme, after Hutchinson (1988).

<table>
<thead>
<tr>
<th>Slope Movement</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebound</td>
<td>Movement associated with human excavated &amp; naturally eroded valleys</td>
</tr>
<tr>
<td>Creep</td>
<td>Superficial, seasonal creep</td>
</tr>
<tr>
<td></td>
<td>Deep-seated, continuous creep, mass creep</td>
</tr>
<tr>
<td></td>
<td>Pre-failure creep, progressive creep</td>
</tr>
<tr>
<td></td>
<td>Post-failure creep</td>
</tr>
<tr>
<td>Sagging of mountain slopes</td>
<td>Single-sided, associated with initial stages of landsliding</td>
</tr>
<tr>
<td></td>
<td>Double-sided, leading to ridge spreading</td>
</tr>
<tr>
<td></td>
<td>Associated with multiple toppling</td>
</tr>
<tr>
<td>Landslides</td>
<td>Confined failures - natural &amp; man-made slopes</td>
</tr>
<tr>
<td></td>
<td>Rotational failures - single, successive &amp; multiple slips</td>
</tr>
<tr>
<td></td>
<td>Translational failures - planar, stepped, wedge &amp; debris slides</td>
</tr>
<tr>
<td></td>
<td>Compound failures - non-circular, listric or bi-planar slips</td>
</tr>
<tr>
<td>Debris movements of flow-like</td>
<td>Mudslides (non-periglacial)</td>
</tr>
<tr>
<td>form</td>
<td>Periglacial mudslides - gelification of clays</td>
</tr>
<tr>
<td></td>
<td>Flow slides - in a variety of material types</td>
</tr>
<tr>
<td></td>
<td>Debris flows - very to extremely rapid flows of wet debris</td>
</tr>
<tr>
<td></td>
<td>Rock avalanches - rapid flows of dry debris</td>
</tr>
<tr>
<td>Topples</td>
<td>Topples bounded by pre-existing discontinuities (single/multiple)</td>
</tr>
<tr>
<td></td>
<td>Topples released by tension failure at rear of mass</td>
</tr>
<tr>
<td>Falls</td>
<td>Primary, involving fresh detachment of material (rock &amp; soil)</td>
</tr>
<tr>
<td></td>
<td>Secondary, involving loose material, detached earlier</td>
</tr>
<tr>
<td>Complex slope movements</td>
<td>Cambering and valley bulging</td>
</tr>
<tr>
<td></td>
<td>Block-type slope movements</td>
</tr>
<tr>
<td></td>
<td>Abandoned clay cliffs</td>
</tr>
<tr>
<td></td>
<td>Landslides breaking down into mudslides or flows at the toe</td>
</tr>
<tr>
<td></td>
<td>Slides caused by seepage erosion</td>
</tr>
</tbody>
</table>
Figure 3.3 Landslide features, as defined by WP/WLI-IGS (1991).
It could be suggested that the most important information about a landslide is predicting where a future landslide is likely to fail in the future. The recognition of an existing landslide’s failure type, mechanism and its causes is very important for predicting where future landslides will occur. Brunsden (1984) and Crozier (1986) suggested characteristic surface features of landslides (summarised in Table 3.2) which are useful for field and remote identification.

Table 3.2 Features useful for landslide recognition (after Crozier, 1986; Brunsden, 1984).

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Features of active landslides</td>
<td>Scars and open fractures with sharp edges. No secondary filling. Main units show secondary fracture and pressure ridges. Polished and striated surfaces, with fresh appearance. Ponds and disrupted drainage. No soil development and only fast-growing vegetation and tilted trees. Distinctive form, roughness, texture and vegetation (between slide and non-slide areas).</td>
</tr>
<tr>
<td>Features of inactive landslides</td>
<td>Weathered and indistinct scars and fractures (often infilled). Developing soil, surfaces weathered and vegetated, and regrowth of trees (vertical). Established drainage (may have irregular pattern) and subdued, infilled depressions. Margins and hummocky textures indistinct except in air-photographs.</td>
</tr>
</tbody>
</table>

3.2.3.2 Water content or Liquidity Index

The Liquidity Index (LI) is calculated by the ratio between moisture content (%) and the Liquid Limit (%). The Liquid, Semi-Solid and Solid are Atterberg limits, so named after a Swedish soil scientist who developed methods for describing the effect of water content on fine grained soils.

The water content of mass movements is variable. As the Liquid Limit is exceeded (i.e. increasing water contents), the type of mass movement changes from a slide or slump to a flow Chorley et al. (1984). Table 3.3 (and Figure 2.9) describes phenomena associated with varying Liquidity Indices, from liquid mudflows to movements of dry rock (toppling).

Table 3.3 Slope movement type classified by water content or Liquidity Index (LI).

<table>
<thead>
<tr>
<th>Group (Liquidity Index)</th>
<th>Type</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flows (High LI)</td>
<td>Mudflow</td>
<td>Sudden snow melt, heavy rain or volcanic triggering</td>
</tr>
<tr>
<td></td>
<td>Bog burst/ flow</td>
<td>Becomes a landslide at low LI values</td>
</tr>
<tr>
<td></td>
<td>Flow slide</td>
<td>Liquefaction from a landslide in loose soil e.g. quick clays.</td>
</tr>
<tr>
<td>Slides (LI 0.8 - 0.5)</td>
<td>Mudslide</td>
<td>Translational with basal sliding, temperate/ periglacial climate</td>
</tr>
</tbody>
</table>

38
3.2.3.2 Degree of activity

Mass movements can also be classified into groups depending on their state of activity. Figure 3.4 illustrates different states of mass movement activity, as recommended in WP/WLI-IGS (1993), and four broad groups are identified:

- Active landslides - those moving at present or which have moved the last cycle of seasons
- Inactive landslides - those which have not moved in the last cycle of seasons and are dormant
- Stabilised - those where structures have been emplaced to prevent further movement, and the soil and vegetation cover have become re-established
- Relict - an inactive landslide which developed under climatic or geomorphological conditions markedly different from those at present; vegetation and soil development are advanced

3.2.3.3 Underlying materials

Further terms are used which describe movements in terms of their relation to the underlying materials:

- Asequent landslides - mass movements occurring in homogeneous cohesive soils
- Cosequent landslides - movement occurs along, or parallel to, bedding or other planes of separation inclined downslope
- Insequent landslides - movement cuts across bedding or other planes

Such terms are descriptive but do not necessarily infer morphology

3.2.3.4 Morphological descriptions

Brief descriptions of the mechanism and characteristics of the main mass movement categories (Figure 3.5), defined in WP/WLI-IGS (1993) are as follows:

<table>
<thead>
<tr>
<th>Slide (L1 0.5 - 0)</th>
<th>Landslide (soil &amp; soft rocks)</th>
<th>Rotational, non-circular, translational, spreading, block falls</th>
<th>Slip surface generally through intact material.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slides (L1 &lt;&lt;0)</td>
<td>Rockslides</td>
<td>Block-slides, wedge slides</td>
<td>Masses bounded by discontinuities</td>
</tr>
<tr>
<td></td>
<td>Toppling</td>
<td>Rotation of columns or blocks of soil or rock about a fixed base</td>
<td></td>
</tr>
</tbody>
</table>
A dormant landslide is an inactive (4) landslide which can be reactivated (3) by its original causes or by other causes. The displaced mass begins to regain its tree cover, scarps are modified by weathering.

A reactivated landslide is an active (1) landslide which has been inactive (4). Another block topples, disturbing the previously displaced material.

An inactive landslide has not moved within the last 12 months and can be divided in states (5) - (8).

A stabilised landslide is an active (4) landslide which has been protected from its original causes by remedial measures; the wall protects the toe of the slope. A relict landslide is an inactive (4) landslide which developed under climatic or geomorphological conditions considerably different from those at present; uniform tree cover has been established.

Figure 3.4 States of activity of landslides, as defined by WP/WLI - IGS (1991).
Figure 3.5 Landslide types as defined by WP/WLI - IGS (1991), a) Fall; b) Topple; c) Rotational slide; d) Translational slide; e) Lateral spreading; f) Flow.
**Falls** - the free movement of material from a steep slope, or a cliff. The detachment and fall is followed by impact on the slope below. Several terms are used to describe the material involved in the fall, e.g. rockfall. Recent research has centred on the possible trajectories of the material as it falls. Differentiation is also made between primary falls (uninterrupted throughout) and secondary falls (the block is interrupted by bouncing, for example, on a slope or wall). Falls are caused by a number of factors including widening of fissures (due to climatic variation or root growth); chemical deterioration; or exceedance of the limit of static friction due to seismic activity, explosion or increase in hydrostatic pressure. Falls are very common in mountainous regions. General morphology is illustrated in Figure 3.5a.

**Topples** - the forward rotation of a mass of rock, debris or soil about a pivot on a slope. The topple may consequently become a fall or a slide but the movement involves tilting without collapse. The blocks of material involved are formed by irregular bedding planes, joints or cleavage which are parallel to the slope crest. Erosional unloading often precedes toppling. Swelling and shrinking of clay-rich materials, and undercutting of slopes are other causes. Well known examples include topples, falls and slides at Bindon, Devon and the sea-cliffs at Stonebarrow Hill, Dorset. General morphology is illustrated in Figure 3.5b.

**Rotational slides** - the rotational movement of material along a recognisable circular or spoon-shaped shear surface. A further subdivision is made between single, multiple and successive slides. They may also be subdivided into rock, debris or soil slides. General morphology is illustrated in Figure 3.5c.

Varnes (1978) defines a single rotational slide or slump as a ‘more or less rotational movement, about an axis that is parallel to the slope contours, involving shear displacement (sliding) along a concave upward curving failure surface, which is visible or may be reasonably inferred’. There is usually only a small amount of internal deformation which distinguishes it from flow-like movements. Rotational slides can vary in size from only a few square metres to large complexes of several hundreds of square metres. Rotational slides display a variety of morphological features, useful for field identification, such as disrupted drainage, irregular contours, hummocky ground, ponds and peaty areas and gully erosion. They often develop in formations where strong and weak materials are interbedded, e.g. sandstones and marls; discordant stratigraphy is often produced by rotational movements. Movements rates for rotational slides can vary between a few centimetres per year to several metres a month (Varnes, 1958), whereas soils slump velocities may reach 3m/sec. Causes include undercutting by waves or rivers, excavation or construction, and triggers include earthquakes, explosions or sudden increases of overburden weight.
(e.g. high water tables during storms). Old, relict slides are particularly hazardous and often responsible for many recent failures.

Multiple rotational slides are failures with two or more sliding units where sliding surfaces intersecting with the basal shear surface. Successive slides involve a series of individual slides one above the other (Skempton & Hutchinson, 1969).

**Translational slides** - defined as non-circular failures involving translational movement on a near-planar surface (Figure 3.5d). Failure is controlled by surfaces of weakness within the slope material, such as joints, faults, bedding planes, all of which have varied shear strengths. They may occur in rock, debris or soils. Block-slides (involving coherent rock) on gently inclined discontinuities have very distinct morphology and special conditions are required for failure to occur and they are usually referred to as infinite slope failures. Rock and debris slides occur on much steeper slopes and failure surfaces, and generally display higher velocities.

1. Block-slides - they are often part of compound landslides, which may involve some rotational slide movement at the toe or head of the slide. The shear surface is often controlled by bedding and multiple shear surfaces are common. They may move continuously, in frequent pulses, providing the shear strength is lower than the driving forces. Rates of movement are variable depending on the volume of material involved. The primary causes include: abrupt changes in rock type; a bedded sequence inclined towards the free slope surface; discontinuities parallel to and in the face of the slope, e.g. bedding planes (Barton, 1977 & 1988); excavation at the toe; high pore pressures (which are also a cause of renewed movement when strength conditions are residual).

2. Slab-slides - distinguished from block-slides by the nature of the material. Slab slides usually involve only soil or debris, as opposed to rock, though they have similar morphology and mechanism. The angle of failure is related to the degree of weathering in the slope profile, regolith depth and material strengths. Where the slip surface is irregular, the ground surface commonly has a series of grabens and blocks, with a buckled appearance. They are usually shallow and very sensitive to seasonal changes in groundwater levels and temperature (e.g. freezing and thawing).

3. Rock-slides - generally a near planar or undulating failure, this time occurring almost entirely in rock material, and usually in mountainous rocky areas. They are characterised by a well formed head scarp with little debris, a displaced mass which remains accumulated in-track, and a spreading toe. Morphology also varies according to the degree of jointing of the parent material. There are many forms of movement and velocities are equally variable. Triggers include vibrations and earthquakes, undercutting of tow support.
4. Debris-slides - these are failures of unconsolidated material which slide downslope. The geometry of these failures is characteristic. They have low depth to length ratios (D/L < 0.05) and high length to breadth ratios (L/B = 5-10), Hutchinson (1988). The material involved is colluvium and weathered, fractured rock. The failure surface develops at the contact between regolith and rock, usually involving a thickness of 0.5 - 1.5m. They often display high velocities, which increase with slope angle and decrease with clay content. They can develop into debris flows when water content is high. They are usually triggered by intense rain, or by earthquakes. The likelihood of their occurrence is increased by deforestation and fire. Most common situations are first order drainage channels and north-facing slopes. The steepness of the slopes involved, makes stability very sensitive to small changes in cohesion and pore pressures. Hutchinson (1988) stated that debris slides are predominantly translational often occurring rapidly to very rapidly and commonly on slopes of 25-45°.

5. Mudslides - a form of mass movement involving masses of softened, argillaceous, silty or fine sandy debris, sliding on discrete shear surfaces and usually in long, lobate forms. A well known example of this type of movement is the Black Ven slide, Dorset (Brunsden & Prior, 1984). They usually occur in saturated, fissured clays, mudstone, siltstone and overconsolidated clays. Movement rates vary from 1m to 25m/year. Movement is normally seasonal, beginning in late autumn, peaking over mid-winter and ceasing in late spring. Causes include a build up of water pressures, loading at the head by debris from above, influx of snowmelt or permafrost melt.

Lateral spreading - this term is used to describe the lateral extension of a cohesive rock or soil mass over a deforming mass of a softer material. There is usually no well defined shear surface within this softer layer. Lateral spreading is caused by deep seated, plastic deformation in a rock mass. A variety of other related features are often mentioned in the literature, e.g. valley bulging and cambering. General morphology of a spread is illustrated in Figure 3.5e. There are two varieties:

1. Rock-spreading, e.g. Sasso do Simone, N. Appennines, Italy (Pasuto & Soldati, 1996) which consists of the lateral extension in a homogeneous or a cohesive rock, overlying a ductile material. Volumes often exceed one million cubic metres and velocity is comparatively low, between $10^{-4}$ and $10^{1}$ m per year (Dikau & Brunsden, 1996). They are strongly controlled by geological structures. The causes are complex and not well known though both brittle and ductile components are sensitive to earthquakes.

2. Soil-spreading, which is caused by plastic deformation in a soil mass and a loss of strength over a long period of time, e.g. Rissa, Norway (Buma & Van Asch, 1996). The morphology of soil spreading is similar to that of rock spreading.
*Flows* - there are three types of flow, categorised by the nature of the material involved. General morphology is illustrated in Figure 3.5f.

1. **Rock-flows** - movements in which the individual particles travel independently in a moving mass. They are characterised by large volumes of material (several 1000m$^3$ and several 10m thick). The deforming mass is not necessarily bounded and the total displacement is small compared to the size of the mass. The structural elements are high angle extensional shear planes (upper part), grabens and ridges in the main body, and compressional features (bulging and low angle shears) in the lower portion. Some show a slow creep like movement. They usually occur in mountain areas and high coastal cliffs. Triggering mechanisms include tectonic activity and earthquakes.

2. **Debris-flows** - these involve a mixture of fine material (sand, silt and clay), coarse materials (gravel and cobbles) and varying quantities of water, forming a muddy slurry which moves downhill in surges under gravity. They commonly occur on slopes which have a thin covering of unconsolidated material, especially where vegetation has been stripped. Their morphology consists of features common to many types of movement, i.e. a source area, main body and depositional area. They often follow pre-existing drainage channels which are commonly v-shaped, and are common in most climates (e.g. North Island, New Zealand (Stephens et al., 1988a and 1988b)). They can be highly destructive where sudden water influx mobilises the debris. They are triggered by sudden and excess water from rainfall, snowmelt and glacier lake overflow.

3. **Soil-flows** - there are three forms: wet mudflow, wet sand flow and dry sand flow. They are very mobile, variable in speed, and often quite small scale. They are common on slopes of 25° - 40°, in volcanic environments, and at the contact between steep rock slopes and talus slopes. They are common on unconsolidated material, steep slopes, with a lack of vegetation and plenty of water.

*Complex* - this term refers to mass movements where the failure type changes as the mass moves downslope. Two specific types which fall into this category are termed: **Rock-avalanche** - involving initial rockfalls, translational sliding, then impact and fragmentation into a rock and debris avalanche, e.g. Valpola, Italian Alps (Angelet al., 1996); and **Flow-slide** - whose origins are often in artificial material, which is loose or highly porous, e.g. the failure of colliery waste at Aberfan, Merthyr Valley, S. Wales, involving a rotational slip at the head becoming a debris flow lower downslope (Bishop et al., 1969). Flow-slides are usually described as high magnitude events both in terms of velocity and destruction, occurring in a few minutes and burying or destroying buildings in their path.
3.2.3.5 Compound landslides

These form when the main or host landslide becomes segmented into several smaller, secondary landslides involving the same type of failure (as distinct from a complex landslide), the whole mass being referred to as a compound landslide. It is probable that most landslides can be identified as compound structures. It is often their compound nature which causes the complexity and variety of form, and which creates such difficulty for classification. A slide which may appear, at one scale, to represent a simple structure, will always reveal complexity and heterogeneity upon detailed examination and at smaller scales.

Large landslides often host smaller, secondary ones which require smaller forces to initiate movement. Secondary landslides usually have greater surface areas and are therefore more rapidly saturated with water, they also occur more frequently. It has also been noted that this multiple movement of secondary landslides can result in a chain of instability, one landslide triggering the initiation of another (Figure 3.6). The rapid loading by a landslide of the ground beneath it, causes increased fluid pressures and ensuing instability in the lower block. Conversely one landslide may remove toe support from the block above thus reducing resisting forces and triggering movement. Cronin (1992) suggests that surface topography has a role to play in the initiation of secondary landslides, e.g. increased slope gradient at the toe of the landslide, or along head scarps. The surface of a landslide becomes hummocky as a result of internal deformation, where the mass moves over an irregular slip surface, see Figure 3.6. Internal deformation is not however homogeneous and often large bodies of relatively undisturbed rock can be seen within the mass of the compound slide.

Cronin (1992) also stresses that the multi-level structure of compound landslides is significant in creating hydraulically isolated bodies of material, perched aquifers and areas of diminished recharge, which lead to multi-level instability. The importance of ground water and recharge, and the significance of rainfall in the triggering of slope failure is well documented and undisputed (e.g. Nilson and Turner, 1975; Schuster and Krizek, 1978). Faults and fractures within landslides become natural conduits for ground water flow, result in increased internal erosion and micro-fracturing, and contribute to multiple failure surfaces.

3.3 Remote sensing used for landslide studies

3.3.1 Image parameters and data selection

Prior to data selection, the specific spatial, spectral and temporal requirements and the climatic aspects of a case should be examined.
Figure 3.6 Schematic representation of linkage between slides, to form a compound slide movement: a) original slide configuration; b) middle (II) portion moves, so loading the lower portion (I), and removing support from the upper portion (III); c) the lower portion (I) becomes unstable and active, due to increased shear stress, and the lower part of the middle portion (II) breaks up to form (II'); d) the unsupported upper portion (III) then becomes active and moves (modified after Cronin 1992).

Figure 3.7 Cartoon illustrating the effect of pixel dimension on the ability to resolve a theoretical scarp feature in digital imagery.
3.3.1.1 Spatial information

The size of the landslides and the scale of the study determines the level of spatial resolution required to adequately detect and map the landslides. It may be necessary to use airborne photography or imagery if detecting small landslides or working at a large scale (Mantovani et al., 1996). Table 3.4 illustrates the magnitude of landslides that can be resolved in imagery of varying spatial resolutions. Figure 3.7 illustrates the sensitivity of landslide detection to spatial resolution if the imagery being used.

Table 3.4 Estimated minimum dimensions of features which can be detected in various image types, and various scales. Units in metres (after Mantovani et al., 1996).

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Landsat MSS</th>
<th>Landsat TM</th>
<th>SPOT XS</th>
<th>SPOT Pan</th>
<th>Aerial photos 1:50,000</th>
<th>Aerial photos 1:25,000</th>
<th>Aerial photos 1:10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>0.5</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>High contrast landslides</td>
<td>800</td>
<td>300</td>
<td>200</td>
<td>100</td>
<td>5</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>Low contrast landslides</td>
<td>3200</td>
<td>1200</td>
<td>800</td>
<td>400</td>
<td>20</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

New satellites with new sensors, with ever improving spatial and spectral capabilities, and coverage are designed and launched ever year. Table 3.5 lists some of the new satellite launches, carrying sensors with very high spatial resolution, which are planned for 1998. The French satellite SPOT 5, whose launch is planned for 2000, will provide stereo imagery with 5m resolution and this will rival airborne ATM resolution of 7.5m.

Table 3.5 New satellite launches in 1998.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor resolution</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ikonos-1</td>
<td>1m</td>
<td>March</td>
</tr>
<tr>
<td>Clark</td>
<td>3m</td>
<td>Post-March</td>
</tr>
<tr>
<td>CRSS-1</td>
<td>1m</td>
<td>Spring</td>
</tr>
<tr>
<td>EOS AM-1</td>
<td>15m</td>
<td>June 30</td>
</tr>
<tr>
<td>EROS A (USA/Israel)</td>
<td>1m</td>
<td>Summer</td>
</tr>
<tr>
<td>Ikonos-2</td>
<td>1m</td>
<td>October</td>
</tr>
</tbody>
</table>

3.3.1.2 Spectral information

The topographic expression of a landslide may be subtle or may have been eroded and in such cases, both spatial and spectral detail may be needed to identify and map the landslide. Image spectral features which form good indicators of landslides include:
- Abrupt spectral variations (localised colour changes) caused as fresh rocks are exposed and different lithologies are juxtaposed.

- Spectrally distinct vegetation is an indicator of near surface water in semi-arid areas. Recent debris flows have identified in SE Spain, using Airborne Thematic Mapper (ATM) imagery to map subtle spectral variations (both IR and thermal) produced by localised vegetation growth and increased soil water content (Wright, 1995; Eyers, 1994; and Eyers et al., 1995).

- The presence of water itself, in ponds within a landslide mass, is spectrally distinct and easily distinguishable from rock and soils.

- Where soils and vegetation are well developed (typically in humid-temperate areas) the exposure of soils and rocks by landslides produces localised spectral changes. For example, the landslide at Folkestone Warren involves a large stretch of coast in Chalk cliffs, which are characteristically white in appearance. The slipped ground in this instance is distinctive as the white Chalk debris is visible between areas of dense vegetation.

3.3.1.3 Temporal information

Landslides which are currently active or recurrent require regular and periodic coverage to monitor movement. One of the advantages of satellite-borne sensors is their continuous orbit and regular coverage of the area of interest. High resolution imagery from low altitude airborne sensors can provide greater spatial detail but provision of repeated coverage requires advanced planning, would be very expensive and is not normally possible. Rapid response to a catastrophic landslide event or regular monitoring requires access to routinely available data, and this is only feasible using satellite data.

3.3.1.4 Influence of climate

The climate of the region of study, whether temperate, tropical or arid, affects the nature of the terrain, and is likely to affect the normal weather conditions. Clear haze-free atmospheric conditions are common over desert regions, occasional in temperate regions and rare in humid-temperate and tropical areas, where cloud cover is also a problem. The use of cloud-penetrating radar may then be necessary.

3.3.1.5 Significance of Wavelength

Visible and Infra-Red (near-IR and mid-IR) are common choices as reflectance is higher at these short wavelengths and therefore the image information is greater. As mentioned in 3.3.1.2
thermal wavelengths may be very useful, because of the contrasting inertial properties of rocks, soils and water.

Radar represents an obvious choice because of its sensitivity to topography and surface roughness. There are many potential sources of radar imagery with differing specifications. If radar data is selected, the illumination geometry, wavelength, climate, weather conditions and topography of the target must be considered in the selection of a suitable sensor and image type. These factors can significantly affect the quality and content of the topographic and textural information that the image provides. Table 3.6 lists various types of radar data currently or potentially available, with their geometric and image characteristics.

Table 3.6 Radar sensors, current and planned, and their specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AIRSAR</th>
<th>ERS-1</th>
<th>ERS-2</th>
<th>ERS-C</th>
<th>X-SAR</th>
<th>RADARSAT</th>
<th>ENVISAT</th>
<th>ERS-1</th>
<th>ALOS</th>
<th>ALMAZ-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar band</td>
<td>P,L,C</td>
<td>C</td>
<td>C</td>
<td>C,L</td>
<td>X</td>
<td>C</td>
<td>C</td>
<td>L</td>
<td>L</td>
<td>8</td>
</tr>
<tr>
<td>Polarisation</td>
<td>ALL</td>
<td>VV</td>
<td>VV</td>
<td>ALL</td>
<td>VV</td>
<td>HH</td>
<td>HH/VV/HV</td>
<td>HH</td>
<td>HH</td>
<td>HH</td>
</tr>
<tr>
<td>Incidence angle (deg)</td>
<td>17-60</td>
<td>24</td>
<td>24</td>
<td>17-60</td>
<td>17-60</td>
<td>17-50</td>
<td>20-25</td>
<td>35</td>
<td>30</td>
<td>30-60</td>
</tr>
<tr>
<td>Resolution (m)</td>
<td>5</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>10-100</td>
<td>30</td>
<td>18</td>
<td>18</td>
<td>*</td>
</tr>
<tr>
<td>Swath width (km)</td>
<td>10-15</td>
<td>100</td>
<td>100</td>
<td>15-100</td>
<td>15-40</td>
<td>50-170</td>
<td>50-400</td>
<td>75</td>
<td>75</td>
<td>20-45</td>
</tr>
<tr>
<td>Altitude (km)</td>
<td>7.3</td>
<td>790</td>
<td>785</td>
<td>225</td>
<td>225</td>
<td>790</td>
<td>800</td>
<td>568</td>
<td>700</td>
<td>300</td>
</tr>
<tr>
<td>Orbit inclination (deg)</td>
<td>97.7</td>
<td>97.7</td>
<td>97.7</td>
<td>57</td>
<td>57</td>
<td>98.5</td>
<td>100</td>
<td>97.7</td>
<td>98.2</td>
<td>72.7</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>10-20</td>
<td>13.5</td>
<td>13.5</td>
<td>10-20</td>
<td>10-20</td>
<td>12-30</td>
<td>14</td>
<td>50</td>
<td>50</td>
<td>*</td>
</tr>
<tr>
<td>Lifetime (years)</td>
<td>N/A</td>
<td>3</td>
<td>3</td>
<td>11 days</td>
<td>11 days</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>3-5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

3.3.1.6 Textural expressions of landslides

A selection of landslide terrain features which are most relevant to image/photo interpretation are summarised in Table 3.7. These features all have potential textural expressions in imagery. Some produce expressions too subtle even to be detected at the finest spatial resolutions, e.g. hummocky surfaces. Others tend to be more easily definable e.g. arcuate crown walls.
Table 3.7 Useful landslide characteristics for photo-interpretation (after Schuster & Krizek, 1978).

| Land masses undercut by rivers or waves. |
| Sharp break of slope at the main scarp. |
| Arcuate shape of crown wall. |
| Deep fissures or tension cracks in turf, soil or rock. |
| Hummocky surface of the slipped mass. |
| Spoon shaped troughs in the terrain. |
| Disrupted drainage channels. |
| Vegetation changes indicating changes in ground moisture. |
| Displaced roads, fences and walls. |
| Accumulation of debris in drainage channels and valleys. |
| Stripped regolith, soil & vegetation revealing fresh rock surfaces. |
| Exposed slip plane. |
| “Levées” between debris flows and slides |

The detection of these features in imagery usually requires enhancement and interpretation and is often problematic as they may be very subtle. Image texture, its enhancement and interpretation, are discussed in more detail in Chapter 5, but significant textural features which assist in landslide interpretation often include the following:

- linear features (e.g. fractures and tension cracks)
- displaced or disrupted linear features (e.g. roads and rivers)
- irregular textures (e.g. hummocky slipped debris)
- high frequency information, irregular and distinctive brightness variations (e.g. blocks of rocks and soils exposed by a landslide)
- topographic features (e.g. trough and spoon shaped hollows at the head of a landslide)

Each of these aspects may not be sufficient alone to identify and map landslides, but all three aspects together may contribute to confident identification.

3.3.2 Research concerning remote sensing applied to landslide studies

The application of remote sensing techniques to the study of landslides is comparatively poorly documented. In many cases the use of imagery is limited to landuse classification and regional mapping using broad band, routinely available imagery, e.g. Landsat TM and SPOT
(Murphy & Bulmer, 1994; Djamaluddin, 1994; Fujita et al., 1996). In many cases these data are the only source of image information.

Textural processing of remotely sensed imagery by Eyers et al. (1995) and Mason et al. (1995a and 1995b) illustrate the characteristic appearance of landslide terrain in various types of imagery and in a variety of geological settings. Clearly there are common features which can be used to identify landslipped ground, in a semi-automated and predictive way, on the basis of digital tonal and textural change in binary images. Eyers et al. (1995) demonstrated that thermal information, indicating the presence of water courses, enabled the mapping of a recent debris slide. Stephens et al. (1988a and 1988b), used SPOT Pan images as a mapping tool to identify vast numbers of superficial slope movements.

McKean et al. (1991) used remote sensing as part of a landslide hazard assessment method in the San Mateo and Marin Counties of California. Landsat TM images and a DEM were integrated and used to identify debris flows. Part of their debris flow hazard assessment involved the prediction of soil depths using TM vegetation indices, from multi-temporal images taken at seasonal extremes, so that changes due to senescence could be mapped. They observed difficulties in getting adequate geotechnical information for their study region to enable stability analysis.

Murphy & Vita-Finzi (1991) and Murphy & Bulmer (1994) used Landsat TM (in addition to aerial photography and DEMs), in Southern Italy and in New Zealand respectively, to map seismically triggered landslides, associated with major faults. Interestingly they use landslides as evidence of past (pre-historic) seismicity.

Fookes et al. (1991) noted that even using traditional technique of air-photograph interpretation, errors and omissions can be made. They refer to eight separate interpretations of landslides in Papua New Guinea, made from the same aerial photographs. Interpretations made by individuals with prior knowledge of the most recent landslides identified previously existing ones as well (three of the eight). Interpretation made without that prior knowledge failed to detect all landslides and those which were identified had different configurations.

Rengers et al. (1992) and Mantovani et al. (1996) have provided comprehensive reviews of appropriate scales and resolution of remotely sensed image data, and the power of images for detecting landslides. Mantovani et al. (1996) produced an inventory of research in the field of landslide hazard zonation using remote sensing. They referred to uncertainty (a phenomena which is only considered in recent studies) and the need to distinguish between error and uncertainty, the latter being inherent to natural systems and processes. They suggest that the ideal slope instability
hazard map should show the spatial and temporal probability, type, magnitude, velocity and run-out distance of the landslides.

3.4 GIS used for landslides studies

GIS and remote sensing are often thought of together and it seems a common misconception that they are used for the same thing. This is an over simplification and it is better to say that the two complement each other. There are areas of overlap between the two, in their ideology and technology, but they are tools which have many different applications. Remote sensing commonly provides data which contributes layers in a GIS (refer to Figure 1.2), which are then integrated and processed as part of a ‘stack’ with other data. It is in this way that remote sensing and GIS are linked in the study of landslides.

3.4.1 Data and methodologies applicable to landslide studies

The data used in such studies will always vary slightly from one case to another but generally will involve topographic information (slope angle and elevation), geological (solid and drift) information, water table data, and geotechnical information about the materials.

3.4.2 Research concerning landslide studies and hazard assessment

A great deal of research has been done in this field, both in terms of developing techniques and software and applications (e.g. Rosenbaum & Jarvis, 1985, Van Westen et al., 1994 and Rosenbaum & Popescu, 1996). GIS relies on the availability of at least some hard ground data. Guillaume et al. (1991) demonstrate that the very simple technique of sieve mapping (of slope angle and lithological data) can be used successfully to map landslide hazard in the Andes.

3.4.2.1 Studies involving slope stability and probabilistic analyses

Rosenbaum & Jarvis (1985) used Janbu’s method of slices in conjunction with geological data and the Monte Carlo simulation for calculation of probability of slope failure within a GIS environment. Their input included three significant factors: geotechnical properties, slope geometry and position of the shear surface, and from these pore water pressures, stresses on each slice and an approximation of F was calculated. The method then re-calculated F iteratively, until satisfactory precision is attained. Bonham-Carter et al. (1988) used the Monte Carlo simulation method in probability analyses to generate predictor maps for gold exploration. Liener et al. (1996) developed a GIS based method which they termed SLIDISP, to calculate a slope hazard map also using Janbu’s simplified method for shallow and Bishop’s simplified method for medium-seated,
rotational landslides. Wolf (1996) used probabilistic analysis to deal with decision-rule uncertainty in the study of slope stability.

Brass et al. (1991) used a form of infinite slope model in conjunction with a DEM, in a GIS context, to analyse landslide potential on natural (rock and soil) slopes in the West Indies. They were concerned with overall stability of the slopes rather than the dynamics of landslide motion and generated a map of factor of safety (F).

3.4.2.2 Studies involving computerised hazard assessment methodologies

McDonald et al. (1995) developed a rapid-response hazard system for landslides in a large scale study of Papua New Guinea, with limited data. They used a linear combination of hazard attributes which proved to be successful though they found that the relationship between hazard attributes was not in fact linear. Cross (1995) uses an objective computer based medium scale system referred to as the Matrix Assessment Approach (MAP) which derives landslide susceptibility for large areas using a few key parameters, all of which can be relatively easily obtained, the method is however, rather too simplistic to consider data and threshold uncertainty.

