5 SITE INVESTIGATION AND DATA MANAGEMENT

5.1 Purpose of site investigation

The purpose of site investigation is to compile an appropriate information base. As site investigation is the foundation for all subsequent decisions and actions, it must: (i) be properly designed and executed by appropriately skilled personnel, (ii) provide an interpretable information base that addresses all potential hazards, runout routes and potential targets, and (iii) pose minimum risk to personnel, the general public and the environment. The consequences of insufficient groundwork can lead to an inappropriate remedial strategy with potentially catastrophic results, as witnessed in Peru in 1950. During works to lower Laguna Jancarurish, in Quebrada Los Cedros, it was not realised that the adjacent reconstituted glacier tongue was undercut below the waterline and hydrostatically supported. Consequently, as the lake was lowered and the buoyancy forces upon the glacier were removed, part of the glacier collapsed into the lake initiating a wave that burst through the moraine dam, killing approximately 500 people (Lliboutry *et al*., 1977).

5.2 Scope of site investigation

An integrated hazard and risk assessment requires the investigation of all the criteria that can influence the hazard at source and the potential runout routes, thereby having a bearing on potential targets (Table 2). There are no hard and fast rules as to the procedure for an investigation; budgets, tender scopes, and the nature of the site will all dictate the form of an investigation strategy. It may also not always be possible to examine all aspects of the glacial system and the potential flood or avalanche route due to constraints in budgets and accessibility.

Table 2: Examples of the aspects to be considered during the investigation of glacial lake and ice avalanche hazards.

ASPECT	GLACIAL LAKE HAZARDS	ICE AVALANCHE HAZARDS
Parent glaciers	Style of glacier (e.g. hanging or valley type?) influences type of lake and potential trigger mechanisms. Glacier surface gradient (<2°), mass balance characteristics, retreat/thinning rate, glacier hydrology influence lake development.	Glaciological/morphological setting influences style & volume of potential avalanche (ramp- or cliff-type?); crevasse patterns may highlight fracture points (although can be misleading); flow velocity accelerations aid prediction (short term).
Lake systems	Bathymetry and water depth in relation to dam influence potential volume of flood. Water temperature affects sub-aqueous melting rates in supraglacial settings. Drainage outlets - lowest freeboard and focus of erosion during peak water flow. Absence of outlet - potential for lake growth (volume); possible discharge to groundwater	Interaction with lakes affects glacier stability (hydrostatic support); impact upon lakes (triggering of lake outbursts) important for secondary hazards.
Moraine complexes (dams)	Geology, morphology (H:W ratio), freeboard above lake, groundwater (seepage), presence of (melting) buried ice influence stability of moraine dams. Geotechnical characteristics affect the type of remedial action that can be undertaken.	Incorporation of proglacial moraine sediments can increase avalanche volume; material types affect roughness, impacting on runout distance.
Local environments	Adjacent environments may affect potential hazard (e.g. possible avalanche triggers from rock/soil slopes) or influence the consequences of an outburst (e.g. floods impacting on lakes downstream).	Climate (specifically mean annual air temperature) influences angle of sliding for ramp-type avalanches (>25° for temperate (warm-based) glaciers; >45° for cold-based) (Alean, 1985); incorporation of slope material, laying snow, water from local lakes can increase volume/runout.
Regional environments	Regionally extensive factors that affect potential hazards include seismic activity and extreme weather events (e.g. Asian monsoon, El Niño).	
Pathways and targets	Valley morphology and geology affects runout distance and volumes of flood/incorporated debris. Secondary landslides and blockage points exacerbate hazard.	Empirical values of maximum volume & minimum average slope of runouts from past events (e.g. debris flow - 11°, floods 2-3° (Haeberli, 1983); ice avalanches - 17° (Alean, 1985). Channel roughness & morphology affects runout distances.

