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The value of geoscience information in less developed countries

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The value of geoscience information in less developed countries

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Front cover

Using a geological map in the field, Silali caldera, Kenya.

Examining aerial photographs through a stereoscope for landslide hazard mapping, Jamaica.

3D stereo interpretation of coastal geomorphology using Image Station.

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Preface

Geological conditions and processes profoundly affect all our lives, though few ordinary people in the ‘developed’ world are perhaps aware of this. Those living in more deprived regions, struggling to secure the bare necessities of life, such as a safe supply of potable water or a secure dwelling place, may develop an intuitive but unexpressed awareness of the importance of geology in sustaining, and sometimes threatening, their existence. But wherever people live, local geological information and knowledge provides the key to our successful coexistence with a fundamental but often ignored aspect of the natural world — the earth beneath our feet.

Most countries possess a national geological survey organisation that effectively operates as a national geoscience information service. Traditionally, such organisations are financed either by national or provincial governments. However, with pressure on governments to spend less of the national GDP on publicly funded services, the actual ‘value for money’ spent on those services is increasingly under investigation. Many geological survey organisations are now being asked to justify the continuation of government investment in national geoscience information services. This requires an evaluation of the benefits resulting from the provision of geoscience information.

In this report we concentrate only on the economic benefits that may accrue from the provision of new geoscience information and its application to mineral and groundwater exploration projects. For many, the former of these applications is a controversial topic, and they would argue that the environmental and societal costs of the resulting natural resource exploitation might exceed the economic benefits. However, the world demand for minerals continues unabated and their production makes an important contribution to the economies of many developing countries, while access to a clean water supply is now seen as a basic human right.

We briefly review the uses of geoscience information and discuss how a value may be placed on such information. This is explored both theoretically and by examining the outcomes of several large UK-funded technical co-operation projects that resulted in the production of geoscience maps and other information of use to the mineral exploration industry in South America, Africa and Asia. Finally, we demonstrate a quantitative cost-benefit evaluation of a recently completed project to collect and apply new geological information to groundwater exploration in Nigeria. It is hoped that this report will encourage more geological survey organisations to critically examine the value of their own projects in a climate where users of publicly funded geoscience information increasingly expect value from their investment.

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*All information has potential value
but that value can only be realised
if the information is used*

Contents

Preface iii

Acknowledgements iv

Contents vii

1 Geoscience information 1

- 1.1 Introduction 1
- 1.2 What is geology? 1
- 1.3 The importance of geoscience information 1
- 1.4 Geological and geochemical maps 1

2 Placing a value on geoscience information 8

- 2.1 Valuation in context 8
- 2.2 Valuation issues and concepts 9
 - 2.2.1 The nature of societal value 9
 - 2.2.2 Users and uses of geological information 9
 - 2.2.3 Defining benefits in terms of decision-making. 10
 - 2.2.4 Estimating benefits in terms of ‘with’ versus ‘without’ scenarios 10
 - 2.2.5 Estimating costs 12
- 2.3 Valuation approaches: some examples 12
 - 2.3.1 Anecdotal approach 12
 - 2.3.2 Formal assessments 13

3 The value to mineral exploration of systematic regional geological and geochemical surveys 17

- 3.1 Introduction 17
- 3.2 Mining in developing countries 17
- 3.3 Targeting mineral exploration investment 18
- 3.4 Case studies 18
 - 3.4.1 Proyecto Precámbrico: the Precambrian geology of eastern Bolivia 19
 - 3.4.1.1 Introduction 19
 - 3.4.1.2 Project implementation and information outputs 19
 - 3.4.1.3 Project cost 20
 - 3.4.1.4 Impact 20
 - 3.4.1.5 Conclusion 21
 - 3.4.2 Regional geological and geochemical mapping of Sumatra, Indonesia 21
 - 3.4.2.1 Introduction 21
 - 3.4.2.2 Project implementation and information outputs 21
 - 3.4.2.3 Project cost 22
 - 3.4.2.4 Impact 22
 - 3.4.2.5 Conclusion 23
 - 3.4.3 Geochemical exploration of northern Peru 23
 - 3.4.3.1 Introduction 23
 - 3.4.3.2 Project implementation and information outputs 23
 - 3.4.3.3 Project cost 24
 - 3.4.3.4 Impact 24
 - 3.4.3.5 Conclusion 24

- 3.4.4 Midlands Goldfield Project, Zimbabwe 24
 - 3.4.4.1 Introduction 24
 - 3.4.4.2 Project implementation and information outputs 25
 - 3.4.4.3 Project cost 25
 - 3.4.4.4 Impact 25
 - 3.4.4.5 Conclusion 27

4 Evaluating the cost effectiveness of groundwater exploration 28

- 4.1 Introduction 28
- 4.2 Finding groundwater 28
 - 4.2.1 Groundwater exploration 28
 - 4.2.2 Assessment methods and information levels 28
- 4.3 Economic evaluation of alternative approaches 30
 - 4.3.1 Cost-effectiveness analysis 30
 - 4.3.2 Empirical approaches 30
 - 4.3.3 Synthesis 30
- 4.4 Cost-effectiveness case study: hydrogeological assessment in Benue State, Nigeria 32
 - 4.4.1 Background 32
 - 4.4.2 Groundwater assessment 32
 - 4.4.3 Cost-effectiveness of groundwater assessment in Oju and Obi 34

Appendix Help notes — cost effective analysis of groundwater assessment in Oju, Nigeria 37

- A.1 Introduction 37
- A.2 Analytical approach and structure 37

References 42

FIGURES

- 1 Part of the Dambulla-Pallegama 1:100 000 scale geological map of Sri Lanka 2
- 2 Gridded geochemical image showing distribution of copper in drainage sediment samples, southern Sumatra 3
- 3 Extract from single-element proportional symbol map for copper, Painan and Muarasiberut Quadrangle sheet, southern Sumatra 3
- 4 Computer screen showing BGS Geoscience Data Index (GDI) with selected themes 4
- 5 Example of hazard zone map, Villarica volcano, Chile 4
- 6 Comparison of historic and modern geological maps of the same area illustrating the marked improvement in the quality of information available from a modern resurvey, Inverness, Scotland 5
- 7 Methods of communicating landslide hazards and landslide susceptibility for the Rio Minhó area, Jamaica 6

- 8 Application of geochemical maps to integrated coastal zone management: example demonstrating land-derived contaminant influx to Jakarta Bay, Indonesia 7
- 9 Location of Precambrian shield of eastern Bolivia 19
- 10 Location of project area in Western Cordillera of Peru 23
- 11 Structural information interpreted from Landsat TM satellite imagery overlaid onto existing geological information for the Midlands Greenstone Belt, Zimbabwe 26
- 12 Location of hydrogeological assessment project in Nigeria 32
- 13 Simplified groundwater protection map of Oju and Obi, eastern Nigeria 33

TABLES

- 1 Geological information: user sectors and applications 11
- 2 Some previous valuations of geological information 16
- 3 Products of the Bolivian Precambrian Survey Project 20

- 4 Financial summary for mineral exploration, mine development and mineral production in the Bolivian Precambrian shield 21
- 5 Systematic map and report series products of the Northern and Southern Sumatra Projects 22
- 6 A logical approach to groundwater exploration 29
- 7 Information on the project area (Oju-Obi) used in the economic analysis 35
- 8 The value of hydrogeological information in Oju, Nigeria: evaluation results 35

BOXES

- 1 Data, information and knowledge 9
- 2 The valuation challenge 12
- 3 Applying statistical decision theory to benefit estimation 14
- 4 Some key concepts in cost-benefit analysis 15
- 5 The rise of small-scale mining in Zimbabwe 27
- 6 The cost-effectiveness of acquiring geological information: hydrogeological investigations for livestock watering in Botswana 31
- 7 Estimating drilling success rates for the economic analysis (Oju-Obi) 36

1 Geoscience information

1.1 INTRODUCTION

The significance of geological information for decision-making in land-use and development planning is not fully appreciated by many key decision makers in both developing and fully industrialised countries. The consequences of this are twofold: the national institutions responsible for providing relevant geoscience information, usually state-funded geological survey organisations (GSOs), are frequently inadequately financed, and poorly informed planning decisions are made which may result in significant economic and social losses. The purpose of the investigation summarised in this report was to review simple methodologies for the cost-benefit analysis of projects designed to produce geoscience information. In this way the economic value of various categories of information applied to planning decisions for different types of land-use and resource exploration can be quantitatively calculated or qualitatively estimated. In the course of this enquiry we have focused on the information resulting from the systematic geological and geochemical surveying activities usually undertaken by national GSOs. As examples, we describe a number of case studies that illustrate the impact of geological and geochemical maps on decision-making in the exploration for mineral and groundwater resources in a variety of less-developed countries. The methodologies employed however are applicable to geological survey information used in a wide variety of land use planning issues.

1.2 WHAT IS GEOLOGY?

Geology is broadly defined as the study of the solid Earth. It is concerned with the materials and structure of the planet and the processes that have acted, and continue to act, upon and within it to effect its composition and morphology. The terms 'geology' and 'geoscience' can be considered as synonymous. Important sub-disciplines include geophysics, which is concerned with the physical properties and dynamics of the earth; and geochemistry, which includes the study of the abundance and distribution of the chemical elements in, for example, minerals, rocks, rock weathering products, and underground and surface waters.

In practical terms it is the composition and dynamics of the outer part of the earth — the earth's crust — which is of most immediate relevance to human activity and thus to national and local land-use planning and economic and social development.

1.3 THE IMPORTANCE OF GEOSCIENCE INFORMATION

Each nation is the guardian of a unique sector of the earth's crust that underlies its territory and which, both

literally and metaphorically, forms the foundation of its economic and social planning and development. It is the source of the nation's mineral, groundwater and much of its energy resources. Its interaction with the biosphere, hydrosphere and atmosphere determines the character of the nation's soils and the content of the essential and toxic trace elements that they contain. Its internal structure, dynamics and morphology governs the distribution of natural geohazards such as volcanoes, earthquakes and landslides.

Data can be systematically collected and interpreted to provide the information that characterises a nation's geological environment. This information can be used to inform decisions concerning land-use and national economic planning. As all decision-making involves an element of risk, the aim is to provide relevant information that reduces geological uncertainty and allows superior decisions to be made.

In the case studies developed in subsequent sections of this report we have focussed on a number of geological and geochemical surveying projects aimed at producing geological information that contributes to the assessment of a nation's wealth in terms of earth resources. Such resources can be assigned a potential value, and information concerning their availability is an important factor in national land-use and industrial development planning.

1.4 GEOLOGICAL AND GEOCHEMICAL MAPS

A geological map is constructed from a combination of observed and interpreted data derived from both field and laboratory studies. As such it constitutes a graphical information display that uses a combination of colours, lines and symbols (Figure 1) to depict the composition and structure of geological materials and their distribution beneath the landscape (Bernknopf et al., 1993). It thus represents a fundamental source of information for geoscience applications that require a predictive capability such as, for example, geohazard evaluation, resource assessment and environmental assessment.