Guzzetti et al. (1996) presented a study of the influence of lithology and structural setting on distribution and type of landslides in Umbria, Italy. They noted that regardless of lithology, discontinuities provide strong mechanical anisotropy which controls the development and geometry of failures. This in turn leads to the formation of perched aquifers and local increases in water pressures which initiate failures. Montgomery et al. (1994) developed a model of the topographic influence on shallow landslide initiation, by coupling DEM data with a near surface flow model and slope stability models. Their model, referred to as TOPOG predicts the degree of soil saturation in response to steady state rainfall on topographic elements defined by elevation contours and flow boundaries.

A number of studies of landslides, involving inventories and GIS hazard zonation studies have been present by Guzzetti et al. (1996) and Carrara et al. (1995); Guzzetti himself advocates caution in the classification of landslides and in the application of complex computing techniques to hazard assessment, because natural systems cannot be rigidly categorised (pers. comm. Guzzetti, 1995). McNoleg (1996) also stressed the need for simplicity from the interpreters and managers point of view, in the face of increasing terminological and technological complexity from the researcher.

Rengers et al. (1992) stressed the need for integrated studies involving remote sensing and GIS and the standardisation of approaches and classification. They also recommended the inclusion
of remote sensing and GIS in education at all levels and in the developing as well as developed world.

Van Westen et al. (1994) reviewed the application of remote sensing within their landslide hazard assessment program (GISSIZ). Several scales of observation were identified: 'national' (<1:1,000,000), 'regional' (1:1,000,000), 'medium' (1:25,000 to 1:50,000) and 'large' (>1:10,000); for landslide hazard zonation using GIS. These categories appear to be useful but Van Westen et al. (1994) suggest that the use of satellite imagery is restricted to the 'regional' scale of study, whereas both SPOT and TM imagery have shown to be well suited to studies in the 'medium' scale range. It is clear that with the increasing appearance of new, high resolution satellite sensors (as mentioned in 3.3.1.1), that this range of studies will be lowered further.

GIS has proved to be a highly effective tool for the assessment of a variety of hazards. In the majority of cases though, especially where rapid response is required, such risk assessment has to be done with the minimum of data. It seems worth remembering though that 'classification' is a tool to assist our understanding and should not be rigidly applied to natural phenomena.

3.5 Summary

There is clearly a great variety of landslide phenomena of varying types and forms but there are features which are common, and the identification of these is most important. There is a need for universally recognisable nomenclature and the WP/WLI-IGS (1993) has gone a long way to satisfying that need.

It is important to consider different types of classification scheme, i.e. not just morphological but also geotechnical. Though for image based study the most significant information is morphological as it is these features which are visible to the sensor. There are certain key features of landslides which are key to their identification because of their distinctive appearance, e.g. arcuate scarp, tension cracks and hummocky displaced ground. Detection of landslide features in imagery does not necessarily require prior knowledge of the mechanism or the state of activity, but the understanding of these is important for stability analysis and hazard assessment.

Image information relating to landslides is complex and has two key component parts: texture and spectral detail, though it could be argued that texture is the most significant. Remote sensing has been widely and successfully used to detect landslides. It provides a very convenient source of data for identifying, mapping and monitoring surface features. There has also been a variety of ways in which remotely sensed data has been used - in terms of scale and in the intensity with which the imagery has been processed (from reconnaissance mapping to detailed textural and spectral studies).

GIS has been and is used extensively in landslide hazard studies. It provides a flexible and effective tool for multi-attribute studies in many different situations. The spatial analysis tools inherent to GIS are particularly suited to the hazard assessment and the production of thematic maps thereof.
Chapter 4  Descriptions of Study Regions

This chapter summarises the geological, morphological, geomorphological and climatic characteristics of the landslides in the Langhe, Rio de Aguas valley and at Folkestone Warren. Attention has been focused on the description of features which are relevant to the analysis of hazard potential in later chapters. Comparison of characteristics of each landslides locality assists in the identification of significant hazard parameters.

4.1 Langhe, Piemonte, NW Italy

Landslides are documented throughout the Piemonte region but they are particularly important in the area known as the ‘Langhe’, which is a range of hills south-east of the town of Alba, in southern Piemonte, NW Italy (shown in Figure 1.1, Chapter 1).

4.1.1 Geology and geomorphology of the Piemonte region

4.1.1.1 Geology and structural setting

The map in Figure 4.1 shows the location and geological context of the study area. The Langhe lies on the flank of the southern-most arc of the western Alps and on the margins of a classic piedmont, hence the regional name ‘Piemonte’, which is dominated by the river Po plain. The south-westerly part of the Alps curves around near the coast of SE France, then eastward to connect with the Apennines. The Langhe and Monferrato hills are situated on the northern flank of this upland region. On a clear day it is possible to view this western part of the Alpine arc, in a spectacular sweep, and to appreciate the Langhe hills in their regional setting.

The geology of the Po plain comprises Oligocene to Quaternary flysch and molasse sediments, derived from the Alps. Further to the south east (approaching Genoa), the topography of the pre-Tertiary basement and cover rocks of the Pennine Alps, becomes more rugged. The pre-Tertiary basement rocks consist of calc-schists, quartzite and quartz-schists, dolomites and some migmatitic-granitoid rocks (La Societa Geologica Italiana, 1954).

The Langhe comprises a series of gently dipping Tertiary sediments, of Oligocene (Aquitanian) age, comparable to the lower Upper Oligocene/Miocene in the UK, (ca 26 ma). A part of the 1:50,000 scale geological map is shown in Figure 4.2. A monocline structure, striking NE-SW, has produced gentle north-westerly dipping strata in this area. This structure and the north-easterly flowing drainage has produced a series of distinctive asymmetric valleys with
Figure 4.1 Map of western Alps showing the study area in its regional geological context (after Ager, 1980; and Coward & Dietrich, 1989).

Figure 4.2 Geology of the Langhe study area (from S. G. I., Ceva, 1970).
south-east facing gently dipping slopes and north-west facing steep scarp slopes. The sediments young north-westwards (towards 315°) and dip at angles of between 7° and 12° (see Figure 2.7).

The term mudrocks is generally and collectively used to describe fine-grained argillaceous rocks, such as claystones, mudstones, siltstones and shales. These are dominant in this region and usually occur in alternating sequences with resistant and porous sandstones and siltstones. Stratigraphy of this nature is particularly prone to differential weathering and erosion, which may in turn lead to undercutting in certain situations. The stratigraphy of the study area is described briefly in Table 4.1.

Table 4.1 Stratigraphy of the Langhe (translated from Servizio Geologico D'Italia, 1970).

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tortonian-Serravallian</td>
<td>Lequilo Formation</td>
<td>Yellow, cross-laminated sands and sandstones (10-50 cm thickness), alternating with grey silty marls and siltstone in layers of 5-40 cm.</td>
</tr>
<tr>
<td>(Mid-Miocene)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serravallian-Langhian</td>
<td>Murazzano Formation</td>
<td>(a) Ash-grey marls with indistinct stratification, intercalated with grey sandstones in layers of 5-15 cm; (b) Yellow sands, sometimes graded, in layers of 10-50 cm, interbedded with grey siltstone in layers of ca. 10 cm and ash-grey marl.</td>
</tr>
<tr>
<td>(Mid-Lower Miocene)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serravallian-Langhian</td>
<td>Cassinasco Formation</td>
<td>Yellow-grey sand in layers of 10-150 cm, often graded, with alternating layers of thin grey sandstones and lenses of sand and marly clay.</td>
</tr>
<tr>
<td>(Lower Miocene)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Langhian-Aquitanian</td>
<td>Cortemilia Formation</td>
<td>Grey sandstones in layers of 10-40 cm with current structures (internal and basal), with alternating marl and blue-grey mudstone layers, and with intercalations of yellow-grey sands.</td>
</tr>
<tr>
<td>(Base Miocene - Top</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oligocene)</td>
<td>Paroldo Formation</td>
<td>Grey marl, often silty, with major and minor intercalations of thinly alternating sandstone and sand.</td>
</tr>
<tr>
<td>Aquitanian - Upper</td>
<td>Monesiglio Formation</td>
<td>Yellow sand in beds of 50 cm - 4 m thick with large sandstone nodules and lenses; and grey mudstone, often fissile, locally alternating with sandstones.</td>
</tr>
<tr>
<td>Oligocene)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.1.2 Post-glacial uplift-induced dissection of the Langhe region

The area has been isostatically active since glacial times and there is evidence of regional rotation and uplift. The geomorphology of the upper Langhe river basins suggests that the area has undergone Quaternary remodelling (Biancotti, 1981). Following the Plio-Villafranchian (Pliocene-Pleistocene) glaciation, there was a period of erosion which produced SE-NW transverse valleys (Embleton, 1984).

Between the Upper Pleistocene and Lower Holocene, uplift and tilting, which was more active in the south-western part of the region, caused a marked change in drainage characteristics (see Figure 4.3a). The overall effect was a rotational tilting of the area causing river capture away from the Cuneo plain into the Alessandria plain (which is several hundred metres lower), and produced the NE-SW oriented valleys of today. The most notable of these is the Tanaro which
1. Pre- and syn-Pleistocene topography

2. Uplift and tilting at end of Pleistocene

3. Erosion to form present topography

Figure 4.3 a) Uplift and tilting of valley geometry; b) Geomorphological map of southern Piemonte region, showing diversion of the Tanaro and Belbo rivers during Upper Pleistocene uplift (after Embleton, 1984 and Biancotti, 1981).
was captured in the Lower Holocene near the town of Bra (Figure 4.3b). The capture of the river Belbo (from a north-westerly flow to its present north-easterly channel) is indicated by the noticeable bend at Mombarcaro (Figure 4.3b).

Continued uplift in the Middle Holocene resulted in renewed erosion and the formation of river terraces which can be seen in the Bormida di Millesimo and Bormida di Spigno valleys.

These tectonic movements have continued to present times over much of the region (Biancotti, 1981). These indicate that several of the major rivers (Middle Tanaro and Rea) once flowed north-westwards. Research at the Politecnico di Torino, suggests that the area is still undergoing uplift (pers. comm. Bottino, 1995). Close examination of the elevation data from the area reveals relics of this north-westerly drainage system (illustrated in Figure 4.3b), detectable as cross-cutting saddles well below ridge-top mean heights.

4.1.1.3 Evidence for recurrence intervals

The only evidence for the recurrent nature of slope instability in the Langhe comes from published literature and some scant reports from local inhabitants who remember instances of towns being destroyed by landslides. Much of Italy has been at considerable risk to slope instability for thousands of years so this recurrent risk is not unusual. What is interesting is that the Langhe region experiences very heavy rains every winter yet literature does not suggest that it experiences major landslides every winter. Published literature suggests that major landslide events occur roughly every 20 years (e.g. 1941, 1948, 1972, 1974 and 1994).

Geomorphological studies indicate that the region as a whole is dynamic in terms of post-Alpine, post-glacial crustal uplift and that the landslides are a natural, slope-dynamic consequence of this uplift (Biancotti, 1981, and Embleton, 1984). This suggests that landslides are a long standing problem in this area and are likely to continue to be so.

4.1.3 History of landsliding in the Langhe

The history of landsliding in the Langhe has been documented sporadically since the last century (Sacco, 1903; Tropeano, 1989; and pers. comm. Mr Giuseppe Corsini, Castelleto, 1996). The map shown in Figure 4.4 illustrates the distribution of landslides produced during the last three major landslide events. This map suggests that much of the area has experienced landsliding at since 1972.
Figure 4.4 Composite block-slide map overlain on geological boundaries (shown in Figure 4.2). Modified after Luino et al. (1996).
Other indirect evidence of the severity of the landslide problem and the seriousness with which it is treated by the regional authorities, is shown by the introduction, in 1908, of Law 445 by the Ministry of Public Works in Italy. This act enabled the defence and even movement of towns threatened by landslides, at the expense of the state (Luino et al., 1993).

4.1.4 The November 1994 landslide event

In November 1994 the region of Piemonte was affected by a deep and severe cyclonic weather system which produced exceptional rainfall within the space of a few days. Several hundred millimetres fell between the 4 and 6 November. This event came a year after the storm and floods which hit the western Alpine arc, in September 1993.

In the November 1994 event, seventy people were killed, several thousand people were rendered homeless, 200 towns were affected and over one hundred bridges were damaged or destroyed. In total damage estimated at approximately US $10 billion was caused over an area comprising ca 30% of the region (Polloni et al., 1996). Details are listed in Table 4.2.

Table 4.2 Some statistics of the 1994 flood and landslide event in the region of Piemonte (courtesy of CNR/IRPI Torino)

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>200-300 superficial debris flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 500 block-slides</td>
</tr>
<tr>
<td></td>
<td>At Ceretto, the area involved in debris slides reached ca 80-170 km²</td>
</tr>
<tr>
<td></td>
<td>The increase in stream and sediment discharge during the storms, is estimated at</td>
</tr>
<tr>
<td></td>
<td>&lt;100% above normal maximum discharge</td>
</tr>
<tr>
<td>Damage</td>
<td>8500 km² (30% of total area of Piemonte) was involved in floods or landslides</td>
</tr>
<tr>
<td></td>
<td>1000 km² was subject to flooding along the Tanaro and Po river valleys</td>
</tr>
<tr>
<td></td>
<td>200 settlements were affected (including the main towns of Asti, Alba &amp; Alessandria)</td>
</tr>
<tr>
<td></td>
<td>70 deaths (50 in flooding and 20 by landslides)</td>
</tr>
<tr>
<td></td>
<td>ca 100 bridges destroyed</td>
</tr>
<tr>
<td></td>
<td>10’s km of roads damaged</td>
</tr>
<tr>
<td></td>
<td>2226 people were evacuated from homes</td>
</tr>
<tr>
<td></td>
<td>Total cost estimated at ca $10,000 million</td>
</tr>
</tbody>
</table>

4.1.4.1 Rainfall

Average monthly rainfall for November in this Piemonte is normally 140 mm, the average daily rainfall during the storm was 33 mm (Polloni et al., 1995). In fact 200-300 mm of rain fell between 2-6 November, with 90% of this falling on the 5th November (Tropeano, 1995, Polloni et al., 1996). Rainfall began moderately on the 3rd November and continued on the 4th and 5th
although it seems this was not much greater than seasonal norms (Tropeano, 1995). From the morning of the 5th and throughout the 6th November, the most critical rainfall fell. On the 6th November, the region received the greatest recorded rainfall in eighty years. In many areas, particularly high intensities were recorded, up to 25 mm/hour were reached. The rainfall data were recorded at 90 stations across the region and produced from METEOSAT and ground based radar data (Figure 4.5a).

A very large volume of rain fell on Piemonte and storage capacities of the basins were quickly exceeded and the water table reached surface levels, so that all rainfall became effective precipitation. Rainfall was concentrated in a corridor along the borders of the Tanaro valley and the study area lies in the area receiving the highest rainfall (Figure 4.5b). The elongate rainfall maximum extends north of the study area but the distribution of landslides does not reflect this. The nature of the terrain becomes less rugged and less elevated, north of the town of Alba and west of the town of Dogliani, and flattens out into the flood plain of the Tanaro and Po rivers. In these areas, the exceptionally high rainfall resulted in severe flooding. Video coverage presents a frightening account of the flooding in many towns in these parts of Piemonte, with trees, cars, trucks and buildings, being swept away.

4.1.4.2 Eye witness accounts

The eye-witness accounts of some of the residents of San Benedetto, provide interesting reading and valuable details of the timing and velocity of the landslide events during the night of the 5th/6th November.

The large compound block slide, located on farm land facing the town of San Benedetto (Figure 4.6), measures ca 500 m x 200 m, involved millions of cubic metres of rock and soil, rendered a hillside useless for farming and destroyed two access roads. Mr Cora Benedetto, whose house faces the hillslope which failed, reported that from 10.30am Saturday 5th November, the line of trees at the bottom of the hill, along the stream, was disturbed and gradually tilted downslope. He also stated that very large tension cracks appeared in the field every few hours, and the ground seemed to swell. He noted that at about 8.45-9.30am on Saturday, a small landslide occurred at the NW corner of the field adjacent to the stream, and that during this time the rain was constant.

Mr & Mrs Salvatore Ardizzone, of Casa di Lu (a hamlet situated ca 150m west of the landslide), stated that around 11pm on Saturday, it was still raining when they were alarmed by loud rumbling and cracking noises and by a vigorous shaking of the ground for a few seconds. At the time they concluded that an earthquake was responsible. They also claimed they saw
Figure 4.5 a) Hydrological stations in Piemonte; b) Maximum intensity rainfall (mm) recorded at hydrological stations in Piemonte between 4-6 November 1994.
Figure 4.6 a) Map of San Benedetto area, indicating the locations and slip directions of block-slides (A, B, C & D); b) photograph of the large block-slide (B) at San Benedetto (looking south-east).
lightening, clouds of smoke, flames coming from the field and heard noises resembling an explosion.

The Mayor of San Benedetto, Mr Renato Fresia stated that between 9.30pm and 11pm on November 5th, smoke and flames billowed from the hillside. He claimed that this occurred in 2 bursts of activity, the first for 1/2 hour and the second for a slightly shorter time, about 10 minutes later. The main movement of the landslide began at 11pm and continued for 5-6 hours, though there was some settling during Sunday 6th. The Mayor also stated that large cracks had been known to exist in the wooded area above the crown of the landslide, for several years. A similar landslide, about 1/5th the size of the larger one, a kilometre to the east, began at about the same time but came to rest at about 1-2am on Sunday (block-slide C in Figure 4.6a).

This pattern of events seems to hold for the majority of block slide failures that occurred during the night of 5th November 1994. All occurred around midnight and taking, depending on the dimensions, between 1 and 6 hours to come to rest.

4.1.4 Climate and agriculture

The climate of the region is a typical northern Mediterranean one with hot, humid summers and cold wet and snowy winters. The climate is conducive to a long growing season and intensive cultivation. Agricultural practices have probably changed little in this area for centuries, though there has been a recent expansion in the growth of hazelnuts as well as the traditional growth of grapes for the wine industry. The local economy is almost entirely agricultural and many farms are quite small scale, family based and technology simple.

The asymmetry of the valley morphology results in a distinctive pattern of cropping. The steep scarp slopes are generally covered by dense deciduous and coniferous forest. The gently dipping slopes are heavily cultivated by nut trees, wheat and pasture. In the north-western corner of the study area, the valleys are not of such characteristic elongate form or aspect, the climate is slightly warmer and more humid and vineyards dominate the slopes, regardless of aspect or angle.

Just as agriculture has its distinctive patterns in the area, so has settlement. Towns are almost always on ridges or conical hills, usually topped by a church, or a castle if the town is significantly large. Interconnecting roads generally run along the valley ridges until a suitable crossing point is reached and then they descend to the valley floor and wind sharply up the steep scarp slope on the other side. Villages and hamlets are usually strung out along the ridge-top roads or sometimes part way down valley dip-slopes but not usually far from the main roads.
4.1.5 Nature of landsliding in Piemonte

The slope movements which affect this region form two main groups, *debris-flows* and *slides*, and translational *block-slides*. The block-slide group can further be sub-divided, into simple translational slides and compound slides. The division between these types is sometimes not clear and so they will be referred to as one group. From now on the term *landslides* will be used in collective reference to all types of slope movement which are observed in the Piemonte study area. Otherwise they will be referred to as *block-slides* and *debris-flows*. The different types of landslide observed in the Langhe are illustrated in Figure 4.7.

4.1.5.1 Debris-flows

These comprise shallow (1m - 3 m) sheet flows and slides, on steeper slopes of *ca* 20°-40°, at high angles to bedding (see Figure 4.7a). They are characterised by W/L aspect ratios of 0.05 - 0.3, except where several occur in close proximity and coalesce to form large, broad scars on the hillsides (Figure 4.8). They involve only the top soil/regolith (<1m thickness) and vegetation. They commonly occur in wooded areas and in great numbers (see Figure 4.9a and 4.9c). They are highly destructive, move quite rapidly (a few metres/second) and are visually very distinct from the surrounding, undisturbed ground. Their movement is typified by an initial slide, developing quickly into a fast flow, often channelled by drainage incisions, and sometimes growing into large volume flows. The debris-flow material is generally fluid and disperses laterally where drainage channels emerge at the main valley floor. As a result there is often no evident accumulation of material at the toe, only a long veneer of debris on the surface. The debris-flows produced during the 1994 storm event, severely disrupted the winding road system which connects the numerous hill-top towns. Occasionally buildings are at risk when situated at the base of slopes experiencing voluminous debris-flows. These also contribute considerably to the sediment load of the already swollen river systems in the upland parts of the region (Tropeano, 1984 & 1995). Guzzetti *et al.* (1996) note that shallow colluvium failures of surficial debris (top soil) occur at each major rainfall event and are seemingly randomly distributed with respect to lithology, bedding and structures. Such superficial failures are commonly related to slope concavities, drainage gullies and hollows which concentrate ground water flow and maintain pore water pressures (Wieczorek, 1987).

4.1.5.2 Translational block-slides

These form two ill-defined groups which occur in very similar situations (see Figure 4.7b and 4.7c). In both cases, rock and soil materials are involved and the slides have characteristic crown/back wall, tension cracks and noticeable compression zone where the ground surface is
Figure 4.7 Types of landslide observed in the Langhe.
Figure 4.8 Debris-flows at Ceretto, Langhe.
Figure 4.9 Some statistics about the 1994 landslides in the Langhe a) landslide type  b) crown height  c) landslides on grassland and woodland  d) landslides and slope types.
hummocky and buckled but not ruptured. The block-slides often appear to be bounded by sub-vertical joint and fracture systems, which are usually stained with iron-oxides. The slip surfaces form at or near mudstone horizons. In most cases the block-slides occur on slopes which show evidence of similar movements in the past, and in some cases may be reactivations of old block-slides.

- Single slip-plane block-slides. These occur on slopes of between ca 5° and 15° and there is usually a large area (usually ca 30% of the total) of the slip surface exposed below the crown. Aspect ratios are commonly between 0.3 and 0.5. The depth to the failure plane varies but is generally between 1 m and 10 m (Figure 4.9b).

- Multiple slip-plane, compound block-slides. These are deeper (20-30 m), and occur on slopes between ca 5° and 15°. There is usually much greater disruption to the ground surface. These comprise the largest slides in the area involving <3 million m³ of material. They tend to have aspect ratios of between 0.3 and 0.4. The depth to the basal failure plane is generally <20 m and thicknesses between individual slip surfaces is usually between 1 m and 10 m (Figure 4.9b).

A distinct sequence of events leading to sudden catastrophic failures of this type has been observed in the region. Deep, open fractures and tension gashes, in the upper parts of slopes, have been observed months, years, even decades, prior to failure. The incipient phase is characterised by a swelling of the ground and an increase in fracture density in the vicinity of the head of the slide (Govi & Sorzana, 1982). Sliding begins and a rucked appearance develops on the previously unaffected slope below the fractured area (Govi, 1974). Peripheral fractures and gullies develop and small, localised slumps occur. The final stage involves the sudden and extensive sliding of whole blocks of rock (sometimes on many layers) and the consequent exposure of the slip plane. Disjointed and reoriented blocks and large quantities of debris develop in the lower portions of the slide. Movement rates vary but can be very rapid, between 10m/hour to 100m/hour. Some statistics are shown in Figure 4.9.

4.1.5.3 Recent slope movement examples

The map in Figure 4.4 illustrated the locations of the block-slides which are described in this section. Notable examples of translational block-slides are described Table 4.3 and illustrated in Figures 4.10 to 4.13.
<table>
<thead>
<tr>
<th>Locality</th>
<th>Bedding</th>
<th>Bed dip (deg)</th>
<th>Dimensions (m)</th>
<th>Slip direction (deg)</th>
<th>Fracture spacing (m)</th>
<th>Nature of fractures</th>
<th>Fracture controlled scarp</th>
<th>Slip-plane(s)</th>
<th>Slope form</th>
<th>Comments and related Figure number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murazzano A</td>
<td>Pale yellowish-grey siltstones with thin mudstones layers.</td>
<td>10</td>
<td>150 (W) 400 (L) 25-30 (D)</td>
<td>340</td>
<td>Variable, 0.02m - 1.0m</td>
<td>Open and strongly iron-stained</td>
<td>Yes, major fracture-controlled blocks visible across the slide surface</td>
<td>Multiple, maximum depth 25-30m. Basal plane not exposed.</td>
<td>Convex</td>
<td>Severely disrupted surface, large, fracture-controlled blocks still with soil and vegetation (trees) growing intact. Figure 4.10</td>
</tr>
<tr>
<td>Murazzano B</td>
<td>Pale yellowish-grey siltstones with thin mudstones layers. Thickness: 0.1m - 1.0m</td>
<td>9</td>
<td>70-80 (W) &lt;200 (L) 3 (D)</td>
<td>318</td>
<td>0.02m - 0.7m</td>
<td>Open and iron-stained</td>
<td>Yes, several deep and parallel fractures at and above crown wall.</td>
<td>Single, exposed and occurring at or within mudstone layer.</td>
<td>Rectilinear</td>
<td>Slide crown occurs just above road cut. The morning after the 1994 storm, water was seen to pour from the base of the crown wall over the slip surface. Figure 4.11</td>
</tr>
<tr>
<td>Pianezza</td>
<td>Pale yellow, siltstones and sandstones, often iron-stained at bed contacts. Thickness: 0.01m - 2.0m</td>
<td>8</td>
<td>150 (W) 400 (L) 6 (D)</td>
<td>318</td>
<td>0.02m - 1.0m</td>
<td>Open and strongly iron-stained. Polygonal fractures commonly observed.</td>
<td>Yes, fractures observed in crown wall.</td>
<td>Single, exposed and occurring at or within mudstone layer.</td>
<td>Convex</td>
<td>Lower, accumulation zone bulged and hummocky but soil and vegetation intact. Well at base of slope (&gt;500m below crown) displaced ca 0.2m during sliding. Figure 4.13</td>
</tr>
<tr>
<td>Roddino</td>
<td>Pale yellow siltstones and sandstones. Iron-stained bedding. Thickness: 0.06m - 0.5m</td>
<td>10</td>
<td>150 (W) 300 (L) 25-30 (D)</td>
<td>310</td>
<td>0.01m - 0.2m</td>
<td>Open and severely iron-stained</td>
<td>Yes. Several fracture-controlled 'slices' at the scarp.</td>
<td>Unclear -debris obscures basal slip-plane</td>
<td>Concave</td>
<td>Many disjointed and tilted blocks with vegetation intact on top</td>
</tr>
<tr>
<td>Serravalle</td>
<td>Pale grey, slightly weathered siltstone (breaks with almost conchoidal fracture). Thickness: 0.2m - 2.0m</td>
<td>10</td>
<td>150 (W) 250 (L) 5-15 (D)</td>
<td>315</td>
<td>Unclear, &gt;0.5m</td>
<td>No iron-staining visible in exposed portion</td>
<td>Unclear, several 'slices' exist at the crown</td>
<td>Unclear, not exposed</td>
<td>Concave</td>
<td>Complex surface morphology. Soil and vegetation forms hummocky surface with transverse ridges. Crown occurs just below a road cut.</td>
</tr>
<tr>
<td>Location</td>
<td>Description</td>
<td>Fractures observed in vicinity</td>
<td>Comments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>San Benedetto</td>
<td>Pale yellow-ish grey interbedded silstones and mudstones. Thickness: 0.01m - 1.5m.</td>
<td>Multiple - at least 3.</td>
<td>Fractures observed in vicinity of crown wall prior to sliding. Some blocks standing intact near crown but considerable disruption to lower parts - little surviving soil and vegetation. (See Figure 4.6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feisogho</td>
<td>Dark grey, highly to completely weathered sandstones interbedded mudstones. Thickness: 0.05m - 1.0m.</td>
<td>Single, exposed and occurring within mudstone layer Slickensides observed.</td>
<td>Completely weathered sandstone horizons are saturated and water oozes from the contact with underlying mudstone at the slip plane.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costalunga</td>
<td>Pale yellow siltstones interbedded with thin mudstones. Surfaces often iron-stained. Thickness: 0.1m - 3.0m.</td>
<td>Single, exposed, occurring at or within mudstone layer</td>
<td>Accumulation zone causes distinct bulging of the ground. Soil and vegetation still intact. (Figure 4.12)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocca Ciglie</td>
<td>Pale yellow siltstones interbedded with thin mudstones. Surfaces often iron-stained. Thickness: 0.1m - 0.5m.</td>
<td>Single (uncertain). Incipient form - no exposed slip plane.</td>
<td>Only detectable as a series of cracks transverse to the slope dip, which are often several metres wide. Soil and vegetation are intact over much of the slope. Highly susceptible to further movement.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Fractures observed in vicinity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Benedetto</td>
<td>Pale yellow-ish grey interbedded silstones and mudstones. Thickness: 0.01m - 1.5m.</td>
<td>Multiple - at least 3.</td>
<td>Fractures observed in vicinity of crown wall prior to sliding. Some blocks standing intact near crown but considerable disruption to lower parts - little surviving soil and vegetation. (See Figure 4.6)</td>
</tr>
<tr>
<td>Feisogho</td>
<td>Dark grey, highly to completely weathered sandstones interbedded mudstones. Thickness: 0.05m - 1.0m.</td>
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</tr>
<tr>
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</tr>
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<td>Single (uncertain). Incipient form - no exposed slip plane.</td>
<td>Only detectable as a series of cracks transverse to the slope dip, which are often several metres wide. Soil and vegetation are intact over much of the slope. Highly susceptible to further movement.</td>
</tr>
</tbody>
</table>
Figure 4.10 a) Map of the Murazzano area showing the locations of compound slide (A) and simple planar slide (B); b) photograph of slide (A).
Figure 4.11 a) Photograph and b) sketch of block-slide at Murazzano, Langhe.
Figure 4.12 a) Photograph and b) sketch of the block-slide at Costalunga, Langhe.
Figure 4.13 a) Photograph and b) sketch of the block-slide at Pianezza, Langhe.
4.1.6 Review of research in this area

4.1.6.1 Slope movements in Piemonte

Despite the lengthy history of landsliding in the Langhe there seems to be relatively little published research on this topic (e.g. Sacco, 1903; Boni 1941; Cortemiglia & Terranova 1969; Govi & Sorzana, 1982; and Govi, 1974). Until recently, publications mainly concerned field and air photography studies of specific landslide localities. Tropeano (1989) provides historical records of landslides associated with major flooding events dating back to 1485, in the Bormida valley, Piemonte. The CNR (National Research Centre) have offices in several regions of Italy, including Piemonte, and are active in the research of flood and landslide hazards.

Prior to the 1994 event there seems to have been no research on the regional susceptibility to landsliding in Piemonte, or on the development of a method to analyse and predict on this scale. Boccardo (1995), Boccardo et al. (1995), Mason et al. (1995b) and Mondino (1996), represent the first research involving digital data applied to a general study of the landslide problem in the Langhe.

Boni (1941) studied landslide which occurred near the village of Cissone, in April 1941. The landslide moved in two successive years, the first involved the formation a large crack and an incipient slide, the main movement occurred during the second year (1941). The slip plane was observed at a depth of 30-40 m, and the slide is reported to be ca 400 m wide and 400-500 m in length. Boni reports that the houses were transported by the slide, almost intact.

Cortemilia & Terranova (1969) studied the landsliding of the village of Ciglie (Cuneo province, in the Langhe), which recurred over many years, and is still a problem for inhabitants today. They observe many similarities between the Ciglie case and that of Cissone. The slopes are steeper at Ciglie than further east, and Cortemilia & Terranova (1967) suggest that erosion at the toe of slopes, by natural drainage is a significant trigger at Ciglie. They also note that downward penetration of water through the extensive fracture network is significant in causing instability. They also refer to fluidification of clay rich layers after prolonged rainfall.

Sorzana (1980) studied the landslide of Cherasco which occurred in February 1974. He has studied landslide reactivation in terms of six rainfall parameters including: cumulative rainfall during the 30 days prior to landsliding; rainfall intensity in the 24 hour period before landsliding; antecedent precipitation index; and monthly and seasonal rainfall surplus. He observes that landslides only occur if critical values of all six parameters are exceeded. He also refers to the long term landslide problem caused by post Pleistocene rejuvenation.
The landslide near the town of Somano, which moved first in 1972 and again in 1974, is documented by Govi (1974) and is the largest known landslide in the Langhe. Govi & Sorzana (1982) present a summary report of many slides which occurred between the town of Diano D'Alba and Bonvicino, in February and March of 1972 and 1974. This paper was probably the first in which similarities between the various landslides was remarked. They state that a close relationship exists between the timing of the landslides and the period of rainfall at the time of movement and over the preceding weeks. They observed translational slides which varied in their stage of development, from a few large tension cracks, to the devastation of a hillside (as in the case of Somano), and that some occurred on slopes which had been affected by similar landslides in the past. They also infer that human activity, in the constructions of road cuts, terraces, alteration of natural drainage systems and filling of fissures with wood and soil, is significant in causing slope instability.

Jibson et al. (1994) made a series of observations about landslides in the Republic of Georgia, which are almost identical in their morphology, mechanism and setting. The area experienced translational block-slides on gentle slopes, failing parallel to bedding with a dip of ca 10°, in thinly bedding limestones, sandstones and shales (which are highly plastic when saturated). These landslides differ from those of Piemonte in that they are seismically triggered.