5.3 Planning an investigation

Figure 7 shows an example of a theoretical project structure encompassing all elements from project specification through to remediation. Although individual projects will have their own objectives, they must have at least one or a combination of elements of hazard assessment (yellow boxes), vulnerability assessment (green boxes), risk assessment (orange box) and risk management (pink boxes). Hazard or vulnerability assessments may be means to an end themselves, leading to hazard or vulnerability management respectively. Risk assessment can only be undertaken if both the hazard assessment and vulnerability assessment phases are completed. Risk management may take the form of recommendations for further actions through to the selection, design and implementation of risk control measures.

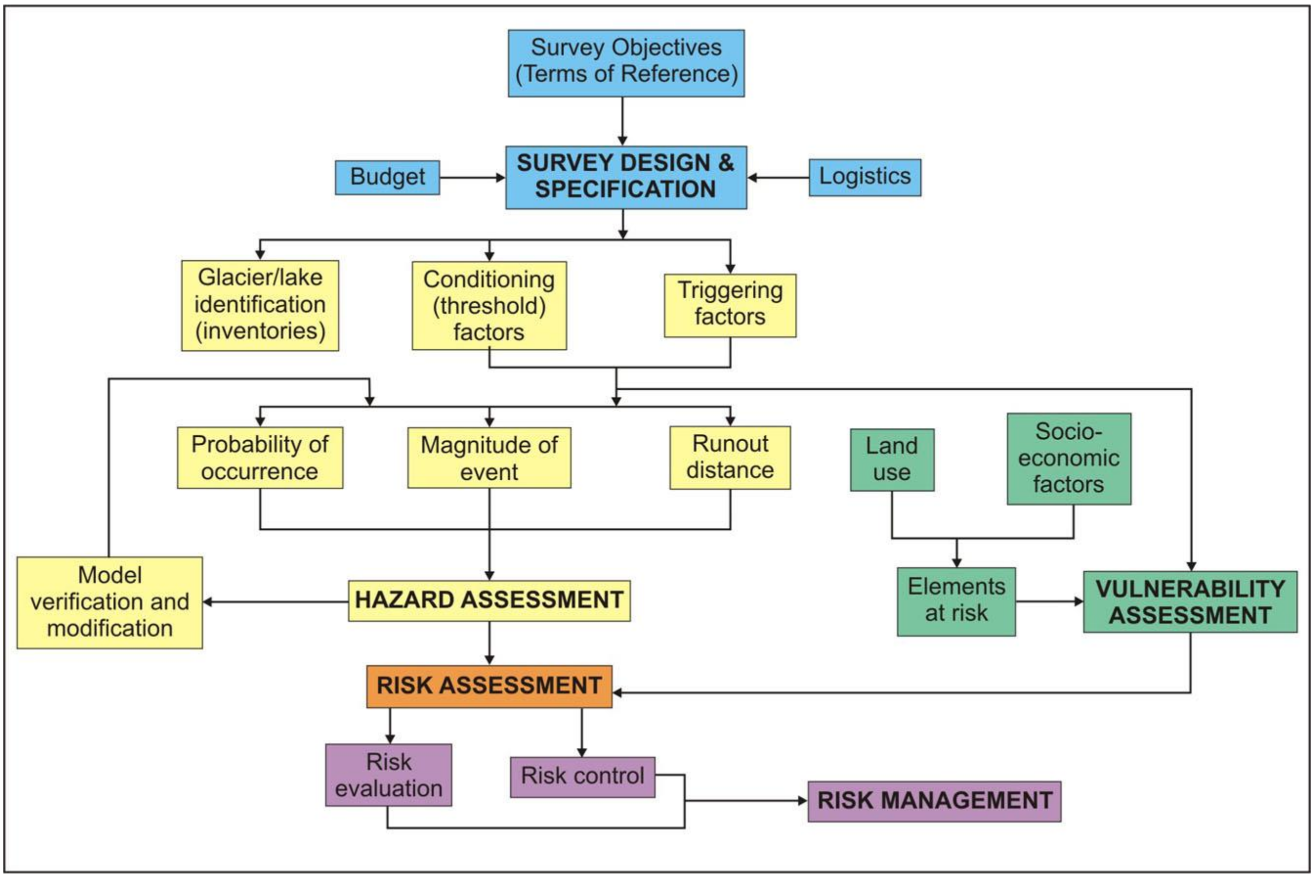

Fig. 7: Example project structure for glacial risk assessment and management.