The scale of a map will have an important bearing on its utility as a source of information for different applications. Thus a small scale regional geological map at 1:1 million will indicate gross variations in geological attributes recognisable over distances of the order of 10 km (1 cm on the map = 10 km; 1 cm² = 100 km²), while a larger scale map, for example at 1:1000, will allow much more detailed variations over distances of a few metres to be presented (1 cm on the map = 10 m; 1 cm² = 100 m²). The former map would be useful in broad regional assessments of, for example, geological resources; the latter in more site-specific assessments such as the likely foundation conditions for a major civil engineering structure. The optimum scale for presentation of the information in the form of a map will depend not only on its intended application (see Table 1) but also on the density of the dis-

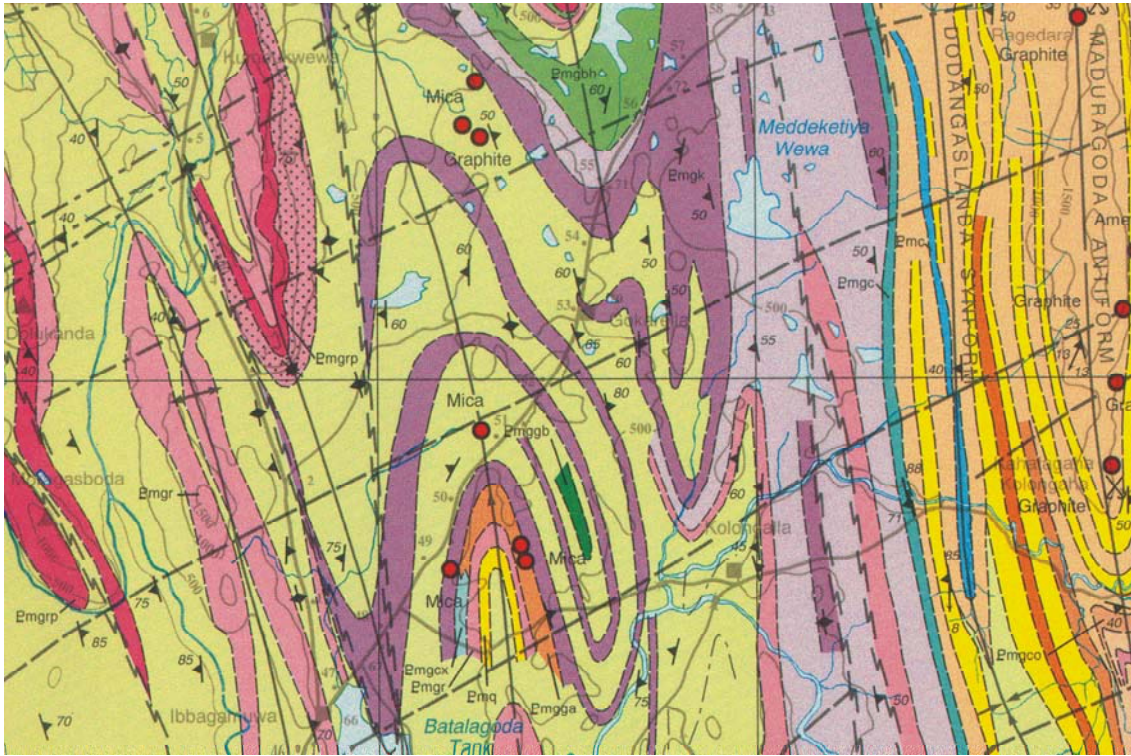


Figure 1 Part of the Dambulla-Pallegama 1:100 000 scale geological map of Sri Lanka (Geological Survey and Mines Bureau of Sri Lanka, 1996; compiled and published in collaboration with BGS)

tribution of observations made during the geological survey work and the precision with which the observations have been spatially located.

Geochemical survey data presented in map form can likewise have important applications both to resource and environmental assessments. It was in Russia that geochemical surveys were first directed towards the search for and exploitation of economic mineral deposits. In the late 1950s the Western world also began using geochemistry in this way and its application led to the development of geochemistry as a significant component in modern mineral exploration. Currently geochemistry is undergoing a further transformation and geochemical mapping now has important applications in environmental and health studies.

The methodology used in geochemical mapping has been described in detail by Darnley et al. (1995). This methodology involves collecting a sample from the surface of the earth, usually a stream sediment or soil sample, and analysing it for a range of chemical elements. A number of samples are collected over an area at a sampling density varying from 1 or 2 samples per square kilometre through to 1 sample per 200 square kilometres. The sampling density and range of elements determined depends on the purpose of the survey. Results from a number of sample points can be extrapolated to predict the likely elemental abundance in the intervening ground and thus over the entire sampling area. A stream sediment for example will represent an 'average' composition of the drainage basin upstream from the point where the sample is collected. The geochemical data can be presented in numerous ways, again depending on the objectives and aims of the work. Small-scale regional geochemical surveys looking at broad geochemical patterns and trends will present the data as a

generalised coloured geochemical image (Figure 2). A more detailed survey, targeting for example sites rich in copper minerals, would use specific sample point maps, indicating the amount of copper in each sample to define more precisely an area of interest (Figure 3).

Table 1 summarises some of the many types of activity that may benefit from the provision of geoscience information, much of which is provided in the form of geological or geochemical maps. For many such activities the important information may be limited to only a few geological parameters and hence a map displaying the spatial variation of these parameters, uncluttered by additional non-critical detail, will be particularly useful. The production of such 'thematic' maps is greatly facilitated when all the geological data for the map area in question are held in digital format. A good example of the utility of a thematic map would be its use as a source of information for planning a major new trunk road. Geological factors that might be important in planning an optimum route could include, for example, the distribution of rock units within the area having particular engineering properties that might govern their utility as road aggregate or pose particular problems for tunnelling or the excavation of road cuts. In this case a thematic map might be produced which displayed the distribution of only those rock units known, or predicted, to have a defined range of engineering properties. The particular 'themes' that can be selected for such maps will be limited only by the types of geological data available for the area in question. The scale selected for production of the thematic maps will be governed by the nature of their intended use and the density and spatial distribution of thematic data points within the area.

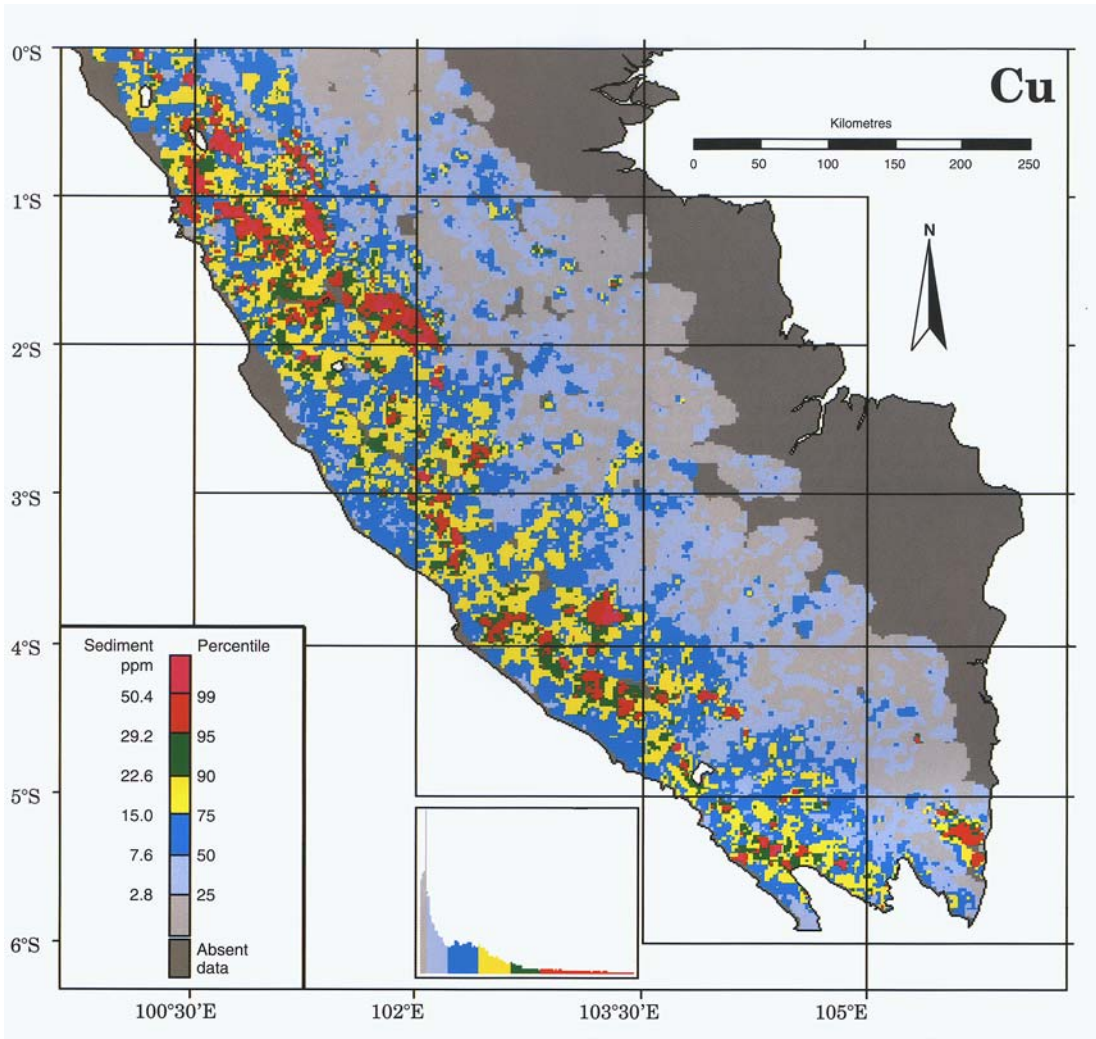
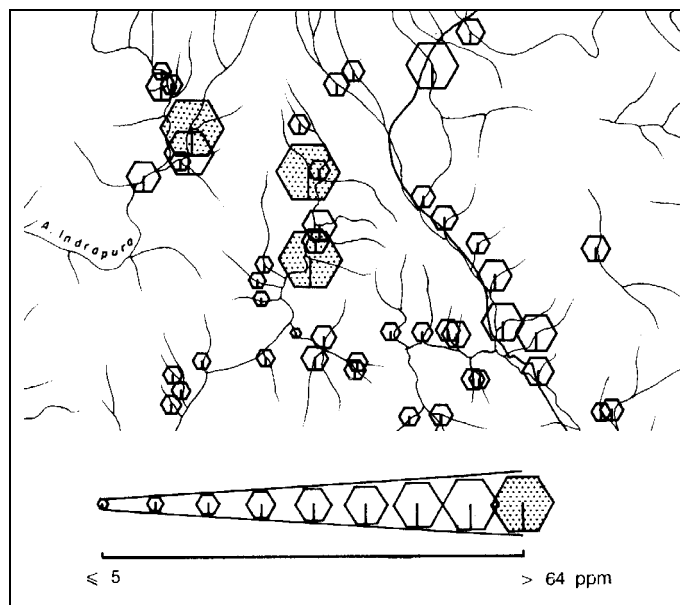


Figure 2 Gridded geochemical image showing distribution of copper in drainage sediment samples, southern Sumatra (from Machali Muchsin et al., 1997)

Figure 3 Extract from a single-element proportional symbol map for copper, Painan and Muarasiberut Quadrangle sheet, southern Sumatra (Directorate of Mineral Resources, Bandung, 1992; compiled and published with funding assistance from DFID)



A further step in the above process is to combine the digitally held geological and geochemical map data with further layers of information for the same area in a Geographic Information System (GIS). The added layers may be non-geological, depicting for example the distribution of roads and railways and other features of the physical infrastructure, current land use or any other relevant features for which the spatial distribution is known. Integrating geoscience and non-geoscience infor-

mation in a GIS can create a powerful analytical tool for development planning, allowing the user to select electronically any combination of mapped features and view them as a single map (Figure 4).

