R7815

Landslide Risk Assessment in the Rural Access Sector

Report on Project Activities undertaken in Bhutan

May – October 2002

January 2003

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Version/Revision	Dated	Prepared By	Reviewed By
Draft	January 2003	GJ Hearn/AB Hart	GJ Hearn
Final	January 2003	AB Hart	DN Petley

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Contents

Appendices

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1 Introduction

The project entitled 'Landslide Risk Assessment in the Rural Access Sector' (Landslide Risk Assessment-LRA) is sponsored by the UK Department for International Development (DFID) as part of their Knowledge and Research Programme. The project aim is to develop and test rapid means of landslide susceptibility mapping for road alignment purposes in remote rural areas in hilly or mountainous terrain. The project will also produce guidelines on how best to apply the techniques as well as recommendations for the management of road corridors in landslide-prone areas. The project has been implemented in Nepal in association with the Ministry of Local Development and in Bhutan in conjunction with the Department of Roads.

The principal activities and outputs of the project are as follows:

- Establishment of a Geographical Information System (GIS) within Department of Local Infrastructure Development and Agricultural Roads (DoLIDAR) Nepal and Department of Roads (DoR) Bhutan
- Procurement and interpretation of satellite imagery and aerial photography for landslide hazard and risk assessment
- Development of GIS datasets for the selected study areas (three in Nepal and three in Bhutan) covering *inter alia* geology, topography, land use and landslide distributions
- Confirmation of landslide locations and geology through field mapping
- Development and testing of landslide susceptibility maps for the study areas
- Field surveys to assess engineering and land use management practices with respect to landslide problems in road corridors
- Development of best practice guidelines in remote sensing, landslide hazard mapping, route corridor planning and route corridor engineering
- Training, knowledge transfer and dissemination through secondment and workshops.

This report briefly summarises the progress and outputs achieved by the LRA Project to date within Bhutan. It is important to note that these achievements would not have been possible without the support and commitment of the DoR. The Department of Geology and Mines and the Department of Survey and Land Records also provided assistance with data and seconded staff.

2 Programme

Project activities in Nepal commenced in November 2000. A regional seminar was held in Kathmandu in April 2001 to introduce the project to invited delegates. Two officers from the DoR Bhutan attended this seminar and gave presentations.

Project activities commenced in Bhutan in May 2002 by way of an Introductory Seminar in Thimphu on 17 May 2002. After that date the full LRA team was mobilised and project investigations and associated activities were completed according to schedule at the end of September 2002. The project completion was marked by a seminar on the 27 September in Thimphu, organised jointly between DoR and Scott Wilson. It was followed by an intense training workshop organised at the request of DoR.

The programme of activities undertaken in Bhutan is shown on the following page.

3 Study Team

Details of the study team, their role, responsibility and arrival and departure times (where applicable) in Bhutan are given in the table below.

Name	**Position**	**Responsibility**	**Arrival Departure**
Gareth Hearn	Project Manager	Project management Engineering input & training	13-27 May 12 Sep-6 Oct
David Petley	Research Manager	Office/field QA and Risk Assessment & training	12 - 26 August
Andrew Hart	Local Team Leader & Principal Researcher	Full time Technical Co-ordination, field mapping, GIS & training	20 May-17 October
Ivan Hodgson	API Specialist	Landslide mapping from air photos, API training	10 June-1 July
Will Crick	Remote Sensing Specialist	Interpretation of satellite imagery, & RS/GIS training	10 June-4 July
Chris Massey	Geologist	API, field mapping & training	23 July- 24 August
Sushil Tiwari	Seconded Engr MLD Nepal	Social surveys and GIS	20 May-1 Aug 26 August-3 October
N K Giri	Seconded Engr DoR, Bhutan	Project co-ordination with DoR, office and field management, part-time technical input	Not applicable
K Chopel	Assistant Seconded Engr DoR, Bhutan	Office and field assistance	Not applicable
Phuntsho Norbu	Field Geologist seconded from Dept Geol & Mines	Field mapping of geology	Not applicable
Shanti Ram Sharma	Field Geologist seconded from Dept Geol & Mines	Field mapping of geology	Not applicable
Lalit Chhetri	Digitiser seconded from Dept Geol & Mines	Digitising and training	Not applicable
Phuntsho Wangmo	Digitising Assistant seconded from DoR	Assistance with digitising	Not applicable
Kiran Humagai	Local Project Co-ordinator	Project co-ordination in Bhutan	Not applicable

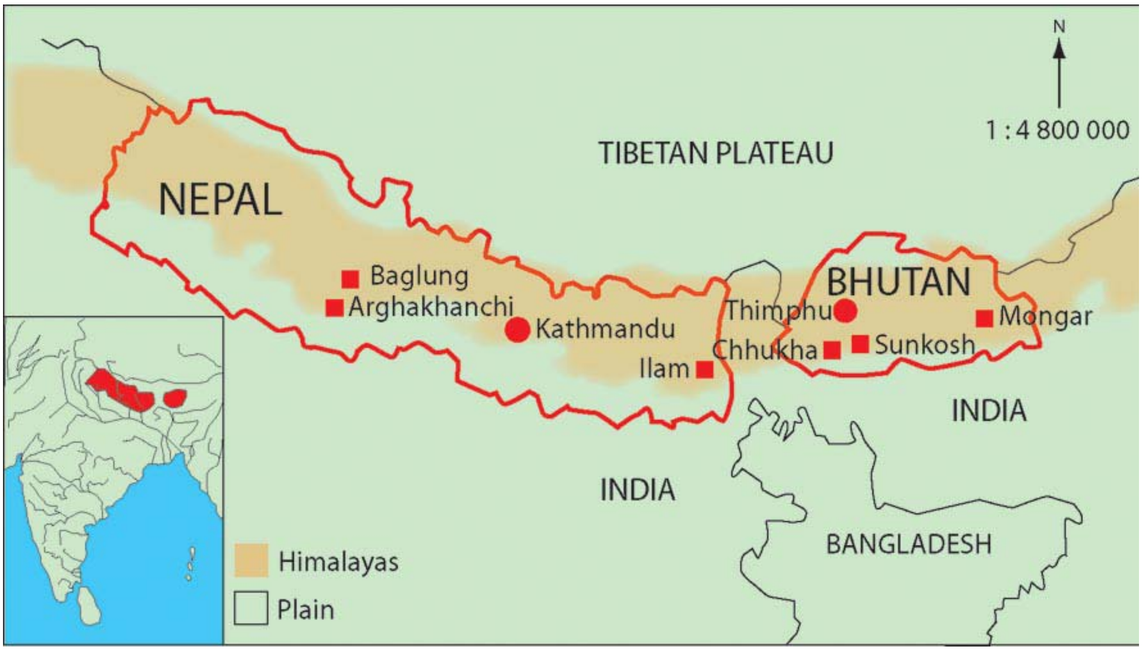
4 Selection of Study Areas

Three study areas were selected following discussion with DoR. At the time of selection, the DoR was considering a realignment to the Thimphu-Phuentsholing Highway between Damchu and Chhukha. DoR therefore requested that this area be included in the study. Two other study areas (Mongar-Trashigang in the east and Sunkosh-Daga in the west) were also selected to cover a wider range of geology and topography and to cater for the variability in aerial photograph cover within Bhutan. The various attributes within each of the study areas are described in the table below, and illustrate the range of conditions incorporated into the study.

Attribute	**Damchu-Chhukha**	**Mongar-Trashigang**	**Sunkosh-Daga**
Location	SW Bhutan	East Bhutan	SW Bhutan
Area (sq kilometres)	202	346	251
Topography	Moderate-steep valley sides	Mixed with variable steepness	Mixed with low to moderate steepness
Land use	Mostly forest	Mixed forest/cultivation	Mostly cultivation
Geology	Schist, gneiss, quartzite & limestone.	Schist, gneiss, quartzite, phyllite & limestone	Schist, gneiss, quartzite, phyllite & granite
Structural Geology	Folding & minor faulting	Folding & thrust faulting	Folding & (thrust) faulting
Infrastructure	Thimphu-Phuentsholing Highway and hydropower installation	Main East-West Highway and agricultural roads	Sunkosh-Daga road
Available geological mapping	Whole area at 1:50,000 scale	Partial coverage at 1:50,000 scale	Partial coverage at 1:50,000 scale
Available topographical mapping	Whole area at 1:50,000 scale	75% at 1:25,000 + 25% at 1:50,000 scale	Whole area at 1:50,000 scale
Available air photos	Full coverage	Full coverage	Full coverage
Available satellite imagery	Landsat, IRS	Landsat, IKONOS	Landsat

5 Study Area Locations

The location of the three study areas in Nepal and the three study areas in Bhutan.



6 Outline Objectives of the Bhutan Study

The outline objectives of the Bhutan study are to:

- Examine the use of satellite imagery in the assessment of landslide occurrence in Bhutan
- Develop a landslide dataset for each of three study areas in Bhutan, namely: Mongar-Trashigang, Damchu-Chhukha and Sunkosh-Daga
- Analyse this landslide distribution with respect to geology and topography to determine whether the susceptibility models developed for Nepal are applicable
- Use these analyses to see how best a universal susceptibility model can be developed for the Bhutan and Nepal study areas
- Carry out a social survey to assess the impact that landslides have on livelihoods and land use in selected road corridors
- Carry out an engineering survey of landslide problems on selected roads
- Carry out training, dissemination & knowledge transfer through workshops and on-the-job demonstration.

7 Methodology

A preliminary field visit was made to each of the three study areas in May 2002 in order to collect preliminary data and the fieldwork. Following this visit discussions were held with the Department of Geology and Mines and the Department of Survey and Land Records to determine the levels and availability of existing geological mapping, aerial photography and topographic data.

7.1 Establishing the GIS

ArcView 3.2 was chosen to store and analyse all of the data that was collected and used by the project. This included the data that was collected during the field visits and the remote sensing stages of the project. Where digital contour data was available it was purchased from the Department of Survey and Land Records. This saved a considerable amount of time as it avoided the lengthy operation of manually digitising the contour data. The Land Use and Statistics Section of the Ministry of Agriculture provided digital land use data for all of the three study areas. The project team digitised all other necessary data, namely:

- Published and field mapped geology (including structural geology)
- API and field mapped terrain classification
- The locations of new infrastructure and roads that are not marked on the published topographic maps
- Any other relevant information.

7.2 Remote Sensing

Landsat ETM, IKONOS and IRS satellite imagery was purchased for the study areas. The Landsat scenes covered the majority of the country, while the IKONOS image purchased from available archive covered a small area in the north east of the Mongar-Trashigang area. The IRS imagery covered in the Damchu-Chhukha study area. This imagery was interpreted to see how well landslides and related terrain features could be identified. A separate report has been prepared on the findings of the satellite image interpretation for the three study areas.

Aerial photographs were purchased from the Department of Survey and Land Records for each of the three study areas. A summary of the photography used is given in the table below.

Attribute	**Damchu-Chhukha**	**Mongar-Trashigang**	**Sunkosh-Daga**
Scale	1:35,000	1:50,000	1:50,000
Date	1978	1990	1988
Quality	Extremely variable	Variable	Good

The aerial photographs were viewed in stereo using a stereoscope and the following details recorded:

- The location and areal extent of landslides (a proforma was completed for each landslide interpreted. This proforma contained data on landslide classification, land use and runout length.)
- Terrain classification incorporating rock, residual soil and colluvium
- Structural geology lineations

Both the satellite image interpretation and the aerial photograph interpretation were supported by field validation. This allowed comparison between features seen in the field and their appearance in aerial photographs. The final output from the remote sensing was digitised as a separate layer into the GIS.

7.3 Field Mapping of Landslides

Field mapping of landslides was undertaken through systematic traverses of all three study areas, using GPS to accurately determine location. The field mapping was undertaken by team members comprising an expatriate geologist and the seconded engineer from the Department of Roads. Landslides were mapped directly onto the available topographic maps and digitised later in the office. A proforma was filled in for each recorded landslide.

Much assistance was given by the local community in the identification of landslides, including information on their initiation and impact.

7.4 Compiling the Landslide Database

The three landslide datasets (from satellite imagery interpretation, aerial photograph interpretation and field mapping) were compiled into a single dataset. The table below summarises the number of landslides identified from each source in each of the study areas.

Source of Data	Damchu-Chhukha	Mongar-Trashigang	Sunkosh-Daga
Satellite Imagery	27	106	68
Aerial Photography	30	159	247
Field Mapping	10	120	58
Total Number	**49**	**229**	**220**

Note that "Total Number" refers to the number of landslides used in the analysis. It will be less than the sum of the three data sources because some of the landslides were identified from more than one source. The number of landslides identified by either of the remote sensing methods will also differ slightly from the number used in the analysis, because this number represents the number of landslides mapped prior to field verification.

7.5 Field Mapping of Geology

1:50,000 scale geological mapping exists for much of Bhutan, carried out principally by the Geological Survey of India. In each of the three study areas this mapping provided only partial coverage. Unfortunately, this mapping has not been carried out in a co-ordinated way, and there are several questions remaining over the exact outcrop patterns in some areas and the differentiation between different geological units.

This mapping was therefore augmented by field survey. This was undertaken by project staff and two geologists seconded from the Department of Geology and Mines. The final mapping for each area was then digitised into the GIS as a separate layer.

7.6 Land use and Engineering Surveys

In both the Mongar-Trashigang and Sunkosh-Daga areas, a survey was made of the interaction between the main road and surrounding land use with respect to slope stability. A study was made of the incidence of landslides within the road corridors. This incidence was compared with the incidence of landslides outside the road corridor to assess the extent to which road construction (mainly earthworks) is responsible for increased levels of instability. Also, discussions were held with local farmers to ascertain how they managed their land to prevent or reduce landslide problems. This study is the subject of a separate report.

A rapid slope engineering survey was made of the road between Chhukha and Phuentsholing on the Thimphu-Phuentsholing Highway, at the request of the DoR. The survey summarised the findings of a brief review of current slope problems affecting the road and gave preliminary recommendations for slope management. A separate report has been prepared and issued to DoR. In addition, the study team inspected the area in the vicinity of the slope failures in the vicinity of Damchu-Chhukha and along the new expressway to the immediate south of Thimphu and separate memos have been prepared and issued to DoR.

7.7 Data Analysis and Results

The distribution of landslides was compared systematically with the following factors:

- Rock type (taken from the final geology map)
- Geological structure (taken primarily from air photographs with some field mapping)
- Elevation (derived using the contour data held within the GIS)
- Slope angle (derived using the contour data held within the GIS)
- Slope aspect (derived using the contour data held within the GIS)
- Land use (taken from published data from Division of Land Use, Ministry of Agriculture)

This comparison was undertaken using the Spatial Analyst extension within ArcView. It was found that when all of the three Bhutan study areas were combined only rock type and slope angle was systematically correlated with the distribution of landslides. Consequently, these datasets were combined with those from Nepal, where a similar conclusion had been reached to yield a regional (Nepal and Bhutan) listing of landslide density according to rock type-slope angle category. Thus, for any given area containing rock types found in the regional list (this should include most of Bhutan) it will be possible to determine the predicted landslide density and thus relative susceptibility once the rock types and slope angles present are known. This has significant advantages for the preliminary assessment of route corridors.

In the Sunkosh-Daga area the interpretation of aerial photography combined with field verification was taken a stage further. The interpreted and mapped geological structure was compared against the distribution of landslides and it was found that significant correlation exists between the orientation of joint planes (the structural windows) and landslide incidence. Furthermore, differentiation of the study area into the following terrain categories: rock, residual soil and colluvium, allowed further differentiation. The technique was then applied to the Damchu-Chhukha area using aerial photograph interpretation only and the results proved positive when compared with the mapped distribution of landslides.

7.8 Quality Assurance

At every possible opportunity QA practices have been applied to check data collection and analysis. This has usually involved senior project staff checking the work of others following a sampled procedure. Dr David Petley from the University of Durham has undertaken much of this QA of the Bhutan work.

8 Outputs

The principal outputs of the project in Bhutan are listed below:

- GIS database, remaining with the DoR
- Satellite imagery for the study areas, remaining with the DoR
- Topographical, geological, landslide distribution and landslide susceptibility maps of the three study areas, remaining digitally with DoR and reproduced as Appendix A of this report
- Reports on:
    - Remote sensing
    - Land use/engineering review in route corridors
    - Report on a visit to the Chhukha-Phuentsholing road
    - Workshop report
- Best Practice Guidelines in the following subjects:
    - Rural Access Corridor Management and Land use Planning
    - Route Corridor Engineering
    - Remote Sensing for Landslide Studies in the Rural Access Sector
    - Landslide Hazard and Risk Mapping
- Summary Guidance Notes on Satellite Image Interpretation, Aerial Photograph Interpretation, Field Assessments and Regional and Small Scale Susceptibility Mapping.

The draft Best Practice Guidance Notes have been commented upon by DoR and will be finalised by March 2003. The Summary Guidance Notes were issued at the November 2002 international seminar in Kathmandu and are contained in Appendix B of this report.

9 Training

Training has comprised on-the-job training through secondment and workshops held at intervals. The on-the-job secondment has principally involved three staff from DoR, operating an approximately 60% time basis on the project. The seconded staff have variously been trained in the following subjects:

- Digitising
- Establishment of GIS
- Remote sensing, including satellite image interpretation but mostly aerial photograph interpretation
- Field recognition and mapping of landslides and geology
- Factor analysis and susceptibility analysis
- Hazard and risk assessment.

This training has progressed as the project has proceeded. Over the project duration it has not been possible to train DoR staff as experts, and indeed this was never the intention. However, sufficient exposure and practice has been provided to allow those staff involved to proceed with the application of the techniques. They will require further training as their depth of involvement increases. A summary of the topics covered by the training is included in Appendix C.

Workshops have been held in satellite image interpretation, aerial photograph interpretation, GIS and landslide susceptibility analysis. These workshops have been attended by DoR staff, together with other officers from the public sector, especially those in the Department of Geology and Mines, the Department of Survey and Land Records and Land Use (Ministry of Agriculture). Questionnaires have been distributed at the end of these workshops to gauge the response of delegates to the content and value of the workshops, and without exception delegates' responses were very positive. A collection of workshop reports and questionnaires has been prepared separately. The schedule of workshops given in Bhutan under this project is summarised below.

Type of Workshop	Date	Number of Delegates
Introductory Seminar	17th May	50
Remote Sensing	17th – 19th June	22
GIS	17th – 19ht June	22
Remote Sensing	22nd – 23rd August	22
Final Seminar	27th September	50
GIS/Landslide Susceptibility	7th – 9th October	10

10 Recommendations for the Future Application of Landslide Studies in Bhutan

The value of the Landslide Risk Assessment Project is that it has helped bring together a number of government departments involved in, and concerned with a) the management and analysis of geo-environmental data by GIS and b) the assessment of landslide potential for rural development and conservation purposes. Furthermore, staff within the DoR have been given a good introduction to remote sensing, field mapping, GIS development and landslide susceptibility mapping for route corridor evaluation.

It is important that this process is taken forward in the future. DoR needs to progressively build up its database of topography, geology, land use and landslides, while at the same time acquiring copies of aerial photographs for specific areas on a project needs basis. DoR also needs to strengthen its staff capabilities in the application of LRA techniques, so that it is not dependent on one or two individuals. Those trained under LRA are in a position to train others, though some assistance will be required externally from time to time.

It is important that DoR does not work in isolation. It needs to strengthen its links with DGM and Department of Survey and Land Records. It can do this through sending selected officers for training at the various GIS workshops organised by other government departments. Also, if the techniques and procedures developed and tested under LRA in Bhutan are formalised within DoR then it will presumably become mandatory to follow up links through the acquisition of aerial photography, topographic and geological mapping.

Finally, DoR needs to strengthen its capability in geotechnical engineering: landslide recognition, investigation, analysis and design. Again, it is unwise to invest expertise in only one or two officers.

The above recommendations relate primarily to capacity building within DoR. A number of recommendations can be made that should benefit the wider public sector in Bhutan as well as DoR. These are listed below:

- There is a critical need for up to date, medium scale (1:25,000) and small scale (1:50,000) good quality black and white aerial photography for the entire country outside the High Himalayas
- The topographic mapping, currently being updated by DSLR needs to be made available for the whole country digitally at 1:25,000 scale with a 10m contour interval
- A country-wide terrain classification at 1:50,000 scale would greatly assist with the assessment of terrain for development purposes
- Comprehensive and field-verified geological mapping should be made available for the entire country
- A procedural framework for incorporating LRA procedures into the Environmentally Friendly Roads Policy needs to be established and put into operation
- A central GIS Unit needs to be established that is able to acquire all GIS and geographically referenced digital data from government departments and subsequently make this data available within the public sector
- Experimentation is required with new satellite technology to determine how well it can assist with the above, especially with respect to the geo-referencing of datasets.

11 Acknowledgements

Scott Wilson would like to thank the Department for International Development, UK for sponsoring this research. The commitment and contributions to the study made by the Department of Roads, Bhutan is also grateful acknowledged along with the personal commitments of Mr R Dorji, Director and Mr NK Giri, Engineer.