Conducting the investigation in phases is often seen as a valuable means of identifying and refining site investigation priorities, ensuring safe working practices and potentially minimising costs. There are a number of technical advantages associated with the phased approach. There may be few, if any, records of the site prior to study, so collection of baseline information from a desk study or a preliminary field visit will almost always be necessary. If it is decided that further information is required, the desk study information can be used to target key areas in the glacier/lake system and/or along the potential flood/avalanche/debris flow runout route(s). Desk study using historical data sets or multiple site visits will also allow for the rates of change in the glacial environment to be determined. Often these rates provide the only indication of the urgency for remediation. The design of mitigation works may also require information different from that used for a hazard assessment, necessitating the use of different specialists and additional data collection. Phases therefore may include a combination of preliminary desk studies, reconnaissance visits and monitoring, detailed on-site investigation, and remote monitoring. The degree to which these can be achieved will be dictated by individual project specifications.

5.4 Investigation techniques

A range of techniques exist for characterising the glaciological, geological, geotechnical and hydrological conditions of a site. The advantages and disadvantages of each technique should be judged on a site-specific basis at an early stage. Typical issues to be addressed when choosing site investigation techniques include the following:

- What level of precision is required for this stage?
- What type of analysis/testing is required?
- Are samples required (what sort, sampling pattern, collection, transportation and storage)?
- What spatial resolution is required?
- Is a temporal picture needed?
- Recording/storage of data.
- Reporting of data (format, timing).
- Quality Assurance (QA) procedures.

Examples of some of the main techniques employed in glacial risk management projects are provided in Table 3; and summarised below.

Table 3: Suitable techniques available to the scientist specialising in glacial hazards and risks.

FIELD OF STUDY	EXAMPLE TECHNIQUES	REFERENCES
Engineering geology	Mapping; material descriptions; slope stability determination; design of remedial works (including temporary works)	This project
Geographical Information Systems	Data storage & management; topological analysis; runout modelling	Huggel *et al*., 2002
Geophysics	Electrical resistivity profiling; Ground Penetrating Radar	Pant & Reynolds, 2000; Hanisch *et al*., 1998
Glacial geology and geomorphology	Mapping; description of materials earth science approaches to slope stability assessment	Richardson and Reynolds, 2000b
Glaciology	Structural glaciological mapping; glacier hydrology tracing; mass balance studies; flow measurements and modelling	Reynolds *et al*., Submitted
Hydrology/limnology	Discharge measurements; temperature profiling	Yamada, 1998; Delisle *et al*., 2003; Chikita *et al*., 1999, 2000
Meteorology	Temperature, precipitation, humidity measurements	
Remote sensing	Aerial photograph interpretation (API); satellite image interpretation; spectral classification; radar interferometry	Clague & Evans 2000; Haeberli *et al*., 2001
Socio-economics	Personal/group interviews; workshops; questionnaires	This project
Surveying	Topographic profiling; topographic mapping	Watanabe *et al*., 1995

- *Engineering geological techniques*

Geotechnical considerations are fundamental to many parts of the hazard and risk assessment process; from, for example, the appraisal of unstable slopes as potential triggers through to ground investigations for the design of remedial works. Engineering approaches to risk modelling are particularly suited to the quantifiable assessment of the criteria that influence hazard and risk, although it can sometimes be difficult to obtain the necessary values for geotechnical calculations and assumptions have to be made. More information on the techniques for engineering geological descriptions, engineering geological mapping, and slope stability analysis within glacierised terrain is provided in the Appendix.