4.1.6.2 Geotechnical studies

Recent studies have included geotechnical evaluations and back analyses of the two groups of slope movement which occur in the Langhe. Bandis et al. (1996) conducted approximate analysis for debris-flows based on cohesive soils and inferring steady seepage at the surface, and calculated critical thicknesses \( z_0 \) via the following formula:

\[
z_0 = \frac{c' \sec^2 \alpha}{\gamma \left( \tan \alpha - \left( \frac{\gamma_s}{\gamma} \right) \tan \phi' \right)}
\]

where \( \gamma_s \) = buoyant unit weight of soil, \( c' = 5 \text{ kN/m}^2 \), \( \phi = 25^\circ -30^\circ \), and \( \alpha = 20^\circ \). From this they predicted the maximum thickness of soil at limit equilibrium to be between 2.2m and 3.8m which is quite close to the observed thicknesses of ca 1.5 m.

Polloni et al. (1996) concentrated their work on the debris-flows which were produced by the 1994 storm. They also claim that the flood/landslide storm was a '1000 year' event. Their work is centred around the timing of debris-flow initiation with respect to rainfall incidence. During the 1994 event the cumulative rainfall at soil slip initiation was 124 mm and that antecedent rainfall (over the previous 15 days) was 62 mm. The same figures for the 1972 and 1968 events were ca
120 mm (ca 60 mm) and 195 mm (28 mm) respectively. They suggest that it is antecedent rainfall which controls the pre-storm soil moisture content and which is critical to the initiation time of the debris-flows. They sub-divided the debris-flow phenomena into three groups: (i) soil slips with W/L ratios of ~1, which are very shallow and approximately planar, and which occur on quite steep, cultivated slopes; (ii) debris flows with W/L ratios <<1, which are characterised by steep slopes and viscous movement; and (iii) debris avalanches which are highly viscous and occur on wooded, steep slopes. It all cases they state that the most frequent slope angles for ‘soil slips’ are between 30° - 40°. They observe that clay content of the soils is dependant on that of the bedrock but is commonly < 22%. They also state that observed shear strengths are <150 kN/m², residual friction angles are 26-31°, and cohesion values are 2-4 kN/m².

Ng & Shi (1998) state that the position of the initial groundwater level and the rainfall intensity significantly affect the stability of the slope. They suggest that using rainfall intensity thresholds as a landslide warning could be very misleading since a slope can remain stable even under extreme rainfall if the initial groundwater level is low. They also state that the antecedent rainfall profoundly affects the stability and that the factor of safety decreases as the duration of rainfall increases.

In their analysis of block-slides, Bandis et al. (1996) note that failure planes are pervasive, 100-200m in length and are covered with a layer of clay material 5-20 mm thick. For given shear strength and shear plane inclination (α), critical thickness (z_c) of a block (b x z_c), under self weight loading (W = b z_c γ) and hydraulic loading (v = 1/2 γ_w h_w z_c and u = γ_w h_w z_c) they derived critical block thickness (z_c) from the following formula:

$$z_c = \frac{2b \left( \tan \phi \left( \gamma \cos \alpha - \gamma_w \right) - \gamma \sin \alpha \right)}{\gamma_w}$$

for $\phi = 22^\circ$, $\gamma = 24$ kN/m², $\gamma_w = 10$ kN/m², and $\alpha = 10^\circ$. Calculated thicknesses (z_c) were as follows:

<table>
<thead>
<tr>
<th>block length (m)</th>
<th>10</th>
<th>20</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>block thickness (m)</td>
<td>2.7</td>
<td>5.4</td>
<td>13.4</td>
</tr>
</tbody>
</table>

They also measured typical cohesion values for mudstones and sandstones in the area as being 3.0 kN/m² and 5.0 kN/m² respectively. They identified two types of failure in the region: first time debris flows; and reactivations of older block-slides. They do not differentiate between block-slides and compound slides, nor do they mention the control of geomorphology in the distribution of
the types of slope movement. Their model suggest that the maximum displacement occurs in the lower part of the slope and that the central part translates en mass.

Laboratory research (Forlati et al., 1996) yielded interesting results about the role and behaviour of the clay minerals in this area and find that smectite (a clay mineral family with swelling properties) is significant in the failure mechanisms of the sediments in the Langhe. They conducted swelling tests, XRD and SEM analysis on sediments from the Langhe, in response to the 1994 storm event. Their work was concentrated on the significance of smectite, vermiculite and carbonates in the study of planar slides in the area. They found that planes of failure occurred within and between the mudstone layers. They also noted that the formation of fractures in the upper parts of the failures was accompanied by swelling of the soils in the lower parts. Their laboratory analysis found a high percentage of smectite on the outer surfaces of sliding planes and that the content of quartz and carbonates was lower along the failure planes. SEM also revealed iso-oriented fabrics along cleavage planes and inside the material. They attributed the loss of strength in stratified mudrocks which have been exposed to water, to the swelling of materials which have expansive structures (highly active clays), e.g. smectite and vermiculite. They attribute the block-slide failures in the Langhe to swelling and mineralogy, and suggest that the presence of smectite is a decisive factor in causing instability. They also consider that slope inclination is less significant than microstructure and smectite percentage.

4.2 Rio de Aguas valley, Sorbas, SE Spain

SE Spain is characterised by a semi-arid climate, thin and poor soils, very low soil moisture, thin vegetation cover and almost complete rock exposure. Groundwater levels are low, rocks are composed of poorly lithified, easily erodable materials and erosion rates are very high. These factors and sudden heavy winter rains produce frequent landslides in SE Spain. The area of study is located in the province of Almeria, along the Rio de Aguas valley, in the Sorbas basin (Figure 1.2a in Chapter 1, and Figure 4.14).

4.2.1 Geology of the Sorbas area

The Sorbas Basin, located in Almeria province, SE Spain, comprises an elongate, low-lying, synformal structure. The basin is bounded to the North and South by crystalline metamorphics of the Betic nappe complexes, of Pre-Cambrian to Cretaceous age (Sierra Alhamilla and Sierra de los Filabres) and is filled by sediments of Tortonian (Miocene) to Quaternary age (Crosta & Moore, 1989). The unconformable contact between the mountainous basement regions and basinal fill is often fault controlled.
Figure 4.14 Geological map (a) and schematic cross-section (b) of the Sorbas area and Rio de Aguas valley, SE Spain.
The Betic zone comprises two units, the Alpujarride and the Malaguide complexes. The Alpujarride unit consist of greenish facies phyllites and mica-schists, whilst the Malaguide unit is composed of largely unmetamorphosed, tectonic slices between detachment zones.

The Tortonian basinal fill in this area consists of a series of marine sandstones and marls. These are overlain unconformably by a series of massive, granular bioclastic limestones. Both sequences have been cut by normal faults (Platt et al., 1983). A simplified geological map of the Sorbas area, indicating the approximate locations of major landslides is shown in Figure 4.14.

4.2.2 Nature of slope movements

The landslides in the Rio de Aguas valley are commonly rotational slides and slumps rooted in the Tertiary marls which are exposed in the floor and slides of the valley. The gypsum plateau exposed in the northern side of the valley forms a resistant cap rock to the erodable marls and large blocks and benches of gypsum are visible in amongst the landslide debris (Figure 4.15). Glacially induced sea-level drop and tectonic uplift caused river rejuvenation at the start of the Pleistocene. This caused pronounced erosion by the Rio de Aguas and has resulted in continual undercutting and instability on the lower slopes. Recently, movement has also been triggered by blasting and engineering work for the motorway construction along the valley. Individual slides have a typically arcuate rear scarp but the elongate valley has to some extent controlled their shape. They have become linked together to form what appears to be a very wide, single landslide but which is in fact a series of similar but discrete landslides. Similar landslides have occurred on the southern side of the valley where Tertiary Limestones form the cap rock here (see geological map in Figure 4.14). Some planar sliding occurs where large slabs of limestone move over the marls before slipping rotationally. Debris-flows have also been identified on the northern side of the Rio de Aguas valley (Wright, 1995; and Eyers, 1994 and 1995), involving superficial or re-worked material, triggered by heavy winter rains.

4.3 Folkestone Warren, SE England

The study area is located on the south coast of Kent, SE England (Figure 1.1, 4.16 and 4.17). The area has a typically cool-temperate, mid-latitude climate, with mild winters, moderately high seasonal rainfall, tidal influence on water levels, a thick soil profile and dense vegetation cover.
Figure 4.15 Photograph (a) and sketch (b) of the Rio de Aguas valley.
4.3.1 Geology of the Folkestone Warren area

The area known as Folkestone Warren is situated at the eastern tip of the scarp of the South Downs. The Warren is the name given to the area of landslipped undercliff that extends along the coast between Folkestone and Abbot's Cliff. The cliffs are of Middle and Lower Chalk (120 m - 165 m thickness), at the base of which is a layer of glauconitic sandy “Chloritic Marl”. This is underlain by the Gault Clay which is approximately 30 m - 50 m thick, and which in turn rests on the upper surface of the Folkestone Beds (Lower Greensand). The whole section dips at ~1° toward NE-NNE. The geology of the area is shown in the simplified map and cross-section in Figure 4.17a and 4.17b. Details of the history, geology and landsliding in this area can be found in several texts e.g. Osman (1917); Hutchinson et al. (1980); Haselock (1988); Smart et al. (1966); and Hart (1985).

4.3.2 History and nature of slope movements

The first recorded movement occurred in 1765, with the first major slip in 1877, when 100 yards of tunnel was reported to have been destroyed (Hart, 1985). The second major slip occurred in 1915, when debris ran out over 500m from the foot of the rear scarp and the volume of material was estimated at 50,000-1,000,000m³ (Osman, 1917). Just before the second World War, developments in soil mechanics enabled greater understanding of the slip mechanism and geotechnical characteristics of the site. Engineers realised that the slip was not just a product of the eroding sea and the slippery nature of the clay, but that the weight of the chalk mass increased greatly after heavy rainfall and this caused reduced shear strengths in the clay. The most recent slips were recorded in 1987.

Movements are rotational slides or slumps, which are rooted at the junction between the Gault Clay and the Lower Greensand (Figure 4.17b). The foreshore is composed of an assemblage of Gault and Chalk blocks and debris, where numerous dipping shear surfaces (<55°) can be traced on the shore and into the cliffs (Smart et al., 1966).

Each movement is accompanied by the upthrowing of the foreshore into ridges, which are then eroded by wave action. Tension cracks in the cliff-top have commonly been observed prior to a slide movement. Loosened masses of chalk often then collapsed as rock falls. Movement was also remarked as being initiated at low tides, when hydrostatic pressures in the foreshore were lowest (Smart et al., 1966).

The first sea wall was constructed in 1939 and remedial measures got underway in 1948 with the boring of a series of drainage tunnels, the addition of toe weights (consisting of masses of chalk debris), and the construction of a concrete apron to protect the clay outcrop from the sea.
Figure 4.16 Photograph of the Folkestone Warren landslide (facing west).
Figure 4.17 a) Geology of Folkestone Warren area; b) sketch cross-section through cliffs at Folkestone Warren; c) sketch of Folkestone Warren landslide.
4.4 SUMMARY

This chapter summarises the geological, morphological, geomorphological and climatic characteristics of the landslides in the Langhe, Rio de Aguas valley and at Folkestone Warren. Attention has been focused on the description of features which are relevant to the analysis of hazard potential in later chapters. Comparison of characteristics of each landslides locality assists in the identification of significant hazard parameters.

Images of the three study areas are used in the analysis of image texture described in Chapter 5. The Langhe case study is dealt with in greatest detail as the landslides are numerous and their characteristics lend themselves to a detailed analysis of landslide hazard using remote sensing and GIS and this is described in Chapters 5, 6 and 7.

The literature review of landslides in the Langhe provides evidence of the long standing landslides problem and of key factors in the generation of instability i.e. litho-structural and geomorphological setting, mineralogy and valuable geotechnical information.

In all three areas, instability is caused by varying interactions of climate, lithology, vegetation cover and soil development and the triggering mechanism is rainfall. These variations have significant control on the morphologies of the landslides which then pose different problems for detection using remote sensing. The numerous landslides in the Langhe are spatially, temporally and mechanically related, and of the three case studies, the causes of instability are the least obvious.
Chapter 5 Textural and Spectral Enhancement

5.1 Introduction

This chapter describes the image processing section of the research, including the evaluation, processing and interpretation of textural and spectral characteristics of imagery from satellite and airborne sensors. The chapter deals firstly with the textural enhancement of landslide features. Images of landslides from the three study areas (Langhe, Rio de Aguas and Folkestone Warren) are used to illustrate characteristic morphological features. The second part concerns multi-spectral enhancements of imagery of the Langhe only. The aim is to derive thematic information for input to the GIS hazard assessment. The objectives of the chapter are as follows:

1) General objectives
   • to evaluate the contribution of texture to image interpretation for landslide studies
   • to assess how image type and specification affects the textural expression of landslide features
   • to investigate methods for textural enhancement and classification

2) Objectives specific to the Langhe landslide case
   • identification of features produced by landslides using SPOT imagery
   • enhancement of soil (iron oxide and clay minerals), vegetation and land use information in multi-spectral imagery

Landslides modify the topography and produce image texture features which distinguish them from undisturbed terrain. Certain rocks and soils are more susceptible to slope instability than others, and exhibit spectral variations which can be mapped using imagery. The purpose of this work is to demonstrate how textural and spectral information from imagery can assist the identification of landslides.

5.2 Data selection

The images were processed digitally using ER Mapper (raster-based processing software) on SUN Sparc stations at Imperial College. SPOT Panchromatic, Landsat TM and Airborne Thematic Mapper (ATM) have been processed to examine and enhance textural features which may be
related to landslides. Multiple images of any one location have been rectified to common co-
ordinates so that integrated processing can be done. Table 5.1 lists project datasets of the three
study areas.

Spot-Panchromatic image data is a common choice for textural studies as it provides the
lowest spatial resolution (10m) that is readily and routinely available from a satellite platform. The
stereo-scopic capability of SPOT also makes it a logical choice for terrain studies. Sub-scenes from
two SPOT-Pan scenes (acquired on 29 June 1994, 9 November 1994 and 8 April 1995) were
obtained for the Langhe. The SPOT scenes are from slightly different orbits but were not useful for
stereo viewing because of differing illumination conditions at acquisition dates. The November
image is also of poor quality and has extensive topographic shadowing due to the low winter sun
angle. The June 1994 and April 1995 images have similar illumination conditions but the post-
storm changes in the April image and low base-height ratio make stereo-viewing impractical.

Landsat TM imagery is cheap and readily available. It provides only 30m spatial resolution
but has the benefit of multi-spectral capability. The coarser resolution limits its ability to detect
small scale features, but its multi-spectral facility enables the enhancement of vegetation, rocks,
soils and soil moisture.

Table 5.1 Image datasets for the three study areas

<table>
<thead>
<tr>
<th>Study area</th>
<th>Image type</th>
<th>Acquisition date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langhe</td>
<td>SPOT Pan (level IA) 055/260 RAW</td>
<td>08/04/95</td>
</tr>
<tr>
<td>Langhe</td>
<td>SPOT Pan (level IA) 055/260 RAW</td>
<td>29/06/94</td>
</tr>
<tr>
<td>Langhe</td>
<td>SPOT Pan (level IA) 055/260 RAW</td>
<td>29/11/94</td>
</tr>
<tr>
<td>Langhe</td>
<td>ERS-1 SAR.GEC.5.3 GHz/VV (rectified to UTM 02)</td>
<td>09/11/94</td>
</tr>
<tr>
<td>Langhe</td>
<td>Landsat TM 7 Bands 194/029 RAW</td>
<td>16/06/84</td>
</tr>
<tr>
<td>Rio de Aguas</td>
<td>Spot Pan (level IA) 039/275 RAW</td>
<td>12/04/88</td>
</tr>
<tr>
<td>Rio de Aguas</td>
<td>Landsat TM 7 bands 199/034 RAW</td>
<td>19/7/84</td>
</tr>
<tr>
<td>Rio de Aguas</td>
<td>ATM 11 bands 1989 RAW</td>
<td>20/5/89</td>
</tr>
<tr>
<td>Folkestone Warren</td>
<td>ATM 11 bands 1992 (Day and Night-thermal) RAW</td>
<td>25/6/92</td>
</tr>
</tbody>
</table>

ATM imagery has a similar spectral range to that of Landsat TM, but contained in 11
spectral bands. Being at a much lower altitude, its spatial resolution is considerably higher
(normally 7.5m) and is variable. The disadvantage is that airborne sensor data are not routinely
available.

Radar should be an ideal tool for the detection of landslides, as it is sensitive to topographic
variations and surface roughness but there are many other factors which affect image quality. For
example ERS-1 SAR (Synthetic Aperture Radar) imagery of the Langhe was acquired but found to
be of extremely limited use for landslides study. The image was acquired on the 9th November, 1994 just a few days after the height of the storm-landslide event, at which time the soils were still saturated with water. The combined effect of wavelength and illumination geometry (on this pass) meant that the image was unsuitable for analysis of the terrain surface. The angle and direction of incidence are such that the radar beam is at a low angle relative to the dip slopes, so that very low returns are recorded. Conversely, the steep scarp slopes are nearly perpendicular to the radar beam and very strong returns are produced from these slopes (Figure 5.1). In addition, the short wavelength of the beam, at 5.3 cm (C band), means that a great deal of the beam energy is absorbed by water in the soils and vegetation. The result is an image almost devoid of texture and with misleading topographic detail. A longer wavelength beam, such as L band, or image acquisition when soil water content is much reduced, coupled with illumination from the opposite direction (different orbit) might produce significantly more topographic and textural information.

5.3 Image rectification

All images contain geometric distortions as a result of platform instability, earth rotation and topographic relief. All except relief distortion can be corrected for by registration of the image pixels to a map base. This is done, not only to correct for distortions but to register images to a known map projection and co-ordinate system, or to co-register two images to a set of arbitrary but common co-ordinates. This registration is performed using a series of ground control points (GCPs) extracted from identifiable ground features visible in both image and map (or reference image). The map co-ordinates are assigned to the pixel co-ordinates for each ground control point. A pair of polynomial equations, which describe the translation of image to map co-ordinates in two dimensions, are constructed (the form of these equations depends on the number of control points used) as follows:

\[
X_{\text{map}} = a + bX_i + cY_i + dX_i^2 + eX_iY_i + fY_i^2 + gX_i^2Y_i + hX_iY_i^2 + iX_i^3 + jY_i^3
\]

\[
Y_{\text{map}} = z + yX_i + xY_i + wX_i^2 + vX_iY_i + uY_i^2 + tX_i^2Y_i + sX_iY_i^2 + rX_i^3 + qY_i^3
\]

where \(X_{\text{map}}\) and \(Y_{\text{map}}\) are the output map co-ordinates and \(X_i\) and \(Y_i\) are the input image co-ordinates. The image is warped to the new co-ordinates using a 'rubber sheet' like operation. The accuracy of the warp is indicated by a Root Mean Square (RMS) error value for each GCP. The RMS represents the normal expression of measurement error for a point or attribute, and is expressed by the following equation:
Figure 5.1 Influence of radar geometry and topography on the quality of signal from landslide features

Figure 5.2 Normalisation of multi-temporal SPOT Pan images (of the Langhe).
\[ RMS = \sqrt{\frac{\sum (x_i - t)^2}{n}} \]

where \( x_i \) = a measurement; \( n \) = number of measurements; and \( t \) = the true value (the mean, unless stated otherwise).

This calculation is based on the assumption that errors arise from random variations which are normally distributed around the true or mean value. When the true value equals the mean, the RMS is the standard error of estimation. This approximates the standard deviation and is a measure of the spread of the data. The image GCPs can be deleted or shifted until a satisfactorily low RMS value is achieved.

The warp operation produces a rectified image where the co-ordinates are correct but the pixels are no longer square. The original digital numbers (DN) are then assigned to a new pixel grid using a nearest neighbour resampling method. This is a simple method but it retains the statistics of the original data. More precise resampling can be performed using cubic (or quadratic) convolution, where values from the surrounding 16 pixels are used in a distance-weighted mean operation.

Further details of the image rectification process can be found in many texts, e.g. Burrough, 1984, Drury, 1993, and Lillesand & Kiefer, 1994.

SPOT and TM images of the Langhe study area have been rectified to co-ordinates consistent with UTM (Universal Transverse Mercator) northern zone 2 projection and reference ellipsoid (referred to as 'MonteMario'). GCPs were derived from the ERS-1 SAR image which was georectified by ESA at source. GCPs were obtained from distinctive geomorphological features (e.g. river confluences, ridge tops). The SPOT Pan, TM and ATM images of the Rio do Aguas area were warped to a set of common co-ordinates using arbitrary GCPs, as map registration was not necessary for integrated processing. ATM imagery of Folkestone Warren was processed as raw data.

5.4 Textural enhancement of SPOT imagery

5.4.1 Pre-processing of multi-temporal Langhe SPOT Pan data

Prior to enhancement, the multi-temporal SPOT images of the Langhe were normalised to compensate for seasonal illumination variations. DN values were extracted from April and June images, from features constant in both images, such as factories and urban centres. The June image, acquired on a hazy, summer day with high sun angle, is much brighter than the April image, so that
its DN range is greater and broader than that of the April image. The June DN are plotted (Figure 5.2) against the difference between June and April DN (i.e. June minus April). The regression of the two provides a value for subtraction from the June image DN to bring its values down to those of the April image. Mondino (1996) found this to be a successful technique using these same images. He also plotted April vs June and April vs June-April, but found that the results were not as good.

5.4.2 Textural enhancement of multi-temporal imagery

Texture is a property which the human eye and brain judge and interpret intuitively. Performing a similar interpretation on a digital image, using a computer is not a trivial process. Image texture is a function of both the magnitude and frequency of tonal change in a raster image (Drury, 1987), i.e. it is a product of DN in x, y and z directions, and is therefore a three dimensional property. Perhaps the best approach to its treatment is a semi-automated one, involving spatial enhancement and classification, followed by interpretation.

Algebraic operations on multi-temporal image data and generation of change-detection images provides an efficient means of isolating terrain features, such as landslides, produced during known periods of time or by catastrophic events (e.g. storms, earthquakes).

The images in Figure 5.3a - 5.3c illustrate SPOT-Pan images of June 1994, April 1995 from the Langhe and the change detection image produced by the subtraction of one from the other. The change detection image (Figure 5.3c) illustrates localised changes in brightness produced by the landslide events of November 1994. The June (pre-storm) image has been subtracted from the April (post-storm) image and then stretched interactively to fill the dynamic 8-bit display range. Brighter tones indicate greater change, dark tones indicate little or no change between the two dates. These changes include instances where landslides have disrupted the ground surface and revealed rock and soil surfaces with higher albedo than the weathered soil and vegetation which usually blankets them.

Figure 5.4 illustrates two examples, from the Langhe, where landslides have produced significant identifiable changes in the ground surface which have been detected by this method. Two types of slope movement are represented: Figures 5.4a and 5.4b illustrate debris-flows near Ceretto Langhe (illustrated in Figure 4.8), which occur on steep slopes and which are characterised by scars on slopes where vegetation and soil have been stripped.

Figures 5.4c and 5.4d illustrate the block slides near Murazzano (illustrated in Figure 4.10 & 4.11). Complex textures are produced by the disrupted ground surface of the compound slipped mass.
Figure 5.3 Spot Panchromatic images (from the Langhe study area) of a) June 1994; b) April 1995; and c) change detection image (April minus June).
Figure 5.4 SPOT Panchromatic images of the Langhe study area: a) pre-storm; and b) change detection sub-scene of debris-flows at Ceretto; c) pre-storm; and change detection sub-scene of block-slides near Murazzano.
Areas recently disturbed by debris-flows and block-slides expose rock and soil which is fresher, spectrally distinct and therefore brighter than weathered surfaces. Using a threshold operation, the brightest pixels in the change detection image pixels (representing significant change) can then be isolated from the unchanged areas.

5.4.4 Digital convolution filtering

Digital convolution filters and moving window operators, provide a method for enhancing spatial brightness variations at different frequencies and they have been well documented by many authors (e.g. Niblack 1986, Drury 1993 and Schowengerdt, 1983). Simple filtering techniques have been found to be effective for landslide enhancement in a number of environments (Eyers, 1994; Mason et al., 1995a; and Eyers et al., 1995).

Digital convolution is based on linear system theory, where the filtering system (S) has an original input \( f(x,y) \) and a filtered output \( g(u,v) \). The output image of the filter operation can be expressed as a two dimensional convolution of a filter with an input image:

\[
g(u,v) = \iint f(x,y) h(u-x,v-y) \, dx \, dy \quad \text{or} \quad g = f * h
\]

where \( h(x,y) \) is referred to as the Point Spread Function. Filtering in the image domain is equivalent to masking in the frequency domain using Fourier Transforms (Schowengerdt, 1983; Lillesand & Kiefer, 1994), but is less time consuming. For digital images, summation over a neighbourhood of input pixels (within the filter kernel) is involved, where \( w \) and \( t \) are half the size of the filter kernel:

\[
g(u,v) = \sum_{x=-w}^{w} \sum_{y=-t}^{t} f(x,y) h(u-x,v-y)
\]

Most kernel operations alter the form of the image histogram and so degrade the image information, and they should therefore be used with caution. Varying the size of the kernel also affects the result. An increase in kernel dimension can improve the result but it also slows the processing. If the filtering operation is to be aimed at a specific target then how important is target size and image resolution relative to the kernel size?

A number of kernel types have been evaluated during this study and prior to their application to real image examples, each kernel was applied to several small test images. These display simple tonal and textural patterns with known input DN values, so that the kernel effects could be clearly understood before they were applied to the image data. The format of each kernel type is shown in Figure 5.5 and their effects on the test images are shown in Figure 5.6.
5.4.4.1 First derivative filters

These are known as gradient filters, which represent boundary and slope information. Two common forms are discussed and the form of the kernels is shown in Figure 5.5. The gradient operator is directional and can be expressed by the following formula:

\[ \nabla f = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} \]

**Sobel filters** - these are sensitive to vertical, horizontal and diagonal gradients. Their form and the effect they have on simple test images are shown in Figure 5.5 and 5.6. They can be passed over an image individually and the products viewed separately, or added together to enhance multidirectional linear features and textural regions.

Figure 5.7 shows ATM band 9 with ‘Sobel’ filters imposed and then added together to enhance linear features produced by gully erosion of the soft landslipped material in the Rio de Aguas valley. The distinctive patterns highlight the sudden rock type change between the resistant gypsum cap rock (forming the plateau in the upper part of the image) and unconsolidated marls beneath, and the arcuate break of slope marking the landslide crown between the two rock types.

**Directional filtering** - this refers to gradient filters used for the enhancement of linear features of specific orientation, e.g. faults, joints, folds and structural contacts. Sobel filters, applied separately, can be used to identify vertical (N-S) or horizontal (E-W) features but similar diagonal filters can also be designed and examples are illustrated in Figure 5.5. In the Langhe, crown walls often coincide with fractures which are oriented approximately NE-SW. Application of a NE-SW directional filter to the April (post-storm) SPOT Pan image reveals many topographic features of this orientation, some of which represent crown walls and fracture controlled elongate blocks within landslide bodies (Figure 5.8). There may be many others similar.
Figure 5.6 Effect of various convolution kernels applied to simple test images

Figure 5.7 Sobel filters applied to ATM band 9 (Rio de Aguas; red line indicates crown wall of rotational slides; green line indicates extent of recent debris flow).
Figure 5.8 Directional gradient kernel (NE-SW) applied to the change detection image of the Langhe (Figure 5.3c)

Figure 5.9 Laplacian add-back kernel applied to ATM band 9 of Folkestone Warren landslide.
features which represent landuse boundaries and roads, but directional filtering is one way of identifying structurally controlled landslide features which may be too subtle to detect directly.

5.4.4.2 Second derivative filters

These are known as Laplacian filters, which represent the second derivative or the rate of change in gradient, and therefore retain only sharp edge or boundary information. The Laplacian is a non directional operation and can be expressed by the following:

\[
\text{Laplacian} \quad \nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}
\]

Laplacian (centrally weighted) filters - these are frequently used for general edge sharpening. The central weight (see Figure 5.5) controls the relationship between the original image and the edge information. Increasing this weight produces what is known as an add-back image, which resembles the original image but with sharpened edge information. The effect of a Laplacian filter on simple test images is shown in Figure 5.6. The result is an exaggeration of points and linear features in the image by creating a pronounced edge to areas with sharp tonal gradients. The effect of a Laplacian filter on a texturally complex ATM band 9 image of Folkestone Warren, is illustrated in Figure 5.9.

Centrally weighted texture filter - this is a modification of the gradient filter but with a central weight. It is useful for enhancing and highlighting areas of high frequency information (rough textures) from areas of relatively uniform texture. The form of this kernel and its effect on simple test images is shown in Figure 5.5 and 5.6. This kernel produces a 'boundary' value between areas of different digital texture whilst suppressing lower frequency variations and hence topographic variation.

An ATM band 9 of the Folkestone Warren landslide is shown in Figure 5.10a (unfiltered) and 5.10b (filtered). The image in Figure 5.10b has been texturally enhanced using a 3x3 texture filter. The hummocky textures which characterise the 'main body' and the 'accumulation' are quite distinct in the filtered image from the undisturbed ground (clearly visible in the upper part of the image).

A sub-scene of the April SPOT Pan image (of Ceretto, Langhe) is shown in Figure 5.10c and 5.10d. The debris-flows are clearly enhanced against the background of the undisturbed ground around them.
Figure 5.10 Panchromatic images of: ATM band 9 of Folkestone Warren (a) and (b); and SPOT Panchromatic of Ceretto, Langhe (c) and (d). A centrally weighted texture kernel has been applied to images (b) and (d). Unfiltered images (a) and (c) are shown for reference.
5.4.5 Textural classification

Since texture is by definition a three dimensional property (as described in 5.3.2), in order to classify it, both the value of the pixel and its relationship with its neighbours must be taken into account. If we take a pixel at the centre of a given window and compare its value to that of all its neighbours, then record that value, the result is a measure of the change in DN across the window.

Calculating the difference ($d$) between the central pixel and its neighbours, summing those differences, then repeating this operation on adjacent pixels, produces an image representing the magnitude of tonal change in all directions within the kernel window. This difference calculation can be performed very simply by applying a standard Laplacian kernel (without a central weight) to the image. The edge information produced by the Laplacian operation represents the difference between two adjacent pixel values.

Examination of the image histogram produced by this operation (Figure 5.11a) shows a normal distribution where the values, either positive or negative, represent increasing difference values (and textural complexity) away from zero. If the values inside the kernel area are equal (i.e. the image has a uniform texture) then $d$ equals 0. When DN variation in the window is very high, the value of $d$ is correspondingly high. Multiplying the negative values of the difference image by -1 makes the image histogram entirely positive and enables a simple classification by thresholding into two or more categories of relative textural irregularity or roughness.

Considering the application of a Laplacian filter to two simple and extreme cases below: a) the central pixel value is very different and b) little difference between the central and neighbouring pixels (Figure 5.11a). The results illustrate the widely differing $d$ values produced by local changes in pixel DN.

The difference image can then be thresholded (Figure 5.11c) to produce binary classified image of rough and smooth textured pixels (though this part is of course a subjective operation).

Increasing the size of the kernel produces a greater range of $d$ values in the difference image and should make the method more sensitive to subtle textural variations and to larger features but also slows processing. Depending on the size of the texture feature to be classified and the spatial resolution of the image, some experimentation of kernel size should be made. The cartoon in Figure 5.12 illustrates the concept of varying kernel size on sensitivity to size of texture feature in the image.
Figure 5.11 Kernel based classification of digital image texture

Figure 5.12 Effect of kernel size on the size of feature which is classified.
The application of this classification technique to the SPOT Pan imagery of the Langhe produced very confusing results because of the textural complexity of the image (intensely cultivated land with small field parcels and many small settlements) and the small size of the landslides. ATM images of Rio de Aguas are used for illustration instead.

5.4.5.1 Varying Kernel Size
The images of Rio de Aguas ATM band 9, shown in Figure 5.13a-d illustrate the effect of kernel size on the classified image. Figure 5.13a shows the unclassified image for reference. The use of 3x3, 5x5 and 15x15 kernels produces quite different results. Figure 5.13d shows (using a 15x15 kernel) has far fewer spurious pixels than the 3x3 kernel image (Figure 5.13b). The larger kernel is less sensitive to localised high frequency tonal changes. The smooth, uniform gypsum plateau is very clear in all images (in the upper, central part). Definition between rough and smooth areas is better in the 15x15 filter result (Figure 5.13d).

5.4.5.2 Varying Image Spatial Resolution
The images of Rio de Aguas, shown in Figure 5.14a-d illustrate the effect of changing image resolution on the classified image. A reduction in pixel size has a significant effect on the quality and textural content of the filtered and classified image. Figure 5.14a shows the unclassified image for reference. Figures 5.14b, 5.14c and 5.14d illustrate the effect of classification using a 15x15 kernel on 7.5m (ATM), 10m (SPOT Pan) and 30m (TM) pixels respectively. Comparison of Figure 5.14b with 5.14d illustrates the significant improvement in the textural information as image resolution increases.

This classification of the frequency of tonal change can also be performed using Fourier Transforms but the processing is much more intensive and time consuming. Comparison of Figure 5.14c and 5.14d shows that only a slight improvement is produced by a reduction in pixel size from 10m to 7.5m.

5.5 Spectral enhancement of Landsat TM imagery
This section of the processing is concerned with the enhancement of soil and vegetation characteristics of the Langhe TM data only. The products include spectral profiles (TM-DPS and TM-SR) for comparison with field spectral data (Chapter 6) and thematic image input to the hazard assessment (Chapter 7).
Figure 5.13 Effect of varying kernel size on the classification of texture (using Rio de Aguas ATM band 9 image): (a) unfiltered; (b) 3x3; (c) 5x5; and (d) 15x15.
Figure 5.14 Effect of varying spatial resolution on the classification of texture (using Rio de Aguas ATM band 9 image).
5.5.1 Pre-Processing

Prior to spectral ratioing or differencing, the TM data are corrected for atmospheric scattering. Before construction of false colour composites, a BCET (Liu, 1991) stretch was applied to each TM band, and simulated reflectance was calculated from the 7 TM bands for comparison with field spectral data.