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Mr S. Tenzin, Supt Engr, DoR, Bhutan

Mr N.P. Katel, E.E., Survey and Design, DoR, Bhutan

Mr. S. Rinchen, Deputy Secretary, PPD, MoC, Bhutan

Mr D.S. Rai, Public Relations Officer, MoC, Bhutan

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Mr S. Ram Sharma, Geologist, DGM, Bhutan

Department of Survey and Land Records

Division of Land Use, Ministry of Agriculture

District Engineers of the Dzongkhags of Mongar, Trashigang, Chhukha & Dagana

Village Gups and Basic Health Units

Mr S. Tiwari, Seconded Engineer, DoLIDAR, Nepal

Mr K. Humagai, Project Coordinator, Scott Wilson, Bhutan

Appendix A
Output Maps

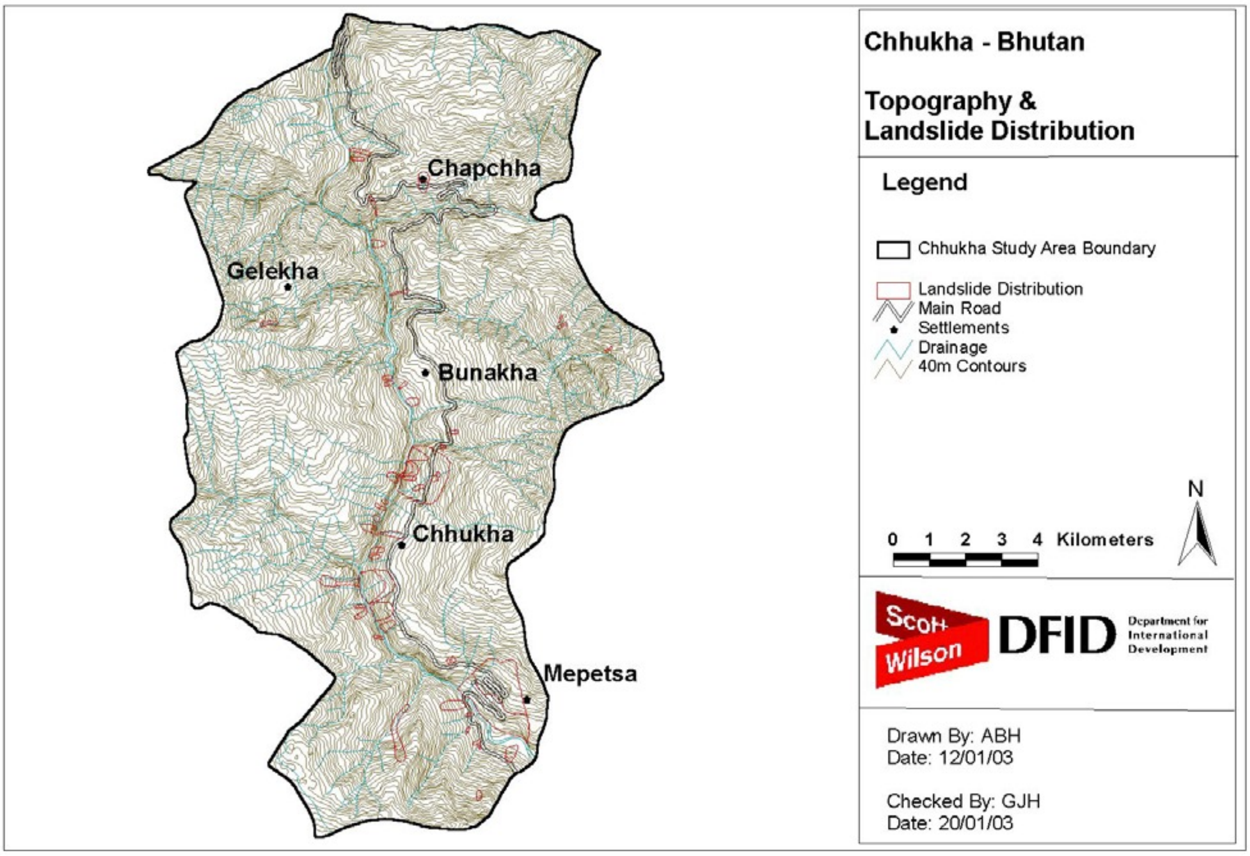
The following output maps are included in this Appendix:

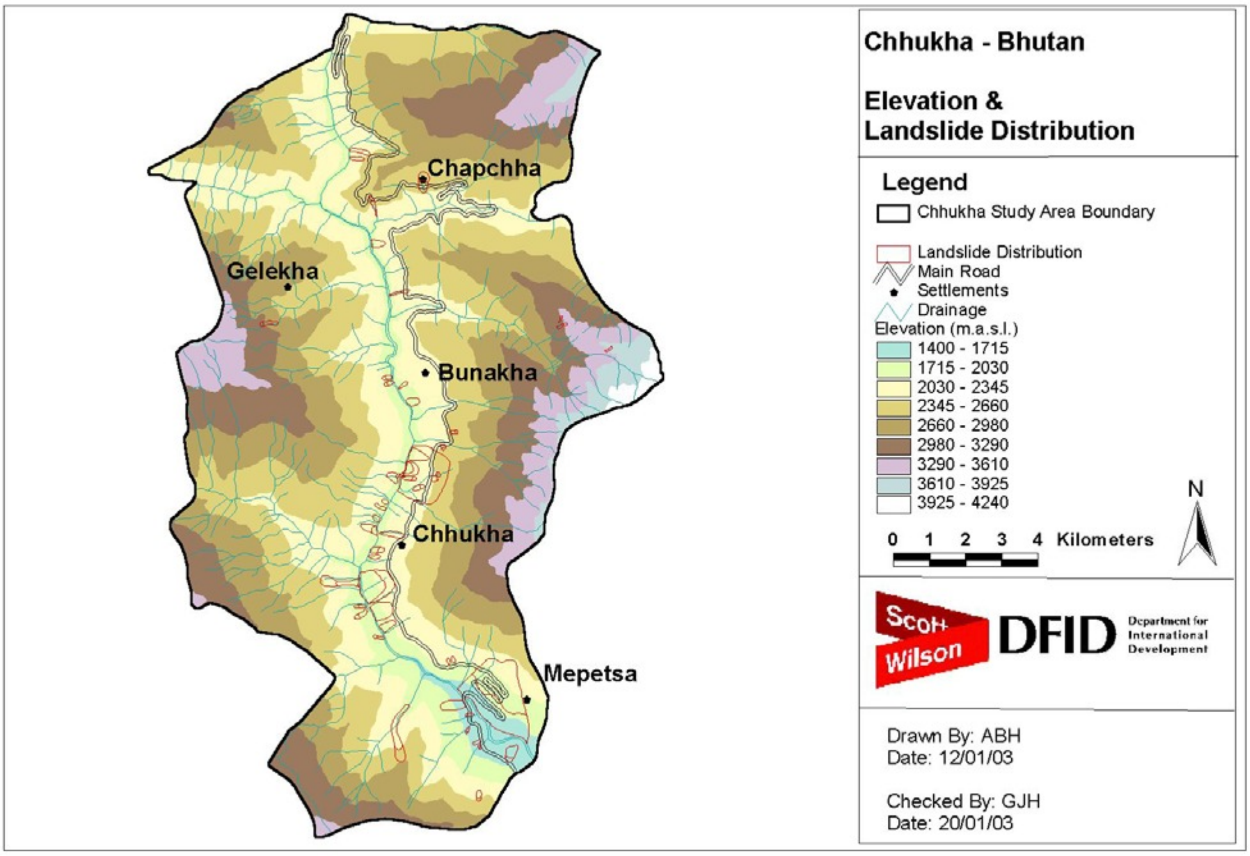
Chhukha Contours & Landslide distribution
Elevation & Landslide distribution
Land Use
Field Geology
Regional Scale Landslide Susceptibility
Regional Scale Landslide Susceptibility with the Landslide Distribution

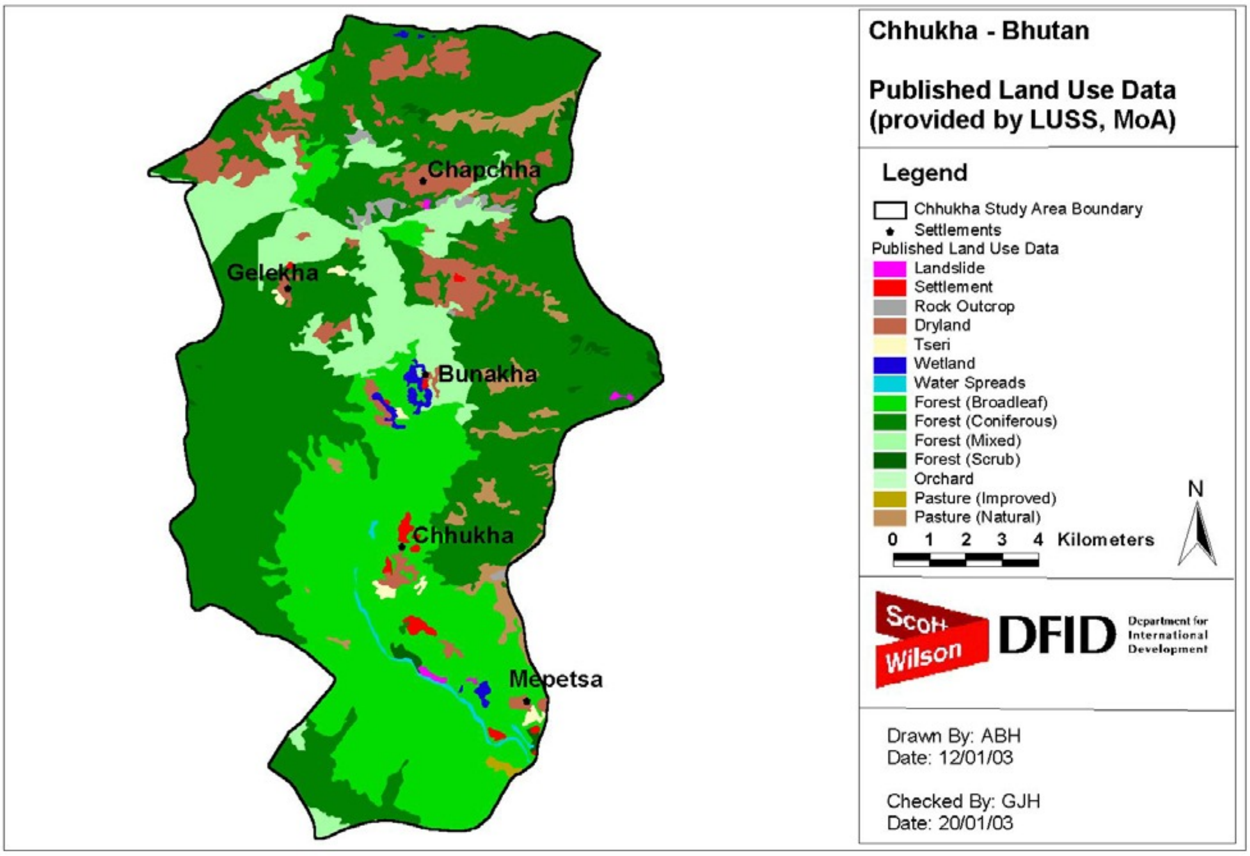
Mongar Elevation
Slope Angle & Landslide distribution
Land Use
Field Geology
Landslide distribution
Regional Scale Landslide Susceptibility

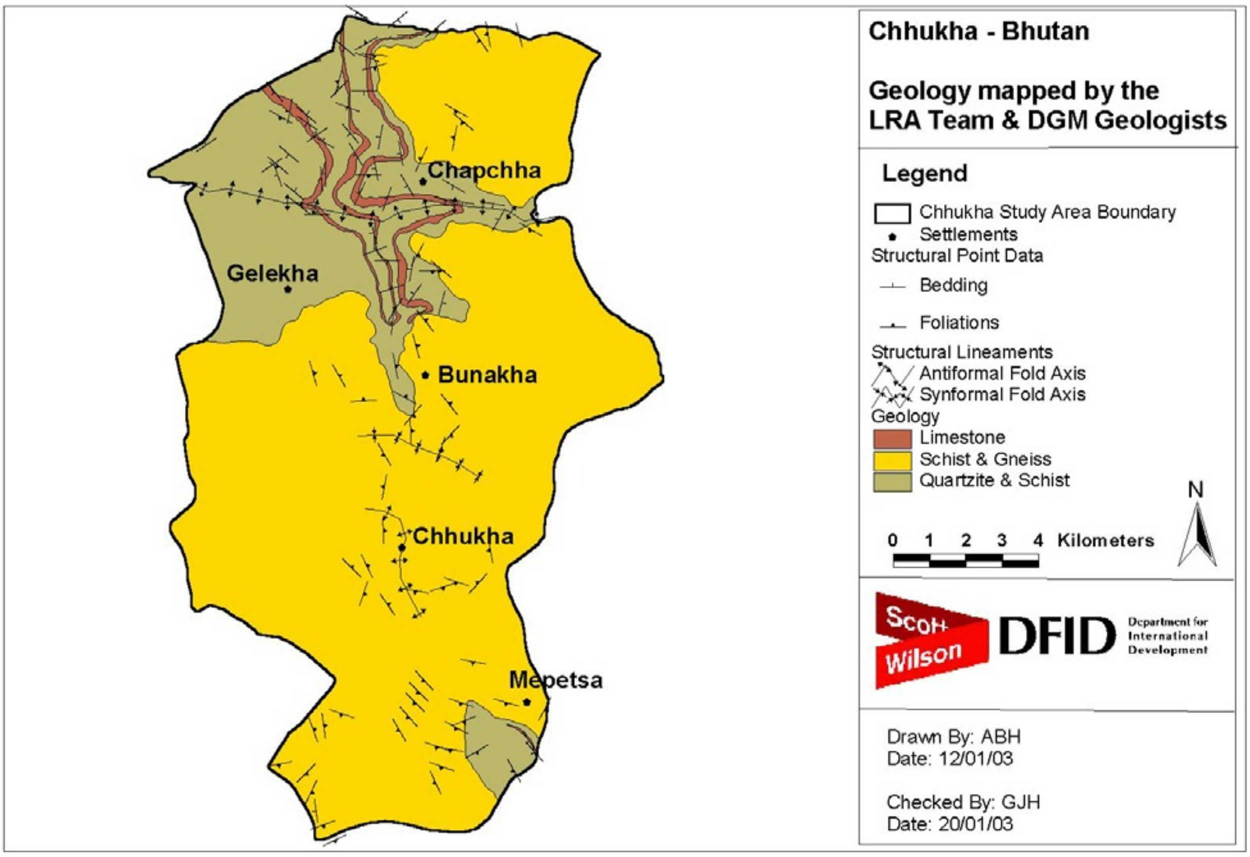
Sunkosh Slope Angle & Landslide distribution
Field Geology
Land Use
Landslide distribution
Regional Scale Landslide Susceptibility

Chhukha Study Area, Bhutan






Chhukha - Bhutan
Published Land Use Data (provided by LUSS, MoA)
Chapchha
Gelekha
Bunakha
Chhukha
Mepetsa
Legend
Chhukha Study Area Boundary
Settlements
Published Land Use Data
Landslide
Settlement
Rock Outcrop
Dryland
Tseri
Wetland
Water Spreads
Forest (Broadleaf)
Forest (Coniferous)
Forest (Mixed)
Forest (Scrub)
Orchard
Pasture (Improved)
Pasture (Natural)
0 1 2 3 4 Kilometers
N
Scott Wilson
DFID Department for International Development
Drawn By: ABH
Date: 12/01/03
Checked By: GJH
Date: 20/01/03


Chhukha - Bhutan
Geology mapped by the LRA Team & DGM Geologists
Chapchha
Gelekha
Bunakha
Chhukha
Mepetsa
Legend
Chhukha Study Area Boundary
Settlements
Structural Point Data
Bedding
Foliations
Structural Lineaments
Antiformal Fold Axis
Synformal Fold Axis
Geology
Limestone
Schist & Gneiss
Quartzite & Schist
N
0 1 2 3 4 Kilometers
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DFID Department for International Development
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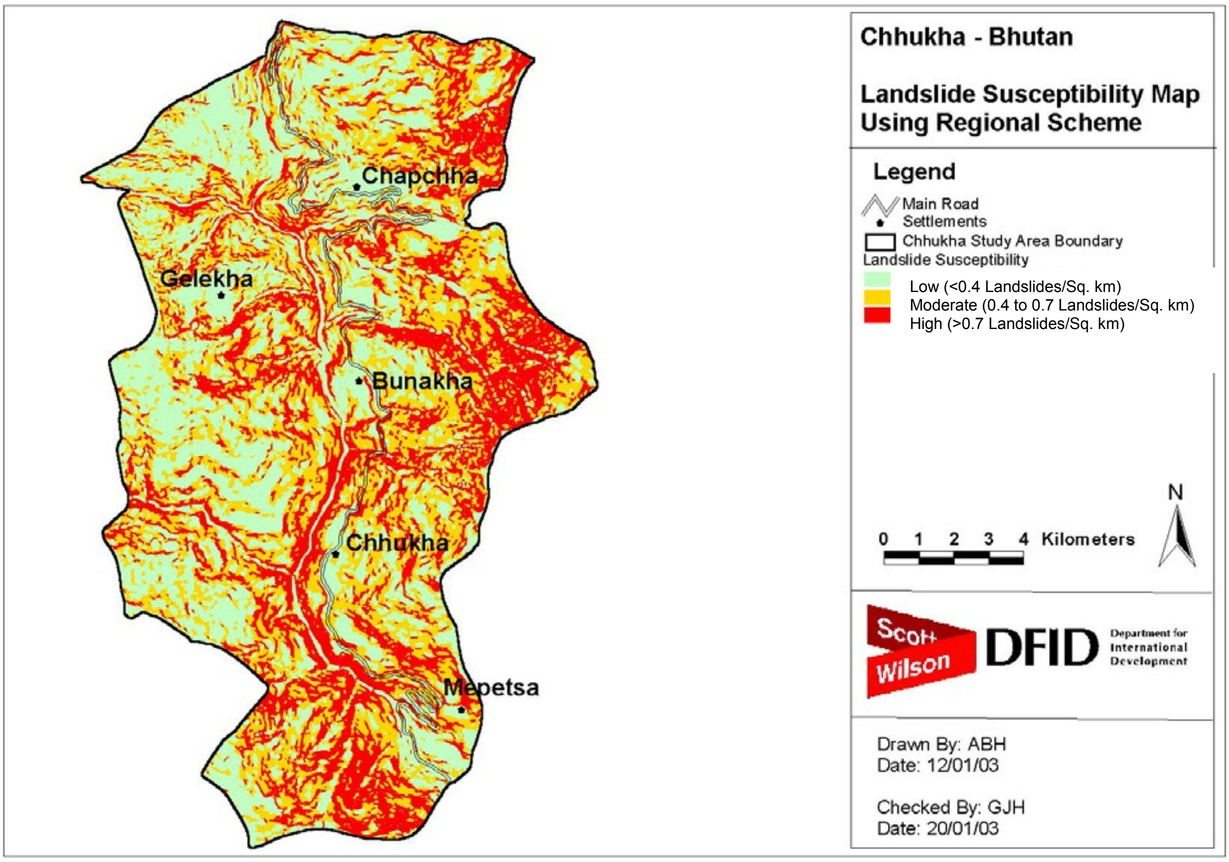
Date: 12/01/03
Checked By: GJH
Date: 20/01/03