- *Geographical Information Systems*

Geographical Information Systems (GIS) have a role to play both in the storage, manipulation and output of spatial data, and as a mechanism of solving problems for the purpose of decision making (Malczewski, 1999). The GIS process ideally suits the geographical data obtained during site investigation. For complete success, the data capture for the project has to be driven by the end requirements of the outputs, be they maps, extrapolated data sets, or models. Data requirements are thus the chief consideration in any GIS project and need to be addressed at the outset.

- *Geophysical techniques*

Geophysical techniques offer several advantages over conventional, invasive methods of site investigation: high sampling frequencies, relatively rapid acquisition rates and non-invasive testing being appropriate for glacial investigations. In addition, most commercial geophysics systems are highly portable and are therefore suited to remote high mountain environments. Geophysical techniques are particularly good for mapping the distribution of buried glacier ice and structures within moraines. Suitable techniques include electrical resistivity, Ground Penetrating Radar (GPR), and seismic refraction soundings (Haeberli and Epifani, 1986;

Hanisch *et al*., 1998; Pant and Reynolds, 2000; Richardson and Reynolds, 2000b). More detail and examples of applications are provided in the Appendix.

- *Glacial geological and geomorphological techniques*

Techniques most often used to describe and analyse glacial sediments and landforms for risk assessment studies include geomorphological mapping, from remote sensing images and/or field mapping, and field-based descriptions of sediments. Mapping and sediment descriptions tend to be undertaken concurrently, the latter assisting the interpretation of the geomorphology map. This approach is variously referred to as terrain systems mapping (Phipps, 1991); land systems mapping (Eyles, 1983), or landform/sediment assemblage mapping (Hambrey, 1994). It is normal to provide summary interpretations based upon the final geomorphology map in order to aid the understanding of the end user. Geomorphological and glacial geological information are important both to the assessment of hazard and vulnerability (see Appendix for more details).

- *Glaciological techniques*

Glaciological techniques applied specifically to hazard assessments are surprisingly few. Structural glaciological mapping techniques have been used to identify a link between glacier structures, the manner of collapse of ice cliffs into lakes and the resulting waves (RGSL, 1998; Reynolds *et al*., Submitted). Mass balance studies are used more frequently as a general indicator of glacier ‘health’, with application to the issue of water resources rather than the more dynamic hazards of floods and avalanches (see section 3.2). Detailed monitoring of flow velocities in order to predict impending ice avalanches has also been applied successfully in the short term, although only in rare cases (Flotron, 1977).

- *Hydrology/limnology*

Hydrological techniques are most frequently employed within a monitoring programme to provide supporting information for risk management. Annual variations in lake discharge records at Tsho Rolpa lake in Nepal have been used to calculate required rates for lake draw down (Yamada, 1998), which were then used during the design of spillway capacities. At the same lake, dye tracing techniques were tested unsuccessfully to try and identify seepage pathways between the lake and springs on the distal face of the dam. Limnological studies of glacial lakes can provide interesting information about the lake basin (Chikita *et al*., 1999, 2000), but these are normally peripheral to a risk assessment and may not be commercially justifiable. Rare exceptions are where water temperature profiles have been used to model the thermal regime of the lake and predict melting rates of dead ice at the base of the lake and in moraine dams (Delisle *et al*., 2003).

- *Meteorology*

Records of air temperature, precipitation, humidity, radiation, *etc*., are relevant to water resource issues related to the disappearance of glaciers, variation in glacier run-off and also impacts upon glacial lakes (Braun *et al*., 1992; Francou *et al*., 1995; Kaser, 1999; Chikita *et al*., 2000; Rana *et al*., 2000). For small mountain glaciers, mean annual air temperature is also practically correlated to firn temperature, which in turn is related to glacier bed temperature. As bed temperature influences the critical slope of the sliding surface for avalanches, mean annual air temperature is seen as a practical way to determine the thermal condition of the glacier and thus its tendency to slide at given slope angles (Huggel *et al*., Submitted). Meteorological information has also been recorded and applied to modelling the ice-water-air thermal regimes at Thulagi Glacier Lake, Nepal, in the example by Delisle *et al*. (2003) referred to above.