Figures 5-8 serve to demonstrate both the variety of application of geoscience maps and the extent to which modern methods of surveying can enhance existing information.

Figure 4 Computer screen showing BGS Geoscience Data Index (GDI) with selected themes (drift geology, borehole locations, and Ordnance Survey topographic base map)

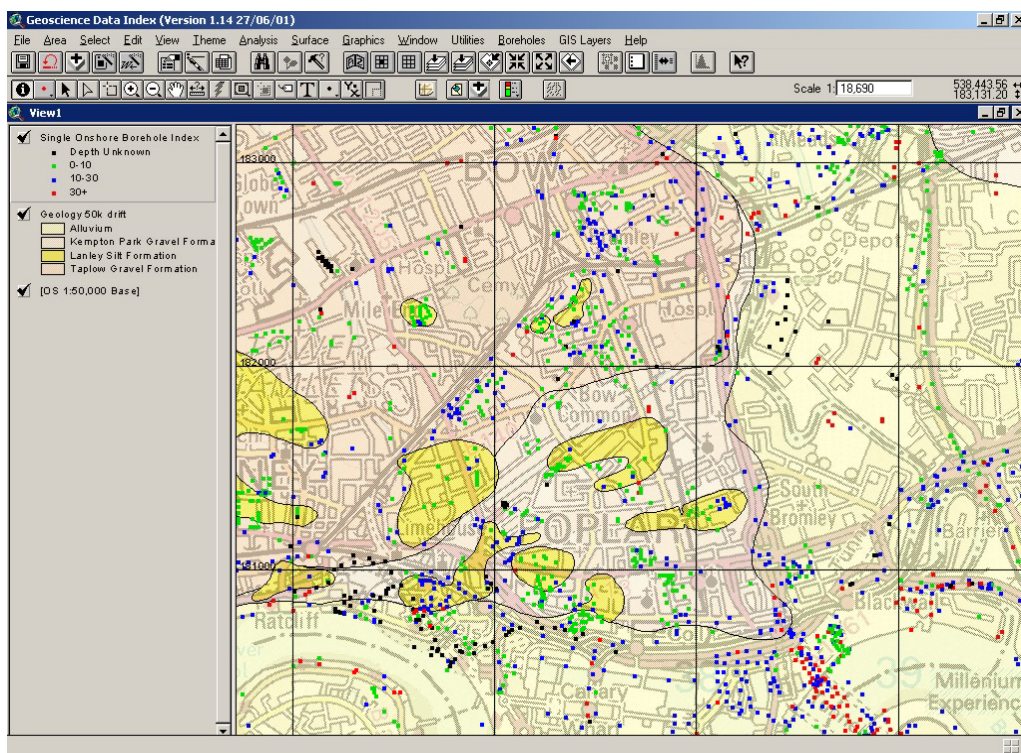
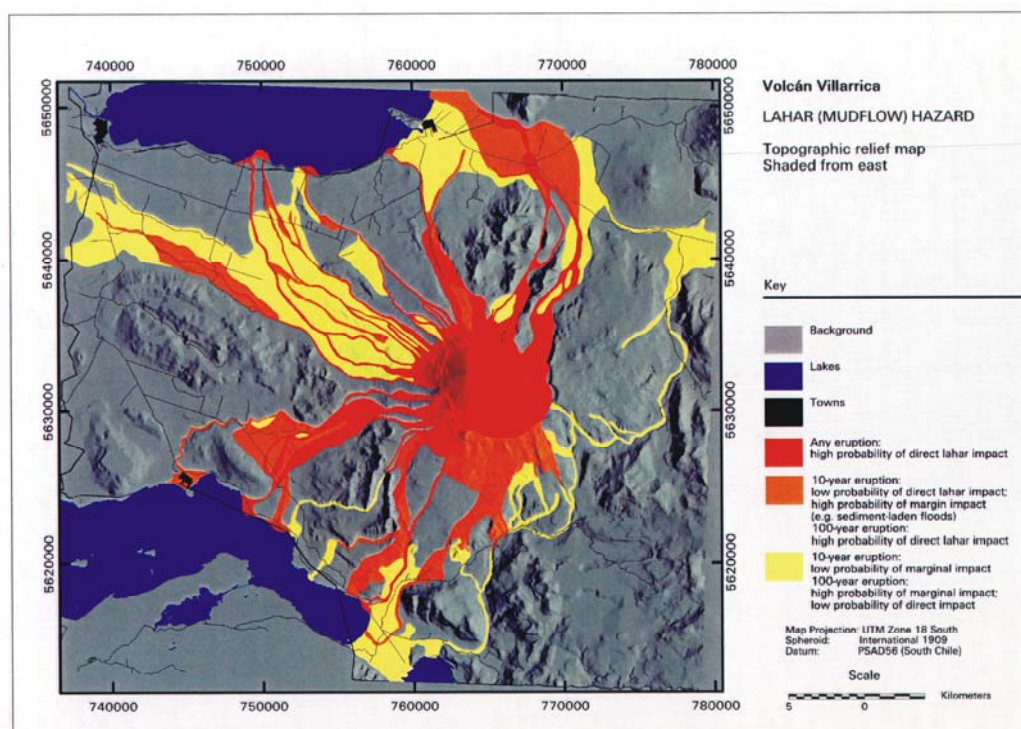
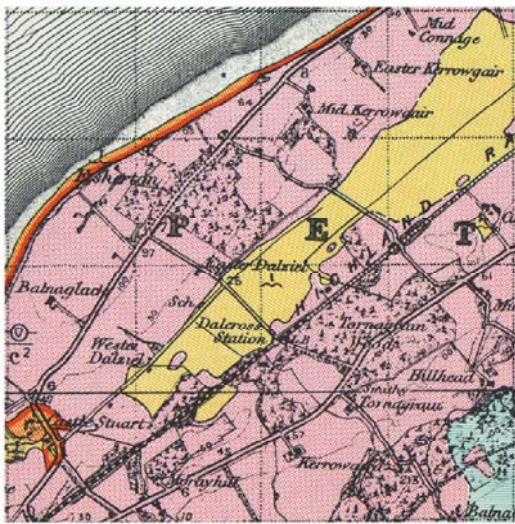
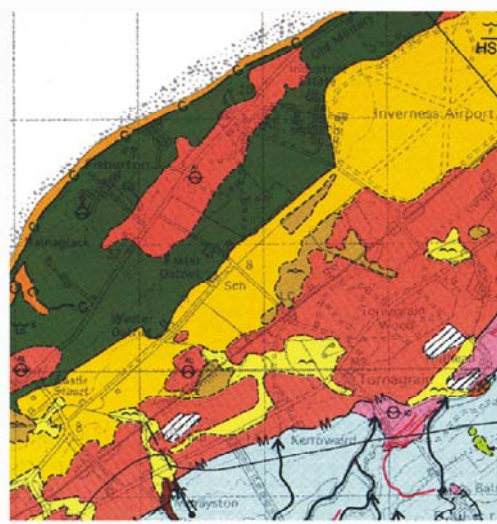


Figure 5 Example of hazard zone map, Villarica volcano, Chile. Reconnaissance geological mapping methods were used to obtain volcanological information, which was combined with information on the topography and volcanic history to produce a lahar hazard zone map using GIS techniques (Dunkley & Young, 2000).



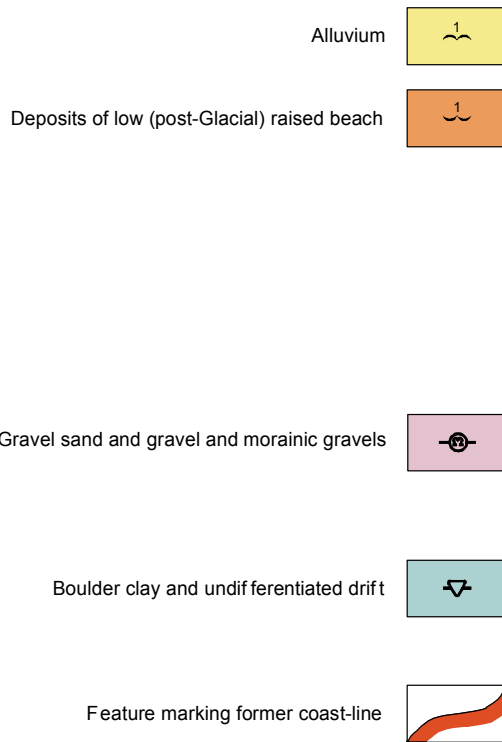


A 19th century map.



B Recently compiled BGS map.

Key to A



Key to B



Figure 6 Comparison of historic (A) and modern (B) geological maps of the same area illustrating the marked improvement in the quality of information available from a modern resurvey, Inverness, Scotland, UK (Foster, Morigi & Browne, 1999).