Chhukha - Bhutan
Landslide Susceptibility Map Using Regional Scheme
Legend
Main Road
Settlements
Chhukha Study Area Boundary
Landslide Susceptibility
Low (<0.4 Landslides/Sq. km)
Moderate (0.4 to 0.7 Landslides/Sq. km)
High (>0.7 Landslides/Sq. km)
N
0 1 2 3 4 Kilometers
Chapchha
Gelekha
Bunakha
Chhukha
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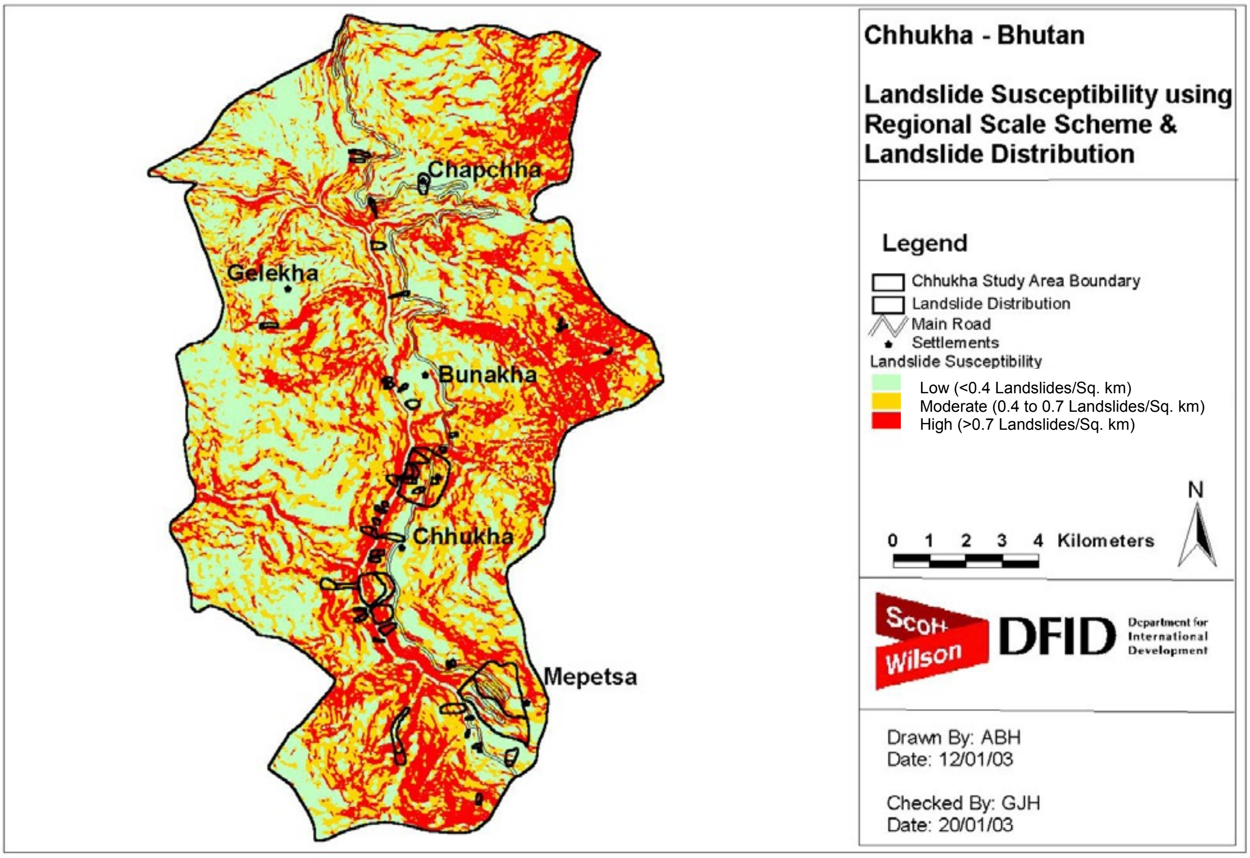
Chhukha - Bhutan
Landslide Susceptibility using Regional Scale Scheme & Landslide Distribution
Legend
Chhukha Study Area Boundary
Landslide Distribution
Main Road
Settlements
Landslide Susceptibility
Low (<0.4 Landslides/Sq. km)
Moderate (0.4 to 0.7 Landslides/Sq. km)
High (>0.7 Landslides/Sq. km)
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Gelekha
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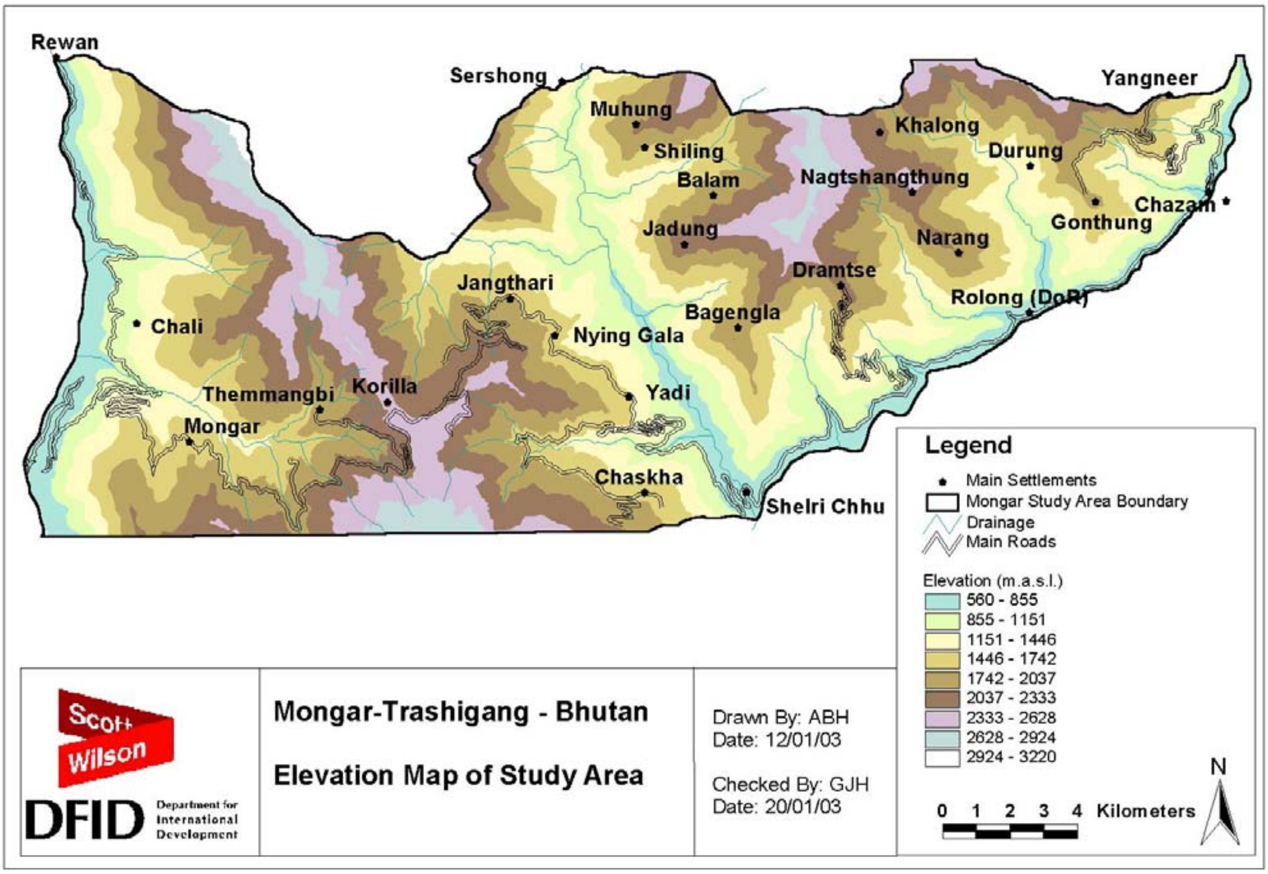
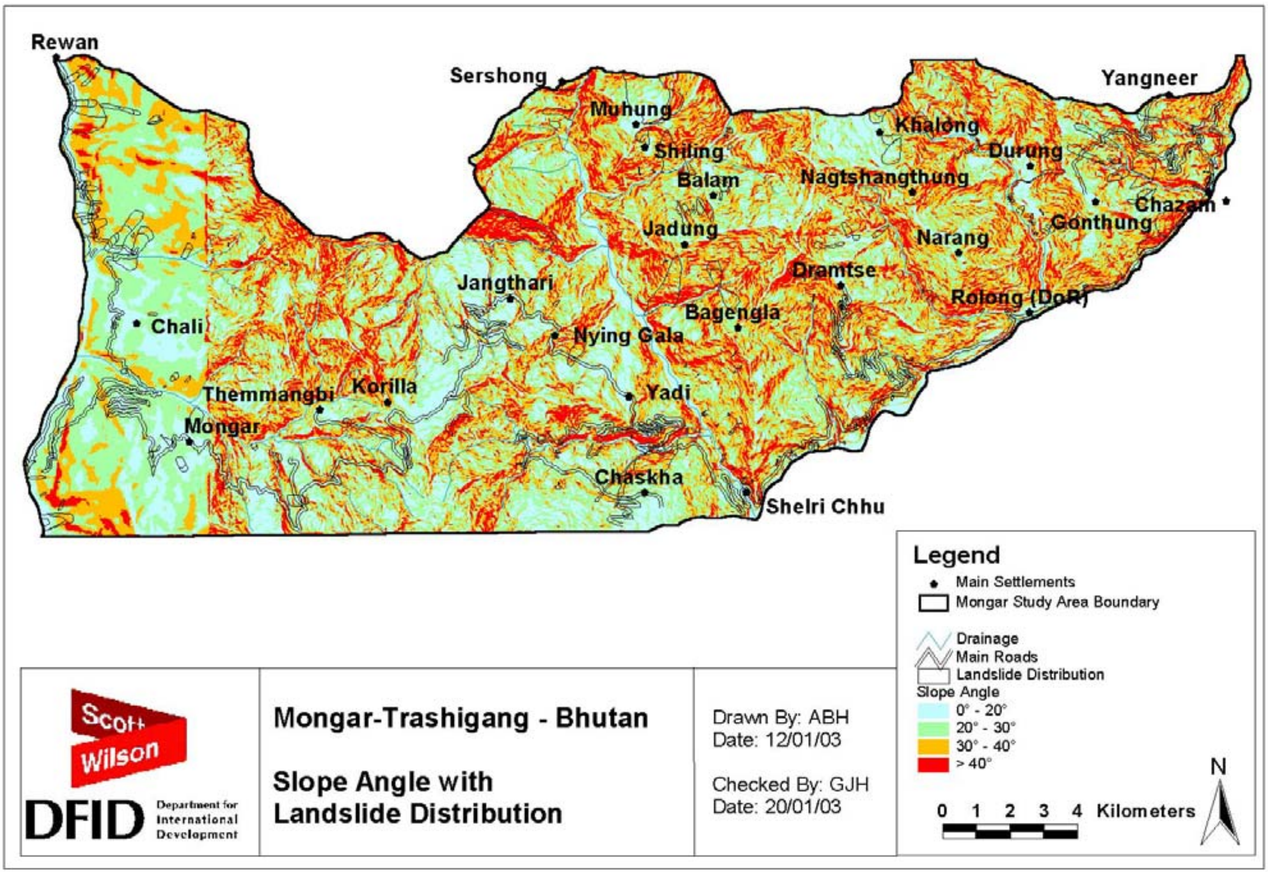
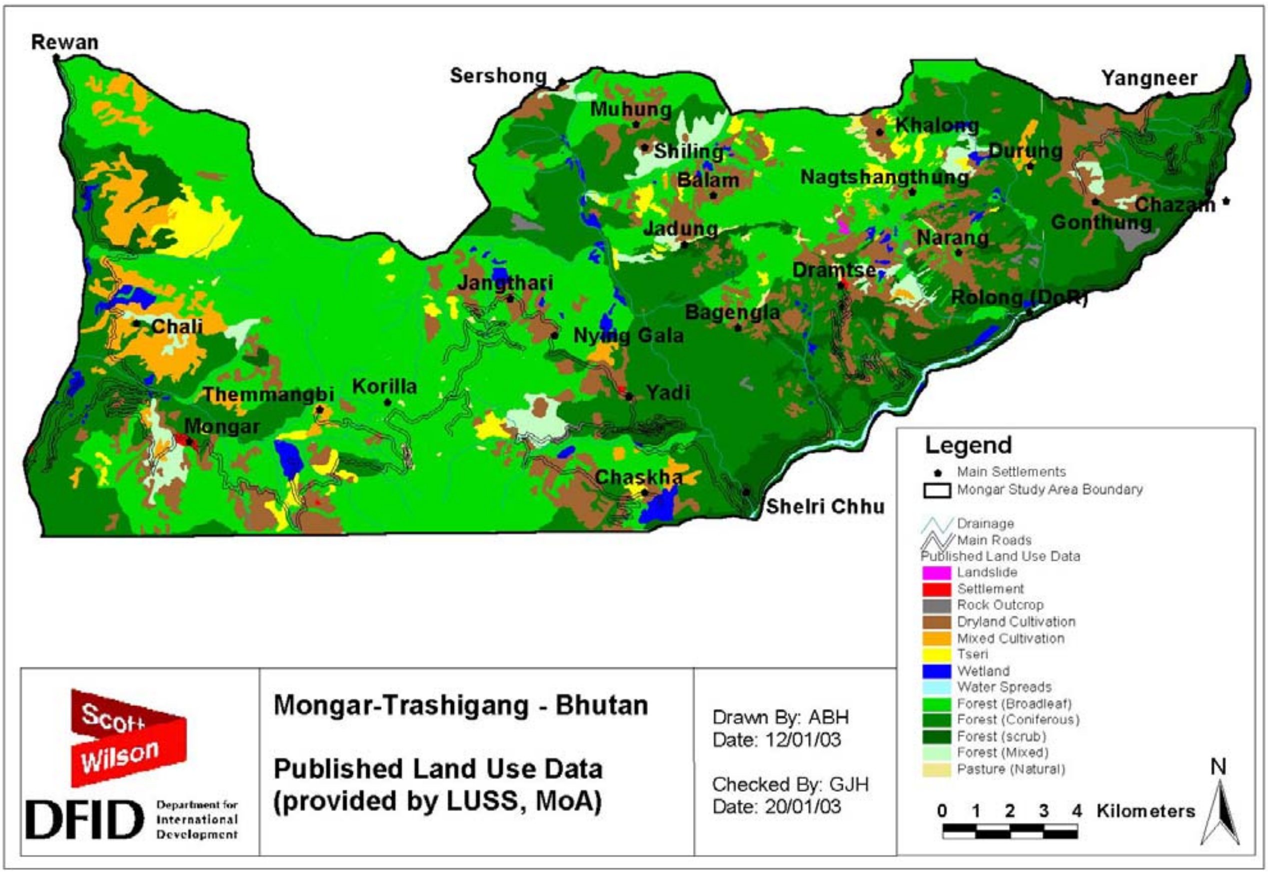
Monger Study Area, Bhutan



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Chazam
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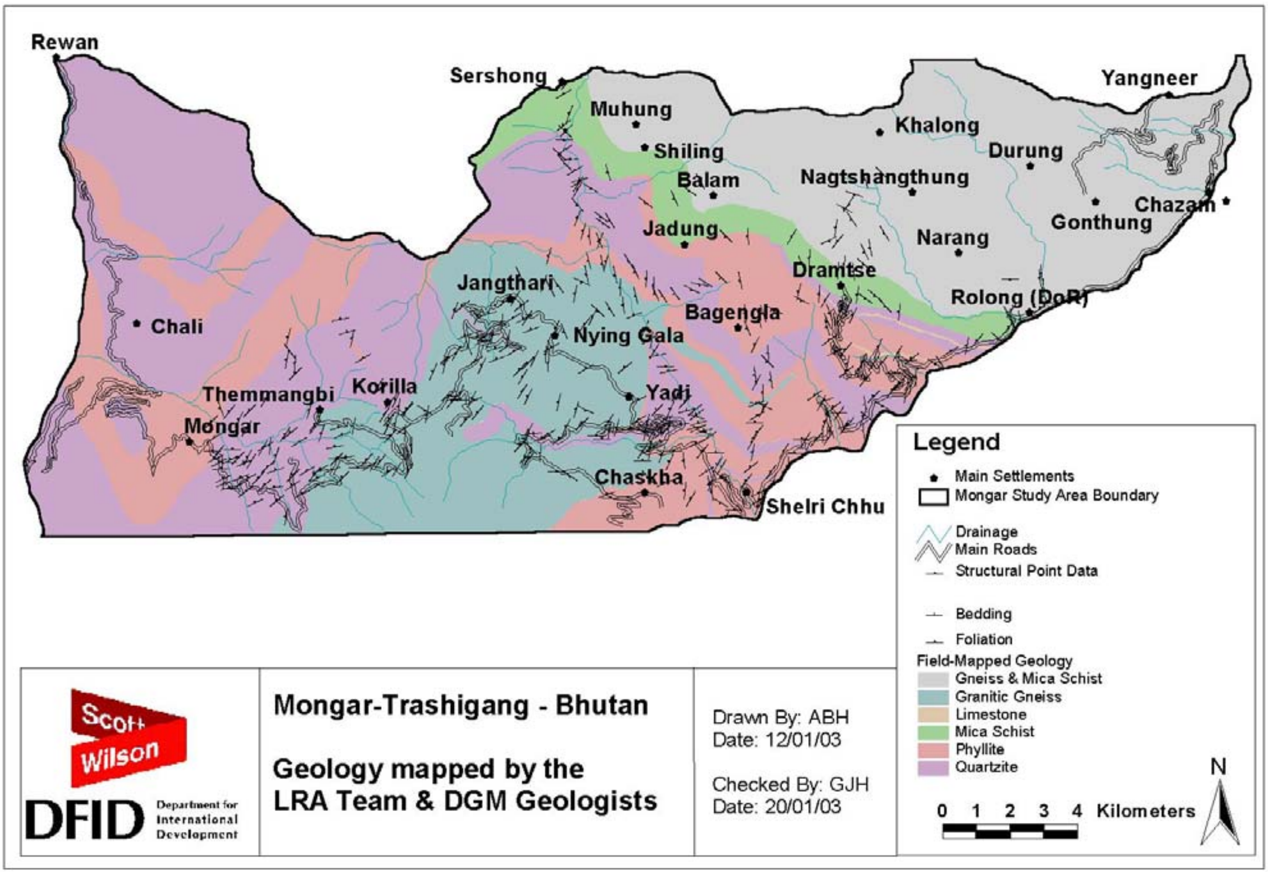
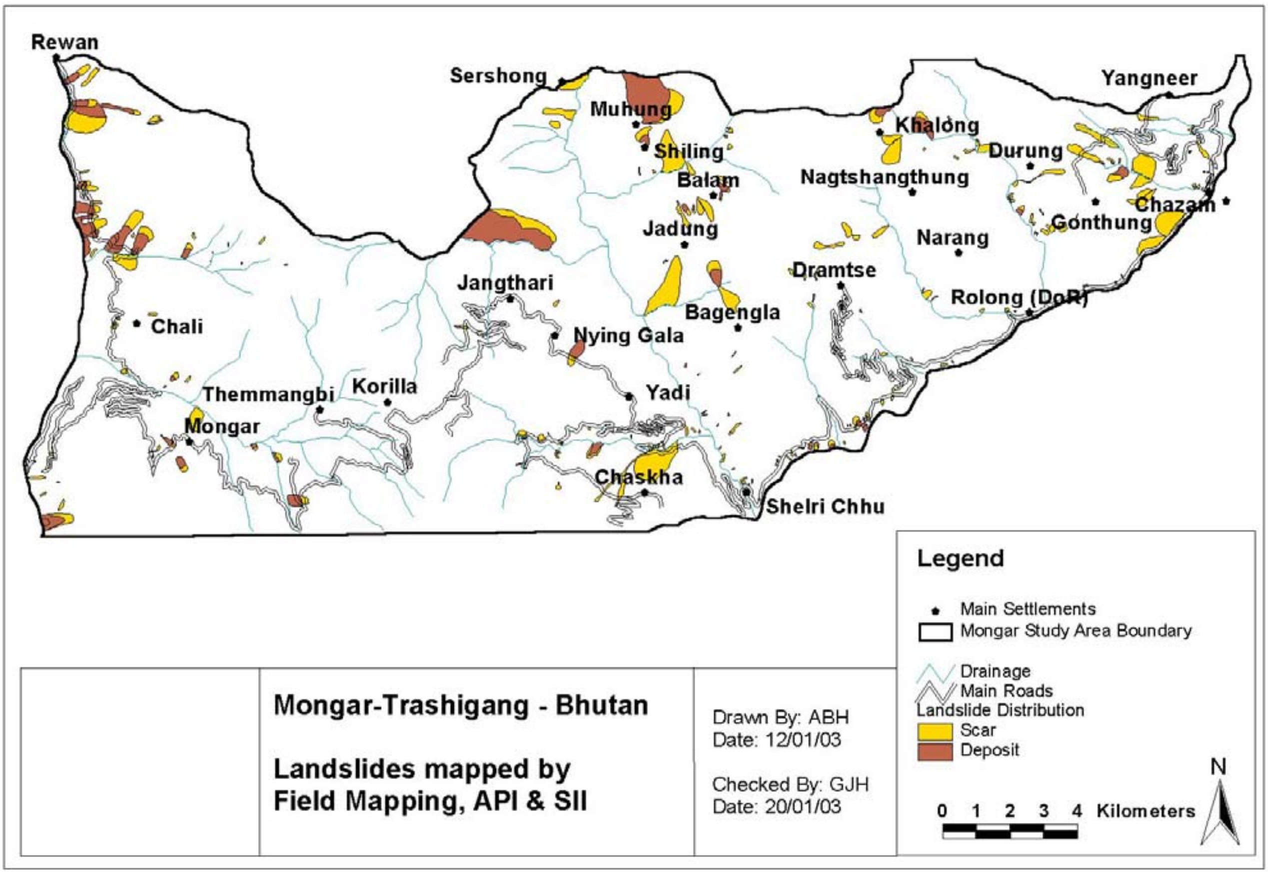
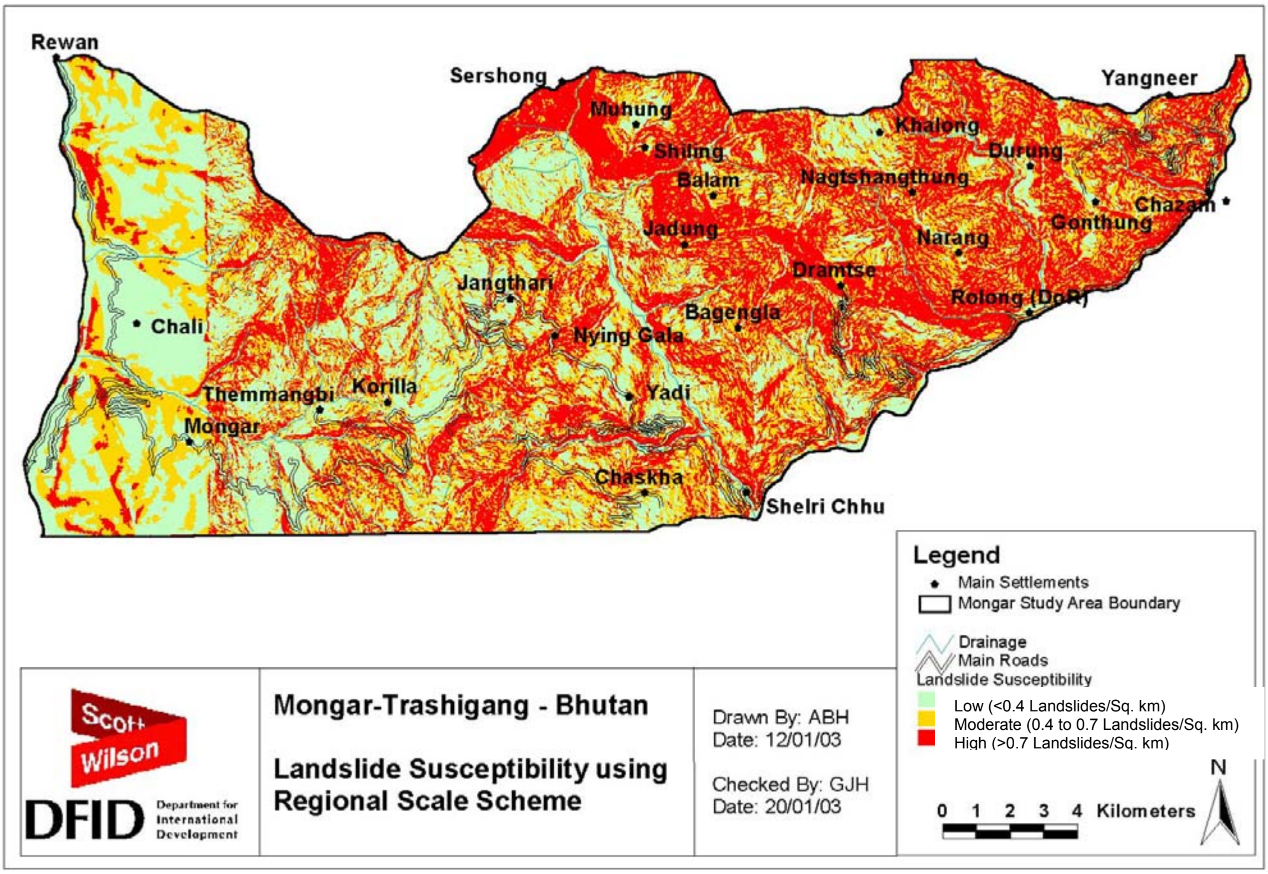
Jangthari
Rolong (DoR)
Chali
Bagengla
Nying Gala
Themmangbi
Korilla
Yadi
Mongar
Chaskha
Shelri Chhu
Legend
Main Settlements
Mongar Study Area Boundary
Drainage
Main Roads
Published Land Use Data
Landslide
Settlement
Rock Outcrop
Dryland Cultivation
Mixed Cultivation
Tseri
Wetland
Water Spreads
Forest (Broadleaf)
Forest (Coniferous)
Forest (scrub)
Forest (Mixed)
Pasture (Natural)
N
0 1 2 3 4 Kilometers
Scott Wilson
DFID Department for International Development
Mongar-Trashigang - Bhutan
Published Land Use Data (provided by LUSS, MoA)
Drawn By: ABH
Date: 12/01/03
Checked By: GJH
Date: 20/01/03