5.5.1.1 Correction for atmospheric scattering

Dark-pixel subtraction (or DPS) is a simple and widely used method for removal of the atmospheric scattering effect in the lower wavelength bands. It is commonly performed prior to ratio and difference operations, where use of un-stretched DN is desired. For this reason it is used here.

The method involves the identification of the darkest areas of the image, usually represented by water, and the identification of their DN values in each band. These dark-pixel DN values are then subtracted from all pixel values in their respective bands. The dark-pixel values and image statistics after DPS are shown in Table 5.2.

The method is simple and quite effective though it is common to over correct some bands by this method and end up with negative DN. Modifications of this method have been proposed, to avoid the generation of negative values (e.g. Chavez, 1988) though the result of this simple version was considered adequate for this work.

The dark-pixel subtracted data (TM-DPS) were then used as input for difference and Tasselled Cap operations referred to in later sections.

Table 5.2 Dark pixel subtraction DN values and dataset statistics after subtraction.

<table>
<thead>
<tr>
<th>Original TM DN</th>
<th>TM1</th>
<th>TM2</th>
<th>TM3</th>
<th>TM4</th>
<th>TM5</th>
<th>TM7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark pixel DN</td>
<td>84</td>
<td>37</td>
<td>30</td>
<td>28</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area In Hectares</th>
<th>32158</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>122</td>
</tr>
<tr>
<td>Mean</td>
<td>16.72</td>
</tr>
<tr>
<td>Median</td>
<td>13</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>11.78</td>
</tr>
<tr>
<td>Corr. Eigenvalue</td>
<td>4.61</td>
</tr>
<tr>
<td>Cov. Eigenvalue</td>
<td>935.82</td>
</tr>
</tbody>
</table>
5.5.1.2 Balanced Contrast Enhancement Technique (Liu, 1991)

This technique redistributes the data in each band of a multi-band image, without altering the basic shape of the histogram, to the same mean and value range, using a parabolic function.

\[ y_i = A (x_i - B)^2 + C \quad \text{for } i = 1, 2, 3, \ldots, n \]

where \( x_i \) = any pixel of the input image (X); \( y_i \) = any pixel of the output image (Y); \( A, B \) & \( C \) are coefficient functions of the minimum, maximum and mean of the input image \( x \); \( i \) = a pixel in image \( x \) or \( y \); and \( n \) = the number of pixels in the input image. The smaller the value of \( A \), the wider open the parabola branches become. \( B \) and \( C \) are co-ordinates of the turning point of the parabola, which determines the part of the parabola to be used by the BCET. The coefficients \( A, B \) and \( C \) are derived from an input image (X) and the specified minimum, maximum and mean for the output image (Y).

BCETP, using a parabolic function, is the commonly used form of this technique. BCET can also be performed using a cubic function (BCETC). This involves more complex processing but also affords greater flexibility.

The BCET method is favoured for production of colour composite images as it avoids colour bias in the composite image. The technique also reduces some of the effect of atmospheric scattering and stretches the data in one process thus the three bands of a colour composite are effectively standardised. The image histogram is not distorted during the stretch, and so the image information is unchanged. This fact is most important for a contrast enhancement which precedes other processing.

5.5.1.3 Simulated Reflectance Technique (Liu et al., 1997)

The purpose of the simulated reflectance technique (Liu et al., 1997) in this context is to produce an image whose values can be compared with absolute spectral reflectance profiles in Chapter 6.

The technique involves the calculation of simulated reflectance and emittance from the relationship between irradiance, thermal emittance, spectral reflectance and albedo based on a simplified model of energy conservation. It differs from other similar methods in that it retains the albedo information. The simulated reflectance of a band \( \lambda \) is defined as:

\[ \rho_{\text{sim}}(\lambda) = \frac{M_r(\lambda)}{M_r + M_e} = \frac{\rho(\lambda) E(\lambda)}{E - B} \]

Where \( \rho_{\text{sim}}(\lambda) \) = simulated reflectance of a band of wavelength \( \lambda \); \( M_r = \) reflected solar radiation; \( M_e = \) (thermally) emitted radiation; \( \rho(\lambda) = \) spectral reflectance; \( E(\lambda) = \) spectral irradiance of band \( \lambda \); \( B \)
= radiation balance. Since both the spectral irradiance and simulated irradiance \((E - B)\) vary with topography, the irradiance ratio is approximately constant for all pixels. The result of this formula is thus directly proportional to true spectral reflectance.

The technique involves the use of the reflected spectral bands and the thermal band, and is most applicable to multi-spectral imagery which has the same spatial resolution in all bands. The technique was originally developed for application to ATM imagery but has been adapted for use with TM data (Liu et al., 1997). The drawback for TM is the reduced spatial resolution of the thermal band (120m) and degradation of the resultant image is a consequence of this.

So for multi-spectral imagery, simulated reflectance is derived by the weighted sum of reflected and thermal bands (simulated irradiance) and then a ratio of each band to this simulated irradiance component. The application of the simulated reflectance technique is preceded by a BCET stretch of all bands. The following formula and weights are then applied to the seven TM-BCET bands to derive simulated reflectance (TM-SR):

\[
\frac{B_n}{B_6} + (0.2 \times B_1 + 0.3 \times B_2 + 0.2 \times B_3 + 0.1 \times B_4 + 0.1 \times B_5 + 0.1 \times B_7)
\]

5.5.2 Composite images

To improve the spatial information of the false colour composite images, integration with SPOT Pan was performed. This is a well established technique, used for a variety of applications (e.g. Mason et al., 1994, Eyers et al., 1995) and can be achieved through the HSI (Hue, Saturation and Intensity) technique via the substitution of SPOT Pan for the TM intensity component, or through the use of the Brovey transform (ERMapper reference manual) which is conceptually comparable but computationally simpler than the standard HSI algorithm. It is restricted to the combination of three bands but as the desired result is a three band colour hybrid composite, this is not a limitation.

In the April (post-storm) SPOT Pan image, stark brightness variations produced by the landslides mean that this image has very low correlation with the TM image and the two do not produce a combined (Brovey) image of good quality. The June (pre-storm) SPOT Pan image has therefore been used with the TM to produce hybrid (Brovey) false colour composite images.

5.5.2.1 Enhancement of vegetation

The false colour composite image of TM-SPOT 432(RGB) is shown in Figure 5.15 and clearly demonstrates the dominant presence of vegetation (red hues) in the study area. Generalised spectral curves of common surface materials are shown in Figure 5.16. The deep purplish reds correspond to densely wooded areas, comprising mixed deciduous and coniferous
Figure 5.15 Hybrid Landsat TM-SPOT Panchromatic colour composite image (TM bands 432) of the Langhe, showing the dominant presence of vegetation.
species and in some areas, cultivated fruit and nut trees. The lighter reds represent grassland and cultivated land (cereal crops). The blue hues represent non-vegetated areas i.e. exposed soils and in some places, rocks. There are many instances of pale bluish pinks and purples and these indicate mixed spectral response from soil and vegetation. These represent areas which have recently been ploughed, where plant growth is not advanced or has been partially stripped by some agent (e.g. fire, recent slope instabilities). Towns and smaller settlements also appear in the same blues hues. This is because they are constructed mainly of local materials which have the same spectral characteristics as the rocks and soils, but with overall lower brightness (Figure 5.16) which allows urban features to be identified.

There appears to be little soil spectral variation across the image. There is a slight change to more cyan blues away from the north-western corner of the image, but soils generally have a similar appearance across the area.

5.5.2.2 Enhancement of soil information

A hybrid composite image of TM-SPOT 531 (RGB) is illustrated in Figure 5.17. The image reveals only subtle spectral variations in soil character. The dominant appearance of vegetation is again apparent though there is a difference in the spectral properties of the vegetated slopes in the central part (reddish browns) to those of the north-western part and eastern side of the Bormida valley (purplish brown). There appear to be no distinct changes in soil spectra character, except toward the north-western corner of the study area where they have a bluish tint rather than the greenish-yellow colour as in the central part. In the south-central parts (south of San Benedetto) the exposed soils have a slightly more yellow colour, indicating a stronger reflectance in TM band 5. Generally, it is difficult to derive any clear evidence of soil variations across the image.

5.5.3 Band ratios and Tasselled Cap transform

The false colour composite images have not provided much clear information about soils, partly because of limited exposure. The removal of vegetation by masking, using a Normalised Difference Vegetation Index (or NDVI), is one solution. The position of the threshold is however subjective and can result in mixed soil-vegetation pixels being omitted from or wrongly included in the masked image. A better approach is to use all pixels and separate the information about soils (water content and chemistry), through selective band indices (ratios) and Tasselled Cap transform.
Figure 5.16 a) Generalised reflectance curves for common surface materials (after Drury, 1993); and b) spectral profiles from surface materials in the Langhe study area.
Figure 5.17 Hybrid Landsat TM-SPOT Panchromatic colour composite image (TM bands 531) of the Langhe, illustrating the limited spectral variation of exposed soils.
Multiple image manipulation concepts, involving spectral ratios and band indices are established techniques detailed in many texts, including Schowengerdt (1983), Niblack (1986), Lillesand & Kiefer (1994). The advantage of ratios is that they convey spectral characteristics regardless of topographic or illumination variations in the image. One disadvantage of ratioing operations is that they enhance the noise component of the images. Ratio operations are often useful for discriminating spectral variations which are masked by illumination variations and they are commonly used to enhance the spectral absorption features of hydrated minerals and iron oxides. A standard formula for spectral ratios is as follows:

\[
\frac{(i1 - \text{min}(i1))}{(i2 - \text{min}(i2))}
\]

where \(i1\) and \(i2\) are input bands; \(\text{min} = \text{band minimum value}\).

### 5.5.3.1 Clay mineral index

Hydrated minerals (including clays) are characterised by lower reflectance at longer wavelengths. High values produced by a ratio of TM bands 5 and 7 represent pixels where there are hydrated minerals present in the surface materials (soils in this case). Figure 5.16a illustrates generalised reflectance profiles of typical vegetation, soil, water and rock, and TM wavebands for comparison.

With the exception of river bed deposits (alluvium and storm washed debris), the soils are residual, i.e. generated by weathering processes from underlying rocks and not transported. The residual soils should reflect the chemistry of the parent rock beneath. High clay content is indicative of mudrocks (mudstones, siltstones, shales and marls) which have low permeability. The presence of mudrocks is associated with impermeability and poor drainage and therefore with slope instability. The ‘Clay’ index image is shown in Figure 5.18 and will be input to the hazard assessment GIS.

### 5.5.3.2 Iron oxides mineral index

Iron oxides are highlighted, in the same way as hydrated minerals, this time using TM bands 3 and 2, or 3 and 1 (see Figure 5.16). TM band 1 in this dataset contains a lot of haze and so a 3/2 ratio was used instead. High values in TM 3/2 indicate iron oxides in the soils (Figure 5.18b).

The presence of iron oxides is indicative of strong leaching of iron minerals in an aerobic (oxidising) environment, by water through natural conduits (fractures, faults and joints). There is a strong link between intense fracturing and landslides in the Langhe. Strong iron oxide signature
Figure 5.18 a) Hydrated mineral ratio and b) iron oxide ratio images of the Langhe study area.
in soils is proposed as an indicator of areas which are intensely fractured and therefore landslide prone.

5.5.3.3 Tasselled Cap transform

The Tasselled Cap transform, referred to by many authors, was developed by Kauthe & Thomas (1976), for analysis of Landsat MSS (Multi-Spectral Scanner) data. The method was modified by Crist (1983) and Crist & Cicone (1984a & b), to manipulate the seven band data from Landsat TM. The transform comprises three parts: 1) understanding of relationships between the bands for classes of interest; 2) compression of \( n \) bands into a manageable number of features; 3) extraction of physical characteristics from the scene (Crist & Cicone, 1984a). They identified TM indices which were equivalent to the indices previously found in the MSS data, those of brightness and greenness but they also identified a third property which they termed wetness. In all they derived six indices from the TM data, termed brightness, greenness, wetness, 4, 5 and 6, and a series of coefficients (Table 5.3 and Figure 5.19) which defined the alignment of the indices or axes within a three dimensional co-ordinate space. These coefficients are then multiplied by their respective TM-DPS band DN and then summed.

Table 5.3 Tasselled Cap coefficients defining the alignment and relationship of the three main indices of brightness, greenness, wetness.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>TM1</th>
<th>TM2</th>
<th>TM3</th>
<th>TM4</th>
<th>TM5</th>
<th>TM7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>0.3037</td>
<td>0.2793</td>
<td>0.4343</td>
<td>0.5585</td>
<td>0.5082</td>
<td>0.1863</td>
</tr>
<tr>
<td>Greenness</td>
<td>-0.2848</td>
<td>-0.2435</td>
<td>-0.5436</td>
<td>0.7243</td>
<td>0.0840</td>
<td>-0.1800</td>
</tr>
<tr>
<td>Wetness</td>
<td>0.1509</td>
<td>0.1793</td>
<td>0.3299</td>
<td>0.3406</td>
<td>-0.7112</td>
<td>-0.4572</td>
</tr>
</tbody>
</table>

The three dimensions of the Tasselled Cap operation define a 3D space where the information falls into different planes (Figure 5.19). The value distributions in the three indices vary scenes but for agricultural scenes, they fall into the following ranges:

Table 5.4 Values ranges for Tasselled cap indices applied to TM 7 band data

<table>
<thead>
<tr>
<th></th>
<th>General</th>
<th>Langhe TM-DPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>0 to 350</td>
<td>81 to 354</td>
</tr>
<tr>
<td>Greenness</td>
<td>-100 to 125</td>
<td>-55 to 85</td>
</tr>
<tr>
<td>Wetness</td>
<td>-150 to 75</td>
<td>-103 to 42</td>
</tr>
</tbody>
</table>

Such images should always be interpreted with caution to avoid confusion of high and low index values with high and low feature values e.g. high wetness DN indicating high moisture
content, or vice versa. As a check, reference was made to the lake situated near the town of San Benedetto, which has a high wetness value (ca 40) and appears as a pure blue hue. So high wetness values correspond to high moisture content, and the same relationship is true for brightness and greenness.

**Brightness** - Areas of high brightness correspond to strongly reflective, exposed soils and buildings (towns). The north-western corner of the image is very distinct in its redness and this is due partly to the hazy cloud which affects TM band 1, but also to the change in vegetation type and density in this area. There is less pasture and cropped land (see Figure 5.15) in this part of the study area. There is also a marked decrease in brightness between wooded southeast facing slopes and cultivated northwest facing slopes.

**Greenness** - this is a function of the development of vegetation, its seasonal growth and production of chlorophyll, through senescence and death. The distribution of greenness is as to be expected in this region, dominated by cereal crops, fruit and nuts, in addition to pasture and naturally wooded areas. The bright green colours, indicating strong vegetation response, are most evident in the South-eastern part of the image and in the north-western corner, where vegetation also contributes to the retention of moisture.

**Wetness** - this is defined by the contrast between the sum of mid-IR bands and the sum of red/NIR bands and is based on the relationship between the spectral characteristics of clear water, wet soil, dry soil and concrete, see Figure 5.19a. This information was referred to as 'wetness' because it is sensitive to variations in soil and plant moisture which are characteristic mid-IR spectral features. The wetness index gives an indication of areas where water is held in the soils longest, and may be one indicator of slope instability. It forms an important piece of information which will be integrated into the GIS for hazard calculations. There is a correlation with vegetation and aspect in that areas of strongest wetness signature are north-facing wooded slopes (Figure 5.20), northerly-facing dip slopes (which have thicker soil cover than steep scarp slopes) and pixels representing rivers and lakes. It is interesting that exposed soils in the north-western part of the area appear to have low wetness, whereas the soils which appear darker (are vegetated) also indicate considerable soil moisture (dark greenish blues). This is a characteristic of the very warm springs that are common in Piemonte where exposed soil surfaces are quickly dried by the sun even though there is a significant amount of moisture at depth. In contrast, early vegetation growth affords some protection from the drying effects of the sun. This is also illustrated by the pattern of wetness in the densely vegetated areas. In general, southward facing wooded scarp slopes with thin soils (<50 cm), appear slightly better drained than northward facing dip slopes which are heavily cultivated and have thicker soils (0.5 to 1.5m). On these northwest facing dip slopes there is further variation in
Figure 5.19 a) Plane of soils illustrating the relationship of brightness and wetness with respect to water content of soils; b) Transitional crop spectral development, showing only the edges of the plane of soils shown in (a); c) coefficients for wetness derivation from Landsat TM (after Crist & Cicone, 1984).

Figure 5.20 Wetness index, derived from Tasselled Cap operation.
wetness distribution, which is controlled by topography.

5.5.3.4 Composite index image

The image shown in Figure 5.21 illustrates the display of the iron oxide ratio, clay ratio and Tasseled Cap wetness index as an RGB image. Each index has been scaled to a 0-255 range, using a linear function, to maximise image contrast. Overlain on this image are white polygons and yellow dots indicating the positions of block-slides produced by 1972/74 and 1994 events.

The image is dominated by red, blue and cyan colours. The cyan colours indicate high values in both clay and wetness indices. The yellow pixels indicate high clay and high iron values and orange colours indicate soils with high iron, moderate clay values and low wetness values. Steep, scarp slopes show orange colours as these are well drained, have thin soils and weather more rapidly than the dip slopes. There are few areas of magenta i.e. high iron and high wetness. High iron values are associated with well drained, fractured areas which should show low wetness values.

5.6 Summary

5.6.1 General contribution of textural and spectral information

This chapter has demonstrated textural enhancement of panchromatic images, using landslide examples from Rio de Aguas, Folkestone Warren and Langhe study areas. The work has shown that morphological features of landslides produce characteristic image textures and that these can be enhanced and used to identify other landslides.

The analysis has shown that spatial resolution is the most important parameter in textural studies of landslides and this determines the minimum size of landslide that can be detected. Using SPOT Pan data, landslides which are larger than ca 500m² in area can be reasonably identified. The limiting condition is that the spectral properties of the sub-surface materials (rocks and soils) should be significantly different from the surrounding, undisturbed ground.

The comparison of 7.5m ATM images with 10m (SPOT Pan) and 30m (TM images) of Rio de Aguas illustrates the control of resolution on textural detail. At 30m resolution no internal features can be detected at all, only crude outlines and brightness changes. Confident identification of the feature as a landslide could not be made from this image. The 7.5m (and 10m) resolution images show the well defined crown of the landslide and illustrate detail within the body of the landslide.
Figure 5.21 Composite image of iron oxide ratio (Red), hydrated mineral ratio (Green) and wetness index (Blue) of the Langhe study area.
The results of this investigation show that multi-temporal processing enables a useful reduction of image complexity and allows the targeting of areas which have undergone localised ground disturbance related to landslides. Following this it was possible to discriminate shallow debris-flows from deeper planar block-slides.

This study illustrates simple filters as an effective tool for the enhancement of landslide terrain. Complex textural filtering techniques, such as those developed by Iron & Peterson (1981), Pietikäinen et al. (1983) and Haralick et al. (1973), can produce results which are rather confusing and difficult to interpret.

The work demonstrates a simple method of classifying texture based on localised tonal variation. The classification results illustrate the effect of pixel and kernel size on the sensitivity to surface irregularities. Once again resolution is the controlling factor though the nature of the terrain is also important. The application of this technique to the Langhe SPOT Pan images produces a result which is almost entirely classified as rough because of the textural complexity of the undisturbed ground. The classification of the Rio de Aguas and Folkestone Warren images was more successful because of the relative textural uniformity of the undisturbed ground.

5.6.2 Contribution to the Langhe case study

The Langhe landslides present very difficult remote sensing targets. The textural complexity of the undisturbed ground and the limited dimensions of the landslides makes identification using satellite imagery problematic. The sizeable area involved and the recurrence of the landslides does, however, necessitate the use of routinely available satellite imagery. Spectral enhancement is important for landslide identification as a complement to the textural information (which is limited in this case).

Landsat TM data is routinely available and provides multi-spectral data but its coarse resolution (30m) limits its ability to identify landslides. It can resolve only landslides larger than ca 300-500m in length (when spectrally distinct) and those of about 800-1000m when spectrally indistinct. Airborne Thematic Mapper (ATM) imagery has the spectral range of Landsat TM and spatial resolution of less than 10m but data acquisition must be planned and funded. Thus it is usually inconvenient and too costly for rapid response or recurrent studies.

The debris-flows though often smaller than the block-slides, are spectrally very distinct from the undisturbed and vegetated ground and have characteristic morphology. The difficulty in directly identifying the block-slides is that the exposed or disturbed portion of the slide usually occupies ca 30% of the total slipped area even in mature examples. The incipient examples are easily identifiable on the ground but are barely detectable at this resolution. Linear features produced by
the fracturing of the ground at the crown are the only indication of their presence. The identification of these linear features is still considered important as published literature suggests that the small, incipient slides tend to develop into much larger features during the next landslide event.

Stereo information might be an advantage. The Langhe SPOT scenes, though from slightly differing orbits are not effective for stereo viewing due to the low base-height ratio of the images and the widely differing illumination conditions in winter and late spring.

Evaluation of ERS-1 SAR data has revealed that the selection of radar image data requires careful assessment of illumination geometry, wavelength, polarisation and ground conditions at the time of image acquisition. ERS-1 SAR data of the Langhe area were found to be of little use (except geo-registration of other datasets) because of its geometry, short wavelength and the saturated ground conditions. It is considered that ERS-1 imagery from a different orbital path, and acquired during drier conditions may provide more information but the wavelength is still not ideal for land-based studies and this expense could not be justified. Other radar data, having more appropriate geometries are, in theory, available but not for this area nor for the required time.

The textural studies described in this section have produced a thresholded change detection image showing pixels which represent debris-flows and block-slides of the Langhe area. This provides evidence of the spatial distributions of the landslides which occur in the area. The spectral studies have produced a composite image containing useful information about soil moisture, iron oxide and clay mineral content (from spectral indices) in the Langhe study area.

Despite the difficulties of extracting geological information from heavily vegetated (cultivated) terrain, with almost no rock exposure, and relatively coarse spatial and spectral resolution of TM, variations in soil mineralogy and moisture can be identified. This information forms indirect evidence of areas liable to slope instability which forms significant input for hazard assessment.
Chapter 6 Mineralogical analysis

6.1 Introduction

Given that from a remote sensing viewpoint, soil mineralogy is the only source of geological data, analysis in greater detail has been carried out using analytical techniques. X-Ray Diffraction (XRD) and spectra-radiometry have been used for analysis at both macro (rock and soil) and crystallographic scales. A data collection programme was undertaken in the Langhe to obtain in-situ data and rock/soil samples. Sample data collection, processing and analysis of both XRD analysis and spectra-radiometry are described. The objectives are to demonstrate:

- that soil chemistry reflects that of the rocks beneath.
- the presence of iron oxides and smectite in rocks and soils;
- the spatial correlation between high iron oxide and clay content (especially smectite) in soils and rocks, and the occurrence of landslides.

This results of chapter are intended to complement the other sections of this study, to provide evidence of factors related to slope instability.

6.2 Data Collection

6.2.1 Rock and soil samples

A total of ten rock and soil samples were collected from several major block-slide localities in the Langhe and prepared for XRD and laboratory spectroscopic analysis. These are listed in Table 6.1 with their location, rock type and position with respect to landslide morphology.

Table 6.1 Samples collected in the Langhe and their position relative to landslide morphology

<table>
<thead>
<tr>
<th>Sample Locality</th>
<th>Grid reference</th>
<th>Sample type</th>
<th>Position relative to landslide morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murazzano 1</td>
<td>423900, 4925240</td>
<td>Grey Mudstone</td>
<td>Slipped block</td>
</tr>
<tr>
<td>Murazzano 2</td>
<td>&quot;</td>
<td>Grey Sandstone</td>
<td>Slipped block</td>
</tr>
<tr>
<td>Murazzano 3</td>
<td>&quot;</td>
<td>Grey Siltstone</td>
<td>Slipped block</td>
</tr>
<tr>
<td>Murazzano 4</td>
<td>&quot;</td>
<td>Soil</td>
<td>Immediately above crown wall</td>
</tr>
<tr>
<td>Murazzano 5</td>
<td>&quot;</td>
<td>Grey Mudstone</td>
<td>Basal slip plane</td>
</tr>
<tr>
<td>Pianezza</td>
<td>422110, 4934625</td>
<td>Yellow Siltstone</td>
<td>Slip mass (rock debris)</td>
</tr>
<tr>
<td>Roddino</td>
<td>422500, 4936725</td>
<td>Yellow Siltstone</td>
<td>Side wall</td>
</tr>
<tr>
<td>Serravalle</td>
<td>425490, 4934150</td>
<td>Pale Grey Siltstone</td>
<td>Slip mass</td>
</tr>
</tbody>
</table>

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The sketch in Figure 6.1a illustrates the positions of the Murazzano samples in relation to the geometry of the landslide from which they were collected (see Figure 6.1b for location of Murazzano). Five samples were collected from the landslide at Murazzano (Figure 6.1a and Table 6.1). The soil above the slide, rocks in the slip mass and from the slip plane itself were sampled, though sample no. 2, a moderately strong, medium-grained, sandstone, was not submitted for XRD analysis as it was not considered to be of mineralogical interest.

6.2.2 Field data collection

Spectral data were collected in the Langhe at a number of sites using two methodologies, depending on the nature of the site, as follows:

6.2.2.1 Grid locations

Approximately 30 sites distributed on a regular grid (ca 2.5 km apart), in undisturbed agricultural land and on naturally vegetated slopes, were plotted (Figure 6.1b). The actual sample localities were identified as closely as possible to the plotted locations (given access difficulties and severe relief) using maps, images and Magellan Nav Pro GPS. Sites in dense forest or very steep terrain were relocated, only one site had to be abandoned due to inaccessibility.

Several GPS readings were taken and then averaged, to reduce the errors, at each location. The geographical precision of the GPS instrument, used singly, is quoted as about 50 m. In practice the positional accuracies obtained were variable but were largely between 50 m-80 m. Use of two GPS instruments in differential mode would have produced better accuracies but unfortunately this mode of operation was not feasible. Combination of GPS co-ordinate fixes, topographic maps and recent satellite images enabled reasonable confidence of the site positioning. The 50 m-80 m GPS accuracy compared to the 30 m satellite pixel resolution is however, a potential source of error. An attempt was made to select sites which were relatively uniform over an area large enough to encompass several TM pixels.

A quadrant of 30m x 30m was measured out at each location and a series of spectra were collected. Exposed and weathered soils and rocks, and representative samples of vegetation were scanned. The approximate percentage of vegetation cover, and therefore the contribution of vegetation to the 30x30 m spectral profile, was estimated for each sample area so that mixed pixel spectra could be generated.
Figure 6.1 a) Section at the Murazzano block-slide, from surface level to slip plane, showing location of samples used for XRD and spectroscopy (numbered 1-5); b) Sample grid (planned and actual) for the Langhe study area.
6.2.2.2 Landslide locations

These sites comprise known sites of rock exposure at block-slide localities (shown in Figure 6.1b). Spectra were collected from weathered, fresh and iron-stained rock surfaces, and from soils immediately above the landslides. GPS co-ordinates were recorded at the approximate centre and perimeters of each block-slide to obtain the best average fix.

Poor weather conditions and atmospheric absorption meant that the quality of Short Wave Infra-Red (SWIR) spectra was often very poor (low signal/noise ratio). The characteristic absorption features of hydrated and hydroxylated minerals were also obscured. Samples (listed in Table 6.1) from these sites therefore had to be collected for later scanning in a laboratory environment free of atmospheric interference.

6.3 Analysis of samples

6.3.1 XRD analysis

The samples were prepared and processed for XRD in a carefully controlled environment to prevent contamination by other substances and to prevent crystal structure damage during crushing. The analysis is automated and enables production of rapid and accurate results.

The Philips P1830 diffractometer system was used for the XRD analysis of sediment powder samples. The powdered sample is bombarded with X-rays and the dispersion of these rays produces a characteristic profile depending on the crystallographic characteristics of the materials in the sample. The X-rays are produced by the striking of a metal anode by high energy electrons from a heated filament in an X-Ray tube. For analysis of clay minerals, and most sediments, a copper anode is used.

Philips PC-ADP software was used to identify the major mineral peaks. Comprehensive details of both theory and instrumentation can be found in a number of texts, e.g. Nuffield (1967), Hunt & Salisbury (1971), Klug & Alexander (1974) and Hardy & Tucker (1988) and will not be described here.

Output is conventionally in the form of an analogue strip chart whose speed is synchronised with that of the detector in degrees of 2θ per minute so that the x-axis of the chart is calibrated in °2θ. The intensity of the response forms the y-axis of the chart and is measured in counts. Additional output is in tabular form, detailing angle (degrees), lattices spacing (angstroms), peak width, peak intensity, background intensity, relative intensity and significance. Two sets of strip charts are produced for whole rock and clay analysis, as the sample treatment is different and the region of
lattice spacings is much reduced in the clay analysis (0-40° for whole rock and 0-26° for clays). An example strip chart is shown in Figure 6.2.

6.3.1.1 Whole rock analysis

This forms the most basic application of XRD to sediment analysis. The samples are first air dried in a warming oven. The original grain size of the sample must be reduced to an average particle size of ~30 μm. Care must be taken not to damage the crystal structure during particle reduction as this can cause diffraction line broadening.

The next stage is the interpretation of the resulting strip chart. The peaks must first be measured and identified. A peak is usually defined as being any reflection reaching a height of twice the background intensity (see Figure 6.2). Phillips Diffraction Software - PC-Identify was used to identify 5-10 likely mineral groups in each sample. At least 2 significant peaks must be identified for confident mineral identification. This automatic peak identification is continued iteratively until all notable peaks are identified. Tables of dominant X-Ray diffraction peaks for minerals commonly found in sediments can be obtained from many texts (e.g. Hardy & Tucker, 1988) and a selection are listed in Table 6.2.

Table 6.2 Characteristic peak location angles (and d spacings) for common minerals, in degrees

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Illite</th>
<th>Muscovite</th>
<th>Chlorite</th>
<th>Quartz</th>
<th>Orthoclase</th>
<th>Albite</th>
<th>Calcite</th>
<th>Dolomite</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 (14)</td>
<td>8.9 (10)</td>
<td>8.9 (9.97)</td>
<td>18.5 (4.8)</td>
<td>20.8 (4.26)</td>
<td>23.6 (3.77)</td>
<td>22 (4.03)</td>
<td>29.42 (3.03)</td>
<td>31 (2.88)</td>
</tr>
<tr>
<td>20 (4.5)</td>
<td>19.8 (4.48)</td>
<td>17.3 (4.95)</td>
<td>31 (2.88)</td>
<td>26.6 (3.43)</td>
<td>26.9 (3.29)</td>
<td>27.8 (3.19)</td>
<td>36 (2.49)</td>
<td></td>
</tr>
<tr>
<td>24.6 (3.6)</td>
<td>34 (2.54)</td>
<td>35 (2.56)</td>
<td>35 (2.56)</td>
<td>39.5 (2.28)</td>
<td>27.46 (3.24)</td>
<td>24.26 (3.66)</td>
<td>43 (2.09)</td>
<td></td>
</tr>
<tr>
<td>35 (2.56)</td>
<td>37 (2.42)</td>
<td>45 (1.99)</td>
<td>48 (1.8)</td>
<td>47.5 (1.91)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 (1.53)</td>
<td>60 (1.53)</td>
<td>60 (1.54)</td>
<td>57 (1.605)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The relative proportions of each mineral group in the samples were derived (semi-quantitatively) by measuring the peak intensity values of certain diagnostic peak locations. The peak counts were multiplied by a weighting factor (specific to each mineral group), see Table 6.3. These values were then summed and individual percentages were derived from the totals.
Figure 6.2 Example strip chart of the X-ray diffraction pattern of pure calcite (after Hardy & Tucker, 1988).

Figure 6.3 Whole rock output strip chart from San Benedetto mudstone sample.
Table 6.3 Standard weights and d spacings of appropriate peak locations for each mineral group used to generate relative percentages.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Weighting</th>
<th>Diagnostic D Spacing (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (general)</td>
<td>2.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Quartz</td>
<td>1.0</td>
<td>4.26</td>
</tr>
<tr>
<td>Low Albite</td>
<td>1.2</td>
<td>4.03</td>
</tr>
<tr>
<td>Calcite</td>
<td>0.33</td>
<td>3.03</td>
</tr>
<tr>
<td>Illite</td>
<td>0.5</td>
<td>9.9-10</td>
</tr>
<tr>
<td>Orthoclase</td>
<td>0.53</td>
<td>3.3</td>
</tr>
<tr>
<td>Smectite</td>
<td>0.45</td>
<td>14-16</td>
</tr>
<tr>
<td>Muscovite</td>
<td>0.3</td>
<td>9.97</td>
</tr>
</tbody>
</table>

6.3.1.2 Clay analysis

Sample treatment for clay analysis involves several stages which are listed in Table 6.4 and are illustrated in the output plots by their representative colours. Clay mineral peaks are identified by eye in conjunction with published tables, and by their position and their behaviour during treatment and heating.

Certain clays are destroyed by heating to known temperatures. Pure clay peaks are observed unchanged throughout the heating process whereas mixed clay peaks tend to shift slightly to higher angles and disappear completely upon further heating. Kaolinite loses its crystallinity at 500°C. It is visible as a shoulder on the main chlorite peak at 12.5° (in the 400°C plot) but is destroyed and absent from the 550°C plot. Illite forms a strong, narrow peak at about 8° and smectite is distinctive as a broad peak at around 5°.