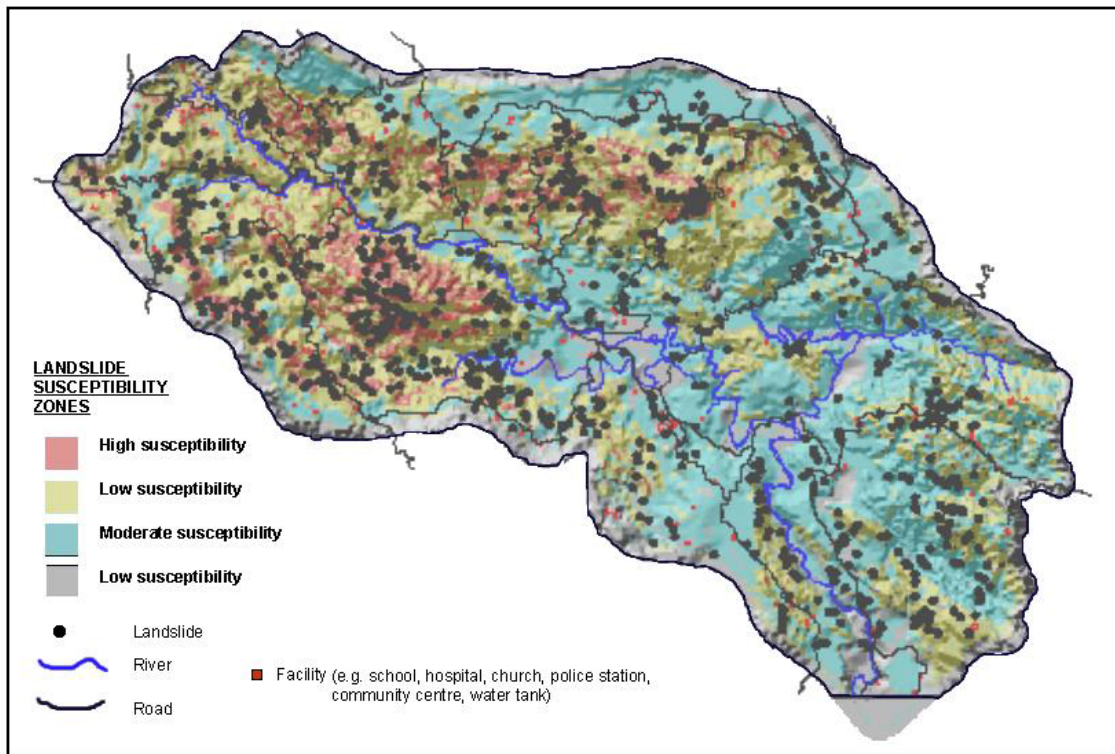


Figure 7.1 Methods of communicating landslide hazards and landslide susceptibility for the Rio Minho area, Jamaica: landslide hazard/susceptibility zones together with points indicating general landslide distributions are ‘draped’ over a shaded relief base to enhance visualisation of the zones in relation to major topographic features, roads, rivers and important facilities in the area (Northmore et al., 2000)

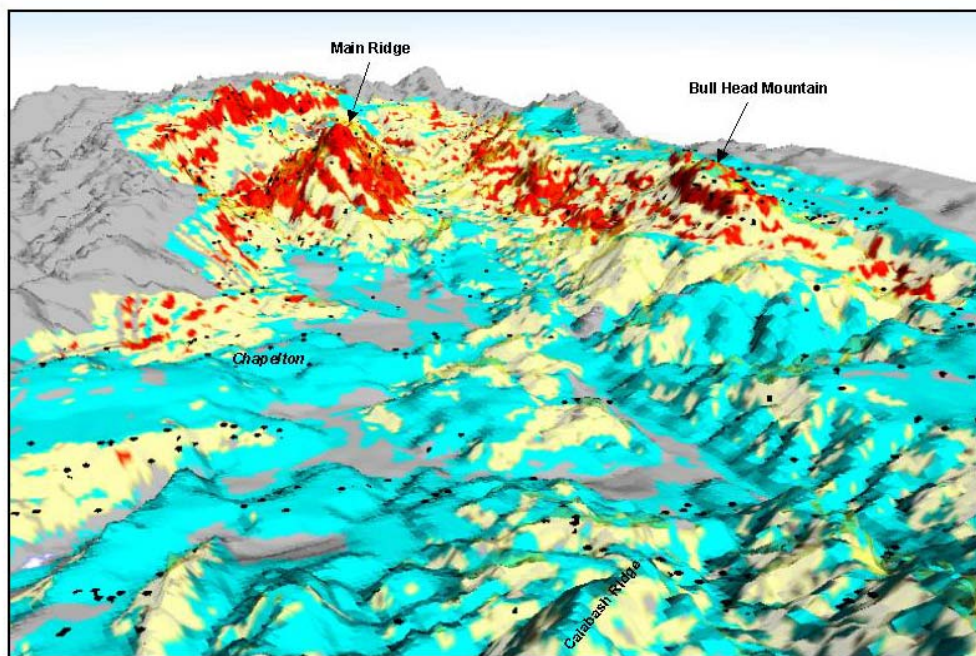
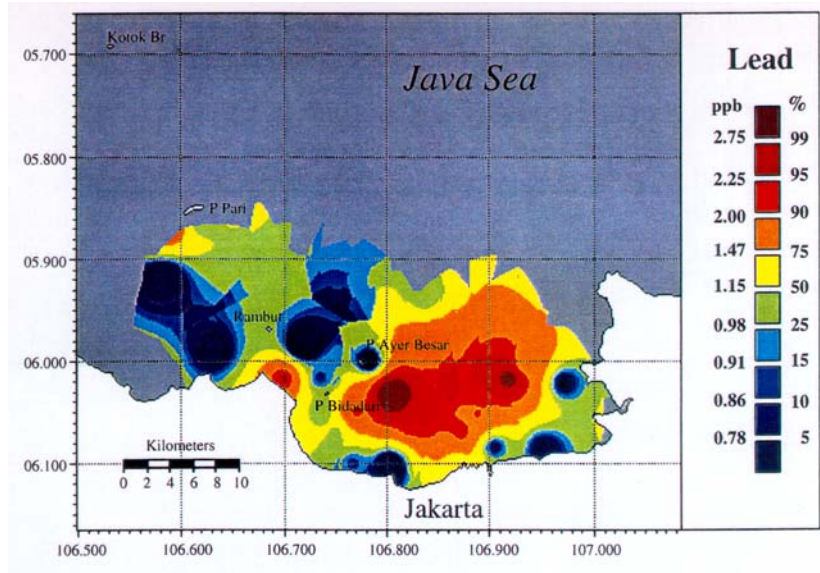


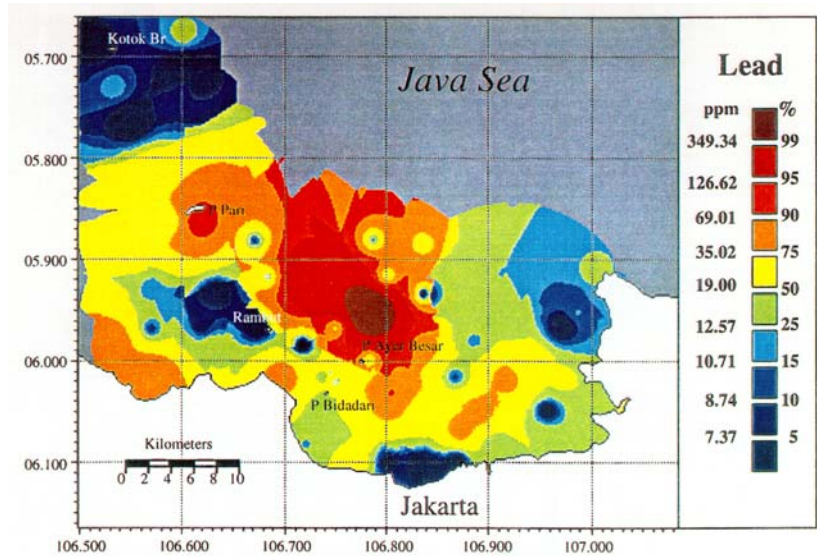
Figure 7.2 Methods of communicating landslide hazards and landslide susceptibility for the Rio Minho area, Jamaica: landslide hazard/susceptibility zones and general landslide occurrences (black dots) shown as a ‘drape’ over a perspective view of terrain in shaded relief. Using Image Analysis and GIS software, perspective views from any direction may be produced to further enhance visualisation of the landslide susceptibility zones with respect to key topographic features. Population centres and infrastructure networks (e.g. roads) may also be included to assist in planning or land-use decision making (Northmore et al., 2000)

Figure 8 Application of geochemical maps to integrated coastal zone management — example demonstrating land-derived contaminant influx to Jakarta Bay, Indonesia (Williams, Rees & Setiapermana, 1997):

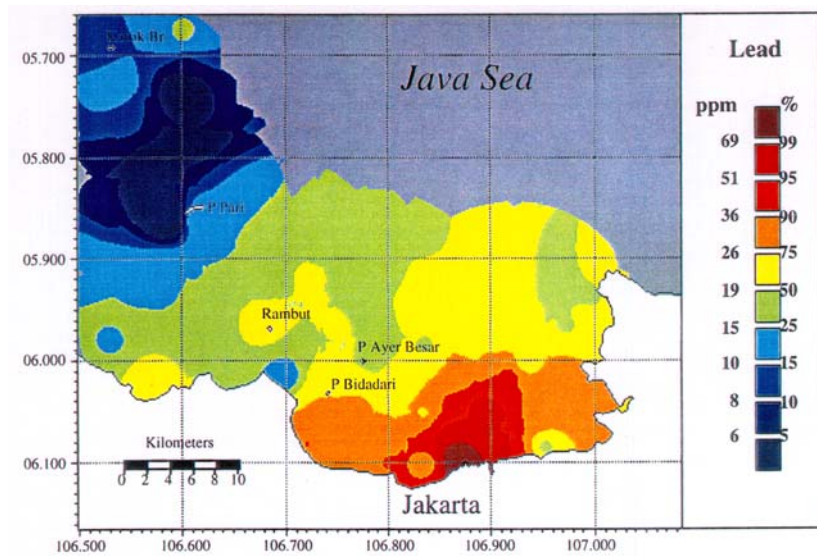
(a) spatial variation of lead in waters of Jakarta Bay



(b) concentration of lead in suspended particulate matter



(c) spatial distribution of lead in surficial sediments.



2 Placing a value on geoscience information

2.1 VALUATION IN CONTEXT

'Detailed, publicly available information concerning the nature and origin of the geology of an area is essential for informed public-policy decision-making and for economic development' (Bernknopf et al., 1993).

One of the main functions of national geological survey organisations is to provide a national geoscience information service. Much of the required data is collected through mapping programmes. A clear assumption underpinning this work is that mapping, resulting in the production of maps and associated databases, releases information that can lead to significant and diverse economic and social benefits.

While such benefits undoubtedly exist, little attempt has been made to evaluate them in quantitative terms. A number of reasons can be suggested to explain this situation. There are, for example, significant difficulties associated with defining and valuing the benefits of activities that generate information, rather than directly marketable goods and services. Thus, while the use of information can be expected to affect the production of goods and services (and thereby impact on general social welfare), such effects may be difficult to attribute directly to changes in the quantity and/or quality of the relevant information. Furthermore, activities designed to produce information may affect parties outside the ambit of the activity itself. This means that 'separable' groups of beneficiaries associated with specific products of a project may be difficult to identify.

In spite of these difficulties there are good reasons for attempting a valuation of the products of information-generating activities such as geological surveying. For example, placing a realistic monetary value against the impacts/outcomes of mapping-based projects should have the political effect of making the funding of such projects more persuasive. Implicit in this argument is the assumption that, though the production of geological information through such activities can result in benefits to society, the failure to monetise such outcomes has led to under-investment in geological mapping projects.

Closely related to the above is the idea that valuation provides a more secure and transparent basis for policy or project development decisions, narrowing the field for 'pure' judgement. It is accepted that values that are difficult to measure are often implicit in decision-making, so there will always be a need for judgement between non-comparable factors. However, the difficulty of making this judgement will be reduced significantly if the effects of information gained from activities such as geological mapping can be expressed in common economic terms, with costs and benefits made as explicit as possible. Valuation also provides a response to growing demands for fiscal austerity, as well as public and/or external pressure on governments and other 'funders' of geological surveying programmes to be more accountable and trans-

parent, and to justify more openly the use of public money. In the developing countries especially, activities that do not have a visible and high profile link with poverty alleviation, and a demonstrable and quantifiable value in such a context, may be increasingly difficult to fund.