Rewan
Sershong
Yangneer
Muhung
Khalong
Shiling
Durung
Balam
Nagtshangthung
Chazam
Gonthung
Jadung
Narang
Dramtse
Jangthari
Rolong (DoR)
Chali
Bagengla
Nying Gala
Themmangbi
Korilla
Yadi
Mongar
Chaskha
Shelri Chhu
Legend
Main Settlements
Mongar Study Area Boundary
Drainage
Main Roads
Structural Point Data
Bedding
Foliation
Field-Mapped Geology
Gneiss & Mica Schist
Granitic Gneiss
Limestone
Mica Schist
Phyllite
Quartzite
N
0 1 2 3 4 Kilometers
Scott Wilson
DFID Department for International Development
Mongar-Trashigang - Bhutan
Geology mapped by the LRA Team & DGM Geologists
Drawn By: ABH
Date: 12/01/03
Checked By: GJH
Date: 20/01/03



Mongar-Trashigang - Bhutan

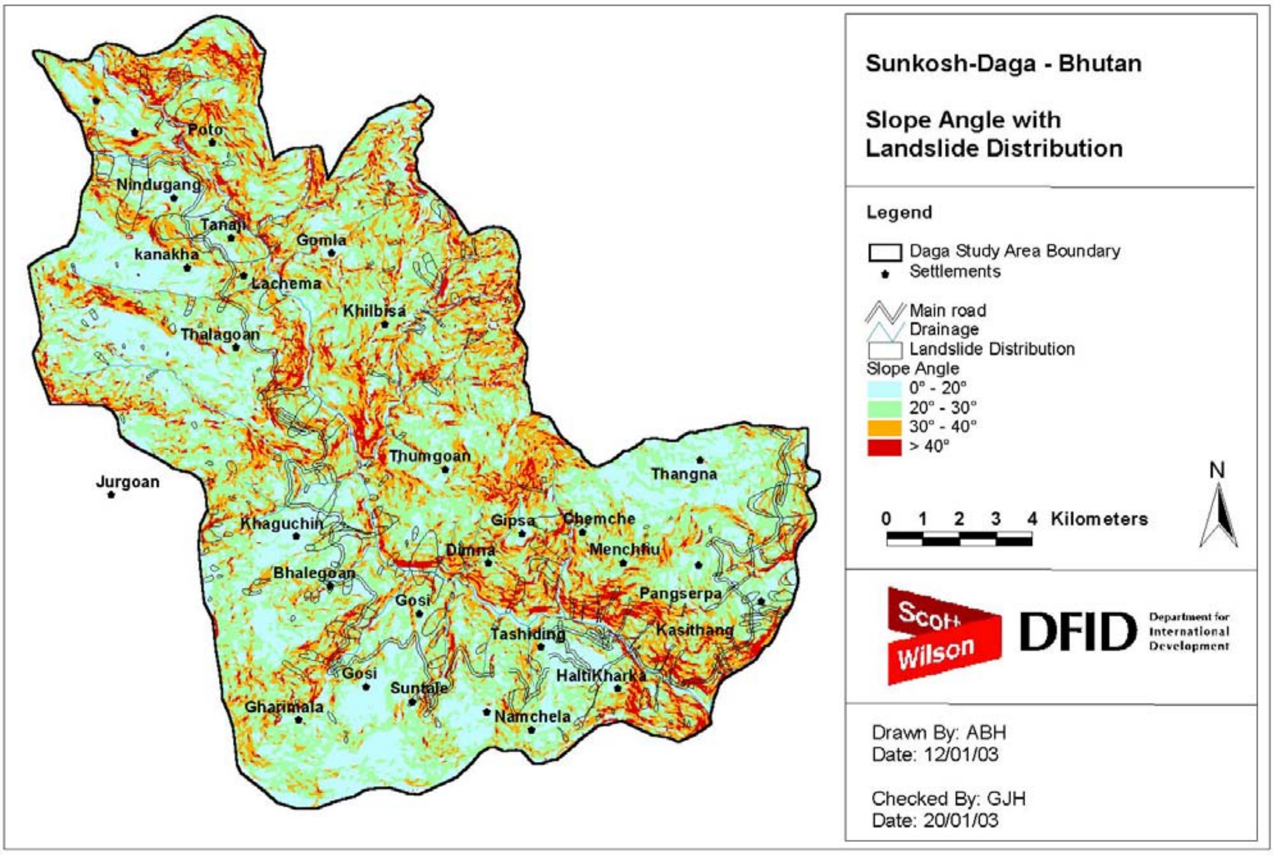
Landslides mapped by Field Mapping, API & SII

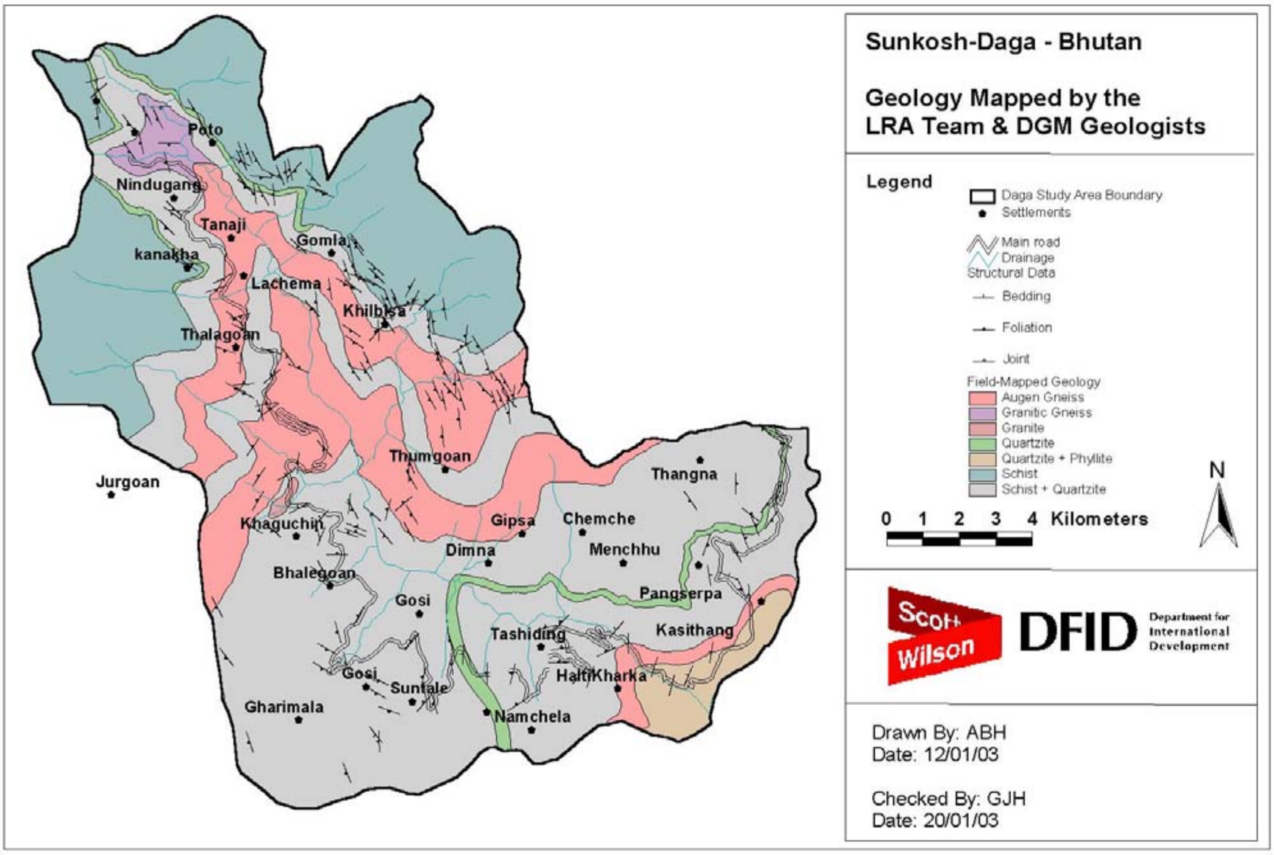


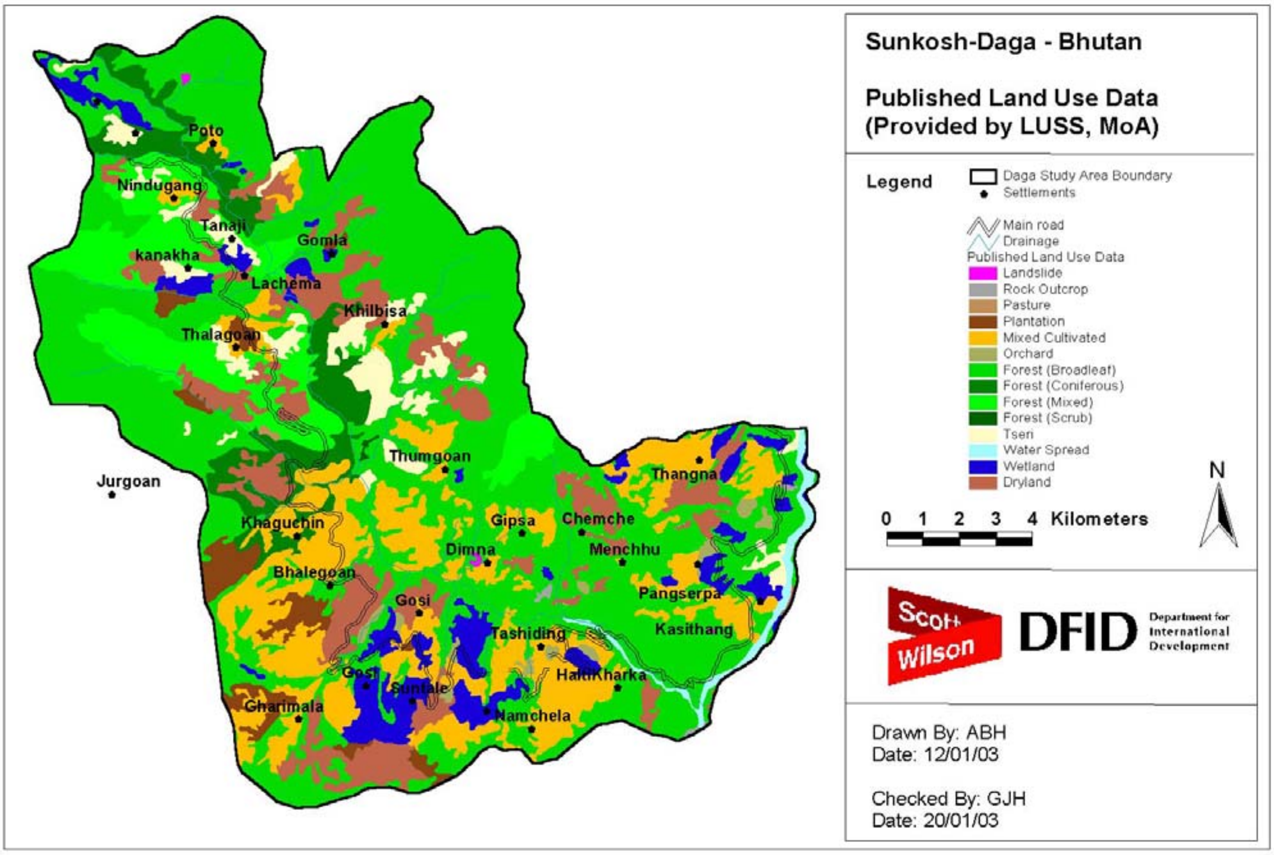
Mongar-Trashigang - Bhutan

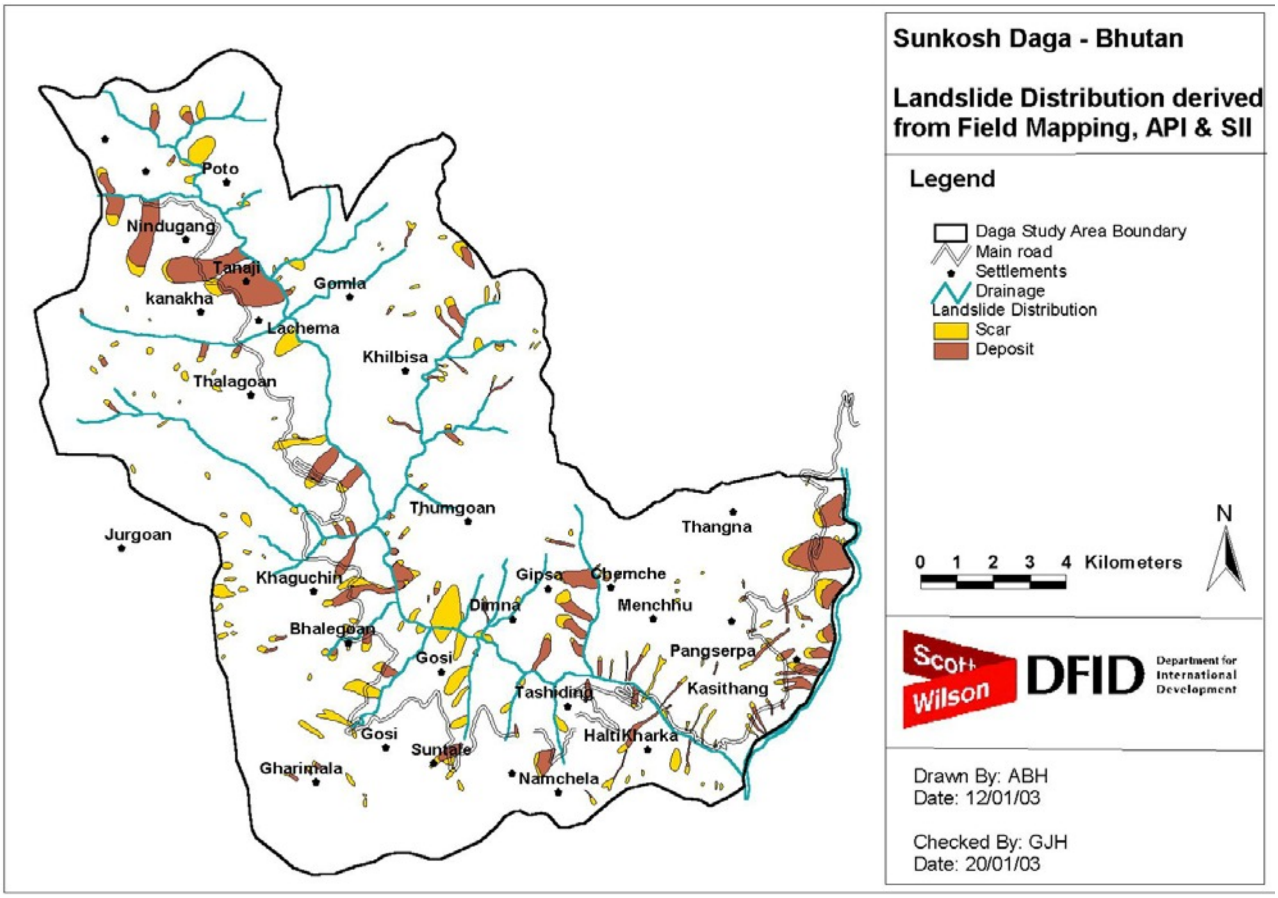
Landslide Susceptibility using Regional Scale Scheme