- *Remote sensing*

Remote sensing techniques are becoming increasingly important for glacial risk assessments and monitoring. Aerial photographs have long been used for glacier inventory studies (e.g. Ames, 1988) and hazard assessments (Yamada, 1993; RGSL, 1998; Reynolds *et al*., Submitted). Advances in satellite sensors and digital analytical techniques now allow for increased objectivity and reproducibility in the compilation of inventory data (Paul *et al*., 2002). Classification procedures allow for the first order assessment of glacial lakes and distinction between debris-covered and debris-free glaciers (Wessels *et al*., 2002). Several satellite systems provide data in stereo allowing ground models to be produced. Topographic data thus derived can be integrated with different imagery types to provide information on glacial lake development, glacier dynamics, and potential outburst locations (Haeberli *et al*., 2001). Topographic data derived from satellite images have also been used within GIS platforms to model the runout paths from ice avalanches and debris flows from glacial lake outbursts (Huggel *et al*., In Press).

- *Socio-economic techniques*

Research into the impact of glacial hazards is frequently justified on grounds of the social and economic consequences, but specific surveys within the population are not generally carried out. During the course of the project from which these guidelines arose, a pilot socio-economic study was undertaken in the Cordillera Blanca region of Peru. It is believed that this is the first survey of its kind, certainly in Peru. Information was obtained through the use of focus groups with local community members and interviews with authorities, entities and key officers involved in risk management and civil defence. Aspects of hazard, vulnerability and the attitude of the relevant communities and institutions were the common themes investigated and the findings proved useful to the formulation of a national management plan. See section 6.4.3 for more detail on the methods and section 7.4.2 for the key findings from this study.

- *Surveying*

Topographic profiling and surveying are often used to tie in the location of other site information (e.g. geophysics profile lines) and, if detailed enough, to provide baseline site plans against which to monitor future changes. In situations where high levels of precision and accuracy are needed optical or laser surveying of fixed targets may be used to monitor glacier velocities or slope movement due to buried ice creep. Repeat topographical profiling is also an effective method of measuring the rate of melt of ice cores in potentially unstable moraine dams (Watanabe *et al*., 1995; Reynolds *et al*., 1998). Ground stereo photogrammetric techniques have been used to monitor rates of glacier retreat (Brecher and Thompson, 1993) and they have a proven track record in the engineering sector for monitoring slope failures (Kalaugher and Grainger, 1997). Global Positioning Systems (GPS) are versatile surveying tools. Measurements with centimetre precision can be obtained as ground control for remote sensing imagery or to directly monitor ground displacement; whilst handheld units are suitable for spatial location at the reconnaissance level.

5.5 Data management

Data management embraces the whole range of activities involved in the handling of data. These activities include Data Policy, Data Acquisition, Data Ownership, Documentation and Metadata compilation (in the case of digital data); Data Quality, Data Access and Dissemination, and Data Audit. The benefits of data management include:

- a clearer understanding of the data;
- better quality, harmonised and coherent data from the use of common definitions, including geographic references, formats, validation processes and standard procedures;
- improved business processes, including better and more efficient use and re-use of data;
- improved awareness and understanding of what data are available for current and future use; and,
- better exploitation of data and efficiency gains.

Good data management also ensures that datasets are capable of meeting current needs successfully and are suitable for further exploitation. The ability to integrate data with other datasets is likely to add to the quality and value of the investigation and improve the accuracy of any results. The use of a GIS, for example, will assist and enhance any project as its specialist processes will quickly expose any flaws in either data quality or processing results.

For projects and other activities that give rise to substantial datasets, it should be established at the outset whether suitable data already exists in a potentially usable form, or whether new data need to be acquired. Before projects begin, it must be established how the data acquired will be exploited to the full, who will be responsible for full exploitation, and how the benefits will be maximised and shared. Subsequent data handling and storage needs should be considered and plans set out to ensure that the databases are maintained in such a way that maximum use can be subsequently made of them. It cannot be known what the future will bring and a primary objective of this work is to plan for the unexpected.