Although therefore we may have sound reasons for attempting to place a value on the information generated by various geological projects, there are some obvious pitfalls that must be avoided. One such is the temptation, during an evaluation, to push limited data too far, especially in developing countries where data may be scarce. This is a valid concern and so the approach taken in this report is to restrain valuation to the limits of good sense and plausibility, and not just to the receding boundary of what might be technically possible. For this reason, we use a mixture of both qualitative and quantitative data.

A related concern is the ease with which economic analyses can be abused, and their objectivity compromised, in order to justify a preconceived outcome. Clearly when judging the worth of any appraisal, the institutional pressures bearing on the analyst must be borne in mind. All appraisals, economic or otherwise, must be approached with a healthy degree of scepticism. Economic analysis is only one of a number of appraisal tools and it does not necessarily provide a definitive answer on whether an activity should, or should not, be undertaken.

Nevertheless, those carrying out economic appraisals can avoid some of the obvious drawbacks if they adhere to the following rules:

- (a) restrain valuation to the limits of good sense and plausibility — for example, only try a quantitative approach when there is a reasonable basis for doing so and numbers can be defended;
- (b) be open and transparent about assumptions, constraints, weaknesses;
- (c) make use of sensitivity analysis as a means of dealing with uncertainty (see below);
- (d) remember that quantitative economic analysis is only one of a number of tools — qualitative analysis can be equally useful, especially to supplement the findings of economic analysis;
- (e) do not lose sight of the basic aim of the analysis — to objectively appraise, not to justify.

In conclusion it can be said that the most important reason for conducting an economic analysis of a project or programme is not necessarily to harvest hard numbers but to gain a clearer understanding of why the project or programme is being, or should be undertaken. Without such a concept it is not unusual for the development of a project to follow the aphorism: "having lost sight of our objectives, we redoubled our efforts". Hence in the case of geological mapping, the most important outcome of the analysis is a clearer understanding of why mapping is of value (Green and Herschy, 1994).

Box 1 Data, information and knowledge

In much of this report, the terms 'data' and 'information' are used interchangeably. However, when thinking about the process by which geological data is collected, processed and used in decisions, it is useful to clarify terminology. Distinctions are important because many 'information systems' have been set up on the presumption that once data are generated, they will automatically lead to better, more informed decisions. As a result, much evaluation and analysis of the performance of information systems has been preoccupied with the extent to which geological observations and measurements meet the criteria of accuracy, timeliness and comprehensiveness, rather than how, and to what extent, they are actually used.

Here, we draw a distinction between data, information and knowledge as follows:

- **Data** are unanalysed facts and figures. In a geological survey, data need to be collected, compiled, interpreted and presented before information is produced.
- **Information** is analysed data, presented in a form useful for making decisions (e.g. a geological map). Geological information may be only one of a number of information sets used to make decisions.
- **Knowledge** is assimilated and understood information. Use of knowledge involves acting on information received, i.e. its application in decision-making.

Key valuation issues:

- Geological surveys collect and process data to produce information. However, it cannot be assumed that this process will in itself lead to better decision-making among end users and to concomitant economic benefits. In any valuation study, it is important to look closely at what happens to information once it 'leaves' the provider, whether information can be easily accessed by end users, and whether the information produced is in an appropriate form for making decisions. In theory, the likelihood (probability) that data will be successfully: (a) converted into information; (b) disseminated to end users in appropriate forms; and (c) then used in decisions should be factored into any valuation study. In practise it is difficult to estimate numerical probabilities, but an analysis of information flows may still be revealing. As noted above, experience elsewhere suggests a tendency to focus too much on generating 'better' data, rather than on the dissemination of appropriate information to end users, or on overcoming other obstacles to uptake and use.
- Even if information can be converted successfully into knowledge, it is important to recognise that the use of geological knowledge in decision-making is not guaranteed, and when used, may not be the determining influence. Decisions concerning land-use planning and groundwater development, for example, are not made solely on geological grounds, but are influenced by a range of 'information sets', and political, social as well as *economic* decision criteria. In attempting to estimate the value of geological information, it is therefore important to consider: (a) the role that geological information plays in decision-making; (b) whether the production of better geological information *in itself* would be (or has been) compelling enough to change decisions; and (c) whether those decisions have economic consequences. On the last point, it should be stressed that if the decisions in question do not have economic consequences, then the provision of 'better' geological information cannot be assessed in economic terms.

2.2 VALUATION ISSUES AND CONCEPTS

Before going on to explore alternative approaches to valuation, it is important to discuss the issues and principles that any approach must address. In particular, we should understand what we mean by 'value', including 'societal value' and the 'value in use' of information in decision-making. Moreover, any analysis of 'value in use' must begin with an exploration of the users and uses of geological information.

2.2.1 The nature of societal value

Arguably, most sectors of society are affected by the availability and use of geological information. In broad terms, we can define the societal value of geological information as the difference between the net benefits associated with using new and 'improved' information, in terms of information quantity and/or quality, and the net benefits

associated with using existing information. By 'net' benefits we mean the overall value in use of the information, minus the costs of producing and disseminating the information. It follows that at the outset of any benefit assessment it will be necessary to identify the users of the geological information, the types of decision to which the geological information will be applied, the contribution it will make in changing (improving) those decisions, and how this improvement will be measured and valued. The cost of producing the information is associated with the collection and transformation of raw data into usable information (see below and Box 1).

2.2.2 Users and uses of geological information

Table 1 identifies twenty broad 'sectors' where geological information is used, with examples of the types of decision that might be affected. This table is intended to be illustrative and is not comprehensive. In practice it can be

seen that such a list may extend to all areas, however large or small, where human society interacts with the earth it inhabits. Geological organisations, such as national ‘Geological Surveys’ may provide information to many such users whilst others, particularly in the private sector, may be much more specialised. Some of the sectors and decisions listed in Table 1 have clear economic consequences, for example those concerned with the avoidance of hazards such as landslides and subsidence. In other sectors it is much more difficult to ascribe the use of specific information to decisions carrying economic consequences (e.g. in education, conservation, and recreation) and it may be much harder to quantify benefits.

In both cases, for the information to realise its potential value, it is important that the suppliers of the information provide it in a form that users understand and can apply to their needs. Information suppliers must therefore commit resources to assessing both the needs of users and the potential uses to which the information may be applied.

2.2.3 Defining benefits in terms of decision-making

Having identified the users of geological information and the types of decision within each sector that might be affected by the production of new information, it is important to clarify what we mean by the ‘value in use’ of information. Specifically, we must attempt to determine the value of the information-gain to future decisions that may be made with the benefit of improved geological information.

In the case of an individual decision, the benefit of the ‘improved’ information is the increase in the economic efficiency of any decision taken *with* the information versus that taken in the *absence* of the information. Economic efficiency here relates to the allocation of resources to achieve some output of goods, such as potable water, a new road, or the production of minerals. Our essential argument is that as a consequence of an increase in the quality/quantity of information, either the same output can be achieved for less input of resources or, for the same input of resources, output can be increased. The benefits of improved geological information are therefore the values of either the decrease in necessary resources required to achieve a given level of output, and/or of the increase in outputs. For example in the case of a groundwater exploration project described later in this report (see Section 4), hydrogeological investigations resulted in a more cost-effective provision of rural water supplies through increased borehole success rates and lower drilling costs.

The application of this decision-based approach to valuing geological information is, however, subject to a number of caveats. Firstly, it is necessary to identify decision types, or areas, which are sensitive to the availability of geological information. Secondly, the ‘decision’ against which the information is to be applied must itself be aimed at achieving economic efficiency. If it is not, then it will be impossible to measure the *economic* benefits of better information. And thirdly, it must be possible to measure relative success or failure of that aim

in terms of the tangible benefits that would result. These issues are discussed further in Box 3.

In theory, all changes that affect the total availability of goods and resources relative to a base-line scenario (see below) should be included in any assessment. In reality however, attempting to identify and value the full range of benefits accruing from the multiplicity of uses of geological information is not practicable. For this reason, most formal valuation studies have focused on specific aspects of use associated with direct (and quantifiable) impacts, often defining benefits in terms of costs *avoided*. Examples include land use decisions linked to geological hazards and potential infrastructure damage costs, and groundwater exploration decisions linked to drilling costs (see Section 4, below). It is also important to note that while evaluations can tell us something about the benefits of investing in geological information *per se*, it is very difficult to draw conclusions about what would be the ‘optimal’ investment.

Focusing on discrete mapping applications raises a *sampling* issue if the desired outcome is meant to be some measure of national economic worth. If this is the objective, two questions need to be considered: firstly, the degree to which specific cases are representative of the wider population of similar decisions; and secondly, the number of those decisions.

2.2.4 Estimating benefits in terms of ‘with’ versus ‘without’ scenarios

In the discussion above, the societal value of geological information was defined as the difference between the net benefits deriving from the use of ‘improved’ information, in terms of information quantity and/or quality, and the net benefits associated with the use of existing information. In other words, any benefit assessment is based on some form of comparison between a baseline condition (usually the ‘do nothing’ option, or ‘without’ project condition), and one or more alternatives – the ‘with’ condition(s). The nature of the comparison will depend on what exactly is being evaluated. However, two broad approaches can be identified:

- an *ex ante* approach in which benefits that are expected to arise from the application of geological information in future decision-making are considered. In this case, for example, the ‘with’ condition might correspond with future use of an updated geological map, or some part of it. Decisions that might be made with the benefit of information contained on the new map would then need to be compared with possible or actual decisions made with the aid only of the old map.
- an *ex poste* analysis in which improvements that have actually accrued in known decisions made with the use of a new geological map are evaluated and compared with a hypothetical situation that predicts the economic outcomes that would have applied if the new map information had not been available.