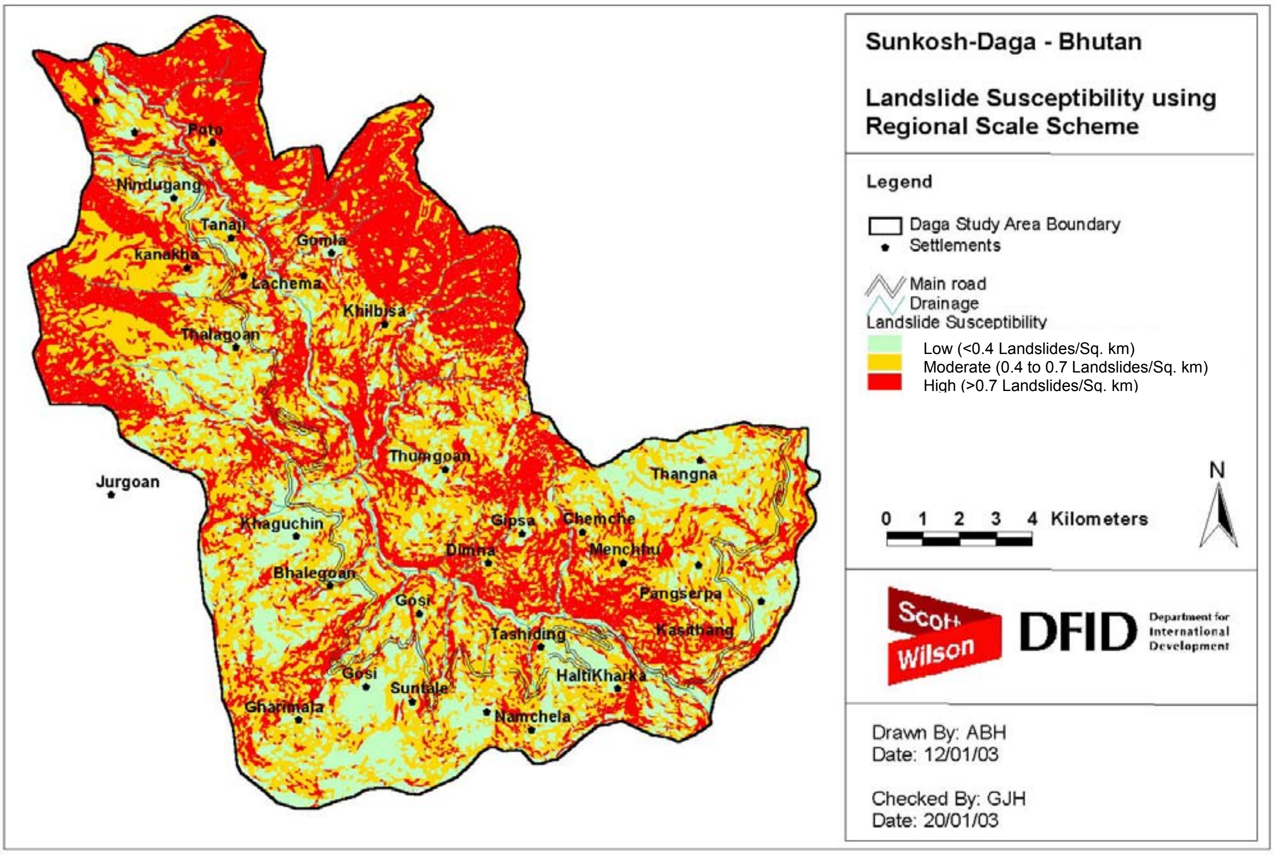
Sunkosh Study Area, Bhutan






Sunkosh-Daga - Bhutan
Published Land Use Data (Provided by LUSS, MoA)
Legend
Daga Study Area Boundary
Settlements
Main road
Drainage
Published Land Use Data
Landslide
Rock Outcrop
Pasture
Plantation
Mixed Cultivated
Orchard
Forest (Broadleaf)
Forest (Coniferous)
Forest (Mixed)
Forest (Scrub)
Tseri
Water Spread
Wetland
Dryland
0 1 2 3 4 Kilometers
N
Scott Wilson
DFID Department for International Development
Drawn By: ABH
Date: 12/01/03
Checked By: GJH
Date: 20/01/03
Poto
Nindugang
Tanaji
Gomla
kanakha
Lachema
Khilbisa
Thalagoan
Thumgoan
Jurgoan
Thangna
Khaguchin
Gipsa
Chemche
Dimna
Menchhu
Bhalegoan
Pangserpa
Gosi
Kasithang
Tashiding
Gosi
Haltikharka
Suntale
Gharimala
Namchela


Sunkosh Daga - Bhutan
Landslide Distribution derived from Field Mapping, API & SII
Legend
Daga Study Area Boundary
Main road
Settlements
Drainage
Landslide Distribution
Scar
Deposit
0 1 2 3 4 Kilometers
N
Scott Wilson
DFID Department for International Development
Drawn By: ABH
Date: 12/01/03
Checked By: GJH
Date: 20/01/03
Poto
Nindugang
Tanaji
Gomla
kanakha
Lachema
Khilbisa
Thalagoan
Thumgoan
Jurgoan
Thangna
Khaguchin
Gipsa
Chemche
Dimna
Menchhu
Bhalegoan
Pangserpa
Gosi
Kasithang
Tashiding
Gosi
Haltikharka
Suntale
Gharimala
Namchela


Sunkosh-Daga - Bhutan
Landslide Susceptibility using Regional Scale Scheme
Legend
Daga Study Area Boundary
Settlements
Main road
Drainage
Landslide Susceptibility
Low (<0.4 Landslides/Sq. km)
Moderate (0.4 to 0.7 Landslides/Sq. km)
High (>0.7 Landslides/Sq. km)
0 1 2 3 4 Kilometers
N
Scott Wilson
DFID
Department for International Development
Drawn By: ABH
Date: 12/01/03
Checked By: GJH
Date: 20/01/03
Poto
Nindugang
Tanaji
Gomla
kanakha
Lachema
Khilbisa
Thalagoan
Thumgoan
Jurgoan
Thangna
Khaguchin
Gipsa
Chemche
Dimna
Menchhu
Bhalegoan
Pangserpa
Gosi
Kasithang
Tashiding
Gosi
Suntale
HaltiKharka
Gharmala
Namchela

Appendix B

Summary Best Practice Guidance Notes

The following Draft versions of the Summary Best Practice Guidance Notes developed by the Landslide Risk Assessment in the Rural Access Sector Project are included in this Appendix:

1. Best Practice Guidelines in Landslide Field Mapping for Engineering Purposes
2. Best Practice Guidelines in Aerial Photograph Interpretation
3. Best Practice Guidelines in Satellite Image Interpretation
4. Best Practice Guidelines in the use of a Geographical Information Systems for Landslide Susceptibility Mapping at a Regional Scale
5. Best Practice Guidelines for Project Scale Landslide Susceptibility Assessments

Draft Best Practice Guidelines in Landslide Field Mapping for Engineering Purposes

Introduction

No matter how useful desk studies prove to be in identifying and interpreting landslides and related terrain features, field mapping will be required for the confirmation of desk study interpretation and the collection of data for design purposes. Field mapping should be carried out as a staged process, commencing with the validation of desk study interpretation by reconnaissance survey and progressing to detailed mapping for inventory or engineering design purposes.

Reconnaissance Surveys

Reconnaissance survey is usually carried out to validate air photo or remote sensing interpretation. Field validation is described in other chapters of these Guidelines and no further elaboration is required here. Nevertheless, it is emphasised that reconnaissance survey is an extremely important critical path activity because, when carried out for a road project for instance, it enables the major constraints on alignment selection to be identified, and provides a rapid overview of slope conditions, drainage features, land use and other factors for early engineering and environmental assessment.

Landslide Identification

Many landslides will have been previously identified by air photo interpretation and/or satellite image interpretation. However, a significant number of additional landslides will probably be identifiable in the field for the following reasons:

- Landslides may be obscured on aerial photography due to cloud cover, shade or tree canopy
- The smaller landslides may not have been identifiable from aerial photography
- Relict landslides may have a morphology that is too subtle to be identified on aerial photographs
- Landslides may have occurred since the imagery or photography was collected

While some landslides will have a distinct and recognisable morphology in the field, others will not, and may constitute areas of generalised slow and intermittent ground movement with very little surface expression. Table 1 lists some of the more common indicators that can be used to identify and confirm landslides, landslide deposits and areas of ground movement.

In addition to the indicators in Table 1, the following factors or attributes can provide an indication of slope failure or the potential for ground movement:

- The distribution of colluvium (colluvium, being at residual strength, is usually susceptible to landslides and ground movements on steep slopes and/or where groundwater is high or where surface soils saturate)
- The distribution of clayey residual soil on steep slopes and/or where groundwater is high or where surface soils saturate
- The location of ‘classic’ landslide features, usually identifiable by head scarps and slipped or flow deposits below
- The location of more subtle landslide features, usually changes in slope morphology, the presence of an unusually large number of boulders on a slope, disturbance to drainage patterns, ground cracking, springs and vegetation anomalies
- Damage to agricultural terraces, walls and buildings
- Old landslide back scarp and side scarp features incorporated into agricultural terracing patterns.

Table 1 Common indicators of landslides and ground movements

Landslide Indicators	***Evidence on the Ground***
Active Landslides	
Tension cracks	Often orientated in an arc and are continuous, they may show vertical displacement from one side of the crack to the other.
Slip scarps	Steps across terraces and other slopes
Disturbed/displaced terracing	Lines of displaced terracing often mark the margins of ground movement
Hummocky ground	Slope surface is irregular and often formed by a series of low hummocks
Cracking to structures and paved surfaces	This can be due to local settlement of fill and foundations, so supporting evidence is required, unless effects are extensive
Dislocation of drainage structures	Either directly observed or seen as seepages
Springs and seepages	Giving rise to marshy ground
Trees leaning backwards or with curved trunks	Both wind, steep topography and ground movement can give rise to non-vertical tree trunks, so care is required in their interpretation.
Relict Landslides	
Spoon-shaped landforms	Steep upper scarp often semi-circular, lower angled, possibly tongue-shaped deposit
Chaotic debris forming landslide deposits	Boulders often protrude above the surface
Hummocky ground	Slope surface is irregular and often formed by a series of hummocks
Steep soil slope located in depression between rock outcrops	Most first-time failures (ie non-colluvium landslides) in mountain areas occur in soils and fail along the weathered rock boundary
Lack of mature soil profile, indicative of disturbed ground	The normal profile of weathered rock and relatively dense in situ soil is replaced by a structureless, loose, soil, frequently grey in colour
Disturbed vegetation, or uncharacteristic vegetation pattern	This indicator could be land use related, so it needs to be interpreted with care. Alder is frequently among the first to colonise recently failed slopes.
Colluvium vulnerable to movement	
Chaotic debris forming landslide deposits	Boulders often protrude above the surface
Hummocky ground	Slope surface is irregular and often formed by a series of low amplitude hummocks
Lack of mature soil profile, indicative of the disturbed ground	The normal profile of weathered rock and relatively dense in situ soil is replaced by a structureless, loose, soil, frequently grey in colour
More steeply sloping ground in clayey and silty soils will be the most vulnerable	This should be observable on the ground
Slopes where water is seen to collect, either from surface water or groundwater	Waterlogged ground and marshy areas
Future first time failures	
Slopes underlain by adverse geological structures and rock types prone to failure	Dip slopes will fall into this category. Smooth and persistent joint surfaces can often be seen forming segments of slopes, and these could be potentially prone to failure
Slopes with high groundwater tables or wet ground in deep low density soils	Slopes where water is seen to converge, either from groundwater or surface water.
Outcrops, slopes and deposits adjacent to active fault zones	Without geological field assistance these zones can usually only be determined from published geological mapping
Slopes likely to be prone to river or stream scour at their base	This should be observable on the ground
Debris flows from upstream	
Existing debris flow terraces bordering main channel indicate that future events are possible	These terraces lack stratification, are predominantly boulders in matrix and often have low amplitude levees parallel to the direction of flow.
Large landslide scarps present on the slopes above with little of the landslide debris remaining	Indicates that the majority of debris was removed instantaneously, possible as a debris flow in the drainage system below.
Relict/slow moving landslide masses located adjacent or above drainage lines could rapidly become debris flows downstream if instantaneous failure were to occur.	This requires a knowledge of existing and potential landslides located on the catchment slopes above.

Landslide Inventory Mapping

Once a landslide is identified then the following information is required for susceptibility analysis and the development of hazard and risk assessment for design purposes:

Location. The location of the landslide should be recorded by GPS, using several survey points in the case of larger landslides. The outline of the failure should be transferred onto a large scale (1:25,000 or better) topographic map directly in the field. If possible the mapping should differentiate between the landslide debris and the rupture surface.
Underlying geology. The location and lithology of the nearest outcrop should be recorded. Information on jointing and foliation/bedding patterns should also recorded in order to determine the extent and nature of structural control on the development of the failure.
Geomorphology. An assessment should be made of the likely causes, triggers and mechanism of movement, the depth of movement, whether it is predominantly in soil or rock, the soil type and slope angle, the water condition on the slope and the geomorphology of the surrounding area.
Activity. The activity or rate of movement should be assessed. It is acknowledged that this may be a difficult and judgemental exercise, but usually differentiation can be made between 'active' and 'inactive' on the basis of tension cracking, freshness of morphology and on-going damage to neighbouring structures (see below).
Risk. The impact of the failure on surrounding land use and structures should be assessed. Furthermore, the potential of the failure to cause future damage should be evaluated.
Investigation and stabilisation/mitigation. If the landslide mapping is being carried out as part of an investigation for road design or rehabilitation, or similar projects, then recommendations should be made for further ground investigation. Preliminary recommendations can also be made for stabilisation/mitigation options.

It is usually preferable to fill out a proforma to systematically record the above data, especially when a landslide inventory is being undertaken. The proforma applied to the LRA Project serves as a useful indication of the type and format of data to be collected, and is appended to this document.

Supplementary Information

If the landslide mapping forms part of an engineering survey, then other topographical and geological data should be collected to advance the selection of the alignment and the design:

- locations of cliffs, river channels and difficult ground conditions that will either need to be avoided or will require special engineering consideration
- confirmation of geology and the broad distribution of colluvium and residual soils
- the locations of buildings that need to be avoided or demolished
- potential sources of materials for construction
- environmental considerations, including social impacts

Assessing Landslide Activity

An indication as to whether an identified landslide or area of ground is still moving, albeit intermittently, can sometimes be determined from the following factors:

- *Freshness of the scarp*. As a general rule recent landsliding is associated with a fresh, sharp landslide scarp. Thus, an investigation should assess whether the scarp is vegetated or bare; whether it is well-defined or not; and how young the vegetation is.
- *Freshness of the failure mass topography*. Recent landslide deposits have a fresh, disturbed topography. An assessment can examine whether the deposits are distinctly different from

the surrounding slope morphology and whether it has a different vegetation cover from the surrounding ground

- *Evidence for active ground stress*. Active ground stress is usually associated with signs of cracking in the ground. The assessment might investigate whether there are active tension cracks above the slide area, within it or at its margins. Active tension cracks usually expose bare, unweathered soils and can be traced across the ground surface into neighbouring 'undisturbed' soils where the ground is seen to 'boil up' rather than crack. This is indicative of incipient crack development or propagation.
- *Damage*. Active cracking and disturbance to neighbouring structures such as walls, houses and outbuildings, may indicate ongoing deformation caused by landslides
- *Evidence of oversliding or flow in the toe area*. The toe area often over-rides other deposits or surfaces. Can the toe of the landslide mass be seen to be overriding unfailed ground and other features, such as walls, paths etc?
- *Evidence of disturbed vegetation*. A classic sign of active slope movements is disruption of trees. The investigation should examine whether trees offset from vertical or otherwise disturbed.
- *Destabilising processes.* Is the slope continuing to be destabilised by high groundwater levels, an inflow of surface water (such as irrigation) or the removal of toe support, such as stream or river erosion?
- *Observed movements.* Does the local farming community report active movements?

Assessing the Risk from First-Time Failures (new landslides) in Natural Terrain

The assessment of the risk posed by slope failure or ground movement to infrastructure and communities is not reliant on the identification of existing landslides alone. First time failures in rock or residual soil are frequent occurrences. In fact, first time failures are likely to pose potentially the greatest risk because they are largely unanticipated and often move rapidly. The potential for first time failures might be assessed through one of the following:

- Slope stability analysis (impracticable over large areas and without the required geotechnical data)
- Susceptibility mapping (this can identify zones of high landslide potential based on the geographical analysis of factors that have been found to influence the location of existing landslides)
- Engineering geological/geomorphological assessment on a slope by slope basis

The latter is likely to prove the most practicable, though it is largely judgemental and often not reproducible between different field mappers. The following factors should be considered:

- The presence of low strength materials occupying steep slopes with high groundwater or seepage water conditions (see Table 2 for illustrative threshold conditions).

Table 2 Observed Limiting Slope Angles in East Nepal

Soil Type	*Residual Soil*		*Colluvial Soil*		*Perched Water Table*
	Dry	Wet	Dry	Wet	Wet
Clayey silt	33-36°	16-17°	28-31°	14-15°	11°
Silt	33-36°	16-17°	28-31°	16-17°	12°
Sandy silt	33-36°	16-17°	31-34°	16-17°	14°
Silty sand	36-39°	19-20°	31-34°	16-17°	17°
Silt & boulders	36-39°	28-29°	31-34°	23-24°	19°
>50% boulders	36-39°	31-32°	33-36°	23-24°	19°

- Adverse geological structure, i.e. joints that dip out of the slope. A potential first-time failure could occur in rock under these conditions or in soil if the potential failure plane or planes form the boundary between residual soil (or colluvium) overlying intact rock.
- If there is evidence of surface water drainage converging into a soil slope
- If river erosion is observed to be undercutting a slope then there is an increased potential for slope failure.

Slope Failures Induced by Earthworks

Slope excavation for road construction can trigger first time failures and, as the LRA Project has shown, there is a clustering of recorded landslides alongside roads in rural access corridors, suggesting that many of the landslide problems encountered by roads are, in fact, self-generated. These relate mostly to cut slope failures that can be dealt with through prescriptive means, mostly retaining and breast walling (see below). However, it is also true that the majority of slope problems encountered during the longer term within road corridors are due to the reactivation of pre-existing landslides or areas of unstable/marginally stable colluvium. Evaluating the potential for earthworks–induced slope failures will necessitate the same data collection as outlined for natural terrain above because the stability of any slope, whether it be natural or man made, will be controlled by its geometry, its constituent strength (both as a mass in the case of soil, and as a jointed material in the case of rock) and its water content.

Risk Assessment and Management

<u>Risk Assessment</u>

The questions usually asked when a road alignment is located across or close to identified landslides or perceived potentially unstable ground are:

- What will happen to the road?
- When will it happen?
- What can be done to prevent it happening?

To answer these questions the following information is required:

Factual

- The areal extent of the landslide
- The depth of the landslide
- The mechanism of failure

- The current rate of movement
- The location of the proposed alignment, both vertically and horizontally in relation to the geometry of the landslide.

Analytical

- The existing factor of safety of the landslide and its variation due to changes in groundwater etc.
- The effects of road earthworks (cuts and fills) on the factor of safety of the landslide
- The predicted effects of remedial measures (earthworks, drainage and retaining walls) on the final factor of safety
- The stability of individual engineering facets, such as cut slopes, fills and retaining walls when located on or close to the landslide in terms of temporary and permanent excavation stability, bearing capacities, etc.

Most of this information can be readily obtained by conventional means, including observation, engineering geological mapping, monitoring, ground investigation, lab testing, and analysis. However, most slope failures affecting roads in Nepal do not warrant this level of investigation, and in fact ground investigation is very rarely carried out to advance the engineering geological interpretation of landslide areas. In many cases a combination of engineering geological mapping and trial pitting has been found to suffice to yield a level of interpretation sufficient for design to proceed.

Risk Management

Once the risk posed by a landslide or earthworks failure has been assessed, then the options for risk management can be considered. If the risk is considered to be low, either because the failure is relict, small or very slow moving, then engineering intervention may not be necessary. This is a common situation in Nepal, where numerous cut slope failures, for instance, have either been ignored or have been dealt with by removing debris from the road or side drain. It is then a matter of judgement as to whether treatment works are required. In the low cost road sector it is frequently the case that the smaller slope problems are left to regain stability without engineering intervention.

Where a decision is taken to apply slope treatment works it is important to consider the following factors:

- The cause of the failure
- Its extent, depth and mechanism
- The geotechnical nature of the slope material
- The drainage pattern on the slope and surrounding the slope
- The effects of any surrounding land use practices
- The performance of any slope treatment works previously applied.

These factors are usually assessed by surface mapping combined with trial pitting, where appropriate. Treatment works can then be selected and designed. They will normally comprise a combination of drainage and toe support through retaining walls or breast walls. Grass and shrub planting is usually incorporated into the final arrangement of slope works for erosion protection purposes and to assist in the stabilisation of surface soils.

Draft Best Practice Guidelines in Aerial Photograph Interpretation

Introduction

Aerial photographs provide a record of the ground surface, drainage, vegetation and land use, and the urban, rural and transport infrastructure constructed upon it. Aerial photograph interpretation (API) therefore allows a range of natural and man-made features to be identified and mapped. With the advent of satellite imagery and GIS-based approaches to acquisition and management of terrain and environmental data, API has probably not been used to its maximum benefit in many countries. The main reason for this is that API is not a new technology, it is not computer-based and it is reliant on judgement. This judgement is based on geomorphological training and experience within a relatively specialist field.

The Landslide Risk Assessment (LRA) Project has demonstrated the immense value of API to landslide and terrain mapping. It also provides useful information on existing land use and infrastructure in any given area and enables terrain to be evaluated rapidly for the benefit of future development purposes. The LRA Project has carried out detailed API in six study areas of Nepal and Bhutan. It has trained seconded staff in the use of API and has organised several workshops that have dealt exclusively with API. The value of API has been recognised by all staff involved or trained on the project and therefore this Guidance Note proposes that the process of decline in the use of API be reversed for the benefit of landslide mapping and infrastructure planning in general.

Benefits

Aerial photographs have many strengths over other types of imagery. Advantages of aerial photographs include:

- Widespread availability in archive form. Many areas have several sets over a reasonable period of time
- Relatively easy to commission the collection of new sets where required
- Good spatial resolution
- Availability of stereo coverage
- Interpretation skills are widely available and quite easy to learn
- Imagery is intuitive to analyse
- Do not require complex analytical techniques.

To this end, in landslide studies for rural infrastructure palnning, aerial photographs are ideal for:

- Identifying and mapping landslides
- Undertaking rapid terrain assessments
- Identifying the factors involved in landslide susceptibility.