Table 6.4 Treatment procedure of samples during clay analysis

<table>
<thead>
<tr>
<th>Sample Treatment</th>
<th>Colour on strip charts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Air dried, oriented (base reflector)</td>
<td>Black</td>
</tr>
<tr>
<td>2. Ethylene Glycol (dropped on to expand the clays)</td>
<td>Red</td>
</tr>
<tr>
<td>3. Heated to 400°C for 2 hours</td>
<td>Green</td>
</tr>
<tr>
<td>4. Heated to 550°C for 2 hours</td>
<td>Blue</td>
</tr>
</tbody>
</table>

The relative percentages of the individual clay mineral groups can also be calculated semi-quantitatively. The area of a particular clay peak, at a certain treatment stage is used to calculate the relative percentages of the individual clays. Using the same Phillips Diffraction Software (PC-APD), the extents of a particular peak are defined (where the plot rises above the background level) and the angular position of the peak (in °2θ) is specified. A best fit curve of the clay peak is then
generated and the area under it calculated. This area, at a specified d spacing, is used to derive the relative percentages in each sample via the following equations:

\[
\text{Ill} & \text{Sm} = \frac{\text{Area}(10 \AA)[400^\circ C]}{\text{Area}(10 \AA)[400^\circ C] + \frac{1}{2}\text{Area}(7 \AA)[400^\circ C]} \quad \text{eqn 1}
\]

\[
\text{II} = \frac{\text{Area}(10 \AA)[\text{Glycolated}]}{\text{Area}(10 \AA)[400^\circ C] + \frac{1}{2}\text{Area}(7 \AA)[400^\circ C]} \quad \text{eqn 2}
\]

\[
\text{Sm} = \text{eqn 1} - \text{eqn 2} \quad \text{eqn 3}
\]

\[
\text{K} & \text{Chl} = \frac{\frac{1}{2}\text{Area}(7 \AA)[400^\circ C]}{\text{Area}(10 \AA)[400^\circ C] + \frac{1}{2}\text{Area}(7 \AA)[400^\circ C]} \quad \text{eqn 4}
\]

\[
\text{Chl} = \frac{\text{Area}(14 \AA)[400^\circ C]}{\text{Area}(10 \AA)[400^\circ C] + \frac{1}{2}\text{Area}(7 \AA)[400^\circ C]} \quad \text{eqn 5}
\]

\[
K = \text{eqn 1} - \text{eqn 2} \quad \text{eqn 6}
\]

Where \text{II} = \text{Illite}; \text{Sm} = \text{Smectite}; \text{K} = \text{Kaolinite}; \text{and Chl} = \text{Chlorite}
6.3.2 Results

6.3.2.1 Whole rock

The results of whole rock XRD analysis showed very similar patterns for all samples used. Many strong peaks were identified and found to be common to all samples. In all samples the most intense peak is at ca 26.5° which has been identified as quartz. The most common minerals identified in the samples from the Langhe were quartz, calcite, muscovite, feldspars (albite and orthoclase) and clay minerals (smectite, illite, chlorite and kaolinite). Figure 6.3 illustrates a representative profile from the Langhe samples with the main peaks identified. These results compare quite well with the results of Anselmi & Crovato (1995), who analysed a sample of siltstone from the Murazzano landslide which contained 29% quartz, 31% carbonate (calcite & dolomite), 25% muscovite, 8% feldspars and 7% clays. Granulometric analysis of the same sample indicated that 30% of the material was sand grade, 60% silt grade and 10% clay grade.

The relative percentages of each major mineral or mineral group were calculated using weighting coefficients shown in Table 6.3; the results are listed in Table 6.5 and are illustrated in Figure 6.4.

Table 6.5 Percentage contributions of major mineral groups to the whole rock analysis.

<table>
<thead>
<tr>
<th>Grid reference</th>
<th>Quartz</th>
<th>Clays</th>
<th>Carbonate</th>
<th>Feldspars</th>
<th>Micas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murazzano 1</td>
<td>423900, 4925240</td>
<td>11.16</td>
<td>9.51</td>
<td>61.76</td>
<td>8.75</td>
</tr>
<tr>
<td>Murazzano 3</td>
<td>“</td>
<td>22.72</td>
<td>16.98</td>
<td>28.71</td>
<td>15.72</td>
</tr>
<tr>
<td>Murazzano 4</td>
<td>“</td>
<td>38.79</td>
<td>15.21</td>
<td>9.62</td>
<td>23.33</td>
</tr>
<tr>
<td>Murazzano 5</td>
<td>“</td>
<td>18.97</td>
<td>8.86</td>
<td>26.95</td>
<td>20.72</td>
</tr>
<tr>
<td>Pianezza</td>
<td>422110, 4934625</td>
<td>20.05</td>
<td>8.97</td>
<td>18.58</td>
<td>32.74</td>
</tr>
<tr>
<td>Roddino</td>
<td>422500, 4936725</td>
<td>12.71</td>
<td>9.71</td>
<td>53.61</td>
<td>13.59</td>
</tr>
<tr>
<td>Serravalle</td>
<td>424500, 4934150</td>
<td>12.83</td>
<td>10.80</td>
<td>53.29</td>
<td>12.76</td>
</tr>
<tr>
<td>San Benedetto</td>
<td>425700, 4926715</td>
<td>20.21</td>
<td>13.59</td>
<td>23.85</td>
<td>23.30</td>
</tr>
<tr>
<td>Feisoglio</td>
<td>429250, 4933500</td>
<td>27.99</td>
<td>10.56</td>
<td>17.04</td>
<td>23.45</td>
</tr>
</tbody>
</table>

The quartz content is quite variable and the highest value calculated (38.8%) is for the soil sample from Murazzano. Clay content varies between 8.9% and 17% and the highest values being for Murazzano, Feisoglio and San Benedetto samples. The carbonate content is extremely variable, between 9.6% and 53.6%. This seems rather incongruous as relatively few carbonate peaks were identified on the whole rock plots and this casts some doubt on the accuracy of these percentages.
Figure 6.4 Percentage contributions of clay minerals to each sample: a) & b) Whole rock and c) & d) Clay analysis XRD results from rock and soil samples collected in the Langhe (ROD = Roddino, SER = Serravalle, PIA = Pianezza, SB = San FEI = Feisoglio, Benedetto, MUB = Murrazano).
6.3.2.2 Clay mineralogy

All samples display similar clay mineralogy. Minerals common to the samples include smectite (montmorillonite), kaolinite, illite and chlorite.

Smectite is characterised by high scattering at low angles, and is easily identifiable by the broad peak at 6° (14 Å). The lower angle peak of regular smectite is especially noticeable where the it shifts and broadens toward larger d spacing (lower angle) on glycolation and where it collapses upon heating to 400°C, to form a low, broad feature at 8.75° (10 Å). A higher angle peak is noticeable at 22° (4.06 Å) which is identified as Na-rich smectite (Na often substitutes for Mg and Ca within the smectite lattice, Kerr, 1977).

Illite is noticeable as two strong peaks, 1st order illite at 9°(10 Å) and 2nd order illite at 17.75° (4.98 Å). Peaks of illite are not affected upon glycolation and heating.

Chlorite and kaolinite are noticeable in all samples as a sharp peak (chlorite) with a smaller peak (kaolinite) on its shoulder at ca 12° (Å) and ca 25° (Å). The kaolinite shoulder collapses and disappears completely upon heating to 550°C as the crystal structure is destroyed.

No identifiable peaks characteristic of specific iron oxide minerals are detectable in the XRD profiles and yet the rocks are believed to contain iron. The iron present must therefore be amorphous or contained within the crystal structures of other silicate minerals. The chlorite-kaolinite peaks in the samples all occur at slightly higher angles than are listed in published tables. This is a result of the high iron content which causes expansion of the lattice structure, thus altering the angle of refraction (pers. comm. M. Gill, 1997).

Examination of the clay analysis profiles from the nine samples reveals noticeable differences in the shape and size of the peaks, and that there is an apparent change with respect to geographic location. There appears to be a stronger clay signature in the samples from the southern sites (Feisoglio, San Benedetto and Murazzano) than from the northern ones (Roddino, Serravalle and Pianezza), particularly in terms of the smectite peaks. The percentage contributions of clay minerals to each sample are shown in Figure 6.4.

Clay-poor samples

i) The Pianezza sample profile shows poorly defined peaks for most clays except Na-smectite, illite and muscovite at 21° (4Å) which are strong. This correlates well with values in Tables 6.5 and 6.6; clay content is relatively low (8.97%) and is dominated by smectite and illite (66.7% and 24.3% respectively).
ii) The Roddino profile shows very low intensity and poorly defined clay peaks, with the exception of regular and Na-smectite which are well defined though not very intense. There is also a peak at 22° (3.86Å) which has been identified as muscovite. Smectite dominates the clay contribution (78.2%), though the overall clay content is relatively low (9.71%).

iii) The Serravalle profile shows poorly defined peaks except regular smectite, though overall clay content is marginally higher at 10.8% (Figure 6.5a).

| Table 6.6 Percentage contributions of clay minerals to total clay content of Langhe samples |
|------------------------------------------|--------|--------|--------|--------|----------|
| Grid reference                          | Illite | Smectite | Chlorite | Kaolinite | Total clay |
| Murazzano 1                             | 35.54  | 30.09   | 2.67     | 31.70     | 9.51      |
| Murazzano 3                             | 28.91  | 54.62   | 0.00     | 16.46     | 16.98     |
| Murazzano 4                             | 18.49  | 72.65   | 2.09     | 6.78      | 15.21     |
| Murazzano 5                             | 25.86  | 54.70   | 0.00     | 19.44     | 8.86      |
| Pianezza                                | 24.27  | 66.69   | 0.00     | 9.04      | 8.97      |
| Roddino                                 | 13.35  | 78.18   | 0.00     | 8.47      | 9.71      |
| Serravalle                              | 17.67  | 67.07   | 0.03     | 15.23     | 10.80     |
| San Benedetto                           | 26.16  | 51.33   | 2.62     | 19.90     | 13.59     |
| Feisoglio                               | 27.50  | 53.16   | 2.81     | 16.52     | 10.56     |

Clay-rich samples

i) The Feisoglio profile shows many well defined clay peaks, notably those of regular smectite, illite and chlorite, though Na-smectite is not well developed. Kaolinite is noticeable at 25° (3.54Å). The overall clay content is still relatively low (13.4%) and smectite is dominant (51.3% smectite, 26.2% illite).

ii) The results from the four Murazzano samples are quite well correlated. They all show well defined but relatively low intensity regular smectite, 1st order illite and chlorite peaks. Na-smectite is quite strong and well defined in samples 1, 3 and 4. The smectite peak intensity of sample 1 (mudstone) is lower than 3 (siltstone), 4 (soil) and 5 (mudstone) and this correlates with the relative percentages in Table 6.6. The clay content of 1 is split evenly, 30% smectite, 35% illite and 31.7% kaolinite, whereas that of samples 3, 4 and 5, is dominated by smectite, especially so in sample 4 (73% smectite). Sample 3 shows the highest total clay percentage, at 20.4%. It is interesting that soil sample 4 shows the greatest percentage of all clay mineral types, this suggests a higher resistance to decomposition on weathering. The soils in the study area are predominantly residual and the concentration of clay minerals in this layer may reflect the continual chemical breakdown of rock minerals into clays during weathering. Vertical variations in clay mineralogy, i.e. through a stratigraphic sequence, may indicate changing source areas of the sediment (Hardy & Tucker,
Figure 6.5 Clay analysis strip chart output of a) clay rich sample (San Benedetto); and b) clay poor sample (Serravalle).
(1988), or deposition which is more distal to the source area.

iii) Samples from San Benedetto show very strong and well defined peaks for all clays (see Figure 6.5b). Table 6.6 indicates that the overall clay content is quite high (13.8%) and that smectite comprises 51.3% of that clay content.

6.4 Analysis of field spectra

6.4.1 VIS - NIR - SWIR Spectroscopy

Reflectance Spectroscopy is a technique which uses reflected energy in the visible (VIS, from 0.4-0.7 μm), Near Infra-Red (NIR, from 0.7-1.3 μm) and Short Wave Infra-Red (SWIR, from 1.3-2.5 μm) wavelength regions to analyse materials.

Rocks are composites of minerals, which are themselves composed of molecules with varying types of bonds, so that rock spectra are assemblages of their constituent mineral spectra. Certain atoms and molecules absorb energy as a function of their atomic structures. The most important processes involved are electronic and vibrational transitions. Electronic transitions within atoms are observed at shorter wavelengths than vibrational transitions within molecules (which are observed in the SWIR), as they require more energy. A brief description of these processes is given here though full details can be found in texts such as Hunt & Salisbury (1971), Hunt (1979) and Clark (1997).

The spectral reflectance characteristics of various minerals are the result of their differing physical and chemical properties. This behaviour is observed as a reflectance spectrum, with absorption features, which characterise and are used to identify the materials present. Absorption features are seen as troughs, and indicate that energy has been absorbed over a range of wavelengths.

The three main regions of spectral reflectance in the electromagnetic spectrum and the mechanisms which cause absorption in each region are listed in Table 6.7.

Table 6.7 Spectral reflectance regions and absorption features

<table>
<thead>
<tr>
<th>Region</th>
<th>Dominant mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>Charge transfer</td>
</tr>
<tr>
<td>VIS/NIR</td>
<td>Crystal field effects</td>
</tr>
<tr>
<td>SWIR</td>
<td>Vibrational transitions</td>
</tr>
<tr>
<td>UV-&gt;SWIR</td>
<td>Conduction bands</td>
</tr>
</tbody>
</table>

The most common components of rocks and minerals are silicon, oxygen and aluminium with varying amounts of iron and other metals. Iron-bearing minerals show features due to electronic
transitions in ferrous ($\text{Fe}^{2+}$) ions. The positions of the features relate to the symmetry, degree of lattice distortion and co-ordination of the feruginous ions in various minerals. These transitions are the results of crystal field effects. Another type of transition, known as charge transfer, is caused by metal ion electrons (which are not strongly bonded to the ions) being transferred from one to another, and gives metals their property of high conductivity.

6.4.1.1 Electronic Processes

Isolated atoms and ions have discrete energy states. Absorption of photons of a specific wavelength causes a change from one energy state to a higher one. Emission of a photon occurs as a result of a change in an energy state to a lower one. When a photon is absorbed it is usually not emitted at the same wavelength. There are two processes responsible for electronic absorptions:

a) Charge Transfer Absorptions - or inter-element transitions, where the absorption of a photon causes an electron to move between ions or between ions. The transition can also occur between the same metal in different valence states, such as between Fe$^{2+}$ and Fe$^{3+}$. In general, absorption bands caused by charge transfers are diagnostic of mineralogy. The strength of these absorptions are typically hundreds to thousands of times stronger than those produced by crystal field transitions (Clark, 1997).

There are a whole suite of iron oxides, iron hydroxides and iron sulphates, all with similar electronic absorption bands in the visible and near-infrared. Haematite has a narrower absorption feature at a slightly shorter wavelength than goethite (Hunt et al., 1971)). A coarse-grained haematite has a broader absorption, similar in position and width to that of a fine-grained goethite. Jarosite, an iron sulphate, has a diagnostic absorption at 2.27 $\mu$m due to a combination OH stretch and Fe-OH bend.

b) Crystal Field Effects - The most common electronic process revealed in the spectra of minerals is due to unfilled electron shells of transition elements (e.g. Ni, Cr, Co and Fe). Iron is the most common transition element in minerals. Absorption of a photon results in an electron being moved from a lower level into a higher one. The crystal field varies with crystal structure from mineral to mineral, so that the same ion can produce different absorptions, making specific mineral identification possible from spectroscopy.

Iron oxides, hydroxides, and sulphates show very strong absorption in the visible and spectroscopy detects at very low levels in this region so that they can be detected below levels of other methods e.g. XRD, and in the case of amorphous materials, when other methods are not sensitive to their presence.
6.4.1.2 Vibrational processes

These are caused by excitation and affect anion groups (OH, CO$_3$ and SO$_4$). The most important vibrational transitions in the VIS are those associated with OH$^-$ ions or water molecules bound in the crystal structure (or as fluid inclusions). Water molecules have fundamental vibrational transitions caused by H-O-H bond stretching at 3.11 µm and 2.9 µm and bond bending at 6.08 µm. The combination of these produces absorption characteristic mineral absorption features at 1.9, 1.4, 1.14 and 0.94 µm. These are however, only useful in a laboratory environment as their effects are obliterated by atmospheric water vapour.

Many silicate minerals contain OH- ions which have a bond stretching transition at 2.7 µm. Common metal-hydroxyl bonds Mg-OH and Al-OH produce absorption features at 2.3 µm and 2.2 µm. These are common to alumnus micas and clays, and are very useful for discriminating chemically different rocks and soils. The broad band nature of Landsat TM limits its potential to the detecting the presence of hydroxylated minerals. Detailed discrimination is made possible using high spectral resolution image data e.g. AVIRIS. Similar vibrational characteristics are displayed by carbonates, which are caused by stretching of the C-O bonds in the CO$_3^{2-}$ ion. A useful characteristic for geological discrimination is that the change from felsic to mafic compositions causes absorption features to shift toward longer wavelengths.

6.4.2 Instruments

6.4.2.1 Field spectra-radiometry using IRIS Mk IV

Field spectral profile data have been recorded using the GER (Geophysical Environmental Research Inc.) Single Field of View (FOV) IRIS Mk IV spectra-radiometer. This is a portable, tripod-mounted device, comprising 2 units: an optical head and a portable MS-DOS computer, linked by a 2m cable, see Figure 6.6a. The instrument was chosen for its broad spectral range, high spectral resolution and the high performance in the field. The features of the instrument are:

a) extended wavelength operation - 0.35 to 3.0 µm under laboratory conditions and 0.35 to 2.5 µm in the field.

b) high spectral resolution: 2 nm over the range 0.35 to 1.0 µm, 4 nm over the range 1.0 to 1.8 µm and 5 nm over the range 1.8 to 3.0 µm.
Figure 6.6 a) GER IRIS Mk IV portable spectrometer; b) ASD FieldSpec FR portable spectrometer.
c) scan control and data storage, performed onboard the instrument and downloaded to a portable computer.

The instrument scans an area of \( \text{ca} \ 34 \ \text{cm} \times 13 \ \text{cm} \) from a working height of \( \text{ca} \ 1.5 \ \text{m} \). This corresponds to an angular field of view of \( 13 \times 5 \) degrees. A boresight allows the instrument to accurately positioned above the target. The single FOV allows the target and reference to be measured sequentially. Total measurement time is about one minute.

Pre-processing is performed by MS-DOS software which corrects the spectra for the dark current of the hybrid Si/PbS detectors and normalises for any variations in sensor gain. The spectra are calibrated in terms of wavelength and reflectance is calculated from target-reference pairs. Radiance calibrations are also possible.

The raw scan files (separate target and reference data) were processed and combined using special software, designed at NERC EPFS (Equipment Pool for Field Spectroscopy), to produce reference corrected spectral profiles. Further routines were used to convert the reference corrected spectra to absolute reflectance values. Profiles from similar target types (and in some cases, from the same target) were also averaged together at this point. These files were then converted to ASCII format in order to import to MS Excel for mixing and plotting.

The component rock, soil and vegetation profiles from each location were combined by weighted summation, according to their estimated percentage contributions, to form mixed reflectance profiles. The mixed reflectance profiles are then plotted with the individual component profiles for comparison.

6.4.2.2 Laboratory spectra-radiometry using ASD FieldSpec FR

The ASD FieldSpec FR was used to collect spectra from selected soil and rock samples in a laboratory environment, free of atmospheric absorption effects. The FieldSpec is a high resolution, portable instrument, with a pistol-grip optical sensor, although it also has a tripod mount (Figure 6.6b). The instrument has automatic dark current correction, collects data as raw DN, irradiance or reflectance, and has fibre-optic input.

The FieldSpec FR contains three detectors: one spectra-radiometer for VIS/NIR; and dual spectra-radiometers for NIR. The spectra from each are automatically joined by inbuilt software to form a continuous profile from 350 - 2500 nm. Scan time is 0.1 second.

A UV-lamp was used as the light source in a blackened room. Under laboratory conditions the signal-to-noise ratio is very high and so the spectra collected are clear of interference. The instrument was used in the laboratory at NERC's EPFS site at Southampton University.
6.4.3 Results

The field spectra were only of use for identifying iron-minerals because of severe atmospheric absorption and consequent low signal/noise ratio at longer wavelengths. Very few spectra were collected with usable data beyond 1.1\mu m. The characteristic absorption features of many clays fall into atmospheric absorption windows and are obscured so that SWIR data had to be derived from laboratory spectra. These data show very high signal/noise ratio but the number of samples is very limited.

6.4.3.1 Iron oxide spectra

Comparison with published iron mineral spectra in texts such as Hunt & Salisbury (1970 and 1971) and Hunt (1977) enable the identification of characteristic absorption features of iron-minerals in the spectral profiles from the Langhe.

Examples of collected spectra which show well developed iron mineral absorption features are shown in Figure 6.7a and selected published iron oxide spectra are shown in Figure 6.7b. All spectra shown are of rocks and soils collected from block-slides at Pianezza, Costalunga, San Benedetto, Feisoglio and Murazzano, whose their locations are shown in the map in Figure 6.1b. The spectra display very strong absorption shoulders at 486 nm and 650 nm and broad absorption feature at 950 nm. The position of these features is characteristic of ferrous Fe$^{3+}$ ion present in iron oxides such as goethite, rather than the ferric Fe$^{2+}$ ion which is characteristic of haematite. Absorption features characteristic of the ferric ion occur at slightly higher wavelengths (see Figure 6.7).

There is commonly a high correlation between the forms of spectra collected from rocks and soils of the same location, indicating that the mineralogy of soils reflects that of the rocks beneath (Figure 6.8).

A great many of the localities where spectra were collected show poorly developed iron signatures or an absence of iron absorption features. The spectra from all the sample localities were examined and classified into three crude but well defined groups on the basis of iron oxide absorption feature development:

I. none detectable

II. poorly defined

III. well-defined, well-developed
Figure 6.7 a) Published spectra of iron-oxide minerals (after Hunt et al., 1971); b) Field spectra collected from rocks samples in the Langhe.
Figure 6.8 Spectral reflectance curves of soils and rocks from the Costalunga landslide, illustrating the similarity of features between rocks and soils at the same site.

Figure 6.9 Spectral curves from three types of soil recognised by strength of iron-oxide absorption features, Type I (no noticeable features), Type II (partly developed features) and Type III (well developed features).
The three types of soil spectra are illustrated in Figure 6.9. The crudely classified spectra were then plotted on the sample map and hand contoured (Figure 6.10). From the pattern produced it can be seen that major block-slide localities fall in areas characterised by strong iron oxide absorption features, where rocks and soils contain a lot of iron of one form or another.

6.4.3.2 Clay mineral spectra

Comparison with published clay mineral spectra in texts such as Hunt & Salisbury (1970), and Hunt (1977 & 1979) enabled the identification of characteristic absorption features of clay minerals in the spectral profiles. Table 6.8 lists the wavelengths of layer silicate minerals detected in rocks and soils of the Langhe. The smectite (or montmorillonite) group refers to a family of clay minerals which are known for their swelling properties, i.e. their ability to take up water into their crystal structure (Chapter 2 and Appendix A). Different families within the montmorillonite (smectite) group include: Hectorite, Saponite (with Mg-OH features at 1.4 and 2.3 μm); Nontronite (with a 2.25 μm absorption feature); and Beidellite (an Al species). The individual species are not easily identifiable in reflectance spectra as their absorption features are commonly at similar wavelengths.

Table 6.8 Absorption features of minerals present in rock and soils in the Langhe.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Absorption feature</th>
<th>Absorbing Molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smectite, Illite &amp; Kaolinite</td>
<td>1.4 μm</td>
<td>OH &amp; water</td>
</tr>
<tr>
<td>Smectite</td>
<td>1.9 μm</td>
<td>Molecular water, atmospheric water</td>
</tr>
<tr>
<td>Smectite, Illite, Kaolinite &amp; Micas</td>
<td>2.2 μm</td>
<td>Al-OH</td>
</tr>
<tr>
<td>Chlorite</td>
<td>2.2-2.6 μm</td>
<td>Fe(OH)</td>
</tr>
<tr>
<td>Carbonates</td>
<td>2.29-2.35 μm</td>
<td>CO₃²⁻</td>
</tr>
<tr>
<td>Chlorite, and Micas</td>
<td>2.3 μm</td>
<td>Mg(OH)</td>
</tr>
</tbody>
</table>

Figure 6.11 shows characteristics clay mineral absorption features of the Langhe samples and selected published clay mineral spectra for comparison. The Langhe sample spectra show the absorption feature of smectite at ca 1.4 μm but this coincides with those of kaolinite and muscovite. The characteristic water absorption feature of smectite is however easily identifiable at ca 1.9 μm. Characteristic features of kaolinite and muscovite at ca 2.2 μm are poorly developed.
Figure 6.10 Variations in iron-oxide spectral signature of soils (spectra collected at samples localities shown) with major block-slide localities and geological boundaries.
Figure 6.11 a) Published clay mineral spectra (after Hunt & Salisbury, 1970); and b) field spectra from selected rocks and soil samples in the Langhe.
but just discernible. Figure 6.11b also shows that subtle differences between individual clay species is not practical using the spectral bands of TM.

Comparison between reflectance spectra and XRD results can be performed to verify the results of spectral analysis (Keeling & Mauger, 1997). In a similar way to that of Keeling & Mauger (1997), the depths of clay absorption features (at a specific wavelength) have been plotted against the corresponding clay peak intensity (counts s⁻¹) from XRD analysis. Smectite absorption at 1.9 μm was used as this wavelength is not shared with other clays in the samples. The results of this comparison are shown in Figure 6.12 and show a reasonable correlation between the results of these two techniques.

Figure 6.12 Correlation of XRD peak intensity with depth of absorption features produced by smectite in reflectance spectra, for samples listed in Table 6.1.

6.4.4 Comparison of reflectance spectra with image spectra

This mixed profiles were filtered (using “MASTER” software routines designed and provided by NERC EPFS) to produce weighted average values corresponding to the band-widths of TM’s six reflected bands within the 0.35-2.5μm range. Image DN values were extracted from the TM-DPS and TM-SR (described in Chapter 5) data at the sample location points using the recorded GPS coordinates and maps. These DN were compared with the filtered reflectance spectra values (Figure 6.13).
Figure 6.13 a) Correlation of filtered IRIS reflectance values with TM-DPS values from selected grid localities; b), c) and d) IRIS, TM-DPS and TM_SR spectral profiles from selected localities (locality 1 (b); 17 (c); and 21 (d)).
At many grid locations the filtered IRIS spectral profiles bear no resemblance to TM spectral profiles using either TM-DPS or TM-SR. At a few of the 38 locations, the filtered IRIS spectra resemble the TM-DPS profiles very closely (selected profiles are shown in Figure 6.13). Figure 16.6a illustrates the good correlation between TM-DPS and IRIS reflectance values ($R^2 = 0.83$) which justifies the use of TM-DPS values over raw DN. The spectral profile in Figures 6.13b (grid locality 1), illustrate a grid location where IRIS absolute reflectance and TM-DPS correlate quite well. Spectra from grid locality 17 show poor correlation due to changes in vegetation cover and surface character (Figure 6.13d). Spectra from grid locality 21 show poor correlation because of widely differing illumination conditions (Figure 6.13c). In Figures 6.13b - 6.13d the TM-SR does not correlate with either IRIS reflectance or TM-DPS values.

The lack of correlation between the collected IRIS reflectance spectra and the TM-DPS at many of the grid locations is caused by:

- poor data quality beyond 1.1μm.
- landuse and vegetation cover changes between TM acquisition and field work.
- significant illumination and haze differences between TM acquisition and field work.

6.5 Summary

This chapter has demonstrated the presence of both iron oxides and smectite in the rocks and soils at block-slide localities in the Langhe study area. It has also shown that the character of soils closely reflects that of the rocks from which the soils are derived.

The XRD results show that smectite is the dominant clay mineral in all samples, though the relative percentages are variable and in some cases, quantitatively a little doubtful. The content of smectite also appears to be variable. This variability suggest perhaps that the quantity of smectite in the rocks is less important than its mere presence and the structure of the rocks bearing it, i.e. numerous, thin and laterally extensive smectite-rich layers. It is unfortunate that no control samples from adjacent areas (not experiencing landslides) could be analysed but it seems unlikely that the sediment composition should vary greatly over such short distances.

From the profiles and relative percentages it seems that the clay content and assemblage of the samples is quite varied (geographically and stratigraphically). A common feature is the dominant presence of smectite. Smectite and illite in mixed-layer form have been found to show significant swelling in the presence of water, resulting in reduced shear strengths, and initiating landsliding (Al-Homoud et al., 1996; El Amrani Paaza & Chacon, 1996; and Hossain et al., 1997). Further sampling and laboratory analysis are required to determine how total clay, smectite and
illite contents vary, or the significance of such variations in the generation of instability and failure initiation.

The XRD profiles show no identifiable iron oxides species but do show signs of the presence of iron, i.e. some peaks occurring at angles higher than in published tables. This suggests that the iron is contained inside other minerals or is an amorphous weathering product. The reflectance spectra of the samples demonstrate the presence of both iron oxides and strong smectite characteristics. Other clay minerals species are not as easily identifiable as smectite, as either their absorption features are subtle or are swamped by those of smectite.

There is considerable variation in the iron oxide spectral absorption features in samples from different localities. This seems reasonable if the iron is an amorphous weathering product brought up into soils by strong leaching through fracture networks. The classification and contouring of the spectra on the basis of the strength of the iron oxide absorption features, seems quite crude but the spectra fall conveniently into these groups. The coincidence of the major block-slide localities with regions of strong iron oxide absorption lends weight to the hypothesis that areas of extensive fracturing are associated with iron-rich soils.

It is clear once again that the area of study is a very difficult remote sensing target. A more uniform surface exposure of soil (or rock), less vegetation and less hazy atmospheric conditions would have made this part of the research less troublesome.

The dominant presence of smectite, a clay whose swelling behaviour is known to lead to instability, has been proven. The presence of iron oxides in the samples has been demonstrated, and has enabled a link to be made between iron oxides features in soil spectra and the location of major block-slides. This link provides evidence of the influence of fracturing and water flow on the initiation of block-sliding. Despite limited samples and poor quality spectra, the mineralogical analysis has revealed significant information about the mineralogy of rocks and soils in the Langhe.
Chapter 7 Slope Stability Analysis and Hazard Assessment

7.1 Introduction to techniques

This section of the research concentrates on the Langhe case study for two reasons: the study is a timely one which has attracted considerable attention in Italy in recent years; and the nature of the case lends itself to GIS analysis in that many landslides have occurred periodically and over a sizeable area. The mudslide disaster, of May 1998 in Sarno, devastated the community, causing millions of dollars in damage, and newspapers reported a local feeling that the disaster could have been prevented or perhaps predicted. Perhaps when digital techniques for routine hazard analysis are in place in all high risk regions, then such a disaster could be predicted.

The objectives of this chapter are three-fold and comprise the following:

• compilation of thematic information from remote sensing, DEM (and its derivatives), and from digitised land survey maps into the GIS database.

• stability analysis of selected slope profiles and of the whole study area

• multi-criteria hazard assessment (using probability and decision tools) to produce a series of hazard and risk maps.

7.1.1 Database preparation and compilation

The main sources of input are the DEM, published topographic and geological maps, remotely sensed image data (from Landsat TM and SPOT-Pan), field information and geotechnical information from a few published articles. The SPOT image data enabled identification and mapping of recent landslides for comparison with past occurrences and with the hazard maps produced analysis of the land survey data.

A necessary criterion for the production of any GIS database is data conformity. All data layers must have identical geographic co-ordinates (raster rows and columns), pixel size and map projection if multi-layer processing is to be possible. This preparation is the most time consuming operation and often proves more problematical than first envisaged.

Initially, the input data were far from uniform and after clipping and resampling, the final working area for the GIS and its location with respect to total data coverage is shown in Figure 7.1. The inputs to the GIS hazard assessment database are listed in Table 7.1.
Figure 7.1 Map showing image data coverage and final working area of the GIS.
7.1.1.1 Digital Elevation Models

The Digital Elevation Model was generated via stereo-matching of 1992 stereo air photography by staff at the Polytechnic of Turin. The data were originally sampled in 80 m swaths (later interpolated to 50 m) and were provided as a series of tiles of approximately ca 33 km² in area. The tiles were joined with reasonable confidence, by checking with drainage networks, to form a mosaic. After mosaicing a few narrow gaps between tiles remained and these were patched by duplication of a line or column of pixels. These errors are easily detectable as vertical or horizontal lines, mainly in the south-eastern part of the study area, and should be ignored. The 50m DEM mosaic was then sub-sampled, by linear interpolation, to 10m comparable to the geo-referenced satellite data. The elevation precision of the DEM depends on the scale being used but according to source, approximates to 1/10,000th of the altitude of the aircraft and at this scale of study between 2 and 6 m.

The DEM has provided a very useful information source from which slope angle (degrees), aspect (degrees) and curvature were derived, and these derivatives have been used for both image and GIS processing. It is important to note however, that local errors in the terrain elevation contribute heavily to errors in slope angle and aspect, and that the 'roughness' of the resultant image increases with the order of the derivative calculated.

DEM derivatives - Slope is defined by a plane tangent to the surface at any given point, and comprises 2 components: gradient (the maximum change in height) and aspect (the compass direction of this change).

- Slope gradient is measured in degrees (or percent) and is calculated as the first derivative of elevation. There is a pronounced asymmetry to the topography in the study area (refer to Figure 2.7 and 4.3). The slopes vary from 0 to 53⁰ and comprise two populations which are easily distinguishable in the field; those which are gently dipping (ca <18⁰) and those which form steeper, scarp slopes (ca 18 - 53⁰). The gentle slopes occupy the greatest part of the study area (ca 64%).