SECTOR	Examples of broad decision-areas that might be sensitive to availability of geological information
Minerals – metallic	<ul style="list-style-type: none"> - mineral exploration - regional resource assessment and extraction planning
Minerals – aggregates and other industrial	<ul style="list-style-type: none"> - minerals extraction planning - identification of new resource areas
Waste management	<ul style="list-style-type: none"> - location of waste disposal sites
Environmental assessment	<ul style="list-style-type: none"> - assessment of pollution potential/risk from anthropogenic contaminants (e.g. heavy metals) - assessment of pollution potential/risk from naturally occurring elements (e.g. radon)
Local and regional planning	<ul style="list-style-type: none"> - geohazard identification and land use planning
Coastal management	<ul style="list-style-type: none"> - coastal defence against flooding and erosion - shoreline management - identification of aggregate resources
Water management – resources	<ul style="list-style-type: none"> - information for siting and designing boreholes - information for predicting surface water/groundwater interactions
Water management – protection	<ul style="list-style-type: none"> - regional data for catchment management plans - delineation of groundwater protection areas
Construction industry, excluding roads	<ul style="list-style-type: none"> - site surveys - site investigation planning and interpretation - excavation conditions
Road building	<ul style="list-style-type: none"> - as above
Insurance, re-insurance, conveyance	<ul style="list-style-type: none"> - swell-shrink clay distribution - general geohazard data
Education	<ul style="list-style-type: none"> - study maps - intellectual basis for understanding UK geology
Academic research	<ul style="list-style-type: none"> - as above
Hydrocarbons – offshore	<ul style="list-style-type: none"> - framework of regional geology
Hydrocarbons – onshore	<ul style="list-style-type: none"> - as above and background 3D geology
Coal	<ul style="list-style-type: none"> - exploration - detailed 3D geology and ground conditions for mining
Conservation	<ul style="list-style-type: none"> - data for protection of valuable cultural sites
Tourism and recreation	<ul style="list-style-type: none"> - basis for guides and information at interpretative centres
Agriculture	<ul style="list-style-type: none"> - pollution risk from pesticides - basic information for soil categorisation
Forestry	<ul style="list-style-type: none"> - basic information for soil categorisation

Table 1 Geological information: user sectors and applications

2.2.5 Estimating costs

The direct costs of geological surveying projects are relatively straightforward to estimate. Where a previous map exists, a re-survey to update and improve the map may be extensive or relatively limited. In either case the new mapping will make use of the existing geological database, the costs of which will already have been met in previous projects and can thus be ignored for the purpose of the present analysis of the value of the 'new' information generated by the 'new' project.

The cost sources relevant to the survey will include the following:

- data collection in the field
- data compilation and interpretation; database development
- data presentation including map compilation and digitisation (where relevant)
- map and accompanying text publication
- map distribution over the useful life of the 'new' map

While the costs associated with producing a new map are mainly incurred over a relatively short period at the beginning of the map's useful life, it is important to remember that the maintenance of databases and map (=information) distribution will result in some costs being spread over the much longer period during which benefits are expected to accrue

2.3 VALUATION APPROACHES: SOME EXAMPLES

In the light of the discussion above, we can consider what approaches *can* be used to evaluate the benefits of geological information. In this section two evaluation approaches are outlined. First, an anecdotal, more qualitative approach to estimating benefits is discussed. Second, a formal cost-benefit approach is described for comparing, over time, the predicted costs and benefits of two or more options. The latter relies on quantitative data and is normally applied to specific (mapping) applications where impacts can be more readily valued in monetary terms. Each approach is illustrated with reference to specific case studies as summarised in Table 2.

Although each approach is considered separately, we recommend that any formal cost-benefit assessment is bolstered with careful qualitative analysis of the broad

range of uses and users of the geological information being considered. This will help develop a balanced understanding of why most geological information is of value across a range of uses. It will also help identify particular 'decision areas' where cost-benefit analysis can be applied most fruitfully.

2.3.1 Anecdotal approach

This approach substitutes rigorous quantitative analysis for a broader, more descriptive assessment of information use, drawing *inferences* about the societal value that might reasonably be ascribed to the use of geological information. As such, the aim is to identify and describe *evidence* from a range of sources – however limited and speculative – that can be applied to project assessment. In contrast to formal cost-benefit analysis (see below) there is no prescribed methodology. However, the basic principles and concepts outlined in the discussion above still apply, so any 'relaxation' of rigour associated with a more descriptive approach to assessment should be acknowledged.

Anecdotal as well as cost-benefit approaches to benefit assessment have been used by the British Geological Survey (BGS) to evaluate the impacts of information gained through geological mapping projects in the UK (Ellison & Calow, 1996). The anecdotal approach was based on the compilation of national, baseline information on policy, guidance, best practice, and government research recommending the use of geological mapping for different activities across twenty user 'sectors', ranging from construction to tourism (Table 1 presents a similar classification of sectors). The value of mapping to each sector was then estimated based on assumptions about:

- how frequently information was used within each sector; and
- the proportion of sectoral output value that could be reasonably attributed to use of the information, drawing on published statistics from a range of government and private sources.

The outcome of these calculations was a subjective, gross value estimate of £18.9 million/year, compared with a geological mapping budget of roughly £3.2 million for the fiscal year 1996/97. The study assumed that such benefits could only be maintained year-on-year if resurvey and revision mapping was carried out so that new data were constantly incorporated into national datasets.

Box 2 The valuation challenge

Information may be said to be the antidote to uncertainty, or the raw material from which decisions are made (Mosley, 1994). However, while we know that the production of the information affects the production of goods and services in many 'downstream' uses, it is difficult to relate incremental (marginal) changes in the former to incremental changes in the latter.

More formally, if dI represents the change in information that is expected to result from an activity, and if dG is a change in the production of goods or services, then in the relationship $dG=f(dI)$ we are ignorant of the form f . The methodology of conventional cost-benefit analysis leaves us well prepared to evaluate a known dG , but tells us little about how to transform dI to dG .

A largely descriptive, or anecdotal study was also undertaken as part of an evaluation of an aid-funded (ODA, now the UK Department for International Development) geological mapping project in Kenya. The project itself was undertaken between 1980 and 1987, and details on the economic evaluation are drawn from an ODA evaluation report of this and two other geological survey projects (Cocking, 1992). For the Kenyan project an empirical estimate of the value of benefits was made, in this instance based on questionnaire responses from map users in Kenya rather than on published statistics. Users were asked to place a value on the costs that would have been incurred by their operations had the maps and reports resulting from the mapping project not been available. Assuming the new maps had a life-span 'in excess of 40 years', net benefits of over £200,000 per year were calculated, and it was concluded that the mapping project had made, and would continue to make, significant beneficial impacts in a number of sectors.

2.3.2 Formal assessments

A formal approach that can be applied – with care – to evaluate the benefits of geological information is cost-benefit analysis (CBA). Cost-benefit analysis is widely employed both by private firms and in the public sector to assist decisions about the acceptance and timing of new investments.

In essence, CBA is a simple method for comparing, over time, the predicted costs and benefits of two or more options. The objective is to determine which, on balance, is the most attractive option from the point of view of the private investor, or of society at large. One of these options acts as a baseline, or benchmark, against which remaining options can be compared. The baseline is typically the 'do nothing', or 'without project' option (see discussion under 2.2.4). The costs and benefits of the remaining options, such as investment in producing a new geological map, can then be calculated as changes from this baseline. While the procedure of CBA is relatively straightforward, applying it to the valuation of information, as opposed to directly marketable goods and services, is more difficult. As noted in Box 2, the main challenge lies in linking changes in the production of geological information to changes in end user decision-making having measurable economic consequences.

In detail, the *process* of CBA can be broken down into five interrelated steps. These are described briefly below and the process and its application to a particular valuation problem are discussed in greater detail in Section 4 of this Report.

- *Step 1: define the nature of costs and benefits and, if possible, identify all the costs and benefits associated with a particular project, programme or policy over an appropriate period of time.* As we have argued previously, developing an understanding of how geological information is used, the kinds of decisions it effects and their likely economic consequences is extremely important, whatever form of appraisal is undertaken (see Section 2.2.2 and Tables 1 and 2). At the same time, it is also important to identify and explain the baseline (without project) condition

against which comparisons are to be made (Section 2.2.4). This may correspond with use of an existing (older) geological map in decision-making for example. The time frame over which comparisons are to be made must also be considered. This will normally correspond with the expected 'lifetime' of the project products, or investment. For a geological map, this may be decades.

- *Step 2: identify the incidence of all costs and benefits over the appropriate time period, and quantify in monetary terms where possible.* Identifying the likely incidence of costs and benefits over time is important because the process of discounting reduces the value of amounts received or paid out in the future (see Step 4 below). Where there is a time lag between project investment and the return on that investment (the normal scenario), it follows that benefits will be discounted at a higher rate than costs, reducing net benefits in present value terms. The starting point in CBA is the construction of a cash flow statement that records, year by year, the expected value of costs and benefits over time. For convenience, years are usually numbered from zero to the end of the project's life. As most projects designed to produce geological information are publicly funded, and are concerned with societal welfare rather than commercial return, economic rather than financial CBA should be adopted. The distinction is discussed in Box 4.

- *Step 3: adjust all values for time using an appropriate discount rate.* Discounting is the process by which future values are deflated by a discount rate to convert them into present values. Discounting is necessary because the time path of costs and benefits attributable to a project usually differs (see above), and society values a 'future dollar' less than a present one, since the latter can be invested to earn a return. The choice of discount rate depends on a combination of factors, and detailed discussion is beyond the scope of this report. However, advice on the appropriate rate of discount to apply in a particular country, and for certain projects, can be easily obtained from government departments and lending agencies. Discounting is discussed further in Box 4.

It should be noted that constant prices are generally used in CBA, avoiding the need to forecast future price levels and adjust future costs and benefits for inflation. This is because relative prices can usually be assumed to remain constant over the life of a project, with inflation affecting costs and benefits equally.

- *Step 4: apply a decision criterion.* Various decision criteria can be used to rank a particular option as compared to the baseline (without project) option. Three well known criteria in use are: net present value (NPV), which is the difference between discounted benefits and costs (see Box 4); the internal rate of return (IRR), which represents the interest rate that makes discounted benefits equal to discounted costs; and the benefit cost ratio (B/C), a simple ratio of discounted benefits to costs. In the case studies described below, both NPV and B/C criteria are used.

Box 3 Applying statistical decision theory to benefit estimation

Information only has a value if decisions are improved as a result of its use. In simple terms, the hypothesis is that geological information leads to an increase in the accuracy with which some variables can be estimated *where the outcome of a decision is determined by the real values of these variables* (CNS, 1991). The benefits of greater accuracy result from an increase in the economic efficiency of decisions that are sensitive to these variables. In other words, either the same quantity of goods can be produced at lower cost, and/or the same resources can be used to produce a more valuable output.

Theoretically, the most appropriate structure for evaluating the benefits of greater accuracy in decision-making is via the use of Bayesian analysis (Davis et al., 1972). This statistical approach is based on a comparison of the prior probability distribution for a chosen variable in the absence of new geological data, with the *a posteriori* probability distribution for the variable consequent upon the availability of new information. Applying this theoretical structure and estimating probabilities is both data intensive and mathematically complex however. For this reason, most studies into the value of information have adopted simpler, more accessible approaches of the type described in this report.

The case studies summarised in Table 2 and outlined below are all concerned with the evaluation of mapping programmes (geological and hydrogeological) at a range of map scales. In each case, the description and/or quantification of benefits is based on the 'losses avoided' approach: in other words, benefits are expressed in terms of expected cost-savings resulting from the use of improved geological information. Three of the studies apply formal cost-benefit techniques of the type described above, though there are differences of approach.