Limitations

Despite the above, the success with which API can be used to accurately and reliably map landslides and geomorphology is dependent upon a number of factors:

- The availability of air photo coverage. In some areas there may be limited availability of imagery or access may be restricted for security reasons
- Up to date air photo coverage. In some areas the photo sets might be very out of date. For example, if the photos were collected before a major earthquake significant alterations to the terrain may have occurred
- Cloud cover and shade effects. Unfortunately the presence of clouds or intense shadows can greatly compromise the interpretation of photographs.
- The presence of only low levels of radial distortion resulting from relief effects.
- Scale: aerial photographs can either be too small scale or too large scale depending upon the scale of the study (for landslide mapping 1:50,000 scale is probably the limit, and scales of 1:10,000 to 1:30,000 are preferred)
- The minimisation of subjectivity in interpretation.

Air Photo Scale

Aerial photographs are typically taken using specially designed cameras mounted in an adapted light aircraft that is flown over the ground surface during good weather (so that the site is free of cloud). The quality of the film in the camera and the flying height of the aircraft determines the resolution of the photographs. Typically, the aircraft flies at a height of 500 – 2000 m, which provides a scale of the photograph of 1:12 500 – 1: 50 000. Even a 1:50 000 photo allows objects of less than a metre to be seen on the ground surface, although the small size of the photograph can make mapping difficult unless the photo is enlarged.

General Principles of Landslide Identification

The general principle for landslide identification from API is that a feature should comprise both source and debris. The absence of debris may be acceptable when the source is clear and some means for the removal of debris, such as stream erosion, is present. Unattributed debris should not be mapped as a landslide – but may be shown as colluvium or disturbed ground. Possible, or even probable, landslides have often been seen in the form of a degraded and forested hollows with an area of terraced land lower down the valley. Such cases have generally not been included as landslides because neither source nor debris exhibit any recognisable landslide morphology. This approach is justified because there is too much uncertainty in the identification of such features.

In general, features should only be mapped if there is a reasonable degree of certainty in the interpretation. Uncertain features are mapped only when the uncertainty arises from factors such as shadow, the small size of the feature, image distortion, or thick vegetation.

To undertake the interpretation each photograph in turn should be covered with a clear acetate sheet on which the annotation is to be made. The first step for each pair of photographs is to mark the drainage in as much detail as possible. Next the location of landslides (active and relict), areas of active erosion, unstable ground or creep, and accumulations of colluvium (unattributed debris) should be mapped. All this information is recorded in ink using a symbol, line and colour system. Locations of deep shadow on the photographs should be marked: these often coincide with steep slopes and may therefore obscure landslides. Any other potentially useful information should be recorded with a chinograph pencil; this might include observations such as structural control, strike and dip, lineations and any unusual features.

API for landslide studies is best carried out in conjunction with the following related activities:

- Comparison of the terrain interpreted from the aerial photographs with that shown on topographical maps
- Comparison with published geological maps
- Ground truthing or verification to help calibrate the API with field evidence

Recording Data

Every landslide should be assigned a reference number and a pro-forma completed for each numbered feature. A proforma should be completed for each feature detailing the site interpretation. The proforma employed on the LRA Project is attached to this document by way of example. Not all of the information required to be entered onto the attached proforma can be provided from API alone, and recourse will need to be made to other sources of data. API should be able to provide an indication of the following: failure mechanism, composition and wetness of debris, activity i.e. active or inactive, rate of movement, structural control, drainage pattern, vegetation and land use. The proforma should be completed only for landslides and not for areas of colluvium, erosion or inferred creep.

Rectification

The effects of high relief and radial distortion can be severe on aerial photographs in mountain terrain. Ideally, ortho-rectification of photographs should be undertaken to remove distortion effects making aerial photographs compatible with base mapping. This allows landslides identified on aerial photographs to be digitised directly as an information layer in GIS. The alternative approach is to transfer landslide locations and outlines onto topographical maps by hand for later digitisation. There are inherent inaccuracies in this method that are most acute when the topographical maps themselves are inaccurate in terms of the reference data they portray, namely contour information and drainage network.

Distortion

Increasing the overlap between photographs, both within runs, i.e. stereo overlap, and between runs, can reduce the level of radial distortion. The following may be found to be helpful when distortion hinders interpretation:

- Viewing the area on all the photographs on which it appeared. This is very important because the interpretation of morphology can be altered significantly with the direction of view in such steep terrain.
- Viewing from opposing directions, especially when the interpretation relied heavily on shape
- Referring to the topographic map to determine the slope angle and true size and shape of the feature.

Clarity of Interpretation

Interpretation is sometimes complicated by the similarity in reflection between landslides/erosion areas, bare natural soil and some forms of cultivation. As a result, photographs have to be viewed carefully under high magnification.

It is often the case that east – west trending ridges and valleys result in darker images on the slopes facing away from the sun (northern slopes in the northern hemisphere) and lighter images on the slopes facing towards the sun (southern slopes in the northern hemisphere), probably as a result of trying to compromise the exposure to accommodate both. The tendency is to overexpose (bleach out) the south facing slopes whereas the north facing slopes often become dark. In many case the detail may be lost although the overall slope morphology should provide an indication of whether landslides are likely to be present.

Feature identification

The following is a review of the ease with which the principal landslide attributes can be identified on aerial photographs.

Property	Comments
Failure mechanism	Can generally be discerned from the morphology of the landslide and the nature of the terrain. Relatively few rock slides were found, most failures were debris slides, debris flows or composites. The distinction between flow and slide may not be clear if the debris is degraded or eroded.
Composition and degree of wetness of debris	Wetness may be inferred from local changes in vegetation but textural changes that may have been interpreted as soil moisture were often not confirmed in the field – so this should be done only with caution. The best indication of moisture is probably the presence of springs and percolines which can often be seen even through forest cover.
Activity	Activity is generally seen only as the absence of vegetation in the scar. Tension cracks may be seen behind backscarps and sometimes in creep and disturbed areas.
Rate of Movement	Cannot be determined from a single set of APs except by association with the mode of failure.
Ground Conditions	Broad ground conditions may be inferred, from location, landform and absence/presence of structural control (see below).
Soil Thickness	Thin soil cover in areas of sharp ridges and peaks, may be differentiated from thicker soil forming more rounded topography and areas of cultivation.
Structural Control	Structural control of topography is often present, even in forested areas (although not in the more dense forests of Bhutan) and failure control can be inferred. However structurally controlled failures are not common.
Height, aspect and angle of slope	Very difficult to judge because of extreme distortions. It is preferable to plot onto the topographic map and then interpret from the contour data, or to extract from the GIS.

Property	Comments
Drainage pattern	Drainage patterns are usually well defined. Springs are not easily seen on medium to small scale photographs, but their location may be inferred in some cases by small topographic features (e.g. oversteepened gully heads), drainage pattern and vegetation.
Vegetation	Differentiation between forest, scattered trees and bushes, grassland and cultivation.
Land Use	Cultivated areas can usually be identified, especially when terraced.
Terrain Classification	1:50,000 APs are good for this purpose, usually with low power viewing.

Field Validation

Ground truthing is very useful for studying the interplay between landsliding, geomorphology and land use, which can provide an insight into some of the older features. However, ground truthing may not always be definitive, especially for old features and in dense vegetation, where the API may be more reliable. Similarly, some features mapped in the field may not be identified clearly on the photographs even when their location is known.

When a slope is seen on the ground to contain a number of small active slips, creep and maybe some erosion, which cannot be individually identified on the photographs, then it is recommended that the whole area should be mapped as an area of disturbed ground. Such composite areas should not be shown as a single landslide.

If the interpreter has no previous field experience of the terrain under investigation it is recommended that a short site visit should be made early in the study period. If the interpreter is experienced, and especially if only one site visit is possible then it is preferable to complete the majority of the API study before making a site visit. Sufficient time should also be available for reviews and revisions after the validation exercise. The field validation should be planned to provide the following, more or less in descending order of priority:

- a geomorphological overview of the site and of the types of failure present
- views of as many different failure types as possible
- views of as many different types of terrain and geology (rock type) as possible
- detailed visits to as many areas of uncertainty of interpretation as possible.
- visits to areas obscured by cloud, shadow or high reflectance where landslides are considered likely to be present.

The first three aims essentially require one or more traverses through the site. Routes should be chosen to provide the maximum coverage of the site even when viewed from some distance. The extent to which the latter two aims can be achieved will depend on access and time available. The first two aims are generally better met by viewing from a distance, eg from the opposite valley side and even the third may not require close inspection.

Draft Best Practice Guidelines in Satellite Image Interpretation

Introduction

Although satellite imagery has been available for 30 years, until now its use in the identification of landslides has been limited. There are a number of reasons for this, including cost, the need for technically-complex equipment, the availability of people with the necessary skills, and limitations in the ability of the instruments to detect objects other than those that are very large. However, if these problems can be overcome the technique on paper offers many advantages. By providing a view of the landscape from above, in theory imagery might allow a planner or engineer to identify landslides, to determine their type, and to map their location with some accuracy, even in very difficult terrain. Furthermore, it might allow the mapping of factors that cause landslides if, for example, areas of wet ground can be identified on the image. Finally, it can also allow the mapping of infrastructure and objects that might be affected by landslides, such as roads, buildings and even communities.

In recent years, great advances have been made in all aspects of satellite imagery. These include the availability at low costs of computers that can analyse images, the availability of user friendly software that allows non-specialists to interpret and analyse images, a substantial reduction in the costs of many image types, and great steps forward in the resolution of the images. As a result, satellite imagery is increasingly attractive as a tool for landslide identification and analysis. This has been demonstrated during the Landslide Risk Assessment (LRA) Project, in which satellite imagery has been used in most sites. To the surprise of even the researchers on the project the techniques developed and used proved to be highly effective. Therefore this Guidance Note has been provided to give an introduction to the use of satellite imagery in landslide studies.

Uses of satellite imagery in landslide studies

There are five main ways that satellite images can be used in landslide studies:

a. *Landslide detection*: Satellite images can be used in the same way as aerial photographs to find landslides in the landscape and, sometimes at least, to decide what type of landslide they are. Of course, the landslide must show up on the image. The ability of some imagery to provide information about, for example, the emission of heat from the surface can be very useful in this respect.

b. *Factor mapping*: Satellite imagery can provide information about factors, such as soil moisture, that might be significant in landslide initiation..

c. *Landuse interpretation and classification:* Satellite images can be used to assist in the mapping of landuse, which might be important in terms of increasing susceptibility to landslides, or of making the impacts of landslides more significant.

d. *Vulnerability assessment*: Satellite images can be used to map objects or infrastructure that might be affected by a landslide.

e. *Landslide Monitoring*: If multiple sets of images stretching back over years or even decades are available they might be used to determine when landslides have occurred or reactivated, or even the length of time that the landslide remains visible.

Why use satellite image interpretation?

Apart from the ease with which an image can be examined, why is satellite image interpretation used for landslide hazard and risk assessment? Basically there are five advantages of this technique:

a. Remote sensing can provide a different (vertical or oblique) perspective on landforms. In the case of aerial photographs and a few types of imagery, it also allows stereographic viewing of the terrain, which means that it is easy to interpret relief.

b. Remote sensing uses parts of the electromagnetic spectrum that humans cannot see, such as infrared and even microwave radiation. Landslides that might not be visible with the naked eye might be visible using these parts of the spectrum.

c. The wide-angle view allows the interpretation of the ways that different terrain features are positioned relative to each other. This can help in the determination of whether a particular feature has been created as a result of landslides or some other feature.

d. In some cases automatic classification of landslides by the computer is possible, which can make the mapping of landslides much easier and quicker.

e. Remote sensing can provide images from different time periods and under different conditions that can help us to determine when landslides occurred and how active they are.

Benefits of satellite imagery

Aerial photographs have many strengths, including:

- Coverage of a wide area – typically for example a LANDSAT image includes an area of 10 000 km^2.
- Ability to be manipulated digitally, allowing key features to be highlighted
- Information that covers not just the visible part of the electromagnetic spectrum, but which can also provide data on, for example, the thermal properties of the surface
- Limited radial distortion
- In some cases, relatively low cost
- Increasing availability in archive form. Almost all areas of the surface of the earth now have multiple datasets extending back over 20 years.

To this end, in landslide studies for rural infrastructure planning, satellite images are ideal for:

- Identifying and mapping landslides, especially large features
- Identifying the factors involved in landslide susceptibility.
- Mapping and assessing elements at risk

Limitations

However, there remain substantial disadvantages of the use of satellite imagery:

- Cloud cover prevents imagery from being collected
- High resolution imagery is expensive
- Technical expertise is still required to analyse imagery
- Analysis requires high powered computing facilities and specialist software

- Access to imagery may be restricted for security reasons
- Scale: the spatial resolution of images is often too poor to observe smaller landslides
- Subjectivity in interpretation.

Types of imagery and their uses

Satellite images are available from a wide range of instruments operated both private and commercial organisations. The cost of the purchase of a satellite image can be very high, and this has put off many potential users, although in reality this effect may be slightly exaggerated because the costs are 'up-front', whereas many of the costs of traditional methods, such as ground mapping or aerial photograph analysis, are hidden

The main types of satellite imagery that are available are described in Table 1. There are many images available, but in general landslide studies make use of Landsat and SPOT, although IKONOS and IRS-1 show great potential.

Table 1: Types of imagery that are available and their approximate costs.

Sensor type	Typical image size (km)	Spatial resolution (m)	Minimum feature size (m)	Spectral resolution	Temporal resolution	Typical cost
Landsat 7ETM+	185 x 185	30 m (15 pan)	45	Pan + 8 bands: 4 visible, 4 IR	16 days	$400 per scene
SPOT IV	60 x 60	20 m (10 m pan)	30	Pan + 4 bands: 2 visible, 2 IR	26 days	$3000 per scene
IKONOS	11 x 11	4 m (1 m pan)	3	Pan + 4 bands: 3 visible, 1 IR	11 days	$18-63 per km^2
IRS-1D	142 x 142	23 m (6 m pan)	18	Pan + 4 bands: 2 visible, 2 IR	24 days	$1400 per scene
Radarsat	45 x 45	8 m	variable	Microwave	24 days	$3000 per scene
ERS-1	108 x 108	25 m	variable	Microwave	35 days	$1200 per scene
ENVISAT	108 x 108	30 m	variable	Microwave	35 days	Unknown
Orbview 3 (forthcoming)	8 km x user defined	4 m (1 m pan)	3	Pan + 4 bands: 3 visible, 1 IR	3 days	Unknown

Acquisition of images

In general for landslide studies, except for specific research-led activities, one of Landsat ETM+, SPOT or IKONOS should be used. In most cases, Landsat ETM+ will prove to be the optimum imagery due to its excellent spectral resolution and relatively low cost. SPOT IV may be useful if stereo capability is required. IKONOS provides excellent spatial resolution, but the cost will often preclude its use.

Image correction

In many cases, the image will be provided in digital form and will need to be rectified to remove distortions due to, for example, the increasing distance of the sensor from the terrain away from the centre of the image, imperfections in the sensor itself and/or atmospheric effects. Fortunately, using modern software rectification and correction is a comparatively simple task. The user identifies key points on the imagery for which the location is known very precisely (for example survey base points). These are identified on the image, and the software uses these points to warp the image so that all points are returned to their correct location. Of course the accuracy of this process is dependent upon the precision with which the ground control points are located both on the ground and on the imagery, and on the number of points used. In general, more points means better accuracy.

Direct observation of an image

The simplest way to use a satellite image is to treat it as if it is an aerial photograph and to map directly from it. There are two ways that this can be achieved. The simplest form of satellite data is the so-called panchromatic image, which is effectively a black and white digital photograph of the ground surface. A more complex version is to use data collected in each of the red, green and blue parts of spectrum, and to combine these three images in the same way that a television screen combines such data to produce a so-called true colour composite image.

In both cases the image can be viewed as per a photograph, although if it is examined on the screen there is the added advantage of being able to focus in on any item of interest.

In some cases, this may provide sufficiently good results that further manipulation of the imagery is not needed. If so, the next stage should be the first field validation.

Image enhancement and factor mapping

An advantage of satellite imagery is the availability of image enhancement, which can be used to highlight features in the landscape, whether these are landslides themselves, factors involved in triggering landslides, variations in landuse, or terrain types. The types of enhancement that can be used include:

Contrast Stretching: This technique automatically analyses the relative contrast within an image, or part of an image, and can be used to enhance the contrast level so as to highlight any objects of interest. This can provide maximum discrimination between surface materials and, for example, can be used to emphasise the differences between vegetated areas and those with bare rock and soil. As many landslides have unvegetated back scars or shear zones, this can allow the discrimination of areas affected by landslides.

Filtering: Filtering is a more complex version of contrast enhancement, in which the contrast of each part of an image is enhanced by increasing its contrast with adjacent parts of the image. This has been proven to emphasise landslide features and can aid in the mapping of other features of interest.

Band ratios: Many materials and surfaces can be characterised by the spectral response in different bands – the so-called spectral signature. so, for example, a leaf might have a very high response in the green part of the spectrum but a very low response in the red part. Thus, it is possible to look at the ratio between the responses in the two bands and to use this ratio to characterise the properties of the surface. In the band ratio technique, the software does this automatically. In recent years, several algorithms have been developed using this technique to highlight specific features. For example, Normalised Difference Vegetation Index (NDVI) technique, which is commonly applied to Landsat 7ETM+ data, highlights variations in vegetation type and density and is commonly used for the classification of forested areas. Most image analysis software can undertake this analysis automatically. Several of these band ratio techniques are useful in landslide studies. For example, the NDVI can highlight areas of active instability (unstable ground often causes vegetation stress that can be detected through this method. In extreme cases, active landsliding leads to vegetation clearance that is easily detected.). In addition of course this technique can also be used in the mapping of landslide initiating factors, such as landuse. Some success is also met with the use of other ratios in Landsat data, notably ratios designed to highlight clay (which can sometimes detect landslide debris) and those for iron oxide (which can sometimes highlight areas of high moisture levels).

Unsupervised classification: Image processing software can automatically divide the pixels in an image into a series of classes according to their spectral characteristics. The software allows the user to either select the number of classes into which the imagery should be divided, or it can do so automatically. Whilst research into these techniques in landslide studies remains limited, potentially it offers a powerful technique for the delineation either of landslides themselves (assuming that they have some unique set of spectral characteristics), landslide factors such as vegetation types, or for factor analyses. A number of methods for unsupervised classification are available, including minimum distance to mean, parallel piped and maximum likelihood. Of these, only the maximum likelihood technique has to date shown good results for landslide studies, having been successfully applied to both Landsat and SPOT imagery. In both cases the technique clearly highlighted areas of bare soil associated with recent failures.

Supervised classification: In supervised classification, the user selects one or more areas within the image of interest. so, for example, the user might select a known landslide. The computer will determine the spectral characteristics of the area and will then undertake a classification of the image based upon these characteristics, using one of the techniques described above. This can be a powerful way to find areas of specific interest. For example, the technique can aid in the identification of areas underlain by colluvium once one or more areas have been identified. As before, the maximum likelihood technique would appear to be the most powerful for undertaking supervised classifications.

At the end of this stage a map should be produced of the results of the analysis of the study. This may well cover only about 25% of the total area at this stage, but should represent the best possible attempt to identify and locate the items of interest. If more than one type of data are being collected, a number of maps will probably be required.

Landuse interpretation and classification

Probably the most common civilian use of satellite technology is the mapping of land use, and there is a host of techniques by which this can be achieved. Indeed, the wave bands used by for example the LANDSAT instruments have been optimised to differentiate between vegetation types. Resulting landuse classifications can be used to assist in the detection of landslides, as a factor for landslide susceptibility schemes, or as an input to vulnerability assessment for landslide risk assessments. To this end, the following techniques are commonly employed:

Band ratios: The use for landuse mapping is as per the Image Enhancement and Factor Mapping section. Clearly the NDVI technique described there is also relevant here. There are number of comparable algorithms that allow similar analyses.

Unsupervised classification: Unsupervised classification techniques can also be quite successful for mapping landuse variations. Clearly the success of the technique is heavily reliant upon being able to categorise the outputs from the classification successfully, but in most cases the outputs from unsupervised classifications reflect landuse more than any other factor.

Supervised classification: Supervised classification is also generally successful at assessing landuse, assuming that suitable training areas can be found. This technique is especially successful when applied to Landsat 7ETM+ data due to its high spectral resolution.

Other more complex techniques have been developed, but for the most part they yield results that are little better than the above. Some attempts have also been made to utilise more radar and hyperspectral satellite instruments for landuse mapping, but at the moment these techniques remain experimental and unproven.

Vulnerability assessment

Potentially, satellite data can also feed into vulnerability assessments by allowing mapping of infrastructure and settlement patterns. For the most part however this is not currently used due to the low spectral resolution of the imagery. However, quite good results have been yielded within Nepal in a research project associated with the LRA project. Here, Landsat 7ETM+ imagery was used to examine patterns of settlement in the Baglung area with some success. It was clear that quite specific data could be yielded using this technique. The IKONOS data offers far greater potential in this respect, with an ability to map down to the scale of individual houses. However, as yet the full development of this technique has not been undertaken.