Slope gradient is often described as run (distance x) over rise (distance z) and for square pixels is given by the following expression, where \( G \) = gradient; \( Z \) = elevation (m); \( X \) = horizontal distance in metres Eastings); and \( Y \) = horizontal distance in metres (Northings):

\[
\tan G = \left[ \left( \frac{\Delta Z}{\Delta X} \right)^2 + \left( \frac{\Delta Y}{\Delta X} \right)^2 \right]^{1/2}
\]

Alternatively, for raster image analysis where calculations are made from pixel centres, slope gradient is calculated by the following formula, where \( i \) = column reference; \( j \) = line reference; and \( x \) = distance between pixel centres:
\[ G_x = \left[ \frac{\partial Z}{\partial X} \right]_x = \frac{(Z_{i+1,j} - Z_{i-1,j})}{2\Delta x} \]

- **Slope aspect** - azimuth (deg) obtained by focal calculation from slope angle and elevation data. Values range from 0 - 360°. Again there are two noticeable populations of slopes: those facing north-westward (240° to 020°) and those facing directions between SW and NE (020° to 240°). Slope aspect is calculated by the following formula:

\[
\tan A = \frac{-\Delta Z / \Delta Y}{\Delta Z / \Delta X}
\]

- **Slope curvature** - obtained by calculation of the second derivative of elevation, i.e. the change in gradient. Values are either positive, where gradient increases, or negative, as gradient decreases, or zero where gradient is constant, and are given in units of degrees/100m. Curvature in the study area is extremely variable and little pattern is evident. Slope curvature has been found to be significant to slope instability, e.g. Hovius et al., 1995, but it is difficult to establish any relationship in the Italian case.

- **Slope profiles** - elevation data (m) were extracted, in ASCII form, from several slopes where major block-slides occurred.

### 7.1.1.2 Geological and geotechnical data

- **Bedrock and soils** - The soils in the area are residual and from a remote sensing point of view, they are the visible expression of rock beneath. As no bedrock is exposed, soils (and the geological map) form the only input of geological information to the GIS. Soils on steeper slopes are well drained, rich in organic matter (where wooded) and generally 0.5 - 1.5 m depth. Soils on the gentle slopes are usually friable, well structured and between 0.5 and 3 m in depth. Where the rocks are intensely fractured, weathering is deepest, down to ca 30 m at San Benedetto, though generally the moderately to highly weathered zone extends to a depth of ca 5-15 m. There is no evidence of glacial materials or periglacial activity. With the exception of flood derived and alluvial deposits, the soils are interpreted as residual.

Though there are clear formation boundaries on the 1:100,000 geological map, lithological variations appear to have little effect on a) soils; and b) the occurrence of landslides (refer to section 4.1.1 for stratigraphic column, lithological descriptions and geological map in Figure 4.4).

- **Geotechnical data** - Information for this section of the work has been provided by published geotechnical results (as described in section 4.1.6.2).

There is little information about regional ground water levels due to a rather amusing socio-economic catch. Local farmers prefer not to divulge the number and whereabouts of their wells to
the local authorities, being taxed on the wells and water they extract (pers. comm. Bottino, 1995). No water table maps of the area were readily available for scientific work at the time of this study. For the purposes of the geotechnical evaluation attempted here, the water table has been assumed to be at ground surface level at the time of failure.

Modelling of the two dimensional vertical section is the normal method of geotechnical analysis. A full geotechnical and statistical analysis implies consideration of the fourth dimension of time which is not possible because of data limitations and is not within the scope of this research. The paucity of geotechnical data dictates that a relatively simple approach to the hazard assessment is used.

- Rock fractures - The landslides affect both rocks and soils and although the rocks aren’t exposed, the rock structure and fracturing contributes significantly to slope stability. Fracture orientations and dips were measured in the field and distinct populations were observed. These data formed input for stereo-plotting and kinematic admissibility analysis in section 7.2.2.

7.1.1.3 Remotely sensed data

ERMapper binary (BIL) images of iron-oxide, hydrated (clay) mineral and wetness indices, generated in Chapter 5, were imported to Idrisi.

7.1.1.4 Infrastructure and geographical data

Road and drainage network data were digitised from the only publicly available topographic maps of the area, which were produced in 1945 and updated in 1961 (at 1:50,000 scale). The road data were compared with the 1995 SPOT Pan imagery and a few additional road links were added to the existing road vectors. Many tracks indicated on the 1961 maps now have tarmac and are main roads. Largely though, the road networks in the 1961 maps were unchanged. Drainage network information is very detailed, is unlikely to have changed significantly between 1961 and 1995, and compares well with the SPOT imagery.

Table 7.1 Factor layers in GIS database and their relationship to slope stability hazard

<table>
<thead>
<tr>
<th>GIS layer</th>
<th>Significance based on field observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle</td>
<td>Field evidence suggests a relationship between increasing slope angle and a change from block-sliding to debris-flows. Block-slides are observed on gentle slopes (ca less than 18°) and debris-flows are seen on steeper slopes (ca more than 18°) (Figure 7.2).</td>
</tr>
<tr>
<td>Slope aspect</td>
<td>Field evidence suggests a relationship between slope aspect and landslide type (seen both in the field and in SPOT-Pan images). Slopes facing north-westward experience block-slides and those facing south-eastward experience debris-flows, though the thresholds are less well defined than those of slope angle (Figure 7.3).</td>
</tr>
</tbody>
</table>
Elevation

The relationship between landslides and elevation is unclear, though in general landslides seem to occur above a height of ca 350m (see Figure 7.4).

Distance from roads

Field evidence points to a relationship between roads and landslide susceptibility - perhaps by removal of vegetation, inhibiting surface drainage, channelling run-off, or by enhancing the downward percolation of water (Figure 7.5).

Distance from drainage

Field evidence suggests a link between debris-flows and drainage channels, on steep slopes (indicated in SPOT image data and from filed observation). Block-slides also tend to be bounded by drainage channels (Figure 7.6).

Clay index

Clay content in residual soils reflects, to a degree, the clay content of rocks beneath and its low permeability leads to impeded drainage and instability. See Figure 5.18b

Iron-oxide index

Relationship between iron-oxide stained fractures, iron-oxides in soils and block-slides (control crown wall and often pervasive in displaced blocks). See Figure 5.18a

Soil wetness index

High moisture content of soils results from impeded drainage, low permeability and thus instability. See Figure 5.20

7.1.1.5 Database quality, errors and natural variation

The spatial variation of natural phenomena is a fundamental part of nature which occurs at all scales (Burrough 1986) and so is not merely a function of local noise or inaccuracy that can be corrected. There are however various other sources of error, some of which are listed in Table 7.2.

Table 7.2 Possible sources of database error

<table>
<thead>
<tr>
<th>Error at data source</th>
<th>age of the data - reliability decreases with age (less significant on geological time scales); incomplete or mis-registered aerial coverages; varied map scales; density of sampling; transfer between formats.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Errors arising from processing</td>
<td>numerical errors (computational); mis-use of logic; topological errors; classification and generalisation errors; precision.</td>
</tr>
<tr>
<td>Errors arising from spatial and natural variation</td>
<td>positional measurement error; observer bias; scale and unit of measurement (fractal dimensions).</td>
</tr>
</tbody>
</table>

Precision and attribute value errors are inherent in any database but practice requires these to be recorded in the compilation of the GIS. The normal expression of measurement error for an attribute refers to the degree to which measurements vary from the true value and this is expressed as RMS value, as described in Chapter 5.3, and is illustrated in Figure 7.7. This value is especially important in decision making when calculating the probability that a value is greater or less than a threshold.
Figure 7.2 a) Slope angle image, b) slope angle frequency and c) block-slide frequency for the entire study area.
Figure 7.3 a) Slope aspect image, b) slope aspect frequency and c) block-slide frequency for the entire study area.
Figure 7.5 a) Distance from roads image, b) distance frequency and c) block-slide frequency for the entire study area.
Figure 7.6 a) Distance from drainage image, b) distance frequency and c) block-slide frequency for the entire study area.
For example, the DEM used here is quoted as having an elevation error of between 2 and 6 m, so for the purposes of this study a mean value of 4.0 m would be taken as the RMS for the DEM. As slope and aspect are calculated from this DEM, the RMS value is propagated through, and increased, in any derivatives. The remotely sensed image data are normally distributed over narrow value ranges and their RMS values were taken as the calculated standard deviations, in this case between 0.005 and 0.15. Pen width (ca 0.5 mm) and digitising result in errors (e.g. drainage and road network images) which depend on the scale of study and output; at a scale of 1:50,000 this would produce an error of ca 25m on the ground.

7.2 Slope stability analysis

There are several reasons for analysing slope stability: to assess the likely stability of an existing slope which has not yet failed, or to design remedial measures to stabilise a slope where failure has already occurred, or to anticipate the stability of a slope yet to be excavated, or where land use is likely to change.

7.2.1 Soil slope stability

7.2.1.1 Established methods of analysis

The simplest technique to be applied is the $\phi_s=0$ method, i.e. total stress (Skempton, 1948), where the soil is assumed to be purely cohesive. In drained or partially drained conditions, or with
less cohesive materials, effective stress methods are used. A brief description of the different cases of effective stress analysis is given here, though detailed information and illustrations can be found in other texts (e.g. Skempton, 1948, 1953 & 1964; Skempton & DeLory, 1957; Bishop, 1955; Morgenstern & Sangrey, 1978; Hutchinson, 1988; Chandler, 1970, 1977 & 1984; Bromhead 1992).

Different approaches have been developed to describe and analyse slope failures of varying form. There are three general cases: planar, circular and non-circular surfaces and these are summarised in the following section. The techniques have developed under some controversy over the last century or so and a summary can be found in Skempton (1949). The term 'Limit Equilibrium' has been applied to systems of forces which are just at the point of failure. Limit Equilibrium analysis is repeated with different mechanisms to find the lowest factor of safety, i.e. the least safe situation for a given geometry, strength and pore pressure assumptions.

The general assumptions of Limit Equilibrium analysis method are as follows:

- a mechanism of collapse must be postulated, involving slip planes (planar or curved).
- a failure criterion is satisfied in terms of shear strength (total or effective).
- the static equilibrium of the overall mechanism and of each 'block' or 'slice' must be satisfied, by resolving forces and by taking moments of boundary forces (weights of blocks, external loads, water forces). All Limit Equilibrium methods do not satisfy these criteria but those which do are termed 'rigorous' methods.
- internal stresses in the soil/rock 'blocks' are not considered.
- the 'blocks' are rigid.
- the factor of safety (F) is defined as: \( F = \frac{\text{Total Resisting forces}}{\text{Total Disturbing forces}} \); or as the factor by which the shear strength parameters are reduced to bring the slope into a state of limiting equilibrium on a given failure surface.
- the factor of safety is uniform over the slip surface.

7.2.1.1.1 Planar failure

The simplest form of sliding surface is a plane roughly parallel to the ground and this is approximated to by many translational slides. The term 'infinite slope' refers to a uniform slope of an extent large enough that a typical element can be considered representative of the whole slope, so that irregularities at the toe or head can be ignored.

The general equation for the planar method is described by the following:
\[ F' = \frac{c' I + \left( W \cos \psi_p - V \sin \psi_p - U \right) \tan \phi}{W \sin \psi_p + V \cos \psi_p} \]

Where \( W = \) horizontal stress; \( V = \) vertical stress; \( \psi_p = \) angle of failure plane; \( \psi_f = \) angle of slope face; all external forces are considered disturbing forces; and \( F' \) refers to force equilibrium.

There are also some special cases:

- If \( c' = 0 \) and there is steady seepage at the ground surface i.e. the phreatic surface is at ground level then:
  \[ F' = \left(1 - \frac{\gamma z}{\gamma'}\right) \frac{\tan \phi'}{\tan \alpha} \]

- If groundwater level is at the surface, \( m = 1 \) and \( c' = 0 \) then:
  \[ F' = \frac{(\gamma - \gamma_w)}{\gamma} \frac{\tan \phi'}{\tan \alpha} \]

- When \( m = 1 \) and \( c' = 0 \) in slopes which contain fissured clays or periglacial slide masses, slope may attain equilibrium at very low angles, at roughly \( \phi'/2 \) (Prior & Graham, 1974).
  \[ \tan \alpha = \frac{\gamma'}{\gamma} \tan \phi' \approx \frac{\tan \phi'}{2} \]

7.2.1.1.2 Method of slices for circular failure surfaces

Analysis assuming a circular failure surface is common for rotational slides. Taylor (1937) presented stability analysis in terms of total stress for circular slides in homogeneous conditions. However, in heterogeneous conditions the method of slices is found to be more practical and the method proposed by Bishop (1955) has proved to be accurate for most purposes (Morgenstern & Sangrey, 1978).

Bishop’s simplified method assumes force equilibrium in the vertical direction and ignores the inter-slice shear forces. This implies zero shear between slices and ignores the requirement for equilibrium in the horizontal direction.

\[ F = \frac{1}{\sum W \sin \alpha} \sum \left[ \frac{\left( c' b + (W - ub) \tan \phi' \right)}{1 + \tan \phi' \tan \alpha \sec \alpha / F_m} \right] \]

Where \( \alpha = \) slip surface angle; \( b = \) slice length; and \( W = \) vertical stress.

Bishop’s rigorous method introduces a procedure to allow specification of the inter-slice forces but a significant increase in the computing time of this method only yields a small
improvement in precision and the method is not often performed. The Fellinius or Ordinary method (which neglects the interslice forces) is simpler but is a less effective variation of Bishop's Simplified, as it results in F values which are too low (Morgenstern & Sangrey, 1978).

7.2.1.1.3 Method of slices for non-circular failure surfaces

Where shear resistance in a soil mass is not uniform, slip occurs on surfaces more complex than a circle. This non-circular analysis has been useful in many actual cases with irregular failure surfaces (Morgenstern & Sangrey, 1978).

Morgenstern & Price (1965) developed a method that deals with a failure surface of arbitrary form and which satisfies all equilibrium requirements but which is insensitive to internal variations. Bishop's simplified method can be used for non-circular sliding surfaces, but the centre of rotation is not constant because of the irregular surface. The result is an offset of the normal force at the base of the slice which has to be accounted for.

A more convenient method, referred to as Janbu's Simplified Method (Janbu et al., 1956, and Janbu, 1973) ignores the inter-slice forces and expresses the horizontal force equilibrium. Forces are resolved vertically and assume that total horizontal forces equal zero. The safety factor is derived from consideration of horizontal equilibrium, and the inter-slice forces are accounted for by an empirical correction factor ($F_0$), which is a function of the curvature of the failure surface and soil type, and by which the safety factor is multiplied:

$$ F = F_0 \left( \sum \frac{c' + (W - u) \tan \phi'}{n_\alpha} \right) \left( \sum \frac{W \tan \alpha}{W \tan \alpha} \right) $$

where $W =$ average vertical stress on the base of the slice; $\alpha =$ inclination of the base of the slice; $n_\alpha = \left( 1 + (\tan \phi' / F_0) \tan \alpha \right) \cos^2 \alpha$.

Graham (1984) states that success using these solutions lies in suitable pore water pressure and soil property values, rather than in the choice of method, provided that the slide surface resembles the actual failure surface; and that under such conditions the seeming lack of precision becomes less important.

7.2.2 Rock slope stability

7.2.2.1 Limit equilibrium methods for rock slopes

Stability analysis of rock slopes should be undertaken in terms of effective stress because the permeability of the rock mass can be high and so undrained loading does not normally occur. Shear
strength parameters, pore water pressures and sliding mechanism must be specified but the shear resistance and water pressures of rocks are significantly affected by the pattern and density of discontinuities and can be difficult to predict. It is also very difficult to consider the attitudes and hydraulic conductivity of the discontinuities in order to assess water pressure distributions. Large local differences in water pressures can occur in a fractured rock mass and large fluctuations result from the influx of rainfall (Morgenstern & Sangrey, 1978). The application of limit equilibrium methods to rock slopes is problematical and is not within the scope of this research.

The general conditions and polygon of forces which apply to a sliding block on a planar surface are shown in Figure 7.8.

7.2.2.2 Stereographic projection of discontinuities

The stereographic projection has been in use since the second century BC by Greek crystallographers to study crystal morphology and optics. More recently, prior to the development of personal computer technology, it became a standard method for solving 3D geological problems. The theory behind this is well documented (e.g. Phillips, 1973, Matheson, 1983; Priest, 1985; Hudson & Harrison, 1997). Hudson and Harrison (1997) provide an good overview of the application of the technique to different situations, i.e. planar, wedge and toppling failures. For some slope and discontinuity situations failure is possible, on others it is not. Kinematic admissibility or feasibility is a good initial approach to establishing the possibility of failure or instability (Hudson & Harrison, 1997) although the technique does not provide any numerical measure of stability.

Rock slopes often contain several sets of discontinuities (faults or joints) which can combine to form various wedge block sets. Such discontinuities when dipping toward the free face of a slope, especially a dip slope, at approximately the same angle, constitute a well known landslide-prone condition (Chorley et al., 1984; and Shuster & Krizek, 1978).

Stereograms are very useful for describing relationships between intersecting planes and structural discontinuities that define many types of slope failure. Figures 7.9a to 7.9d simply illustrate the relationship between a theoretical dipping plane and a sphere, and the formulation of a stereogram for such a dipping plane.

Sliding along the line of intersection of two planes can occur when the plunge of the intersection line is less than the slope dip angle (measured in the direction of sliding), see Figure 7.9a and 7.9d. A typical wedge failure occurs when the plunge of the intersection line is greater than the friction angle. Hoek & Bray (1981) state that a slope is potentially unstable when the
\[ I = (H-Z) \csc \Psi \]
\[ U = \frac{1}{2} Z \gamma_n (H-Z) \csc \Psi \]
\[ V = \frac{1}{2} Z \gamma_n \]
\[ W = \frac{1}{2} \gamma H \left( \cot \Psi \left( 1 - \frac{Z}{H} \right) - \cot \Psi \right) \]

For sliding to occur \( \Psi > \psi > \phi \)

Assumptions:
1. the slide has unit width.
2. there is no shearing at the ends of the failure mass.
3. loads do not apply a net moment.
4. the failure criterion is: \( \tau = c' + \sigma' \tan \phi' \)

Figure 7.8 a) Conditions for planar failure; b) polygon of forces (after Hoek & Bray, 1981).
a) Circular failure in soil, waste rock or highly fractured rock. No identifiable structural pattern.

Figure 7.9 Types of slope failure and stereograms of the structural conditions which give rise to them (after Hoek & Bray, 1981)

b) Planar failure in highly ordered rock (e.g. slate, bedded sandstones and siltstones).

c) Wedge failure along two intersecting discontinuities.

d) Toppling failure in rock with columnar structure and steeply dipping discontinuities.
intersection of the great circles of the planes falls within the shaded region (as defined in Figure 7.9) and that sliding occurs when the plunge of the intersection exceeds the friction angle. The plunge of this intersection is important for the definition of wedge failures but less so for planar failures which form a special case. When the intersecting planes are almost equal in terms of dip and direction, a near plane is formed and failure occurs when the dip of this plane exceeds the friction angle. The wedge type is more common but the simple planar type is useful for demonstrating sensitivity to changes in shear strength and groundwater levels.

7.2.2.2.1 Kinematic admissibility envelopes

The potential types of failure occurring in the study area can be demonstrated using the simple plotting of discontinuities by hand on a stereo net or using an interactive plotting program.

An interactive, computerised method has been developed (Maurenbrecher, 1990, 1993 & 1995) for the analysis of potential planar and wedge failures for such possible combinations. The method is intended for the measurement of stability in terms of potential failure modes: planar, wedge and toppling failures. Other graphical techniques for this type of analysis have been described by Hock & Bray (1981), Goodman & Bray (1977), and Richards & Atherton (1987). The advantage of an interactive program for stereographic analysis is that it allows the rotation of structural data and to view the immediate effects of small changes and to quickly generate a best-fit model.

Kinematic admissibility is determined to establish whether the major fracture sets cause planar or toppling failure, or if combinations of fracture sets causes wedge failures. Maurenbrecher has developed an interactive method of producing admissibility envelope diagrams which enable determination of the admissibility of a rock block to sliding or ‘toppling’ from a rock face. Rock sliding involves only a geometric orientation of the rock discontinuities with respect to the slope angle and direction. Discontinuities are plotted as poles and points on the stereographic projection, to show dip direction and magnitude. The rock or slope face is plotted as an ellipse (great circle) from the point of maximum slope angle to the strike, or horizontal line. Discontinuity poles which plot within this ellipse (i.e. they ‘daylight’ within it) as they are less steep, indicate potential sliding, see Figure 7.10. Another envelope which describes the stress elements for further analysis of the sliding mechanism is plotted. This consists of a circle, whose radius represents the internal friction angle, and which intersects the rock slope ellipse. The friction cone envelope represents the vertical force due to gravity. Sliding due to gravity is considered only to occur if the dip of the discontinuity plane is greater than the friction angle. The ‘toppling’ envelope shown in Figure 7.10 also considers the stress component in the rock face and does not refer to overturning, but to the process which
Figure 7.10 General kinematic admissability envelopes for stability analysis of dipping planes and discontinuities.
precedes toppling failure, known as ‘spalling’.

Based on values in Table 7.3, a reasonable value for the internal friction angle for Langhe rocks would be anything between 30 and 40, as they vary from weathered mudstones to moderately strong, moderately weathered, lithified sandstones. However, friction angles have been determined for selected rocks in this area (Bandis et al., 1996) as ca 22° and 10-15° residual. Low friction angles are often attributed to weathering along fractures.

Table 7.3 Estimates of internal friction angles (Bolton, 1979):

<table>
<thead>
<tr>
<th></th>
<th>Peak (°)</th>
<th>Residual (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense, well graded sand, gravel</td>
<td>55</td>
<td>35</td>
</tr>
<tr>
<td>Medium, dense uniform sand, round grains</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>Dense silty sand with some clay</td>
<td>47</td>
<td>32</td>
</tr>
<tr>
<td>Sandy silty clay</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Clay-shale on partings</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>Overconsolidated clay (London Clay)</td>
<td>25</td>
<td>15</td>
</tr>
</tbody>
</table>

Maurenbrecher’s program calculates admissibility and generates a value for the factor of safety (F). A value of less than 1.0 represents instability and greater than 1.0 represents increasing stability. The program was run for two sets of circumstances:

1. gently dipping slopes, at acute angles to bed dip (ca 310 slope dip direction), Figure 7.11a;
2. steep scarp slopes, at high angles to bed dip (ca 130 slope dip direction), Figure 7.11b

7.2.2.2.2 Results

The pole to each discontinuity plane is plotted as a single letter (a to k). Combinations of discontinuity orientations are plotted with their resulting F value (e.g. a-0.6-j). The location of these points is determined by the intersection line plunge and strike. Discontinuity data recorded in the study area is listed in Table 7.4.
Figure 7.11 Stereo-kinematic admissibility envelopes for discontinuities intersecting a) dip slopes and b) scarp slopes.
Table 7.4 Strikes, dips and factor of safety values from discontinuities recorded in the Langhe

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (deg)</th>
<th>Dip (deg)</th>
<th>Combination</th>
<th>FS (scarp slopes, $\phi=25^\circ$)</th>
<th>FS (dip slopes, $\phi=22^\circ$)</th>
<th>FS (dip slopes, $\phi=10^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>140</td>
<td>80</td>
<td>a-j</td>
<td>0.5</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>b</td>
<td>225</td>
<td>90</td>
<td>b-i</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>c</td>
<td>229</td>
<td>87</td>
<td>c-g</td>
<td>0.1</td>
<td>1.0</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>d</td>
<td>80</td>
<td>90</td>
<td>d-h</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>e</td>
<td>314</td>
<td>88</td>
<td>e-b</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>f</td>
<td>320</td>
<td>90</td>
<td>f-a</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>g</td>
<td>341</td>
<td>87</td>
<td>h-f</td>
<td>0.4</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>h</td>
<td>345</td>
<td>85</td>
<td>i-c</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>i</td>
<td>355</td>
<td>90</td>
<td>j-b</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>j</td>
<td>358</td>
<td>86</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All observed fractures are vertical or sub-vertical and therefore plunges of intersection lines are similarly steep and their poles plot around the outer part of the stereogram. All combinations of measured discontinuities generate F values of less than 1.0 and therefore indicate instability.

Figure 7.11a shows no shaded region and therefore no discontinuity intersections fall in the 'daylight envelope', so that there is no possibility of wedge failures on the gentle slopes. The toppling envelope falls outside the stereogram thus no toppling failure is likely either.

Figure 7.11b illustrates the resultant stereogram for steep, scarp slopes. The same discontinuity data and F values are plotted as are shown in Figure 7.11a. For these parameters it seems that toppling failure is possible as indicated by the envelope in the lower right part of the stereogram. Once again there are no wedge failure possible in this scenario.

7.2.4 Slope stability analysis

Both block-slides and debris-flows in the Langhe are considered planar failures (Bandis et al., 1996) and are therefore treated as 'infinite slopes'. The lack of pore pressure and shear strength information and the fact that the slopes consist of both rock and soil means that a more general approach is adopted rather than strict use of limit equilibrium methods. It should also be noted that the slopes are natural (as opposed to cut or filled slopes). The infinite slope method has been used and adapted by many authors, e.g. Taylor, 1948, Haefeli, 1948, Skempton & DeLory, 1987, Skempton & Hutchinson, 1969 and Brass et al., 1991, and the generalised formula used here is that outlined by Brass et al. (1996), see Figure 7.12. Approximate values for cohesion, internal friction angle and bulk density used here are those stated by Bandis et al. (1996).
Figure 7.12 Stress conditions for planar slip (after Brass et al., 1991).

\[ F = \frac{\text{Shear Strength}}{\text{Shear Stress}} = \frac{c' + (\gamma_m - m\gamma_w)z \cos^2 \alpha \tan \phi'}{\gamma_m \sin \alpha \cos \alpha} \]

Where: \( c' = 0.005 \text{ kN/m}^2 \) (\( c'_{\text{min}} = 0 \text{ kN/m}^2 \)); \( \gamma_m \) (bulk density) = 24 \text{ kN/m}^2; \( m \) (ratio of water table height to failure surface depth) = 1.0; \( \gamma_w \) (unit weight of water) = 10 \text{ kN/m}^2; \( z \) = depth to failure surface; \( \alpha \) = slope angle; \( \phi' \) = friction angle.

The general conditions for simple, planar failure on a single plane, as defined by Hock & Bray (1981) are as follows:

- the sliding plane strikes parallel or nearly so, with the slope face (within 20°)
- the failure plane daylights in the slope face i.e. it is shallower than the slope face
- release surfaces which provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries to the slide.
- the dip of the failure plane must be greater than the friction angle

Three of these four criteria are fulfilled. The sliding plane in all known cases is within 20° of the slope face angle. The slopes are also steeper than the failure plane (which are parallel to bedding). There are many potential release surfaces provided by the interconnecting network of vertical fractures. The dip of the failure plane is however, around 10°, which is considerably less than the estimated friction angle (27°) and approximately equal to the lowest estimate of residual
friction angle (10 - 15°), Bandis et al., 1996. Some assumptions are made before applying this model to the data:

- the only failure mode is translational sliding
- the critical slope angles, defining stable and unstable, are the same for each lithology

Prior to application to the data the method was applied to theoretically increasing slope angle values, for varying friction angles, and values of M and Z, to examine their effect on the factor of safety (F). The results are shown in Figures 7.13a to d.

Figure 7.13a and Table 7.5 show variations of F with increasing slope angle for constant M and differing values of φ. The dotted line indicates where F falls below 1.0, i.e. reaches a point where the slope becomes unstable. Variations in the magnitude of friction angle affect the critical slope angle value at which F=1.0. Increasing φ causes this critical angle to increase, so that steeper slopes can remain stable (see Table 7.5, see also Figure 3.1).

Table 7.5 Effect of varying parameter values on stable slope angle (F=1)

<table>
<thead>
<tr>
<th>φ (deg)</th>
<th>Slope angle (deg)</th>
<th>M</th>
<th>Slope angle (deg)</th>
<th>C'</th>
<th>Slope angle (deg)</th>
<th>γm</th>
<th>Slope angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9.5</td>
<td>0.1</td>
<td>21</td>
<td>0</td>
<td>13</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>0.5</td>
<td>17</td>
<td>0.5</td>
<td>13.5</td>
<td>20</td>
<td>11.5</td>
</tr>
<tr>
<td>30</td>
<td>18</td>
<td>0.8</td>
<td>15</td>
<td>5.0</td>
<td>14</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>26</td>
<td>1.0</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.13b and Table 7.5 show how F varies with increasing slope angle for constant φ and differing values of M (ratio of water table height to failure plane depth). This ratio (M) describes the relationship between the ground surface and the position of the water table, i.e. the closeness of the water to ground surface, at the time of failure. If M=1.0 then the water table is at the surface. Critical slope angle increases with decreasing values of M, i.e. the slope is stable at steeper slope angles when the water table is at depth. Figure 7.13c and Table 7.5 show that decreasing cohesion lowers the stable slope angle. Figure 7.13d and Table 7.5 show that increasing bulk density raises the stable slope angle.

The infinite slope technique has been applied to both ASCII XYZ slope profile data and to the raster data using ER Mapper's formula editor. M has been assumed to equal 1.0, due to the very low dip and high rainfall intensities measured at the time of failure. Attlewell & Farmer (1976) suggest that when evaluating F for an infinite slope, the worst case scenario should be assumed, i.e. that the phreatic line is at the surface and M=1.0, unless there is unambiguous evidence to the contrary.
Figure 7.13 Effect of varying geotechnical parameters on factor of safety, a) friction angle; b) water table depth to failure plane ratio, c) bulk density, and d) cohesion.
7.2.4.1 Slope profile results

A number of slope profiles from known block-slide locations were extracted from the raster image data. Elevation, slope angle and curvature data from these profiles were exported (in ASCII XYZ format) and then imported to Excel. The Infinite Slope model was applied to these profiles for stability analysis. Plots of elevation, slope angle and F for selected slope profiles are shown in Figures 7.14 to 7.16.

Variations in the magnitude of F over the length of the slope profiles reveal that sizeable parts of the slope are unstable, i.e. have F values below 1.0. It is interesting to note that the profiles of these slopes display differing morphology (see chart (a) of Figures 7.14 to 7.16). Serravalle (Figure 7.16) shows a concave form with the unstable portion occupying the uppermost part of the slope, just below the road. San Benedetto (Figure 7.14) shows a more or less curvilinear form at the upper part of the slope and convexity at the toe of the slope and in this convex portion F is less than 1.0. The main reason for this variation of F over the length of the slopes is that, for the parameters used, the infinite slope model is most sensitive to changes in slope angle. In the Serravalle example, the steepest part of the slope is the upper part, and in the San Benedetto case, the steepest part is at the convex toe.

Bandis et al. (1996) report that failure is initiated at the toe of slopes and is propagated upwards via the sliding of discrete blocks. They have performed their back analysis calculations using the infinite slope model, so it is interesting that some slopes which failed during the 1994 event display unstable conditions not at the toe but at the head of the slope.

7.2.4.2 Raster image results

Since slope angle is the only input parameter for which there is complete coverage of the study area, the infinite slope equation was applied directly, on a pixel by pixel basis, to the raster slope data. The other parameters had to be assumed and applied as constants. This is of course a gross simplification but under the constraints of this study, it is a working solution to the lack of data. The infinite slope method also makes broad assumptions about pore water pressure and cohesion but again, the lack of data means that this is the only option. The following equation was applied using ERMapper's Formula Editor, where i1 = aspect and i2 = slope angle:

\[
f = \begin{cases} 
0.004 + (24 - 1 \cdot 10) \cdot (10 \cdot (\cos(i1^^^^{\circ})(\pi/180)) \cdot \cos(i1 ^{\circ} (\pi/180)))) \cdot \tan(15 ^{\circ} (\pi/180))) & \text{if } 0 < i1 < 20 \text{ or } 240 < i1 < 360 \\
0.005 + (24 - 1 \cdot 10) \cdot (3 \cdot (\cos(i2 ^{\circ} (\pi/180)) \cdot \cos(i2 ^{\circ} (\pi/180))) \cdot \tan(25 ^{\circ} (\pi/180))) & \text{else if } i2 = 18 \\
\text{else null} & \text{else null}
\end{cases}
\]
Figure 7.14 a) Slope profile (metres); b) Factor of safety (assuming ground water at surface level and residual friction angle); and c) slope angle (deg); from San Benedetto.
Figure 7.15  a) Slope profile (metres); b) Factor of safety (assuming ground water at surface level and residual friction angle); and c) slope angle (deg); from Pianezza.
Figure 7.16 a) Slope profile (metres); b) Factor of safety, (assuming ground water at surface level and residual friction angle); and c) slope angle (deg); from Serravalle.
Following calculations by Bandis et al., 1996, a block thickness \((z)\) of 10m was used for block-slides and a thickness of 3m taken for debris-flows. Field evidence suggests that this is not unreasonable, as block slide depths having been observed at various depths between 3m and 25m and soil thickness are generally less than 3m. Friction angle has been assigned a residual value of 10\(^\circ\) (for the materials on low angle dip slopes) and 25\(^\circ\) (for materials on scarp slopes) based on the work carried out by Bandis et al (1996). Bandis et al., (1996), also record differing cohesion values for materials on these two slope groups, 0.003 kN/m\(^2\) (marls) and 0.005 kN/m\(^2\) (sandstones) on dip slopes, and 5 kN/m\(^2\) for soils on the scarp slopes. Delmonaco et al. (1995) estimate the time delay between the recharge (3 November 1994) and the initiation of slope movements (5 November) as being 48hrs (debris-flows) and 56hrs (block-slides). They also state that the cumulative rainfall received during these periods was ca 100 mm and 200 mm respectively. Rainfall intensities for the days at and preceding the time of failure, were such that, even 24hrs later, water was seen to pour down the surface of the slope where block-slides had occurred (pers. comm. P. Boccardo, 1995). A state of steady seepage at surface level was therefore assumed and \(m\) was taken to equal 1.0.

The results of this operation are shown in a ‘factor of safety’ map, in Figure 7.17. The colour look-up table chosen is such that pixels which have a value of 1.0 or greater (stable) are shown in the blue tone. Any pixels with a value of less than 1.0 are shown in colours yellow through to red in order of decreasing value, red being the lowest value and indicating lowest stability. This ‘factor of safety’ map was input to the GIS to assist in generating the hazard map of the area.