Studies by the British Geological Survey (Reedman et al., 1998; Ellison & Calow, 1996) have followed both anecdotal and formal cost-benefit approaches. The cost-benefit approach was applied to a more objective quantification of benefits accruing from the re-mapping of an area within a small town in the north of England, where gypsum dissolution has led to significant land subsidence and infrastructure damage costs. A simple spreadsheet model was set up to estimate land subsidence costs that could be avoided through the improved recognition and better characterisation of vulnerable areas. In this case, it was assumed that land-use decisions would remain the same, but that better information would ensure that buildings were constructed in such a way as to minimise the risk of costly structural damage in sensitive areas. For this small area, and for this single application, net benefits were estimated at roughly £540 000.

In the United States, the Illinois State Geological Survey has applied cost-benefit techniques to assess the environmental hazards of waste disposal (Bhagwat & Berg, 1991). In this study however, an *ex post* approach was adopted which looked at the costs that could potentially have been avoided in terms of the investigation and clean-up of *existing* waste disposal and industrial sites. The underlying contention here – supported by subsequent cost benefit analysis – was that if sufficient geological information had been available at the time when the siting decisions were made, all or part of the clean-up costs within the area could have been avoided. Actual cost data were obtained from the Illinois Environmental Protection Agency; estimates were used where clean-up had not yet occurred. The authors assumed a 10-year time lag between the production of new information and its use, and also assumed that as little as one tenth of calculated benefits would be realised because not all information would be

used. In this study, the net benefit of geological information obtained from geological mapping, projected from county level to the entire state (but still for only one application), was estimated at roughly US\$21 million.

By far the most comprehensive study has been undertaken by the United States Geological Survey (Bernknopf et al., 1993). In this study, an *ex ante* analysis was undertaken to evaluate cost savings that could be directly attributed to the use of a new map for two planned developments: (a) selection of a road corridor; and (b) selection of a landfill site. In each case, hypothetical land use decisions made with and without the benefit of new mapping information were compared. The aim was to see if the new information would be compelling enough to alter land-use decisions, and to determine the economic impact of such decisions. In this study, costs and benefits were not set out on an annualised basis and discounted along the lines described above. Instead, a GIS model incorporating geological, engineering and economic data was combined with a hypothetical decision-making model to investigate how land-use decisions might change with improved information, and what the economic consequences of such changes would be.

For each of the two planning applications geological map information from both old and new maps was converted, using GIS techniques, into a probability or likelihood map of an environmental hazard. Hypothetical siting decisions, made with the information from the old and new maps respectively, were then compared and in each case environmental hazard costs computed by combining risk data with economic data. In the road corridor example, better siting decisions reduced the probability of slope failures and thus of hazard mitigation costs. In the landfill example, improved siting was assumed to reduce the risk of contamination and any consequent reduction in property values. Although only two of many possible applications of the mapping information within one County were evaluated, net benefit estimates of between US\$1.28 and US\$3.5 million were obtained.

It is important to note that what was being assessed in this study (as in the others) was not the benefits of the road and waste disposal projects themselves. Rather, it was the application of geological information to the relevant land-use planning decisions and the resulting cost reduction.

Box 4 Some key concepts in cost-benefit analysis

Financial vs economic appraisals. Two forms of project appraisal are commonly used: financial and economic. These differ in terms of their perspective, or point of view. Financial analysis is concerned narrowly with the profits and losses of private projects, and uses market prices to estimate actual money costs and benefits to private investors. In contrast, economic analysis is concerned with the total effect of a project or policy on the welfare of society. Economic analyses are required for most public sector projects and for private sector projects requiring government support. In economic appraisals, market prices are examined to see if they provide a good indication of real value and cost. If they do not, then financial prices have to be adjusted to shadow values, or economic prices. This adjustment is typically carried out when market prices are affected by taxes and subsidies, and when environmental effects, which are not captured by market prices, are significant. For example, a government tax on mining profits would be treated as a cost in financial analysis because it would reduce the mine owner's profits. In an economic appraisal, however, taxes (and subsidies, loans and debt service payments) would be excluded because they represent transfers on claims to resources, rather than use of real resources. As such, they do not affect national income.

Example – in the case study on groundwater exploration costs discussed in Section 4, the costs of borehole drilling were looked at carefully to see if rates quoted in Nigeria, and paid for by local NGOs, reflected real economic costs. In reality, drilling in Nigeria is heavily subsidised, so a more realistic (higher) figure for drilling was used in the CBA.

Discount rate. The discount rate is the rate at which our valuation of the worth of a fixed amount of money diminishes over time. In financial analysis, the rate used will correspond with the required return on private capital, which will be greater than the interest rate available in the market. In economic analysis, the rate (the *social* rate of discount) used by government may be related to the commercial rate, but will also be influenced by other factors. In broad terms it can be thought of as a reflection of society's (or the government's) time preferences. For example, if we are advised by the Ministry of Finance that the discount rate for use on a public project is 10%, this means that to be compensated for foregoing \$100 of consumption now, society will have to be offered at least \$110 in a year's time. In other words, the present value of \$110 in a year's time is \$100 ($110/(1+0.10) = 100$). Discounting thus provides us with a technique for making rational decisions about the competing claims of the present and future.

Example – in the case studies summarised in Table 2, where CBA techniques have been applied, discount rates of 10% were used. In the UK studies conducted by BGS, this was the rate used for most government-funded projects at the time. For the case study on groundwater exploration in Nigeria described in Section 4, a 10% discount rate was used as a 'best guess' because no other information was available. In many countries, a discount rate of 8-12% applied to costs and benefits at constant prices is a useful operational guide (ODA, 1988).

Present value. Following on from the above, the present value of an amount accruing in the future is the value of that sum when deflated by the discount rate. The **net present value (NPV)** of an investment therefore measures the difference between present (summed) values of costs and benefits and can be calculated as follows:

$$NPV = \frac{B_t - C_t}{(1 + r)^t}$$

Where: B = nominal value of benefits; C = costs; t refers to a given year; and r + the rate of discount. It follows that when the NPV > 0, the project is economically desirable.

In practice, most computer spreadsheet packages include NPV calculators in their functions menu, making the process of NPV calculation much easier.

Example – in the case study on groundwater exploration in Nigeria described in Section 4, an Excel spreadsheet was used to record annual values (as well as other relevant information) relating to the development and use of hydrogeological information. Although discount factors for each year are recorded in the spreadsheet for transparency, the NPV calculation was made by selecting 'NPV' from the function menu (under 'financial'). All that is required is the specification of a discount rate, r, and a range of values from the statement that are to be discounted.

Valuation Study					
	Bernknopf et al (1993)	Bhagwat & Berg (1991)	Cocking (1992)	Ellison & Calow (1996, unpublished)	Section 4 of this report
Study area	Loudoun County, Virginia, Washington DC, Metropolitan Region, USA	Boone and Winnebago Counties, Illinois State, USA	National, Kenya	National and local (see below), UK	Benue State, Nigeria
Type of benefit assessment	Formal model: GIS including earth science, engineering and economic data combined with decision-making model Remapping of Loudoun County – 1:500 000 to 1:100 000	Formal cost-benefit analysis supplemented with anecdotal description Remapping of Boone and Winnebago Counties	Mainly anecdotal, but based on questionnaire responses from map users Extensive geological mapping programme (primary mapping)	(a) Anecdotal – national remapping programme (b) Cost-benefit – remapping of one local sheet	Formal cost-benefit analysis plus description Hydrogeological investigation, mapping and training programme
Comparisons made	Future land use decisions made with and without benefit of updated geological information	No specific comparisons made (see below)	Ex post evaluation of geological data collection costs avoided by different enterprises extrapolated over future lifetime of maps	No specific comparisons made in (a). In (b), comparison of land subsidence costs with and without incorporation of new geohazard information into planning guidelines	Water supply development costs with and without benefit of hydro-geological investigations
Case studies	Proposed siting of (a) interstate road corridor; and (b) waste disposal facility	General siting of waste disposal sites within the county. Assumed that 'better siting' generally would have led to avoidable losses	No specific case studies. Questionnaires sent out to a number of geological map users to determine costs saved with mapping	In (b), two housing development scenarios evaluated within area vulnerable to land subsidence	Oju Local Government Area within Benue State
Nature of benefits quantified	Environmental hazard costs that could be avoided through remapping. For (a) engineering mitigation costs avoided; for (b) property value losses avoided	Environmental hazard costs which could have been avoided through remapping, in terms of investigation and clean-up costs at existing industrial waste disposal sites	Geological data collection costs that would have been incurred by individual map users had national, public mapping data not been available	In (a), contribution of mapping programme to national sector output values. In (b), benefits as house damage costs (from subsidence) which could be avoided through better land use decisions	Borehole drilling costs that could be avoided through increase in drilling success rates across different hydrogeological zones
Net benefit of mapping application(s) examined	For (a) and (b) combined net benefit estimated at US\$1.28-\$3.5 million (1993 prices). Discounting not applied	Benefit-cost ratios, projected to entire state, estimated at 3:1. NPV for entire state estimated at US\$21 million at 10% discount rate (1990 prices)	Net benefit >£200 000/year (early 1990s prices)	Baseline net value for (a) estimated at £15.7 million (1996 prices). NPV for (b) estimated at £540 000 at 10% discount rate (1995 prices)	NPV of costs saved estimated at £751 000 (1996 prices); 10% discount rate for the period 1996-2006; benefit-cost ratio 1.3
Assumptions/caveats	Model assumes strong regulatory framework for enforcing 'better' decisions	Weaker methodological basis than the USGS study (Bernknopf et al); assumes strong regulatory framework for enforcing decisions	A rapid study	(a) less rigorous; assumes national baseline statistics available. (b) more empirically rigorous, but assumes strong regulatory framework for enforcing decisions	Assumes 200 successful boreholes would need to be drilled in the period 1996-2006 to meet coverage targets. Success rates for without-project condition are estimated

Table 2 Some previous valuations of geological information

3 The value to mineral exploration of systematic regional geological and geochemical surveys

3.1 INTRODUCTION

Most national Geological Survey Organisations (GSOs) were founded to carry out the systematic geological mapping of their country with a major objective being the assessment of the nation's mineral resources. In many countries, regional reconnaissance surveys were followed by more rigorous surveys of selected areas in which indications of a particular mineral resource had been highlighted. Sometimes the GSO investigations went so far as to carry out drilling programmes aimed at establishing the actual amount, or reserves, of the particular resource. In more recent years, however, it has become generally accepted that while systematic nationwide geoscience surveying should be the major responsibility of the national, publicly funded GSO, the detailed exploration and proving of mineral deposits is best left to the private sector. The aim of the systematic regional surveys undertaken at public expense is to provide information upon which private sector investment in mineral exploration projects can be based. This will involve the selection of limited target areas for exploration investment by the private sector based on analysis of the information contained in the geological and other geoscience maps and reports issued by the GSO.

Such policies for GSO functions have been summarised by the World Bank (1996) which has stressed that the role of a GSO 'is to develop and maintain a reliable national earth science database', with the GSO providing 'the basic geological knowledge for the mineral industry'. In addition, the GSO 'should be an important mining investment tool' with one of its responsibilities being 'the provision of geological information to potential investors'. The international mining and mineral exploration industry has, in several recent surveys, confirmed that a very important factor in making their investment decisions for overseas mineral exploration projects is the availability of geoscience information in the form of systematic coverage by geoscience maps.