Landslide monitoring

There is increasing interest in the possible use of satellite images to monitor landslides over time. In general to date this has been undertaken using a series of images that cover a range of years. Such analyses are long and relatively time-consuming, so should only be attempted where really necessary. Here, a series of landslide maps should be compiled, each independently of the other in the first instance. These can then be compared to determine change through time, although correlation between images should be used to ensure that apparent changes have not occurred simply because of misinterpretations or errors.

There are currently attempts being made to develop more sophisticated monitoring tools using satellite images, including the so-called INSAR (satellite interferometry) technique that is based upon radar datasets. However, to date such studies have been only partially successful and the techniques should be considered as experimental at best. However, it is likely that these techniques will be extremely powerful in the future, and will allow millimetre scale mapping of landslide movements.

First field validation

At this stage it is strongly advised that a field check of the interpretation of the imagery is completed. This should involve a visit to the field site, preferably in good weather. A minimum of 20% of the area analysed to this point should be examined in the field. This field validation should check:

1. The quality of the imagery in relation to the features on the ground surface itself.
2. The accuracy of the interpretation made to date, including any misinterpretations or features that have been missed. In both cases notes should be made so that further analysis can be undertaken on the imagery.

3. The occurrence of systematic errors

This ground verification is best undertaken through geomorphological mapping in the field. It is greatly assisted if a hard copy, true colour composite is available in the field as well so that features identified on the ground can be compared with the imagery, and vice-versa.

Final image analysis

Based upon the results of the initial image analysis and the field validation, a final analysis should be conducted. This will probably involve refining the interpretation and analysis methods to more closely correlate with the features on the ground, and an attempt to manipulate the imagery to highlight features that were not previously identifiable. As a result, a final map can be produced, together with a summary commentary.

Second field validation

Once the final map has been produced, a brief field validation visit should be undertaken to ensure that the interpretation is appropriate. This should be brief, covering perhaps only 5% of the total area in detail.

Draft Best Practice Guidelines in the Use of a Geographical Information Systems for Landslide Susceptibility Mapping at a Regional Scale

Introduction

A Geographical Information System (GIS) is a powerful computer-based tool for the storage, management and analysis of spatial data. Until recently GIS was a very specialised tool that was only really usable by specialists due to the complexity and cost of the required software and hardware. However, in recent years the availability of powerful, low cost computers and the development of user-friendly software systems have meant that GIS is now a tool that is applicable to a wide range of projects. In the first part of this guideline the fundamentals of GIS are described and reviewed. The second part the use of GIS for landslide susceptibility mapping is described.

The Landslide Risk Assessment (LRA) Project has demonstrated the value of using a GIS for handling and analysing large volumes of spatial data, and in particular for carrying out rapid assessments of landslide susceptibility over large areas. It has also become clear that GIS is a very powerful tool for the assessment of vulnerability of the infrastructure and population of a given area, and it is thus a powerful tool for planning purposes.

The LRA Project has worked six study areas – three in each of Nepal and Bhutan. For each study area a GIS database has been developed to manage a wide variety of data, including the topography, geology, geomorphology, land use, regional seismicity and infrastructure. Those data have been obtained from a number of sources, including published and unpublished maps and reports; aerial photograph analysis; satellite image analysis; and field mapping. In the LRA project the aim was to examine the factors that were significant in the occurrence of landslides in each study area. The GIS allowed this to be assessed. The results obtained from these analyses have been used to create a set of landslide susceptibility maps for each of the six study areas.

One advantage of a GIS is the ability to produce maps that are of a very high graphical quality. Unfortunately this can lead to a feeling that the information that they are portraying is absolutely accurate. Unfortunately this is not the case. Output data can only be as good as the data that has been used as an input. If the input data quality is poor then the output is will be poor. In addition, it is critically important that the user understands what the computer is actually doing when it undertakes an analysis. It may therefore be necessary to have a GIS specialist working in conjunction with a field specialist so as to utilise the experience, skills and knowledge of both.

Benefits and Limitations

The key benefits of GIS include:

- The ability to store, manipulate and assess large amounts of data
- The capacity to undertake complex mathematical analyses of data
- The ability to work at multiple scales
- The ability to create both statistical and map outputs

In the specific example of landslide susceptibility, hazards and risk mapping studies for rural infrastructure planning, a GIS offers the ability to:

- Manage the large volumes of data
- Identify the factors involved in landslide susceptibility.
- Produce outputs indicating the levels of susceptibility, hazard and risk across the study area

However, GIS has a number of limitations, most notably:

- GIS systems can be complex
- A high quality GIS can take a considerable amount of time to set up
- The acquisition costs of the hardware and software can also be high

General Principles

The aim of a GIS is to represent the real world in a digital form. To do this it uses three types of spatial data:

Point data, in which an object is represented by a single point in space. A house might be represented in this way if a large area is being mapped, or a point might be used to represent the location of a single geological measurement.

Line data, in which an object is represented by a line in space. A line can be used to represent the course of a road or a river, or the line of geological structure such as a fault.

Polygon data, in which an object is represented by a space. A polygon might be used to represent a landslide, land use or a geological unit.

Clearly as a GIS is being set up it is important to decide how to represent each type of data. To a certain degree this will depend upon the scale at which the mapping is being undertaken and the end use of the system. So, for example, a detailed local study might represent a house as a polygon whilst a regional study might represent it as a point.

In all cases the user can add data to the point, line or polygon, effectively to describe its characteristics. These data are known as ‘attribute data’, which are usually held as an attribute table within the GIS. So, for example, a landslide map can be digitised as a series of polygons into the computer. An attribute table can then be added to this data showing the area, volume, and failure mechanism for each landslide that has been mapped.

Within the LRA project information has been stored about our study area as a series of ‘factor layers’ within the GIS. Each stores information about a particular aspect of the study site. So, for example, one layer stores information about the spatial distribution of the geological units, here in the form of polygons. Another holds information about the location of all of the houses; in this case in point form. Note however that some information may be represented by more than one factor layer. For example, the geological information might consist of a map of the geological units (polygon data), a map of the structural data that was collected (point data), and the faults and folds (line data).

Data Input

Clearly a key requirement of GIS is that data must be generated and entered into the system.

There are a number of different ways of entering data:

- Tablet digitising: A digitising tablet can be used to trace an existing paper map into the computer. This can be a very time-consuming process.
- On-screen digitising: here a map containing the required data is scanned into the computer, and the information is then converted to line, point or polygon form either by hand or automatically
- Importing: in some cases data are already available in GIS format and can be imported directly into the system.
- Attribute data: information about an object can be entered directly into the computer
- Direct measurement: in some cases data might be entered directly into the GIS. For example, a modern EDM surveying system can often generate topographical data that can be transferred directly into the GIS.

Database Management

A GIS can generate large volumes of data in a short period of time. Some of these data may be revisions of earlier data or results from analyses. Unless care is taken it can quickly become very difficult to manage these data. It is therefore essential to have a set of database management conventions within a project. All those who are working with the database to strictly adhere to these conventions as closely as possible. These conventions should prescribe the file and folder names that should be used, and there must be a clearly defined file structure.

A good management convention will make it easy to find the most recent version of a particular data layer within the GIS. This is particularly important when more than one person is working with the data. To assist in this a metadata file should also be kept recording the data that is contained within the GIS database, the file names that have been used, the reasons for any revisions, and any problems that have been encountered. It should also record when the data was created or revisions made and who did the work. This file could also contain information about when backups of the data have been made. It is very important that the metadata file is regularly checked and kept up to date.

Analysis and Interpretation

The strength of GIS is the ability to undertake complex analyses of the spatial relationships of the data. These functions include:

- querying, which allows the user to select areas with specific properties
- buffering, which allows the user of define a zone around a specific point or object
- overlaying functions, which allow the user to combine data layers using mathematical or logic functions

Field Validation

The data held within the GIS is a digital representation of the real world. Any interpretations and analyses undertaken using the data should, where possible, be verified in the field. The field validation can often also be used as part of a quality assurance check on the data, which should be undertaken by some who is familiar with the terrain.

Landslide Susceptibility Mapping

In this section of the Guidance Note the simple but effective technique that the LRA project has developed for assessing landslide susceptibility using a GIS is introduced. The system is intended for use in, for example, the corridor selection of rural roads and should be used at a regional or district scale (i.e. c.1:200 000).

The analyses undertaken by the LRA project using GIS have shown that, when working at the regional scale, the most significant factors determining landslide activity are the slope angle and the rock type of the material involved. However, at the regional scale, mappable geological units are usually a combination of different rock types. For example, phyllite is often found in conjunction with limestone, and schist will often be found in conjunction with gneiss. Therefore, this project refers to these units as a "Lithotype". For each lithotype, the way in which the slope angle affects the stability of the slopes within the study area, based upon the distribution of existing landslides, has been assessed.

This simple landslide susceptibility scheme is therefore based upon a list of lithotypes, each of which has been divided into four slope angle classes. For each lithotype - slope angle combination the density of landsliding across the six study areas has been determined to provide an indication of the susceptibility to the occurrence of landslides. This list, referred to as the "Regional Landslide Susceptibility Rating Scheme List" is provided in Appendix 1. In many cases the formations on the geological map will not exactly coincide with those in Appendix 1. Some interpretation of the geological data will therefore be required.

Thus, to undertake this assessment it is necessary to collect information about the lithotypes of the study area. This can usually be obtained from published geological maps, ideally at a scale of 1:25 000 or 1:50 000. In most cases these maps will be in paper not digital form, and will thus require tablet digitising. The data should be stored within the GIS in shape file (polygon) format, with attribute data that indicates the lithologies involved. Field mapping can also provide an input and should where possible be used to validate the information being inputs.

Slope angle data are also required. In most cases this is available in the form of contour maps compiled by national mapping agencies. The contour information will need to be tablet digitised or, if the data are available in electronic form, on-screen digitised. However, this digitisation will produce a layer with the data in line form. This needs to be converted to polygon form to allow it to be integrated with the geology data. To do this the GIS is used to generate a slope grid in a new data layer. The first step is to create a 'TIN' model, which is an interpretation of the distribution of elevation, slope aspect and slope angle between the contours. From the TIN model the user derives a slope angle grid file using the 'derive slope' function within the GIS. This file consists of a grid of pixels, each of which is assigned a value to indicate its slope angle. The user needs to specify the pixel size; in the LRA project 10 m has been used.

The slope angle information needs to be in shape file (polygon) format for the susceptibility analysis. To allow this, it is first necessary to reclassify the grid file into the slope angle susceptibility classes (0-20°, 20-30°, 30-40°, >40°). This generates a new grid file in which each pixel is given an attribute that indicates in which of these classes it falls. From this grid file the user generates a slope angle shape file using the 'convert to shape file' function. This shape file stores the slope angle class in polygon form.

The next step is to combine the geological shape file with the slope angle shape file to indicate landslide susceptibility. This is undertaken using the clipping function in the 'Geoprocessing Wizard' or its equivalent. Each lithotype is examined in turn. The function divides each lithotype into the slope categories contained within the slope angle shape file. For each lithotype a new shape file is generated. Each polygon has attribute data associated with it in the form of a grid code, which is an integer between 1 and 4. A grid code of 1 indicates a slope angle of 0-20°; 2 indicates 20-30°; etc. Using the lithotype and slope angles in Appendix 1, a new attribute needs to be assigned to these grid codes indicating the susceptibility. This is done by editing the attribute table for each shape file.

Using the 'merge' function in the Geoprocessing wizard, the shape files for each lithotype are combined to create a single susceptibility map.

In summary, the procedure involves the following steps:

1. Digitising of the geological data into shape file format.
2. Digitising the contour data at an appropriate scale (preferably 10 or 20m contour interval) into shape file format.
3. Using the contour data and functions within the GIS create a slope angle grid file with a 10 m-grid cell size. Reclassify this file so that there are four slope angle classes (0°-20°, 20°-30°, 30°-40° and >40°).
4. Using functions within the GIS, convert the slope angle grid file into shape file format.
5. Clip the slope angle shape file with each unit of the geology shape file so that a slope angle shape file for each lithotype is obtained.
6. Assign the landslide susceptibility rating from Appendix 1 to each of the slope angle class within each of the lithotypes. This will create a landslide susceptibility shape file for each of the lithotypes.
7. Merge these landslide susceptibility shape file to create an overall landslide susceptibility shape file for the area being studied. This is the landslide susceptibility map.

Field Validation and Quality Assurance

It is important to ensure that the outputs from this process are valid and sensible. Because of the number of steps involved it is relatively easy to make an error. Therefore it is important to validate the results. This can best be undertaken by way of a field visit, in which the representative areas of each susceptibility class are examined to ensure that the outputs are sensible. It is also important that someone who is familiar with the study area checks each step of the analysis.

Applications

The outputs from this analysis give an indication of landslide susceptibility within the area under study. It should be considered to be appropriate a regional scale. It does not give a detailed indication of the level of hazard for individual slopes for which greater levels of information are needed. In addition, the landslide densities included in Appendix 1 should be taken to be indicative not absolute. Changes in precipitation and human activity will lead to a change in the landslide density of an area. The maps can be used as part of the planning process for rural infrastructure development, such as the selection of an appropriate route corridor. In addition the map can be used to:

- Provide an indication of which areas will need further detailed field mapping and site and ground investigation.
- Consider the merits of alternative options, such as transportation routeways
- Provide the base for regional scale landslide hazard and risk assessments.

Of course these techniques cannot represent an alternative to detailed field mapping, or to the site and ground investigation parts of any engineering development project.

Conclusions

This Guidance Note introduces briefly the principles of GIS and provides some detail about the way that these techniques can be used to assess landslide susceptibility on a regional scale. The LRA project has proven the usefulness of GIS in rural access projects. It is important to stress that before a GIS analysis is undertaken the user must be sure that this is the most appropriate tool to achieve the aims of the project.

The landslide susceptibility assessment scheme presented here is a relatively straightforward technique for assessing areas in which landslides are likely to occur. It is an appropriate tool for rural access projects, such as corridor selection. It does not represent a replacement for detailed field mapping or site investigations however.

Appendix a: Regional Landslide Susceptibility Rating Scheme

Susceptibility Class	Rock Type	Slope Angle	Indicative landslide density (landslides/Sq km)
Low Landslide Susceptibility (Rating of 1)	Granite	0° - 20°	0.00
	Granite	20° - 30°	0.00
	Granite	30° - 40°	0.00
	Granite	> 40°	0.00
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	0° - 20°	0.00
	Slate/shale with Limestone &/or Quartzite	0° - 20°	0.00
	Quartzite & Phyllite	0° - 20°	0.16
	Mica Schist & Gneiss	0° - 20°	0.20
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	20° - 30°	0.20
	Mica Schist and other minor rock types	0° - 20°	0.22
	Gneiss & Mica Schist	0° - 20°	0.25
	Mica Schist & Phyllite	20° - 30°	0.26
	Mica Schist & Quartzite	0° - 20°	0.27
	Gneiss	0° - 20°	0.30
	Phyllite (with Quartzite &/or Limestone)	0° - 20°	0.30
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	30° - 40°	0.36
	Quartzite & Phyllite	20° - 30°	0.36
Moderate Landslide Susceptibility (Rating of 2)	Limestone/Dolomite with Quartzite, Phyllite &/or shale	> 40°	0.40
	Mica Schist & Phyllite	0° - 20°	0.43
	Phyllite (with Quartzite &/or Limestone)	20° - 30°	0.46
	Mica Schist and other minor rock types	20° - 30°	0.48
	Mica Schist & Gneiss	20° - 30°	0.53
	Quartzite & Phyllite	30° - 40°	0.54
	Gneiss	20° - 30°	0.55
	Mica Schist	0° - 20°	0.56
	Slate/shale with Limestone &/or Quartzite	30° - 40°	0.59
	Mica Schist & Quartzite	20° - 30°	0.60
	Slate/shale with Limestone &/or Quartzite	20° - 30°	0.60
	Quartzite & shale &/or Sandstone	20° - 30°	0.62
	Quartzite & shale &/or Sandstone	0° - 20°	0.65
	Gneiss & Mica Schist	20° - 30°	0.66
	Slate/shale with Limestone &/or Quartzite	> 40°	0.67
High Landslide Susceptibility (Rating of 3)	Quartzite & Phyllite	> 40°	0.72
	Mica Schist	30° - 40°	0.75
	Mica Schist	20° - 30°	0.77
	Fine grained Sandstone (siltstone/mudstone)	0° - 20°	0.78
	Mica Schist	> 40°	0.80
	Mica Schist & Gneiss	> 40°	0.81
	Gneiss	30° - 40°	0.82
	Mica Schist & Phyllite	30° - 40°	0.83
	Phyllite (with Quartzite &/or Limestone)	30° - 40°	0.88
	Mica Schist and other minor rock types	30° - 40°	1.00
	Gneiss & Mica Schist	30° - 40°	1.00
	Mica Schist & Gneiss	30° - 40°	1.02
	Gneiss	> 40°	1.02
	Medium to coarse grained Sandstone	0° - 20°	1.03
	Quartzite & shale &/or Sandstone	30° - 40°	1.15
	Mica Schist & Quartzite	30° - 40°	1.19
	Quartzite & shale &/or Sandstone	> 40°	1.45
	Phyllite (with Quartzite &/or Limestone)	> 40°	1.55
	Mica Schist & Quartzite	> 40°	1.58
	Mica Schist and other minor rock types	> 40°	1.58
	Medium to coarse grained Sandstone	20° - 30°	1.64
	Gneiss & Mica Schist	> 40°	1.89
	Medium to coarse grained Sandstone	> 40°	2.15
	Medium to coarse grained Sandstone	30° - 40°	2.48
	Mica Schist & Phyllite	> 40°	2.62
	Fine grained Sandstone (siltstone/mudstone)	20° - 30°	2.91
	Fine grained Sandstone (siltstone/mudstone)	30° - 40°	3.33
	Fine grained Sandstone (siltstone/mudstone)	> 40°	6.85

Draft Best Practice Guidelines for Project Scale Landslide Susceptibility Assessments

1. Introduction

The purpose of this report is to establish a set of guidance notes for calculating landslide susceptibility from primarily desk study data, at the project scale. The report details the types of data required, the methodology for analysing the data and discussion on interpreting the results. This methodology is similar to that used for the regional scale analysis by incorporating lithology type and slope angle, with terrain classification, slope aspect and geological structure. However it differs from the regional scale analysis because it allows inclusion of area-specific data such as geological structure and terrain type, which will vary from one area to the next.

The analysis incorporates four landslide causal factors:

- Material type (lithology type and terrain classification)
- Geological structure
- Slope aspect
- Slope angle

This report sets out the steps in which the above factors are derived and how each factor is subsequently incorporated into the GIS-based susceptibility analysis, in order to identify areas within the study area that are a) high susceptibility to landslides, b) moderate susceptibility to landslides, c) low susceptibility to landslides.

1.1 Types of Software

A more detailed discussion of the various software packages, and how to use them, has been compiled as part of the regional susceptibility methodology. The following packages proved useful in this study:

1. GIS software (e.g. ArcView 3.2a, 3.2b or 8.0)
2. Specialist GIS add on software (e.g. ArcView 3-D and Spatial Analyst extensions)
3. Stereonet software (e.g. Dips 6.0)

The GIS software acts as a way to both manage and manipulate the data. ArcView was used mainly because of its functionality (i.e. allows image files to be incorporated easily) and ease of use. The specialist GIS add on software allows the manipulation of data, so that digital elevation models can be generated (DEM), which allow slope angle and aspect to be derived. A DEM is generated from contour data, it is in essence a 3-D representation of the ground surface.

1.2 Data Sources

The following desk study information is generally available (at varying scales) in both Nepal and Bhutan.

- Geology maps (the scale and level of detail can vary greatly)

- Topographic maps (1:50,000 scale maps are ideal, with 1:25,000 scale maps available for most of Nepal and some minor areas of Bhutan)
- Aerial Photographs

These sources of data are used to derive the different factors incorporated into the susceptibility analysis.

2. Factor Mapping

Terrain Classification

Differentiation needs to be made between the following terrain types:

- Colluvium
- In-situ soil
- Rock Controlled Terrain

Aerial photographs are primarily used to derive the distribution of the three material types within the study area. Each of the three materials are fundamentally different in both morphology and material properties.

Colluvium – material transported by hill-slope processes. Colluvium tends to form low to moderately inclined slopes (typically 20º to 30º), which display an irregular, undulating morphology when viewed from aerial photographs. Areas of colluvium are usually uncultivated, which tends to be an indication of relatively recent instability. In the field, the material tends to form a poorly graded mass of boulders and cobbles within a finer grained matrix. Occasionally individual boulders may be visible within the colluvial mass from the aerial photographs.

In-situ soil – material derived from the insitu weathering of parent rock, which generally retains the original rock structure, residual soil is also included in this category. Soil tends to form on slope angles similar to that of colluvium (typically 20º to 30º), and in similar topographic positions, however, unlike colluvium, soil can also be found on ridgelines. Areas of soil display a smooth, rounded morphology (when viewed from the aerial photographs), with slopes typically cultivated.