5.6 Quality Assurance

Quality Assurance (QA) is an important means of checking and ensuring the validity of the procedures and data used for risk assessment purposes. All parties involved in the project should be able to provide evidence of their QA procedure. The potential diversity amongst organisations involved in the risk assessment process will inevitably lead to equally diverse Quality Assurance and Quality Control procedures. Using companies which hold, or are actively working towards, a Quality Assurance procedure that is officially recognised within their industry should promote correct working practices. An additional form of quality check can be achieved by using staff that hold a recognised qualification within their area of specialisation, such as Chartered Geologist/Engineer status or equivalent. Given the specialised nature of the subject area, there may not be a scheme for the recognition of staff skills in certain specific areas, such as in glaciology. In this case, evidence of prior experience in successful glacial risk assessment by project personnel is essential.

Aspects of site investigation and assessment that could be subject to QA procedures include:

- reviews of documentary evidence;

- recording of observations and measurements during on-site work;
- procedures used to identify potential hazard-runout route-target relationships;
- application of investigation techniques;
- input to, and use of any models to aid interpretation of data;
- reporting;
- implementation of Health and Safety procedures; and,
- compliance with all legal requirements.

5.7 Health and Safety

Health and Safety regulation relates to substances on site or to the physical environment. The latter is likely to be a more important consideration for glacial hazard projects, although in some countries formal Health and Safety regulations may be unclear. Codes of best practice employed by the governments and professional societies of the contracted parties should be adhered to, in addition to any regulations that are present within the host country. There are examples within Nepal where standards were lowered simply because less was expected than for an equivalent investigation in Western Europe or North America. Such an approach is contrary to the ethics of professional societies such as the Geological Society and the Institution of Civil Engineers (both UK-based organisations).

The very location of glaciers and glacial lakes, in extreme mountain environments and often at high altitude, results in a unique set of potential hazards to the workforce in addition to those normally associated with site investigation. Non-regulatory guidelines provided by organisations such as national mountaineering or mountain rescue associations and official first aid organisations may be adopted to minimise the risk to personnel on site.

5.8 Regulatory and political aspects

Site investigation works may be subject to prior authorisation by the regulatory authorities. Access to the region containing the site may even be strictly controlled due to the potential threat of the hazard itself or because of political sensitivity specific to that region. Many potential sites lie in areas subject to border disputes, rebel activity, or military conflict, such as parts of the northern Pakistan Hindu Kush and certain border areas between Nepal and China (Tibet). Access to resource material, such as aerial photographs and detailed maps, can be especially difficult in this type of area. The legislation governing site investigation in certain countries may not be readily known or may not exist and advice should be sought in relation to individual sites. Host governments and representatives of the investigation team’s own government(s) can be consulted when the legal and regulatory positions are not clear. Other requirements may have to be satisfied by virtue of the Health and Safety implications of the work.

6 GLACIAL RISK ASSESSMENT

6.1 Introduction

Risk assessment involves the three stages of *hazard identification and assessment*, *vulnerability assessment and risk estimation*, and *risk evaluation* (Figure 6). The aims of risk assessment are:

- to determine whether observed glacial hazards are likely to pose unacceptable risks to defined targets now or in the future;
- to provide at least a qualitative statement about the magnitude and nature of the risks, and to quantify if possible;
- to determine the affects of foreseeable events, such as weather extremes, glacier length fluctuations, ice-core melting rates, *etc*., on the likely magnitude of the risks;
- to make judgements about the significance and acceptability of identified risks;
- to determine what measures, if any, should be undertaken to reduce/control risks to an unacceptable level; and,
- to provide a rational and defensible basis for discussion about the proposed course of action with interested third parties.

6.2 Glacier/lake inventory compilation