7.3 Hazard Assessment

The ideal landslide hazard map should indicate both spatial and temporal probability, magnitude, velocity and run-out distance of mass movement phenomena (Mantovani et al., 1996). Varnes (1984) defines a hazard as the probability of occurrence of a potentially damaging phenomenon within a given time and in a given area. The relationship between hazard, risk and vulnerability can be expressed simply by the following:

\[
\text{RISK} = \text{HAZARD} \times \text{VULNERABILITY}
\]

- Hazard \((H)\) = likelihood or probability of the occurrence of the event (0-1 scale).
- Vulnerability \((V)\) = degree of loss to a given element at risk (e.g. population, property and economy). It is a measure of the potential damage and costs, resulting from the occurrence of the phenomenon (0-1 scale).
- Risk \((R)\) can be thought of as the expected degree of loss (probability and financial impact).
Figure 7.17 Factor of safety map produced using infinite slope method applied to the raster slope image data, assuming groundwater is at surface level and residual friction angle, i.e. 'worst-case' scenario.
The key questions can now be listed as:

- How can hazard and vulnerability be quantified?
- How can the parameters and their effect on slope stability be measured?
- What is an acceptable level of risk and how should this be decided?
- Once the level of acceptability is decided, how can the data be analysed to identify those areas at risk?

Whether the analysis involves one piece of information or several, decisions concerning the data must be made and decision rules must be established. There are usually no definitive answers to such questions but analysis using a GIS greatly helps in dealing with inherent uncertainty, generating quantitative results and providing a basis for tackling these questions.

Uncertainty about relationships between parameters and their role in landslide susceptibility creates the need for decision rules. Where the data are complete and in quantitative form, so-called 'hard' decision rules can be formulated but this is not usually possible in reality. Where data coverage is incomplete, or errors are present, uncertainty is involved; rules must then be based on 'soft' decisions established on the basis of experience, prior knowledge, and judgement, i.e. 'belief' in the possible outcomes. Two basic approaches are available for dealing with uncertainty:

- probability theory - this involves calculation of the likelihood of specific values occurring or being exceeded (e.g. the likelihood of a slope being unstable) on the basis of possible parameters combinations;

- weights of evidence - this involves multi-criteria analysis which involves evaluation, relative weighting and combination of selected (significant) criteria which contribute to the hazard.

Since spatial relationships are important for handling mass movement phenomena, GIS provides the tools necessary to establish the likely stability on a regional scale.

The GIS software chosen for this analysis, is Idrisi (Clark University, 1997). This is a raster based system, run on a PC. Idrisi includes a suite of decision making tools which are able to calculate probabilities, fuzzy set memberships and perform multi-criteria analysis. Where relevant and for the sake of simplicity, a specific Idrisi module will be referred to by its command name, e.g. BAYES, MCE. A glossary of Idrisi modules used is provided in Appendix B.
7.3.1 Hazard criteria

The compiled GIS data layers containing values for the 'criteria' (factors or constraints), described in 7.1.1, must now be combined. After consideration of the remote sensing, mineralogical work and field evidence, a series of criteria were selected (described earlier in Table 7.1), for both block-slide and debris-flow hazard, as input layers in the hazard assessment GIS. In all cases, some link between a factor and slope failure can be made with relative confidence but the exact values needed to determine decision rule thresholds are not certain, and perhaps can never be so.

7.3.2 Factor scaling and standardisation

Before combination, each factor needs to be standardised or scaled to a consistent value range and format. Data may be scaled to a 0-1 range (real data) or to a 0-255 range (byte data) depending on the requirements of the program module being used. This difference dictates the way the data is handled and stored, although there is no difference in the result. Different types of function are illustrated in Figure 7.18. A fuzzy set describes a continuous membership function where 0 represents a non-member and a value of 1 (or 255) represents a member, and the values in between represent the possibility of membership.

Training ("ground truth") data rarely provide pure examples of the classes they represent. Boundaries between one type of natural phenomenon and another are rarely crisp or clearly defined. There is usually a continuum between one type and another. To accommodate this behaviour, the module 'FUZZY' (which generates fuzzy set signatures) has been used to evaluate the possibility of a pixel belonging to a particular group by applying one of a series of membership functions.

The fuzzy set membership function can be most readily appreciated with reference to a simple linear function ($\mu_\alpha$), which can be defined by the following:

$$\mu_\alpha(x) = \begin{cases} 
0 & \text{for } x < a \quad \text{non-member} \\
\frac{x - a}{b - a} & \text{for } a < x < b \\
1 & \text{for } x > b \quad \text{certainly a member}
\end{cases}$$

Each value of $x$ and its associated $\mu_\alpha$ and ordered pairs $[\mu, \mu_\alpha]$ comprise the fuzzy set. The type of function and the values used will depend on the phenomenon and desired outcome of the
Figure 7.18 Fuzzy set membership function types: a) general form and b) implementation using turning points in IDRISI (Eastman, 1995).
operation, i.e. the threshold values applied to each membership function reflect their significance on the result.

There are 3 types of membership function: sigmoidal, J-shaped and linear (Figure 7.18). In Idrisi, the membership functions are controlled by four turning points ordered from low to high on the measurement scale. The first represents the point where the membership function begins to rise above 0; the second indicates where the function reaches 1; the third where the membership drops below 1; and the fourth where the function returns to 0 again. If points 2 and 3 are made identical, the function falls immediately after reaching a value of 1.0. If points are duplicated, monotonic or symmetric functions are generated.

The sigmoidal function \( \mu = \cos^2 \alpha \) gives a membership curve with no sharp cut-offs where the curve rises above 0 or falls below 1. A monotonically increasing sigmoidal function is described by the following formula, so that so that when \( x > b \), \( \mu = 1 \):

\[
\mu = \frac{(x - a)}{(b - a)} \times \left( \frac{1}{2} \right)
\]

The fuzzy set images can be combined in a number of ways. The application of Boolean logic represents the simplest method of combining fuzzy sets which have been scaled from 0 to 1. They are combined using fuzzy algebra ('set theory'), e.g. the intersection (logical AND) or union (logical OR) operations. This may be performed using Idrisi's OVERLAY module.

7.3.3 Bayesian Probability approach

A tool becoming increasingly accepted for assessing the probability of a hypothesis being true given the evidence is Bayesian Probability theory. Statistically BAYES has a fundamental problem which arises from the need to know all the possible outcomes at the start. Despite this, BAYES provides a tool which enables the incorporation of new evidence concerning a hypothesis and is able to calculate a value for the probability of that hypothesis being true on the basis of one or more pieces of evidence. Such evidence might be the presence (or absence) of a particular lithology or the steepness of slopes.

Bayes' theorem can be expressed by the following formula:

\[
p(h|e) = \frac{p(h|e) \times p(h)}{\sum p(e|h_k) \times p(h_k)}
\]

Where \( h = \) hypothesis (that there will be a number of possible mutually exclusive outcomes); \( e = \) evidence; \( \Sigma = \) sum of i possible outcomes; \( p(e|h) = \) probability of the evidence occurring given that the evidence is true; \( p(h) = \) prior-probability, i.e. the probability of the hypothesis being true.
ignoring the new evidence; p(\text{j|e}) = posterior-probability, i.e. probability of the hypothesis being true given the new evidence.

A simple 'hard' thresholded binary image, where pixels lie either above or below the threshold are assigned a value of 0 or 1.0; this represents the simplest decision making tool which can be used for comparison with the more sensitive probability result generated by BAYES. The 'soft' decision alternative is to calculate the probability (using the module 'PCLASS') that a pixel exceeds, or is exceeded by, the threshold value based on the RMS (explained in Chapter 5) value contained in the image header, p(\text{j|e}). According to Bayes theorem p(e|\text{j}) equals p(\text{j|e}) when there are only two possible outcomes, e.g. stable or unstable, assuming that the data has a normal distribution.

7.3.3.1 Probability of instability using slope angle as a criterion

If the slope angle can be taken as the most critical input, the first decision involves choosing a threshold between stable and unstable slopes. In the current study there are two major types of failure (block-slide hazard and debris-flow hazard), two such thresholds need to be chosen in order to identify the stability for each type of hazard. PCLASS is run for both types of slope to produce two probability images.

The result can be calculated and presented as a binary image displaying areas of a certain level of risk based on the thresholds. This raises the question as to what an appropriate level of risk needs to be considered. Risk is a contentious issue and peoples' perceptions of it can vary considerably. Zero risk is desirable but not physically attainable. A value of 5% seems a reasonable starting point. Taking this value, probability images have been classified to show areas which have a 5% (or greater) chance of being unstable, based on slope angle and our knowledge of its control on slope stability. A probability image will show larger areas of instability than a 'hard' classified image (using the same thresholds) since it allows for data value error (based on the RMS value).

7.3.3.2 Probability of slope failure based on existing landslides

The next piece of evidence to be incorporated is that of aspect control on landslides which have already occurred. The probability of planar slope failure (including both block-slide and debris-flow) for the whole study area was computed from the aerial coverage of known landslides, as presented in Table 7.6. These probabilities are based on the whole study area but field observation suggests that block-slides occur only with certain directions of slope and that debris-flows usually occur on slopes facing the opposite direction, broadly speaking. This probability was therefore refined to make 2 classes of slope based on aspect. The aspect image was thresholded into two
classes (NW-facing and S to SE-facing) using RECLASS. The calculated probabilities were then applied to the reclassified aspect image. The result is an image representing prior probabilities for unstable slopes \( p(h) \).

<table>
<thead>
<tr>
<th>Total area = 183 km²</th>
<th>Area (km²)</th>
<th>Probability (for the whole area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris-flows</td>
<td>16.5</td>
<td>( \frac{16.5}{183} = 0.09 )</td>
</tr>
<tr>
<td>Block-slides</td>
<td>8.6</td>
<td>( \frac{8.6}{183} = 0.05 )</td>
</tr>
</tbody>
</table>

The IDRISI module ‘BAYES’ was then used to calculate posterior-probabilities from these prior-probabilities. BAYES also requires calculation of conditional probability i.e. \( 1-p(h) \). The result is an image representing the probability of instability based on slope angle which takes into account data value error and spatially variable susceptibility due to slope aspect.

7.3.3.3 Probability of slope failure incorporating data and decision-rule uncertainty

The next step is to incorporate the effect of slope angle variability on stability, using a fuzzy set of slope angle. Two fuzzy sets were created, for block-slide and for debris-flow hazard. These fuzzy sets represent the conditional probabilities that the slope is unstable if slope angle falls within a certain value range. Once again the inverse (conditional) probability was required i.e. that the slope is stable if the angle lies outside that value range.

BAYES was run using output generated from the first BAYES operation (these form the new prior-probability images) and the fuzzy set of slope (and inverse thereof) as conditional probabilities, to generate a new posterior-probability image. The results were reclassified to show images of >5% risk, which encompass value error but decision-rule uncertainty (Figure 7.19). Comparison of these images with the ‘hard’ thresholded images, shows an even greater area of potential instability due to allowance of threshold value uncertainty.

These operations can be repeated to incorporate each new piece of evidence (for each factor in the GIS). The operations are time consuming but can be compiled into a batch file using Idrisi’s IML (Idrisi Macro Language) editor for convenience and then run in batch mode. The process is long-winded and thus a more concise and flexible method is desirable. The batch file is listed in Appendix B.
Figure 7.19 a) Block-slide hazard map and b) Debris-flow hazard map, generated using BAVES and thresholded to show areas of >5% hazard.
7.3.4 Multi-criteria evaluation (MCE)

Multi-criteria evaluation involves the assessment, weighting and combination of the data layers in a collective rather than iterative way (as opposed to the BAYES operation employed earlier). There are two types of criterion: Factors (variable) and Constraints (Boolean); this distinction is fundamental to the effect that the criterion has on the resultant image. The factors have first to be standardised using functions such as FUZZY or RECLASS (as described in 7.3.2) to an 8-bit range. The control point values were chosen on the basis of field observation, statistics and the RMS values calculated for each image (which are then stored in each file header). The control point values are listed for both block-slide and debris-flow hazard in Tables 7.7 and 7.8.

Table 7.7 Control point values chosen for the generation of fuzzy for block slide hazard

<table>
<thead>
<tr>
<th>Factor</th>
<th>Control point values</th>
<th>Function type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle (deg)</td>
<td>0 4 15 20</td>
<td>see Figure 7.2</td>
</tr>
<tr>
<td>Aspect (deg)</td>
<td>20 40 220 260</td>
<td>see Figure 7.3</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>350 500 500 500</td>
<td>see Figure 7.4</td>
</tr>
<tr>
<td>Distance from roads (m)</td>
<td>200 200 200 1000</td>
<td>see Figure 7.5</td>
</tr>
<tr>
<td>Distance from drainage (m)</td>
<td>150 150 150 300</td>
<td>see Figure 7.6</td>
</tr>
<tr>
<td>Iron soil index (dn)</td>
<td>50 150 150 150</td>
<td>anomalous values chosen from index image (Figure 5.18b)</td>
</tr>
<tr>
<td>Clay soil index (dn)</td>
<td>70 200 200 200</td>
<td>anomalous values chosen from index image (Figure 5.18a)</td>
</tr>
<tr>
<td>Soil wetness index (dn)</td>
<td>80 180 180 180</td>
<td>anomalous values chosen from index image (Figure 5.20)</td>
</tr>
<tr>
<td>Factor of Safety (F)</td>
<td>0 0 0 1</td>
<td>Only areas of instability i.e. values &lt;1, are of interest Figure 7.17</td>
</tr>
</tbody>
</table>

The factor of safety image (Figure 7.17) was incorporated into the data stack for both hazard types. The values in the factor of safety image (F) ranged from 0 to infinity (though 99% of the data lies between 0 and 2), and those <1 indicate instability. Since these values also need to be
standardised and areas of instability are of most interest, those values >1.0 (i.e. representing stability) were reclassified to a value of 1.0. All values then represent degrees of instability from 1 down to 0. The reclassified image was linearly scaled to an 8-bit range to conform with the other layers. The multi-criteria evaluation (MCE) program requires that all factors are scaled in the same direction so that increasing values (0 to 255) indicate increasing suitability (instability). A decreasing linear function was used to scale the F image to conform with this requirement.

Table 7.8 Control point values chosen for the generation of fuzzy sets for debris flow hazard

<table>
<thead>
<tr>
<th>Factor</th>
<th>Control Point Values</th>
<th>Function type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle (deg)</td>
<td>5 8 18 20</td>
<td>Values chosen on the basis of field observation</td>
</tr>
<tr>
<td>Aspect (deg)</td>
<td>20 40 220 260</td>
<td>Values chosen on the basis of field observation. See also Figure 7.3.</td>
</tr>
<tr>
<td>Distance from drainage (m)</td>
<td>150 150 150 300</td>
<td>Values chosen from field observation, SPOT imagery and statistics Figure 7.6.</td>
</tr>
<tr>
<td>FS</td>
<td>0 0 0 1</td>
<td>Only areas of instability i.e. values &lt;1, are of interest Figure 7.17.</td>
</tr>
</tbody>
</table>

The Boolean constraints have values of either 0 or 1 and are used to remove certain areas from the aggregate image (they are multiplied by the result after aggregation). Three constraint images have been used in block-slide and debris-flow hazard cases:

1. 'Valley' - removes areas corresponding to valley floors (of the Belbo and Millesimo valleys)
2. 'Gentle' - removes steep slopes (for block-slide hazard)
3. 'Steep' - removes gentle slopes (for debris-flow hazard)

7.3.4.3 Relative factor evaluation

Certain factors have greater effect on slope stability than others. The assessment of their relative importance involves derivation of a series of weighting coefficients. These Factor Weights, control the effect that each factor has on the outcome. The relative significance of each factor, its influence on the other factors and on the outcome need to be compared. This involves the ordering of the factors into a hierarchy of significance, and assessment of their degree of influence on slope stability and on each other. This is usually done using a comparison matrix where each factor is
given a rating value representing its significance relative to every other factor in the matrix. The rating values are assigned from the following scale and the matrices produced are shown in Table 7.9 and 7.10.

- 9 Extremely strongly more important
- 7 Very strongly more important
- 5 Strongly more important
- 3 Moderately strongly more important
- 1 Equally important
- 1/3 Moderately strongly less important
- 1/5 Strongly less important
- 1/7 Very strongly less important
- 1/9 Extremely strongly less important

The module WEIGHT uses the information in the comparison matrix to calculate the Factor Weighting coefficients. The Factor Weights generated by WEIGHT are produced from principal Eigenvectors of the pairwise comparison matrix. These can be approximated by hand using the following procedure:

- completion of the upper-right of the matrix (using reciprocal values for the lower-left triangular half of the matrix).
- summing each column to derive marginal totals.
- generation of a second matrix by dividing each entry by its column marginal total.
- average the weights across the rows to derive the Factor Weights.

Consistency within the matrix is measured by a value which should be <0.05 for the analysis to proceed. All the Factor Weights generated from this matrix sum to 1.0 and these are then multiplied by their relative factor images. Further details of the weighting method can be found in Saaty (1977) and Eastman et al. (1995).

Table 7.9 Pairwise comparison matrix for block-slide hazard

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspect</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEM</td>
<td>1/6</td>
<td>1/6</td>
<td>1/5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dist. (roads)</td>
<td>1/4</td>
<td>1/4</td>
<td>1/3</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dist. (drainage)</td>
<td>1/7</td>
<td>1/7</td>
<td>1/4</td>
<td>1</td>
<td>1/5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetness</td>
<td>1/5</td>
<td>1/5</td>
<td>1/3</td>
<td>2</td>
<td>1/2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### Table 7.11 Pairwise comparison matrix for debris-flow hazard

<table>
<thead>
<tr>
<th></th>
<th>Slope</th>
<th>Aspect</th>
<th>FS</th>
<th>Dist. (drainage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspect</td>
<td>1/4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS</td>
<td>1/2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Dist. (drainage)</td>
<td>1/4</td>
<td>1</td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>Factor Weights</td>
<td>0.500</td>
<td>0.125</td>
<td>0.250</td>
<td>0.125</td>
</tr>
</tbody>
</table>

Consistency ratio = 0.00 (acceptable)

Ideally the production of the pairwise comparison matrix and assignment of ratings should be made not by one individual but by a group to reduce bias. In this case the comparison matrix was reviewed and revised several times.

#### 7.3.3.4 Criteria combination

Each factor is multiplied by its Factor Weight and then the factors are aggregated. Idrisi’s Multi-Criteria Analysis module (MCE) enables trade-off between factors, i.e. suitability in one factor can compensate for unsuitability in another, and by controllable amounts. The degree of trade-off is controlled by a series of Order Weights which, like the Factor Weights, sum to 1.0. There are two modules within MCE, Weighted Linear Combination (WLC) and Ordered Weighted Average (OWA).

The output is in the range 0-255 and represents aggregate suitability or probability. For convenience of interpretation, the results have been re-scaled to a value range of 0-100 (%), representing increasing probability towards 100%.

#### 7.3.3.4.1 Weighted Linear Combination (WLC)

WLC involves automatic equal ranking of the weighted factors (i.e. Order Weights are equal) and so allows full trade-off between them. Whereas a Boolean operation involves either very high or very low risk (AND / OR), WLC represents a mid-way point between these two extremes, i.e. average degree of hazard and full trade-off (Figure 7.20). The results of this operation for the two types of failure in the Langhe are shown in Figure 7.21.
7.3.3.4.2 Ordered Weighted Average (OWA)

OWA differs from WLC in that the user has full control over the size and distribution of the Order Weights, to control the amount of hazard and degree of trade-off. The Order Weights define the rank ordering of factors for any point in the image data. They govern the degree to which the Factor Weights influence the factor aggregation.

After the Factor Weights have been applied to the original factor images, the results are ranked from low to high and the factor with the lowest suitability score is then assigned the first Order Weight and so on up to the factor with the highest suitability being assigned the highest Order Weight. The relative skew to either end of the order weights determines the level of hazard, and the degree to which the Order Weights are evenly distributed across the factor positions determines the amount of trade-off. Figure 7.20 and Table 7.11 illustrate the relation of Order Weights to hazard and trade-off.

To produce a low hazard result for slope instability, greater Order Weight is assigned to the factors nearest the minimum value. If full weight (value ONE) is given to the factor with minimum suitability score and zero to all other positions, then the result will resemble that produced by the Boolean Min(AND) combination of factors and will represent no trade-off between factors. Full weighting to the maximum suitability score will produce the opposite, a high hazard result.
Figure 7.2 (a) Block-slide, and (b) debris-flow hazard maps, generated using the Weighted Linear Combination method (WLC) - representing the 'average' degree of hazard and full trade-off between criteria.
Table 7.11 *Order Weights* for a 5 factor example used by OWA

<table>
<thead>
<tr>
<th>Rank position:</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>_________________________</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order weights:</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Low risk Level, No trade-off</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>High risk, No trade-off</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Average risk, No trade-off</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>Average risk, Full trade-off (WLC)</td>
</tr>
</tbody>
</table>

This rank order for any set of factors may not be the same at any two pixel locations because the *Order Weights* are rank specific and not factor specific. This flexibility in factor combination enables an almost infinite number of possible hazard results. The extremes of AND and OR are controlled by the minimum and maximum factor values but the results from the middle positions are controlled by the averaging of factors which depends on the combination of factor values, the *Factor Weights* and the *Order Weights* (see Figure 7.20).

### 7.3.5 Results

The choice of factor combination parameters for MCE (WLC and OWA) seems to be rather subjective. Since many combinations are possible, it is difficult to know what amount of trade-off and hazard are realistic or appropriate without reference to detailed study areas in which a full evaluation can be used to test the methodology.

#### 7.3.5.1 Block-slide hazard

A good starting point seems to be the WLC method, with full trade-off between factors and associated with an average level of hazard. The resultant image has values ranging from 0 - 94% and much of the area has values of >50% and NW-facing slopes generally show values >10%. Comparison between distributions for the 1972(74) and 1994 block-slides, shows coincidence with the highest hazard areas of the image. Since both a low hazard result and some trade-off (to allow for uncertainty) are desirable, the Order Weight distribution decided upon is listed in Table 7.12 and the resultant hazard map is shown in Figure 7.22a. Thresholding the hazard map to show areas characterised by >10% hazard is shown in Figure 7.22b. Actual block-slides (which occurred in 1994) are indicated by white dots to allow comparison between areas of computed block-slide hazard and observed occurrence.
Figure 7.22 a) Block-slide hazard map generated using Order Weighted Average (OWA) method - representing average to low ‘hazard’ and some trade-off between criteria; and b) the same hazard map shown in (a) thresholded to show only areas >10% hazard (green). The white dots indicate block-slides produced during the 1994 storm event for comparison.
Table 7.12 Order weights used for block-slide hazard

<table>
<thead>
<tr>
<th>Rank position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order Weights</td>
<td>0.4</td>
<td>0.3</td>
<td>0.15</td>
<td>0.05</td>
<td>0.05</td>
<td>0.025</td>
<td>0.025</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

7.3.5.2 Debris-flow hazard

In this case, direct evidence of the distribution of debris-flows has been provided by the SPOT Pan multi-temporal imagery. A desirable hazard result for debris-flows is therefore one which resembles this distribution. A low hazard and no trade-off combination of Order Weights (i.e. full weighting to the lowest ranked position) was found to produce the best result, based on visual inspection with the distribution of actual debris-flows. The resultant image is shown in Figure 7.23a with the thresholded SPOT Pan image shown in Figure 7.23b for comparison. The debris-flow hazard map compares quite well with the distribution of actual debris-flows shown in the thresholded SPOT Panchromatic image.

It is difficult to ascertain which combination of factors and weights, if any, is more realistic than any other without exhaustive comparison with detailed studies of specific field areas where the stability situation is known. What is instructive is the comparison between the variously weighted combinations, and their effects on the resultant hazard images. From the purpose of safety, the high hazard images would suggest caution at every point in the image but this is perhaps not realistic. The low hazard cases suggest little necessary caution and are equally unrealistic. The average hazard, full trade-off images (WLC method) represent a compromise between these two extremes and a gradual scale of increasing hazard, but as a consequence it is difficult to define a threshold for the high hazard, 'danger' areas and where most areas show >10% hazard. What is still unclear is the time scale. If this hazard value represents 10% per year then each site should fail every 10 years, if it represents 10% every two years then each site should fail every 20 years. Block-slides seem to happen with some periodicity, according to the limited literature, every 20 years or so, but each site does not fail every 20 years.

An image representing no trade-off and relatively low risk proved to be a little more realistic than the other no trade-off combinations, with the highest hazard areas having ca 50%, and quite a large portion of the area still >10%. The 1972(4) and 1994 block-slide localities coincide well with the >10% areas. Still 50% chance of failure (i.e. equal probability that there will be a slope movement as not) does not seem realistic for such a large portion of the study area. The most appropriate combination seems to be that which involves a little trade-off and low
Figure 7.23 a) Debris-flow hazard map generated using Order Weighted Average (OWA) method - representing low 'hazard' and no trade-off between criteria; and b) SPOT Panchromatic change detection image (thresholded) showing the distribution of debris-flows produced by the 1994 storm event (light green, yellow and red colours - ca DN 136 and above).
hazard, order weights are fractional and are skewed heavily toward the low hazard end. This image is thresholded to show areas of >10% probability, and this is shown in relation to 1972(74) and 1994 block slide localities, Figure 7.22. It can be seen that the locations of the slides, produced in the last few landslide events, coincide quite well the areas of >10% probability of block sliding.

7.3.5.3 Risk Map

According to the definition provided by Varnes (section 7.3), risk is defined as hazard multiplied by vulnerability. An image of relative vulnerability was generated by reclassification and combination of slope angle, distance from roads and town localities (derived from SPOT Pan imagery). The relative vulnerability classes were assigned values representing estimated relative financial importance, such that towns were assigned the highest vulnerability ranking because of inhabitants and buildings, and wooded areas were assigned the lowest ranking as they are not inhabited nor are they cultivated. Arbitrary values between 0 and 1 were assigned to these classes, in order of increasing vulnerability. Relative vulnerability rank values are listed in Table 7.13.

<table>
<thead>
<tr>
<th>Class</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towns</td>
<td>0.8</td>
</tr>
<tr>
<td>Areas &lt;200m from nearest road</td>
<td>0.6</td>
</tr>
<tr>
<td>Cultivated slopes</td>
<td>0.4</td>
</tr>
<tr>
<td>Woodland</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The relative vulnerability image is illustrated in Figure 7.24. This image was multiplied by the images for both block-slide and debris-flow hazard to produce Risk Maps which are shown in Figure 7.25 and 7.26. Smaller scale versions of Figure 7.25 and 7.26 can be found in the map wallet at the back of this thesis.

The operations involved in defining the fuzzy sets and producing hazard maps for various combinations of weights (in order to derive risk maps) were compiled into batch files for convenience during processing. The batch file structure is listed in Appendix B.
Figure 7.24 Relative vulnerability map (0.2 – woodland, 0.4 = cultivated land, 0.6 = areas <200m from roads and 0.8 = towns).
Figure 7.25 Block-slide risk map generated using the block-slide hazard map and the relative vulnerability map (see text for details).
Figure 7.26 Debris-flow risk map generated using the debris-flow hazard map and the relative vulnerability map (see text for details).
7.4 Summary

7.4.1 Slope stability

This chapter has produced a general method for estimating the stability of slopes in the form of stereogram analysis of discontinuities on dip and scarp slopes, and in the production of a factor of safety maps.

The two types of landslide in the study area both involve translational sliding and so use of the infinite slope method is justified in both cases. The block-slides form a special case in that they involve both rock and soil, so that both the rock properties and structures are considered in the stability analysis. Kinematic instability analysis was performed using discontinuities and dipping planes representing dip and scarp slopes in the study area. The results show that only planar failures are likely to occur on the NW-facing dip slopes, and that if the soil/rock interface is taken as a potential discontinuity, planar failures also occur on scarp slopes. It has also involved the examination of the sensitivity of calculated factor of safety to variations in slope angle and geotechnical parameters. Stability of selected slope profiles has also been estimated using the infinite slope method. The infinite slope method was also applied to raster slope data and a factor of safety map was produced which was input as a layer for GIS hazard assessment.

7.4.2 Hazard assessment

The input and manipulation of all data relevant to slope stability assessment involved a considerable amount of computation. To produce a hazard assessment which can be interpreted and is meaningful, seems a daunting task. The simplest means by which to combine the standardised factors is the Boolean method, but this tends to be too simplistic. Bayesian probability provides a convenient means of aggregating the relevant factors as new evidence becomes available but requires numerical data distributed in continuous functions such as the normal distribution. The probability of a hypothesis being true can be evaluated on the basis of that evidence but the methods requires that all possible outcomes are known at the start. Despite its conceptual simplicity, it is considered to be rather cumbersome and long-winded in digital processing terms.

The multi-criteria approach, using MCE, provides a much more flexible means of assessing the significance of weighted criteria and enables aggregation of diverse evidence (factors) in a few collective operations. It also has additional flexibility in the degree to which individual factors can be allowed to control the outcome. Database and decision rule uncertainty can be incorporated using fuzzy set membership functions. The derivation of weighting coefficients (factor and order)
enables flexibility and control over the result. The matrix comparison and evaluation of the factors also enables revision and reiteration of the process.

Comparison of the final hazard and risk maps with digital and map evidence from previous events shows that the methods have been quite successful. The database (evidence) is far from complete and is not without error but in combination with field knowledge and appropriate analysis tools, a satisfactory and plausible result can be derived. The hypothesis that the factors described contribute in various degrees to the occurrence of landslides in the Langhe study area, is demonstrated by the hazard maps generated from this GIS. The departure of the block-slide hazard map from the distribution of actual block-slide occurrences can be attributed to inadequacies in the database i.e. unknown factors such as variable shear strengths and pore pressures. The close resemblance of the debris-flow hazard map to the actual distribution suggests that the database provides a good approximation of significant factors and that variations in shear strength and pore pressure are less significant than geomorphological factors.

7.4.3 Further work

One other multi-criteria analysis method, known as the ‘Dempster-Shafer Weight of evidence’ involves calculation of probability and recognises ignorance in terms of incomplete information. The method allows derivation of belief and plausibility for a series of hypotheses. This would be my recommended approach for further landslide hazard assessment research in the Langhe. It is conceptually quite complex but is one in which the difficulties of an incomplete database could be compensated for.

7.4.4 Summary of hazard assessment methodology

The sequence of events involved in the multi-criteria evaluation of landslide hazard analysis in the Langhe, is illustrated in Figure 7.27 and can broadly be described as follows:

1. identification of factors which lead to slope instability or landslide initiation (and any constraints) and the production of images of each.
2. standardisation of input images to common area, pixel size, map projection and data type.
3. standardisation to a common data type (real or byte data), using membership functions (linear or fuzzy) and appropriate control points (based on field knowledge/statistics)
4. construction of pairwise comparison matrices and ranking of the relative importance of each factor (from the 9 point scale) to derive a series of factor weighting coefficients.
Figure 7.27 GIS hazard assessment model flow diagram.
5. multiplication of each factor image by its respective weighting coefficient.

6. generation of order weights to control the amount of hazard and trade-off between factors and therefore control the influence of each factor on the resultant hazard map.

7. factor aggregation (including any constraints) using either the Weighted Linear Combination (WLC) or Ordered Weighted Average (OWA) methods to produce hazard maps.

8. multiplication of weighted factors by constraints.

9. generation of vulnerability classes from image and map information.

10. multiplication of the hazard or probability maps by the vulnerability map to produce a risk map for each type of hazard.
Chapter 8 Synthesis and Conclusions

This thesis describes the investigation of landslides using a series of different techniques. There have been four themes to the study and these include, remote sensing, mineralogical 'ground checking', slope stability, and digital hazard analysis using a GIS. The results of these themes and their contribution to the research are summarised here.

8.1 Remote sensing

8.1.1 Methods

This work shows that imagery can be directly used to identify landslides which modify the surface topography and to provide indirect evidence of landslide susceptibility. Figure 8.1 illustrates schematically how evidence of landslides can be captured by the remote sensor, from direct surface modifications or indirect soil and vegetation information.

Digital imagery from a variety of sensors has been applied to the study of slope instability. This study has revealed that through use of the Langhe, Rio de Aguas and Folkestone Warren examples, significant features of landslides can be identified by their textural expressions in digital imagery. The suitability of a particular type of imagery depends mainly on the dimensions, type and setting of the landslides. The following conclusions have been drawn:

- The three case studies (Langhe, Rio de Aguas and Folkestone Warren) have shown that information concerning landslide location, type and morphology can be extracted from remotely sensed imagery.

- The most important factor affecting image texture in landslide studies is spatial resolution. The lower limit of resolution for remotely sensed imagery will govern the size of the smallest landslide that can be detected. For example, the lower limit of known landslides in the Langhe case study, which can be resolved by the 10 m pixels of SPOT Pan is approximately 100 m by 40 m. The resolution of airborne imagery and photography significantly improve this detection limit, enabling detailed mapping and interpretation. It cannot, however, provide temporal information. The ideal tool for detailed landslide, geological and geomorphological studies is a satellite-borne sensor with spatial resolution approaching that of aerial photography, a spectral range similar to that of ATM, and a spectral resolution fine enough to identify specific mineral species.
Soil moisture may become ponded in hollows. Hummocky ground surface produces distinct image textures. Disaggregated soils and rocks may also produce spectral anomalies. Network of open, sub-vertical fractures enabling rapid percolation of rainwater to some depth and provide release surfaces for sliding blocks. Spectrally and texturally distinct bedrock and displaced debris exposed at slip plane.

Exposed soils rich in iron minerals (leached from rocks) and associated with fracture zones. Soil moisture detected by sensor where drainage is impeded below. Potential shear surfaces at/near clay-rich mudstone layers. Porous strata act as aquifers. Impermeable layers (containing swelling clays) impede drainage and contribute to increased pore pressure.