Rock Controlled Terrain – areas of ground that are dominated by in-situ rock. Rock tends to form steep slopes (typically > 40º), which have a thin veneer (typically < 1m in depth) of either colluvium or insitu soil. Areas of rock display a steep angular morphology (when viewed from the aerial photographs).

	**Colluvium** Slope angles typically 20º to 30º. Irregular, undulating morphology Vegetated but typically uncultivated
	**In-situ Soil** Slope angles typically 20º to 30º. Smooth, rounded morphology. Typically cultivated
	**Rock Controlled Terrain** Slope angles typically > 40º. Steep angular morphology. Can be heavily vegetated (not cultivated) towards the lower end of the slope angle range, with rock outcrops dominating the steeper end of the slope angle range.

Figure 1. Summary of the different terrain types.

The distribution of the three material types should be mapped from the aerial photographs and recorded on topographic base maps. The topographic map should ideally be at a scale of 1:50,000 or larger. A stereoscope should be used to view the photographs with a magnification of between x 3 and x 6.

The resultant terrain classification map should be digitised and entered into the GIS, making sure that each terrain type is digitised separately and saved as a unique factor layer.

3. Geological Structure

3.1 Kinematic Analysis

It is common for landslide source areas within both rock and in-situ soil, to display an element of structural control. It is therefore important to include geological structure in the susceptibility analysis as a landslide initiation factor. Typical rock slope kinematic analysis methods analyse the dip and dip direction of the geological structure with respect to the slope aspect. However, site observations have shown, that unlike rock slope analysis (e.g. planar, wedge and toppling analysis), landslides can also fail along structures that do not daylight out of the slope, but which have a similar dip direction to the slope aspect N.B. Daylighting occurs when the geological structure has a lower angle than the slope angle). This is generally a function of the weathered nature of the rock mass, e.g. the landslide may initially slide along the structural discontinuity, with the surface of rupture tending to break through to the slope surface, as the failed mass continues to move. This creates a planar central part of the source area, and a more concave surface towards the toe of the slide.

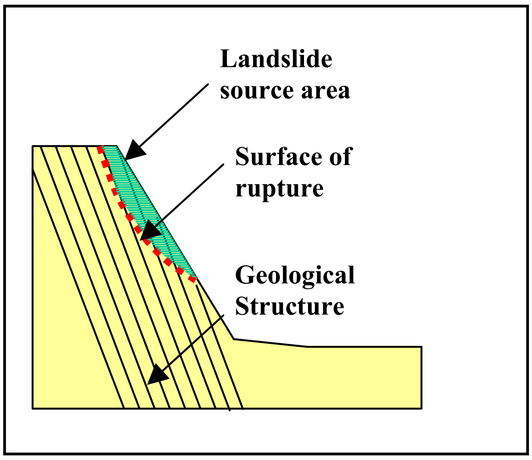


Figure 2. A diagram illustrating the case in which the dip direction corresponds to the aspect of the slope

For the purposes of this analysis kinematic feasibility will be analysed with respect to slope aspect. This is done by creating a dip direction range for each of the dominant structural orientations. Twenty degrees (20º) should be added to either side of the dip direction of the structure, e.g. a structure with a dip direction of 090º would range from 070º to 110º, giving a 40º range. This is termed the structural aspect window.

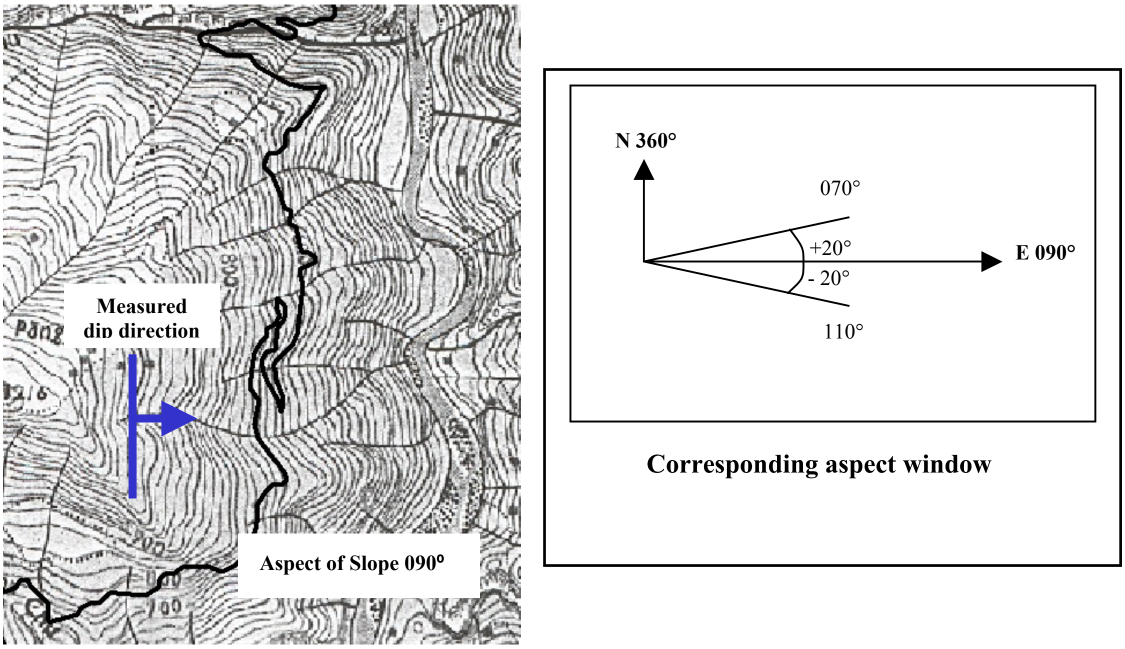


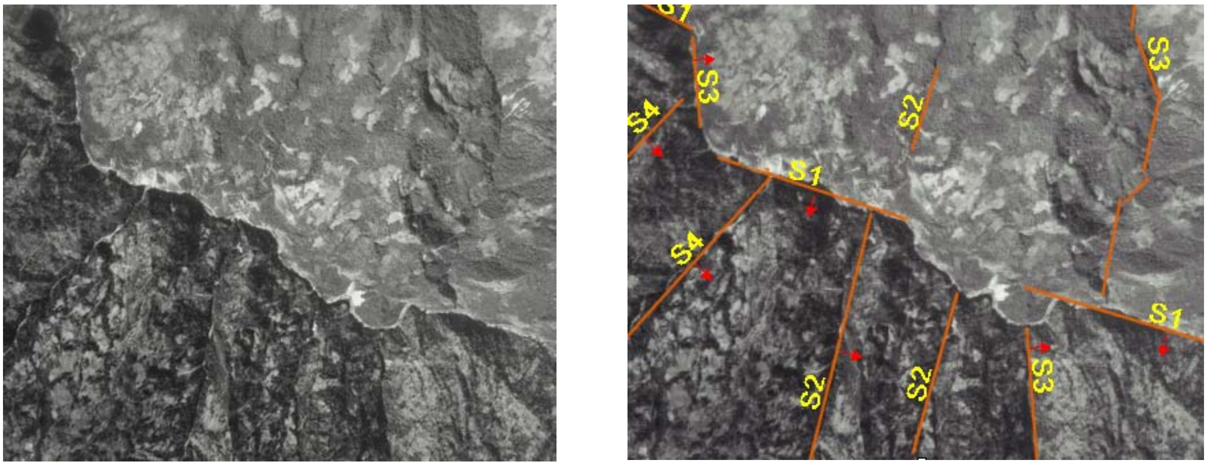
Figure 3. Illustration showing the determination of the aspect window

Based on this criterion the following assumption can be made: it will be kinematically feasible for structurally controlled landslides to occur on slopes that have an aspect that falls within the structural aspect window.

3.2 *Determining the Dominant Structural Orientations Within the Study Area*

The dominant structural orientations within the study area can be determined from both the aerial photographs and from any data present on the geological map. The aerial photographs can be used to determine both the strike, and where possible, dip direction of the dominant structural orientations. To do this it is important to utilise both the aerial photographs and the topographic map. Start by marking on the topographic map (using a ruler) the main orientations of the drainage lines (strike of the drainage line). Then by using the aerial photographs, mark on the topographic map any observed photolineaments and/or linear areas of rock outcrop. If possible also try to determine the direction in which the lineaments are dipping (i.e. dip direction), this can be done by observing areas of rock outcrop using the stereoscope with x 6 magnification. Mark on the map the dip direction (using an arrow pointing towards the direction of dip) at 90° to the observed lineament. Combine all this data with the structural details shown on the geology map.

Once this map has been constructed it is important to classify the different structures with respect to dip direction e.g. structural orientation S1 0°-10°; structural orientation S2 130° to 140° etc. A dip direction range is used so that localised variations in dip direction can be incorporated.



a. ***Aerial Photograph***

b. ***Aerial Photograph with the main structural lineations shown***

Figure 4. Structural orientations observed from an a.p.

Dominant structural orientations taken from the aerial photographs

S1 – 190º to 200º dip dir
S2 – 100º to 110º dip dir
S3 – 080º to 090º dip dir
S4 – 140º to 150º dip dir

4. Field Verification

If possible, a site visit should be incorporated into the analysis in order to check the quality of the data. The field visit should be aimed at checking:

- Terrain Classification
- Lithology Types
- Geological Structure

It is important to validate the desk study data with field observations, as there is little benefit in following these guidelines through to the susceptibility analysis if the data is of poor quality.

5. Landslide Susceptibility Factors

At this stage in the analysis it is now important to bring together the mapped factors with the factors from the pre-existing data sources.

Mapped Factors	**Factors From Pre-existing Data Sources**	**Resultant Landslide Susceptibility Factors to be analysed**
Terrain Classification	Geology Map	**Material Type** (i.e. rock type insitu soil or colluvium)
Geological Structure	Topographic Map	**Geological Structure**
	Slope Aspect (derived from the topographic map)	**Slope Aspect**
	Slope Angle (derived from the topographic map)	**Slope Angle**

Materials Map (Combining the Terrain Classification with the Geology Map)

It is important at this stage to understand how the different materials behave with respect to landslide processes. Generally colluvium is derived from mass wasting, therefore reactivation of this material tends to be governed by factors unrelated to the geological structure.

In-situ soil by definition retains the original texture, fabric and structure of the parent lithology type, but essentially acts as a soil. Therefore geological structure tends to be important when considering landslide initiation factors relating to this material.

Landslides within areas of rock-controlled terrain tend to be governed by both lithology type and geological structure. The regional analysis has shown that landslide susceptibility varies greatly between different lithology types, i.e. schist is more susceptible to landslides than granite, because it has a distinct foliation that can promote both weathering and instability.

On this basis, areas that have been identified as rock should be further classified by lithology type using information from the geology map. The resultant map should therefore include the following materials:

- Colluvium
- In-situ soil
- Rock controlled terrain categorised by lithology type (e.g. schist, granite etc)

A GIS factor layer should then be created for each material type.

5.1 *Geological Structure*

In order to incorporate geological structure in the subsequent susceptibility analysis, the distribution of slope aspect within the study area needs to be established.

5.2 *Establishing Slope Aspect and Slope Angle*

Slope aspect can be established from the digitised topographic map using the GIS. In addition a 3-dimesional representation of the ground surface can be generated, this is referred to as a TIN model. The TIN model is generated by the GIS using an in-built function that interprets the distribution of slope aspects between topographic contours.

Two GIS shape files should be generated, one for slope angle and one for slope aspect. The slope angle shape file should classified into 4 intervals: 0º to 20º, 20º to 30º, 30º to 40º and 40º to 90º. The slope aspect shape file should be classified into equally sliced (i.e 10º) intervals.

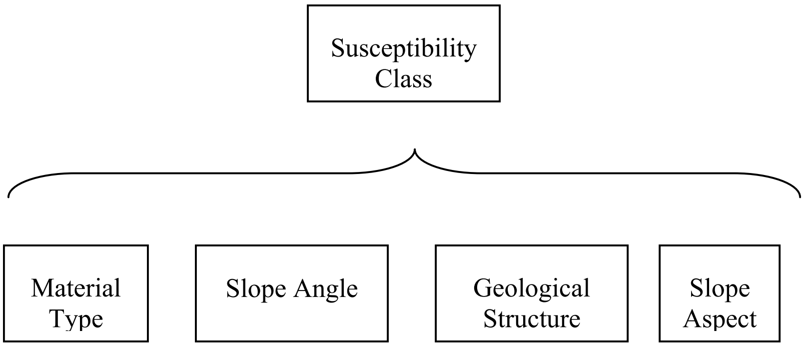
6. *The GIS Database*

The following factor layers should have now been created in GIS format

- Material type (with a separate factor layer for each material type)
- Slope angle (with the factor layer categorised into four slope angle ranges)
- Slope aspect (with the factor layer categorised into 36 slope aspect ranges)

7. The Susceptibility Analysis

The susceptibility analysis brings together the following four landslide susceptibility factors



Step 1. Classification of material type by slope angle

Using the GIS, each of the material type factor layers should be subdivided into slope angle, using the four slope angle ranges. This is undertaken by overlaying each material type layer on the slope angle layer. The slope angle layer is then clipped with the material layer to produce an output layer that contains the material type classified into slope angle ranges.

Step 2. Combining geological structure with slope aspect

The structural geological factor mapping determined the orientation of the dominant structures within the study area and a structural aspect window has been generated for each structural orientation. Using the GIS a slope aspect factor layer is created from the structural aspect windows. By clipping those slopes with aspects (from the aspect layer) that correspond to structural aspect windows. So, if the structural aspect window is 020º to 060º, then the corresponding slopes with aspects between 020º and 060º would be clipped from the original aspect layer. The resultant layer comprises all slopes with aspects that fall within the structural aspect windows.

Step 3. Combining material type, slope angle and slope aspect

It is now possible to classify the material type/slope angle layer (created in Step 1) into two classes:

a) Those slopes within the structural aspect window

b) Those slopes outside the structural aspect window

For example, at the end of Stage3 the following classification will have been derived for in-situ soil (Table 1.)

Material Type	**Slope Angle**	**Slope Aspect**
In-situ Soil	0º to 20º	**In** Structural Aspect Window

In-situ Soil	20º to 30º	**In** Structural Aspect Window
In-situ Soil	30º to 40º	**In** Structural Aspect Window
In-situ Soil	40º to 90º	**In** Structural Aspect Window
In-situ Soil	0º to 20º	**Outside** Structural Aspect Window
In-situ Soil	20º to 30º	**Outside** Structural Aspect Window
In-situ Soil	30º to 40º	**Outside** Structural Aspect Window
In-situ Soil	40º to 90º	**Outside** Structural Aspect Window

Table 2. Structural classification by slope angle for In-situ Soil

A table can then be created for each terrain class or lithology type within the study area. Note however that as landslides within colluvium tend not to be structurally controlled they are not classified in this way. The table should include a separate class for each combination of material type, slope angle and aspect window. For each combination the associated susceptibility rating for the areas in this study are given in Table 2.

The combinations of factors within the study area can be grouped by susceptibility rating to create a susceptibility map.

Table 2. Susceptibility ratings for each material type – slope angle – structural aspect window combination for the Butan study areas.

Material Type	Slope Angle Class	Structural Aspect Window	Susceptibility Rating
In-situ Soil	20-30	In	High
In-situ Soil	30-40	In	High
In-situ Soil	40-90	In	High
Rock Augen Gneiss	0-20	In	High
Rock Augen Gneiss	20-30	In	High
Rock Augen Gneiss	30-40	In	High
Rock Augen Gneiss	40-90	In	High
Rock Phyllite	20-30	In	High
Rock Phyllite	30-40	In	High
Rock Schist	30-40	In	High
Rock Schist	40-90	In	High
Rock Schist & Quartzite	0-20	In	High
Rock Schist & Quartzite	20-30	In	High
Rock Schist & Quartzite	30-40	In	High
Colluvium	0-20	N/A	Low
In-situ Soil	0-20	Out	Low
Rock Augen Gneiss	0-20	Out	Low
Rock Augen Gneiss	20-30	Out	Low
Rock Phyllite	0-20	In	Low
Rock Phyllite	0-20	Out	Low
Rock Phyllite	20-30	Out	Low
Rock Phyllite	30-40	Out	Low
Rock Phyllite	40-90	In	Low
Rock Phyllite	40-90	Out	Low
Rock Schist	0-20	In	Low
Rock Schist	0-20	Out	Low
Rock Schist	20-30	Out	Low
Rock Schist & Quartzite	0-20	Out	Low
Rock Schist & Quartzite	40-90	Out	Low
Rock Schist & Quartzite	40-90	In	Low
Colluvium	20-30	N/A	Medium
Colluvium	30-45	N/A	Medium
Colluvium	45-90	N/A	Medium
In-situ Soil	0-20	In	Medium

In-situ Soil	20-30	Out	Medium
In-situ Soil	30-40	Out	Medium
In-situ Soil	40-90	Out	Medium
Rock Augen Gneiss	30-40	Out	Medium
Rock Augen Gneiss	40-90	Out	Medium
Rock Schist	20-30	In	Medium
Rock Schist	30-40	Out	Medium
Rock Schist	40-90	Out	Medium
Rock Schist & Quartzite	20-30	Out	Medium
Rock Schist & Quartzite	30-40	Out	Medium

Appendix C

Summary of Training

The following table is a summary of the topics that were covered by either the on-the-job-training or the three workshops organised by the LRA Project. The table shows a description of the topics covered and the people who were involved.

Subject	**Description**	**Who, When & Trainer**
Field mapping	• Landslides • Geology • Geomorphology • Terrain Classification • Field Verification of API and SII • Use of GPS	• NKG, KC • On site with LRA and at the workshops • GJH, ABH, CM, WC, DNP, Geologists from DGM
Social Data Field Mapping	• Social data • Land use data • Use of GPS	• KC • On site with LRA • ST
Aerial Photographic Interpretation	• Aerial photographic interpretation principles and techniques • Identification of landslides • Identification of geology and geomorphology	• NKG, KC • In the LRA office and at the workshops • GJH, ABH, CM, WC, IH, DNP, Geologists from DGM
Satellite Image Interpretation	• Identification of landslides • Identification of geology and geomorphology • Geo-rectification of satellite and scanned images • Automatic classification • Satellite image processing principles and techniques	• NKG • In the LRA office and at the workshops • WC, ST
Basic GIS concepts	• Different GIS data types • GIS database structure and design • GIS file naming structures	• NKG, KC, PD • In the LRA office and at the workshops • ABH, CM, WC, ST, LC
Data capture, acquisition & input into GIS. Data conversion techniques	• Map projections and conversion • On-screen digitising • Digitising with tablet • Data conversion process • Probable sources of errors	• PW, NKG, KC, PD • In the LRA office and at the workshops • LC, ABH, ST, WC, CM

Attribute data in GIS	• Importing attribute data • Linking spatial and attribute data • Editing and querying attribute data	• PW, NKG, KC, PD • In the LRA office and at the workshops • LC, ABH, ST, WC, CM
DTM concepts & application	• To gain an understanding of TIN Models and their uses for deriving slope angle and slope aspect data • Use of 3D-Analyst GIS extension software	• PW, NKG, KC, PD • In the LRA office and at the workshops • LC, ABH, ST, CM
GIS data analysis	• Data retrieval, re-classification, overlay functions, measurement options • Data querying • Statistical data analysis techniques	• NKG, KC, PD • In the LRA office and at the workshops • ABH, ST
Landslide Factor Analysis	• Comparison of landslide distribution with other factor layers held in the GIS • Single and multi factor analysis techniques • Use of Spatial Analysis GIS extension software • Statistical data analysis techniques	• NKG, KC, PD • In the LRA office and at the workshops • ABH, CM, ST
Landslide Susceptibility Analysis	• Creation of the LRA Regional Landslide Susceptibility Scheme • Data requirements • Comparison with other landslide susceptibility schemes • Application of the LRA Scheme	• NKG, KC, PD • In the LRA office and at the workshops • ABH, CM, ST, GJH
Landslide Hazard and Risk Assessment	• Data required for hazard and risk assessment • Frequency of landslide occurrence • Landslide run out • Vulnerability assessment of infrastructure	• NKG, KC, PD • In the LRA office and at the workshops • ABH, CM, ST, GJH
Other Applications for GIS within DoR	• Bridge Location Database (discussion with EE from Suspension Bridge Section) • Road Maintenance Database (discussion with Mr S Tenzin) • Impact Assessment of proposed realignments or other infrastructure planned by DoR or other government departments	• NKG, KC, PD • In the LRA office and at the workshops • ABH, CM, ST, GJH

GJH = Gareth Hearn
ABH = Andrew Hart
DNP = David Petley
CM = Chris Massey
WC = Will Crick
IH = Ivan Hodgson
ST = Sushil Tiwari
LC = Lalit Chhetri (DGM digitiser)
NKG = Mr Giri
KC = Mr Chopel
PW = Mrs Phuntsho Wangmo
PD = Pema Dorji