Figure 8.1 Schematic satellite views of the landslide targets: a) direct evidence - a landslide has occurred and has modified the topography; b) indirect evidence - the topography is as yet undisturbed, iron and clay minerals in soils give an indication of rocks and fracture beneath.
• Enhanced imagery can reveal spatial patterns and enable relationships to be established linking landslides to terrain type, climate, landuse, geology, slope angle, aspect, rock type and human intervention.

• Spectral enhancements, guided by field knowledge, can provide information about soil moisture and mineral content which form useful input to a hazard assessment GIS.

The tools used in this work were SPOT-Pan, ATM and Landsat TM imagery. The use of TM was restricted (by its resolution) to indirect methods. This work has revealed that some prior knowledge of the landslides is an advantage in choosing appropriate image data.

This work has shown that a targeted method, tailored to each case, is necessary because of varied landslide character and setting. Textural information is crucial to the identification of landslides and this requires a combination of targeted processing followed by interpretation.

The nature of the terrain (exposure of rocks and soils), climate (and its effect on both the substrate and image data quality), temporal requirements, target dimensions and character (i.e. the landslides) and the scale of the study are all important factors to consider in planning an image based landslide study.

Rapid response to environmental disasters requires regular availability of up-to-date data. The ability to detect landslides directly is restricted by the specification of the sensor and imagery used. Satellite imagery does not so far provide adequate spatial and spectral detail for all scales of landslide study; this is a significant restriction. The extensive vegetation cover, intense cultivation and small dimensions of the landslides in the Langhe study area combine to make the area a very difficult remote sensing target.

8.2 Mineralogical evaluation

8.2.1 XRD analysis

The XRD results from this work have demonstrated the abundant presence of smectite along side other clay minerals. The presence of clay-rich sediments is important because of their effect on drainage and permeability. The swelling behaviour of smectite and its effect on stability is also significant. Polloni et al. (1996) suggested that the presence of smectite is more significant than the slope angle and aspect; this may be true in pre-conditioning terms. This work has shown that the amount of smectite varies stratigraphically and laterally which suggests that the absolute amount of
smectite is less significant than the stratigraphy, i.e. the alternating sequence of laterally persistent, permeable and impermeable (smectite-bearing) layers.

8.2.2 Spectroscopy

Field and laboratory spectra were collected from soils and rocks for the analysis and detection of iron oxides and clay minerals, and to support the results of the XRD analysis.

The clay mineral absorption information was quite limited. The short wave infra-red region was dominated by smectite features, with minor evidence of illite, chlorite and kaolinite. The main interest was provided by the iron oxide features in the visible and near infra-red region of the spectra. The spectra show characteristics of goethite (Fe$^{3+}$), as opposed to haematite (Fe$^{2+}$), in the distinct absorption shoulders at 486 nm and 650 nm and a trough at ca 950 nm. Rather than indicating crystalline goethite, they reflect iron in the lattices of other minerals and the amorphous weathering product present on grain and fracture surfaces. This is supported by the absence of specific iron oxide mineral peaks in the XRD analysis.

It is the amorphous iron coating of grains and fractures which is of interest here, as it indicates high water flow and leaching through rocks and soils. This in turn is associated with intensely fractured zones and contributes to indirect evidence of instability (Figure 8.1). The distribution of strong iron oxide spectral anomalies in the study area correlates with major block-slides rather than to rock outcrop.

8.3 Slope stability and GIS hazard assessment

8.3.1 Tools and methods

Unfortunately in practical terms a complete or perfect database cannot exist. With any real problem there will always be incomplete data coverage due to non-availability or inherent inaccuracy. The analysis must be performed with whatever data is available despite these shortcomings. A practical solution must make the best of whatever is available.

A series of data layers were compiled into a GIS, which include elevation, slope angle, aspect, geology, road and drainage networks, and thematic remotely sensed image information. Elevation data and published geotechnical parameters have been used to construct a slope stability map in terms of factor of safety, using the infinite slope method. This map indicated, on a scale of zero to greater than one, areas of varying slope stability based on estimated geotechnical parameters and a planar failure mechanism, and was used as an input to the GIS hazard assessment.
Discontinuity (fracture) data were collected in the field and have been used for rock slope stability analysis. This demonstrated that wedge failures were not possible but that planar failures were likely on both the steep, scarp slopes and gentle, dip slopes. It also showed that the dip angle, direction and intersecting discontinuities on the gentle, dip slopes produced factor of safety values indicating long-term instability.

A number of multi-criterion analysis methods are possible using Idrisi, ranging from the simplest Boolean approach to the more complex Bayesian probability and linear weighted factor combination (MCE). The ability to incorporate non-linearity using fuzzy sets enables even greater flexibility in the analysis. Idrisi allows very easy import, analysis, display and output. Algebraic operations can be performed using raster data layers as input. The Idrisi Macro Language (IML) allows operations to be compiled and run in batch mode overnight so saving valuable daylight CPU time for other work. The only criticism of the software in respect of this project is that its map composition tools are a little crude and inflexible, and necessitate cosmetic improvement using other software packages such as CorelDraw.

A quantitative approach should be objective but multi-criteria analysis also necessitates subjective decisions. Such decisions should ideally be made by a group rather than an individual, to reduce subjectivity and bias. I have tried to make those decision carefully and on the basis of field observations and experience. They have also been modified, reviewed and iteratively re-processed to achieve a result which best reflects the nature, likelihood and spatial characteristics of the hazard. Comparing the resulting hazard maps with the known distributions of recent landslides reveals the relative successes of the decision making process.

After such comparisons, it is felt that there is reasonable agreement between the resultant hazard maps and the distribution of both debris flows and block slides, as indicated in the SPOT imagery and maps. Upon the inclusion of new and/or better data to the GIS, the hazard assessment model can be modified to produce more accurate results. The beauty of the digital, multi-criteria approach to the study of landslides is that it can be modified and re-iterated relatively quickly and easily.

The DEM employed is far from perfect. There are gaps where the DEM tiles do not fit together properly. There is also inaccuracy in the measurement of elevation, which derives from its method of creation (stereo-matching from aerial photographic pairs) followed by triangulation from contours and then gridding to a raster form. As slope and aspect layers are calculated from the DEM, those errors are translated and exacerbated through the processing. Despite these errors, for practical applications, a flawed DEM is better than none.
Very little research has been done in this region until recently and so there has been little demand for geotechnical data. Lateral variations in geotechnical parameter values could produce significant improvements in the infinite slope stability analysis.

The infinite slope method uses the same DEM data and therefore contains those errors, in addition to others introduced from coarse estimates of geotechnical parameters, and assumptions made about the mode of failure and assumptions of uniform lithology. The result is an informative and interesting indication of failure potential based on uncertain and inaccurate data.

The thematic information from TM (soil wetness, clay and iron content) is very theoretical and subjective. Potential errors in the data are smaller (RMS is usually less than 1.0) but the decision threshold uncertainty factor is very large.

The hazard and risk maps produced should provide useful information for consideration and preparation for the next major landsliding event that will inevitably occur.

8.4 Recommendations for further work

The routine availability of global SAR imagery and the recent development of suitable technology makes SAR Interferometry a potentially good tool for the monitoring of landslide activity. SAR Interferometry, which is sensitive to fluctuations in surface elevations of a few millimetres, could be used to monitor slight movements of active landslides. Spatial resolution (25m in the case of ERS-1 SAR) limits the potential of INSAR to the monitoring of landslides which are several 100 metres in length. Illumination geometry and ground conditions must still be considered. There is potential for the application of SAR technology to the study of landslides, and research in the field of interferometry is currently very active.

Desirable data for further stability analysis and GIS work include cohesion, friction angle, plasticity values for each lithological group, gridded (or equivalent) groundwater data (at peak and residual levels), and a better quality DEM (finer gridding and greater elevation precision).

8.5 Landsliding in the Langhe

The conditioning and triggering factors for debris-flows are summarised in Table 8.1. The high slope angle and increased pore pressure in the soil are significant. Increasing pore pressures reduce shear strengths and the increased weight of the soil mass exceeds the frictional resistance and movement begins. The slide develops along a plane of weakness at the soil-rock interface. As it moves, the material becomes disrupted, the soil and vegetation get caught up and dis-aggregated so
that it becomes a flow of debris. The flow material runs out onto the valley floor, or slows as slope angle decreases sufficiently for the mass to become stable and the flow comes to rest.

Table 8.1 Conditioning and triggering factors leading to landsliding in the Langhe

<table>
<thead>
<tr>
<th>Pre-conditioning factors</th>
<th>Block-slides</th>
<th>Debris-flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inclination of beds toward slope face</td>
<td>Steep slope angles</td>
</tr>
<tr>
<td></td>
<td>thinly bedded, alternating porous and impermeable rocks</td>
<td>Thin, friable and poorly consolidated soils</td>
</tr>
<tr>
<td></td>
<td>Presence of swelling clays in laterally extensive layers</td>
<td>Long period of antecedent rainfall (or snowfall)</td>
</tr>
<tr>
<td></td>
<td>Abundant vertical fractures intersecting basal planes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Impeded drainage through clay-rich layers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long period of antecedent rainfall (or snowfall)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proximity to roads</td>
<td>Proximity to 1st and 2nd order streams</td>
</tr>
<tr>
<td></td>
<td>Open vertical fractures (release surfaces)</td>
<td></td>
</tr>
<tr>
<td>Triggering factors</td>
<td>Intense and heavy rainfall</td>
<td>Intense and heavy rainfall</td>
</tr>
</tbody>
</table>

The pre-conditioning, distribution controlling and triggering factors for block-slides are summarised in Table 8.1. The pre-conditions are the inclination of bedrock towards the slope face, the fissile and fractured nature of the rocks provide many providing sliding surfaces, and the alternating sequence of thinly bedded porous and impermeable clay-bearing rocks. The sand and sandstone layers retain water and the clay-bearing layers impede drainage and gradually swell in the presence of water. Deep and intense fracturing facilitates water infiltration. Pore pressures above the impermeable layers increase and shear strength reduces to the point that failure initiates along planes of weakness (between bedding surfaces and platey clay minerals). Release surfaces are provided by the vertical fractures such that discrete sliding blocks of relatively intact rock are formed. As blocks move, they remove support from the rock and soil mass upslope of them, which then become unstable and slide in the same manner. When multiple sliding surfaces are generated, the blocks collide and collapse on one another producing large volumes of dis-aggregated and
chaotic material. The soil and dis-aggregated rock material at the toe is compressed and bulges, forming a hummocky and rucked surface, often with the top soil and vegetation cover intact. Small scale thrust-like structures are sometime produced in the soil layer of this compressional zone. Due to the disruption and deformation from the multiple failures, compound block-slides tend to produce more chaotic surfaces which are highly irregular, devoid of vegetation and soil cover, and consist of disintegrated rock debris and rock fragments.

The fact that only some block-slides develop into compound (multiple slip-plane) phenomena is puzzling. Only two compound slides were produced by the 1994 storm event, Murazzano (B) and San Benedetto. The reasons for this are not obvious. The rock stratigraphy and structure is similar to that at other locations (e.g. Murazzano (A)) but it is possible that the fracture depth and development was more extensive and mature at these localities. Deeper water penetration was allowed so that release surfaces are provided for deeper blocks.

8.6 Practical application and interested communities

In view of the long-term and permanent nature of the hazard, and the large area at risk, the only practical method of hazard mitigation is to help local inhabitants understand the problem and how to avoid or make preparation for the event. Such steps might include encouraging farmers not to deforest steep slopes, to contour plough cultivated slopes, to improve drainage, to monitor the groundwater levels in their wells and to make their own well data available.

The results of this work will be of interest to local planners and legislators, to other researchers of flood/landslide problems in the region, to researchers interested in the application of remote sensing and GIS to hazard assessment of real problems, and most importantly to the local inhabitants of the Langhe Hills. Combining rainfall forecasts (triggering mechanism) and the spatial identification of high risk areas, presented in this study, should assist local planners, scientists and officials to better cope with their “problem” in the coming years.

In the light of the widespread hazard already posed by landslides, the devastation they can cause and the implications of a changing global climate, preparations should be made for regular predictions of natural hazards. There was much criticism of local authorities after the recent mudslide disasters near Naples (May 1998) and in the Austrian Alps (July 1998). Perhaps such disasters could have been avoided if digital hazard assessment and monitoring systems had been in place.
8.8 Original contributions of the research

The setting and type of landslides experienced in the Langhe are not unusual, in fact they constitute well known landslide-prone conditions. What is unusual is the extent of the phenomena, i.e. the regional susceptibility and the periodic nature of the hazard. This regional susceptibility is directly related to the lithological, geomorphological and climatic homogeneity of the area. This work represents the results of a preliminary regional analysis and quantification of long-term landslide problems in the Langhe. The original contribution of this work lies in the following:

- regional and quantitative landslide hazard assessment of the Langhe Hills, using digital integration and analysis of readily available data employing a GIS
- correlation of mineralogical information with landslide hazard by linking soil mineral content to structure and lithology (discontinuities and sedimentary layering).

8.9 Critical appraisal of the research

The main successes are:

- the enhancement and extraction of landslide features from textural information in imagery without the aid of stereo-visualisation
- demonstration, using multi-temporal images and targeted processing, that landslide distribution is not random
- generation of hazard maps which closely resemble the distribution of actual landslides produced by previous events

The unanswered questions include:

- the difficulties of constructing a truly automated textural classification
- the reason why some block-slides develop into very large, compound slides while others remain simple, single failure plane structures
- the recurrence interval is unknown because the time interval cannot be understood without detailed historical information and the derivation of a recurrence time-scale is currently not feasible. Block-slides do not seem to occur every winter although heavy storms usually do. This suggests that there is a periodicity to the events beyond the influence of weather. Antecedent rainfall, rising groundwater and increasing pore pressures contribute to the triggering mechanism but perhaps the long period of inactivity is related to the length of time necessary for the clays to swell and shear strengths to reduce sufficiently.
8.10 Synthesis

This thesis summarises the steps in a hybrid or integrated landslide hazard assessment process involving varied sources and types of input data. It describes the textural and spectral analysis of imagery, correlation with field data, compilation of a digital database, multi-criteria analysis and the derivation of hazard maps for the landslide-prone region of the Langhe.

The most discriminating factors for the classification of landslides can be considered as (a) landslide morphology; (b) geotechnical properties of the materials; and (c) the mechanism of failure. Remote sensing can provide information concerning the morphology and (to an extent) the materials, field work and laboratory testing provide geotechnical information and mechanisms. GIS enables processing and integrated analysis to describe the spatial characteristics of the landslides.
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Appendix A

Properties of rocks and soils relevant to slope stability

This section deals with the component materials of slope, i.e. rocks, soils, and their physical properties. The most important property is that of shear strength and its influence on ground water pressures and their variations with respect to location and time.

A.1 Mineralogy

Most sedimentary soils and rocks are composed of two classes of particles, i.e. massive minerals (>10mm - 2mm) and platey minerals. Massive minerals, commonly of quartz, feldspar or calcite, are generally equidimensional and have similar physical properties, e.g. unit compressive strength and friction coefficient. The platey minerals or clays have a layer-lattice (or sheet) structure and common examples are kaolinite, chlorite, illite and montmorillonite.

Each of the above has different degrees of affinity for water and this influences their behaviour. The surfaces of clays are active to water and they attract hydrated cations and water molecules. Different clay minerals adsorb different amounts of water and this water content dictates plasticity and frictional properties. This behavioural difference, between the two classes of particle, is due to a) specific surface area (or surface area per unit mass) and b) cation exchange factor which is dependent on the specific surface area and on the density of surface electric charge. To achieve neutrality and therefore chemical stability, hydrated cations and water molecules are attracted to the surface to form an ionic water layer around each particle (a diffuse ionic layer). Cations in this layer can exchange for others, i.e. they are not fixed. Minerals with large specific surface areas and large surface charge densities attract large numbers of cations and water, thus changing the thickness of the particle and the chemistry of the pore fluid. Massive minerals have no attracted ionic layers.

A.2 Phase relationships of soils

Soils have a characteristic 3-phase nature, comprising solid, water and air, and they are described in terms of the relative quantities of each phase (Figure A.1).

Where \( G_s \) = the average specific gravity of solids; \( \rho_w \) = the density of water; \( g \) = gravitational acceleration.

Other properties related to the phases of soils are defined as:
- Porosity (n) - ratio of the volume of voids to the volume of soil \( n = \frac{V_v}{V} \)
- Voids ratio (e) - ratio of the volume of voids to the volume of solids \( e = \frac{V_v}{V_s} = n / (1 - n) \)
- Degree of saturation (Sr) - ratio of the volume of water to the volume of voids \( S_r = \frac{V_w}{V_v} \)
- Water content (w) - ratio of the mass of water to the mass of solids \( w = \frac{M_w}{M_s} \)
- Bulk density (p) - ratio of the total mass of soil to the total volume \( p = \frac{M_t}{V} \)
- Bulk unit weight (γ) - ratio of the total weight (force) to the total volume of soil, and this is used to estimate stress within a body of soil \( \gamma = \frac{M_g}{V} = \rho g \)

A.3 Particle size distribution of soils

This is determined from mechanical analysis involving the use of standard sieves and fine analysis. Particle size has five ranges, following the ‘two-six’ rule, as follows: Clay size < 0.002 mm, Silt size 0.002 - 0.06 mm, Sand size 0.06 - 2 mm, Gravel size 2 - 60 mm, Cobble size > 60 mm; and there are fine, medium and coarse divisions within these ranges.

Particle size distribution gives indications of other soil properties. For example: permeability - soils with only sand size, and larger, are pervious to water whereas soils with ca 10% clay particles are relatively impervious; and shear strength - soils coarser than silt size will have frictional strength properties like sand, but soils >30% clay particles will have frictional properties like clays.

A.4 Plasticity and activity of soils

Plasticity properties are measured by two water-content indices, the Liquid limit \( W_L \) and Plastic limit \( W_P \), the definitions of which are illustrated in Figure A.2.

The Plastic limit is defined as the water content at which a soil is at the transition between brittle and plastic behaviour. The Liquid limit is defined as the water content at which a soil is at the transition between plastic and liquid states. The range of water content between these two limits is referred to as the Plasticity Index \( I_p \): \( I_p = W_L - W_P \)

Plasticity characteristics depend on type and quantity of constituent minerals and Table A.1 lists several major clay mineral groups and their plasticity properties.
Figure A.1 Phase relationships of soils.

Figure A.2 Plasticity properties of soils.

Figure A.3 Relationships between total head (h), elevation head (z) and pressure head (hₚ).

Figure A.4 Compressibility curves of clays.
Another important index property of a soil is its Activity (Skempton, 1953) which is the ratio of $I_P$ to the fraction of clay particles:  \[ A = \frac{I_P}{\text{clay fraction}} \]

**A.4 Fluid flow and effective stress**

The mechanical behaviour of soils and rocks are strongly affected by water pressures in the void spaces between grains of soil or sediment, or in fractures, e.g. slope movements are encouraged by rainfall and water infiltration. These are affected by fluid flow, ground water pressures and effective stress.

**A.4.1 Head and fluid pressure**

Water flowing from one place to another is not necessarily caused by a difference in pressure but by a difference in the total energy between the two places. There are several components to this total energy: elevation (potential energy), velocity (kinetic energy), pressure energy, but also thermal, electric and chemical energies. The pressure head is usually measured by means of a piezometer and the total head is defined as:

\[ \text{Total head (h)} = z + h_p \]

Where $z$ is the elevation of the water column in the piezometer and $h_p$ is the pressure head (which is the ratio of pore water pressure to the bulk density of water). The relationship between total head, elevation head and pressure head is illustrated in Figure A.3. Water flow in soil is controlled by the spatial distribution of total energy of the water.

This water flow is important in the generation of pore pressures in situations were there is impeded drainage from a slope, e.g. when there are alternating permeable and impermeable layers in the rock mass, or impermeable clay soils.
A.4.2 Principle of effective stress

Forces applied to soils and rocks are resisted by both the particles and by the fluid in the voids. Particles resist normal and shear forces but fluids can only resist normal forces. Forces applied to soils and rocks which are supported by fluid pressures in the voids, are not felt by particle contacts and do not therefore influence the behaviour of the soil or rock. The principle of effective stress states that the stress-strain behaviour of a soil or broken rock (e.g. a change in volume or shear strength) is directly dependent on normal stress ($\sigma'$), and not dependent on total normal stress ($\sigma$), nor on pore water pressure ($u$). It cannot be directly measured but must be derived from the total normal stress and pore water pressure.

A.4.3 Permeability

This refers to the quantity of water being conducted through the soil or rock and is also known as hydraulic conductivity. Current understanding of permeability ($q$) is based on experiments by H. Darcy in the 1850's and Darcy's Law is defined by the following:

$$ q = k \frac{Q}{A} = k \frac{(h_1 - h_2)}{L} $$

$$ q = ki $$

Where $Q$ = volume of water; $A$ = cross-sectional area of the material conducting the flow; $L$ = the length of the soil in the flow direction; $h_1 - h_2$ = the loss in total head over the distance $L$; $i$ = the hydraulic gradient or rate of decrease in the total head with distance in the direction of flow; and $k$ = the constant of proportionality or coefficient of permeability, which has units of $\text{ms}^{-1}$. The magnitude of $k$ for a soil depends on grain size, soil fabric, joints and fissures, all of which increase the value of $k$.

A.5 Compressibility and stress history

All materials change volume in response to applied stress. For soils it is the effective stress that controls volume. Increases in effective stress cause a decrease in volume, known as compression, and decreases in effective stress cause an increase in volume, known as expansion. These properties depend on mineral composition and stress history.

A soil can be in one of two states, normally consolidated, when the magnitude of effective stress it is supporting is the maximum vertical stress that it has ever supported; or overconsolidated, where the soil has at some time supported a vertical effective stress much larger than that which it supports now. A measure of stress history is the Overconsolidation ratio (OCR).
Where $p'_{\text{max}} = p'_{0}$). Where $p'_{\text{max}}$ = the maximum vertical effective stress ever experienced; and $p'_{0}$ = the vertical effective stress at the time of interest. The compressibility behaviour of clay soils is shown in Figure A.4. The stress history gives and indication of the denseness of a soil, normally consolidated soils (OCR=1) are loose and are weaker than overconsolidated soils.

A.6 Shear strength

The condition of shear failure refers to the point when the shear stress exceeds the available shear strength. When shear strengths and shear stress within a soil or rock mass have been determined independently, a comparison between the two gives an indication of the stability of the mass. There are two methods of assessment: one is with respect to effective stress (which requires pore water pressure information) and the other is with respect to total stress (which does not require pore water pressure information).

A.6.1 Effective shear strength properties of soils

Sands - these consist of individual equidimensional particles which roll and slide. In loose sand, shear resistance occurs in response to horizontal displacement and the volume of the soil decreases as the particles jostle to more stable positions. When the volume decrease stops and the shear strength becomes constant this is called the Critical State condition.

In dense sand the shear resistance increases more rapidly and there is a volume increase as particles ride up over one another. Shear resistance reaches a maximum when the volume increase is at a maximum (peak strength), then shear resistance decreases and the rate of volume change also decreases until the volume and shear strength equal that of a loose sand. The presence of water on the sand particle surfaces does not affect frictional resistance i.e. it is not a lubricant.

Clays - these are similarities to the properties of sands but the platy particles tend to orient themselves parallel to the direction of motion during shear displacement. The shear strength of a soil, when particles are at their greatest degree of alignment, is termed the Residual Strength. This refers to the minimum shear strength and is similar to pure friction ($\phi'$).

Peak strength values of cohesion ($c'$) and friction ($\phi'$) are determined from laboratory tests. Peak strength is only maintained over a small range of strain, beyond which the strength properties decrease (or 'strain soften'). It is unlikely that all parts of a potential slip surface will reach peak strength simultaneously. More reasonable is Progressive Failure when some parts reach peak strength before others. Thus it is safer to use the residual strength properties in calculations.
To reduce a clay's shear strength to residual usually requires considerable shear displacement along narrow zones and such conditions are not usual in natural slopes. Most natural clays are overconsolidated, i.e. they have experienced greater overburden pressures than exist at present. Their lower water content and close packing initially causes them to display a greater strength than normally consolidated clays but when the overburden is removed, overconsolidated clays develop fissures and undergo a progressive decrease in shear strength.

A.6.2 Undrained shear strength

This relates only to conditions where pore water is immobile relative to the rate of change in stress in a soil. Such conditions only occur in a slope which is undergoing failure. Undrained shear strength is not usually reliable for estimating the stability conditions of natural slopes.

A.7 Friction and cohesion in rocks and soils

The shear strength of a soil or rock, on a surface within the material, is controlled by three factors: i) the magnitude of effective stress (σ') perpendicular to the surface; ii) the frictional properties; iii) dilatency (a measure of volume change when shear occurs); iv) cohesion.

The contact between two surfaces, no matter how smooth, will consist of roughness at some scale. As σ' increases the surfaces are pressed closer together. The coefficient of friction (μ) is a measure of resistance to movement caused by molecular adhesion of one surface to the other. Frictional properties are often expressed as an angle of friction φ' (where \( \tan \phi' = \mu \)) and shear strength (s) (where \( s = \sigma' \tan \phi' \)).

It is the effective normal stress which controls the contact conditions between the two surfaces, so that when fluid pressures exist, it is the effective normal stress which controls shear strength. In order to move the upper block in the direction of shear force, the frictional resistance must be overcome, the upper block must be raised and the potential energy must be increased. This process is termed dilatent behaviour. When volume increases as a result of shear displacement, dilatency is positive and the shear strength is larger than when no volume change occurs.

A rectilinear slope will be stable where the line representing the slope lies below that representing shear strength (Figure A.5) of the slope height. This is true under natural conditions of well drained materials such as sand dunes and screes. Materials which have cohesive properties can be stable at slope angles in excess of friction angle.
Figure A.5 Effect of cohesion and friction angle on slope angle stability; a) and c) represent cohesionless materials; b) and d) represent materials possessing cohesion.
A.8 Rock fractures

Rock slopes often contain several sets of discontinuities, faults and joints which can combine to form various possible wedge block sets. Such discontinuities when dipping toward the free face of a slope, especially a dip slope, at approximately the same angle, constitute a well known landslide-prone condition (Chorley et al., 1984, Shuster & Krizek, 1978). Sliding along fractures and discontinuities is resisted by frictional shear strength, and they owe their shear strengths to two forces:

1. the frictional resistance of two surfaces sliding relative to one another.

2. the resistance to sliding due to the irregularities on the surfaces (surface roughness).

Surface roughness increases initial friction for all rock types.

Water can have several effects on friction during sliding. It can change the coefficient of friction of smooth mineral surfaces; it can lower the surface energy of the individual crystals and decrease their strength; pore pressures can develop; and water can alter the mode of surface damage (e.g. polishing, gouging). On smooth surfaces water behaves as an anti-lubricant on massive minerals and as a lubricant on layer-lattice minerals.

Coulson (1972) recommends that where no laboratory testing is possible, general friction coefficient values of 30° can be taken for flat joints, for limestones this may be increased to 35°, and that special consideration should be made for polished or slickensided surfaces in rocks containing micas and clays, so that $\phi$ can be reduced to 22° - 25°.
APPENDIX B

B.1 Idrisi batch files used in the GIS hazard assessment

The following batch file listing was used for the calculation of Bayesian probability and landslide hazard assessment.

Bayes.iml

reclass x i slopew bs-thrsh 2 1 0 18 0 18 53.1 -9999 Slope thresholded < 18deg
reclass x i slopew df-thrsh 2 0 0 18 1 18 53.1 -9999 Slope thresholded > 18deg

class x slopew xusbs 1 18 Probability that each pixel is <18
pclass x slopew xusdf 2 18 Probability that each pixel is >18

reclass x i xusbs bsrisk10 2 0 0 0.05 1 0.05 1.01 -9999 Risk of bs >5%
reclass x i xusdf dfrisk10 2 0 0 0.05 1 0.05 1.01 -9999 Risk of df >5%

assign x aspclass xunbs un-bs 2 /* creates prior probabilities using values file un-bs */
assign x aspclass xundf un-df 2 /* creates prior probabilities using values file un-df */

reclass x i geolw one 2 1 0 13 -9999 Image with value 1
overlay x 2 one xunbs xst-bs
overlay x 2 one xusbs xstabs
overlay x 2 one xundf xst-df
overlay x 2 one xusdf xstadf

bayes x 2 xunbs xst-bs xusbs xstabs 1 xp /*creates post-probabilities */
bayes x 2 xundf xst-df xusdf xstadf 1 xp /* creates post-probabilities */

reclass x i xpxunbs y-baybs 2 0 0 0.05 1 0.05 1.01 -9999 Slope inst.(block slide) at 5% risk with data uncertainty
reclass x i xpxundf y-baydf 2 0 0 0.05 1 0.05 1.01 -9999 Slope inst. (debris flow) at 5% risk with data uncertainty

fuzzy x 1 slopew 1 xufzbs 4 4 4 32
fuzzy x 1 slopew 1 xufzdf 4 32 32 32
overlay x 2 one xufzbs xsfzbs
overlay x 2 one xufzdf xsfzdf
bayes x 2 xpxunbs xpxst-bs xufzbs xsfzbs 1 y
bayes x 2 xpxundf xpxst-df xufzdf xsfzdf 1 y
reclass x i yxpxunbs y-fuzbs 2 0 0 0.05 1 0.05 1.01 -9999 Slope inst.(block slide) at 5% risk with data uncertainty
reclass x i yxpxundf y-fuzdf 2 0 0 0.05 1 0.05 1.01 -9999 Slope inst.(debris flow) at 5% risk with data uncertainty
delete x x*. *

The following batch file listing was used for the fuzzy standardisation of GIS data layers and MCE combination.

MCE.iml
fuzzy x 1 slopew 2 zslope 0 4 15 20
fuzzy x 1 slpdpw 2 zslpdp 8 8 8 10
fuzzy x 1 aspw 1 xaspx 20 40 220 260
scalar x xaspx xaspy 3 -1.0
scalar x xaspy xaspz 1 1.0
stretch x xaspx zaspect 1 min max N 256
delete x xasp*.img
delete x xasp*.doc
fuzzy x 1 rddstw 2 zrdddst 200 200 200 300
fuzzy x 1 drndw 2 zdrndst 150 150 150 300
fuzzy x 1 demw 2 zdem 350 600 600 600
fuzzy x 1 ironw2 2 ziron 90 240 240 240
fuzzy x 1 clayw2 2 zclay 70 220 220 220
fuzzy x 1 wetw 2 zwet 80 180 180 180
fuzzy x 1 drndw 2 zdrndf 50 50 50 120
fuzzy x 1 slpdpw 2 zslpdf 8 10 10 10
fuzzy x 1 slopew 2 zslopef 15 20 20 20
fuzzy x 1 aspw 1 zaspf 20 40 220 260
mce x xmlc1 mclwlc
mce x xmlwa2 mceowa2
mce x xmlwa8 mceowa8
mce x xmlwa6 mceowa6
mce x xmlwa7 mceowa7
mce x xmlwa9 mceowa9
mce x xmlcf1 mceflw1
mce x xmlaf2 mceflw2
mce x xmlaf4 mceflw4
mce x xmlaf5 mceflw5
mce x xmlaf6 mceflw6

scalar x xmlc1 xoutl 4 100
.scalar x one xoutl 4 2.55
.overlay x 3 xoutl xout2 ywlcb1
.scalar x xmlwa2 xoutl 4 100
.scalar x one xoutl 4 2.55
.overlay x 3 xoutl xout2 yowab2
.scalar x xmlwa8 xoutl 4 100
.scalar x one xoutl 4 2.55
.overlay x 3 xoutl xout2 yowab8
.scalar x xmlwa6 xoutl 4 100
.scalar x one xoutl 4 2.55
.overlay x 3 xoutl xout2 yowab6
.scalar x xmlwa7 xoutl 4 100
.scalar x one xoutl 4 2.55
.overlay x 3 xoutl xout2 yowab7
.scalar x xmlwa9 xoutl 4 100
.scalar x one xoutl 4 2.55

/* scales the 8-bit images to real data (0-1) */
B.2 Idrisi modules used in the GIS hazard assessment

BAYES - A module which evaluates the probability that a single hypothesis is true given certain evidence. The evidence is expressed as conditional probabilities given the hypothesis under examination, i.e. p(ε|h). BAYES also requires prior probability files, i.e. p(hi). The output image expresses the posterior probability that each hypothesis is true, i.e. p(hi|ε). BAYES
allows the incorporation of measures of confidence in the decision rule by using a value representing the expected probability that the evidence required to substantiate the hypothesis is provided by the actual evidence.

FUZZY - Evaluates the possibility that each pixel belongs to a fuzzy set by evaluating any of a series of fuzzy set membership functions. The user-defined function requires the input of control points and their corresponding fuzzy set memberships. These pairs serve to define the shape of the fuzzy set membership curve. Output may be scaled from 0-1 or from 0-255.

MCE - A decision support module for Multi-Criteria Evaluation. A decision is a choice between alternatives (such as levels of influence on stability) and the basis for each decision is known as a criterion. The module combines a set of criteria to achieve a composite result for a decision according to a specific objective.

OVERLAY - An operation which produces a new image from the data of two input images. New values result from applying one of the nine possible operations (add, subtract, multiply, divide or ratio, composite ratio, power, maximum, minimum and cover (first image covers the second except where zero)) to the two input images.

PCLASS - Assesses the probability that any pixel in an image exceeds or is exceeded by a specified threshold value. This is done by integrating areas under the normal curve based on the RMS error specified in the value error field of a raster image documentation file. The RMS error can be a value for the entire image, or can be spatially variable.

RECLASS - Classifies image data or attribute values into new integer categories. Classification is by equal interval divisions of the data range, or by user-defined intervals.
Figure 7.2: Block slide risk map generated using the block slide hazard map and the relative vulnerability map (see text for details).
Figure 7.25: Exhibit flow path generated using the digital flow map and the relative vulnerability map (see text for details).