In this section of our report we use several examples of extensive, GSO implemented geological survey projects in order to examine how the geoscience information they have generated has affected subsequent private sector mineral exploration investment. In this way we have attempted to compare the cost of providing 'new' geological information with the benefits that have accrued in a particular field of natural resource development. We have selected projects that involved both the BGS and the GSO of a less developed country (LDC) and which were jointly funded by the UK Government (Department for International Development, formerly known as the Overseas Development Administration) and the government of the relevant LDC. The projects selected were completed between eight and more than twenty-five years ago so that their impacts, over reasonably long periods of time, could be evaluated. All of the project areas involved very extensive tracts of country (14 000 km² to over 500

000 km²). These varied from areas with previously virtually unknown geology to one where the general geology was fairly well understood but where a particular aspect needed to be investigated in greater detail in order to focus subsequent mineral exploration more effectively.

3.2 MINING IN DEVELOPING COUNTRIES

The minerals industry constitutes an important element of economic activity in many less developed countries. In most countries the publicly funded GSOs were established with the expectation that their activities would result in the discovery of mineral resources that could be exploited so as to contribute positively to the growth of the national economy. The projects that we review below all had the purpose of supplying new geoscience information that could potentially stimulate further economic activity within the minerals sector and all took place in countries where, today, the mining industry has an important role in the nation's economic development.

In Indonesia, for example, a recent survey of the mining sector (PricewaterhouseCoopers, 1999) indicates that in 1998 the total government revenue from the mining industry was US\$570.6 million. In addition, in the same year, US\$27.6 million was spent by the industry on regional and community development and contributions to charities and not-for-profit foundations. Approximately 30,000 Indonesian nationals were employed in the industry. The total contribution to the Indonesian economy in 1998, calculated in terms of five key components – employee compensation (excluding expatriates), domestic purchases, government revenues, dividends paid to Indonesian shareholders and interest paid to Indonesian companies and banks – amounted to Rp9 572.7 billion (US\$1.2 billion at average Rp/US\$ exchange rate for 1998). For mineral production from Indonesia the net sales revenues amounted to over US\$3 billion in 1998, over 96% of which was exported. Estimates of the downside, the cost of environmental impacts, are not available, but during 1998 almost US\$100 million was spent by the industry on reclamation, mine closure and environmental control. This figure is shown to have increased very significantly in recent years mainly due to the increasing expenditure on improved plant and equipment for the purpose of environmental protection.

In Zimbabwe, gold mining has made a significant contribution to the economy for many years. The main objective of the geological surveying project described below (see under 3.4.4) was to provide information likely to lead to the discovery of new gold reserves and contribute to the long-term sustainability of the industry. In 1987, just prior to the start of the project, direct employment in the formal industry amounted to 53 300 persons (Chamber of Mines Journal, June 1987, p. 21) and gold sales accounted for over 10% of the total value of exports from Zimbabwe.

The establishment and expansion of a mining industry also has important multiplier effects for other sectors of the economy. A recent study in Western Australia (Clements, Ahammad and Ye, 1996) for example, indicates that a US\$1 million rise in wages and benefits paid in the mining and mineral processing industries generates nearly US\$2 million of wages in non-mining industries, while for each additional 100 people employed by the mining industry roughly 300 jobs are created elsewhere. In the latter case, substantial gains were seen in such areas as education, health and welfare. The development of mining and minerals processing industries are thus important generators of business for other sectors of the economy.

Although the exploitation of mineral resources is generally acknowledged to have made a significant contribution to economic activity in many developing countries, little account has been taken in the past of the environmental costs involved. Mining is therefore regarded by many as an unsustainable development activity leaving behind it a legacy of environmental damage and associated costs. Nowadays, however, greatly improved government regulation of mining activities in most developing countries, based on proper concern for environmental protection and coupled with an increasingly responsible attitude adopted by the international mining community, has led to improved mining and mineral processing techniques and new regimes of mine closure and environmental restoration, all of which has to be set against a still burgeoning world demand for mineral raw materials. In this context it should be noted that the systematic collection of geoscience data and information is not only essential for mineral exploitation but also for establishing, controlling and mitigating the resultant environmental impacts through well informed regulation.

3.3 TARGETING MINERAL EXPLORATION INVESTMENT

In most countries around the World the bulk of mining output is generated by a relatively small number of large producers. Often these producers, although locally incorporated, are the subsidiaries of multi-national mining concerns with a remit from shareholders to generate wealth from mineral properties across the globe. Where such companies choose to invest is a decision based on the assessment of the relative merits of, and complex interaction between, a number of factors, both real and perceived. The business of mining is unsentimental and global in character. Many of the factors to be considered concern issues much wider than the mining sector and relate, in particular, to the attitude of governments in political, social and economic terms and their performance in policy-making and function. A government concerned to increase investment will move to provide attractive fiscal and regulatory policies and to support those public institutions charged with delivering this functionality to the investment community.

For the minerals industry, territories with long-established mining districts have the advantage of having a larger and more complete information base, a skilled work-force, good mining sector governance and so on. They may, however, be perceived, in mining terms, as too

‘mature’ with low residual value and lacking either suitable remaining deposits of appropriate scale, or available ground for new exploration. In this way, they may be unattractive to investors.

Governments cannot, of course, alter their geological inheritance. They can, however, boost the understanding and perception of that inheritance by commissioning and supporting geological surveying projects undertaken by, for example, their GSO, and by ensuring that data and information relating to the geological potential of their territory is readily available and accessible. The several case studies described and assessed below have been selected to demonstrate the value of information derived from systematic geological and geochemical surveying.

3.4 CASE STUDIES

The projects described here were all undertaken with the common purpose of systematically gathering geoscience data and publishing the information as geological and geochemical maps and reports in order to stimulate further investment in detailed mineral exploration. In assessing these projects we have, as anticipated, faced a number of difficulties in assigning precise financial value to the benefits that have accrued. In particular it is frequently, though not invariably, difficult to trace and prove a direct link between the release of the information generated and published by the GSO and the subsequent discovery and proving of a particular mineral deposit by privately financed exploration.

Furthermore, even where we have been able to establish that such private exploration investment was initiated largely as a result of new information made available by the national GSO, assigning a value to any discovered resource is not straightforward. Here, we have adopted an extremely simplistic approach. Since we are considering the benefits accruing to the ‘nation’ as a result of state investment in its GSO activities, any local investment made by the private sector in pursuing its exploration activities is listed as a ‘benefit’ rather than a ‘cost’. In addition, the potential value to the nation of any discovered resource is calculated at a stated price and counted as a benefit without taking into account the potential cost (to private industry) of the future extraction of the resource. Because of the uncertainties in the exact nature of the links between GSO-generated geoscience information and the results of subsequent private sector exploration, we have been extremely conservative in our estimates of the financial value of such ‘benefits’.

It might be considered that an easily measured financial return from GSO projects of the type reviewed below would be the income received from the direct sale of information, in the form of maps and reports, generated by the projects. However, in all cases these were regarded as ‘public good’ products and sold at nominal prices, which may have covered the costs of publication but not the very much larger cost of gathering and processing the data and the resultant information contained in the products. Nevertheless, the number of publications sold does, where records exist, give an indication of their utility as expressed through demand.

In gathering information for these case studies we have encountered a number of difficulties. The records of the

various GSOs concerning information dissemination, in terms of numbers of reports and maps sold or otherwise distributed, varied from accurate and well documented to non-existent. Furthermore, even when there is a statutory requirement for private sector mining and mineral exploration licensees to submit accounts of their exploration expenditure, such records frequently proved difficult or even impossible to access. Nevertheless, through the cooperation of many private sector mineral exploration companies, mining associations and various government departments, we have been able to make the valuations assembled below. They are, at best, 'anecdotal' or qualitative assessments (as discussed under Section 2 of this report) rather than rigorous 'formal' assessments.

3.4.1 Proyecto Precámbrico: The Precambrian geology of eastern Bolivia

3.4.1.1 INTRODUCTION

The geological survey of the Precambrian shield of eastern Bolivia, covering a total area of almost a quarter of a million square kilometres, or approximately twenty per cent of the total area of the country (Figure 9), was undertaken between 1976 and 1986 by the British Geological Survey (BGS) in collaboration with Servicio Geológico de Bolivia (GEOBOL). The terrain surveyed varied from almost inaccessible jungle to mixed grassland, scrubland and deciduous forest. The geology was virtually unknown prior to the BGS/GEOBOL study. Because of this lack of knowledge it had been considered of limited mining potential, particularly since the virtual cessation of mining activity following the expulsion of the Jesuit missionaries in the late eighteenth century, and later the brief revival and decline of gold mining in the mid-nineteenth century. Such sporadic, small-scale mining activities that did survive ceased in 1975, when the Bolivian Precambrian shield was declared a 'Fiscal Reserve' by the Bolivian government in order to allow the UK/Bolivian government sponsored 'Proyecto Precámbrico' to conduct its geological mapping and mineral exploration project.

The objectives of the project, as defined in the original project document, were to:

- (i) produce a series of 1:250 000 geological maps
- (ii) produce an accompanying series of geochemical maps
- (iii) as a consequence of (i) and (ii) identify areas of mineral potential
- (iv) undertake certain follow-up exploration in promising areas
- (v) provide in-service practical training, and limited training in the UK for GEOBOL staff.

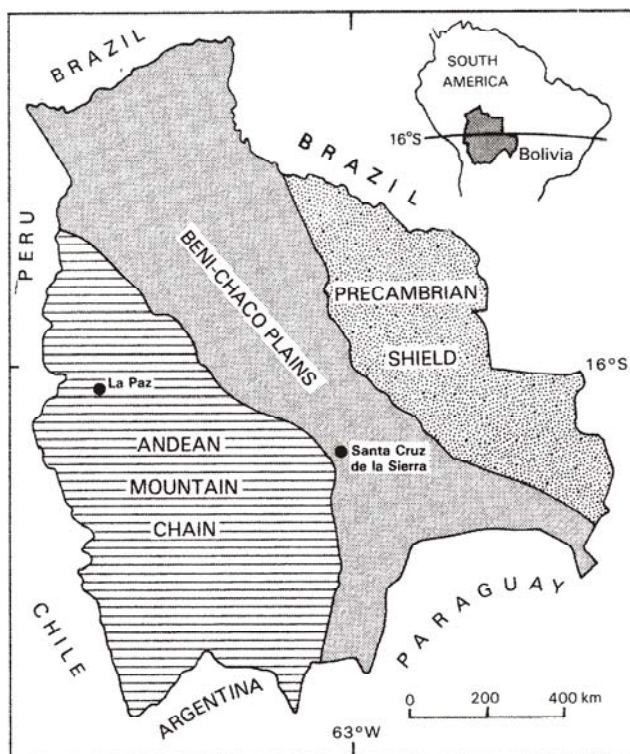


Figure 9 Location of Precambrian shield of eastern Bolivia, mapped by BGS between 1976 and 1986

3.4.1.2 PROJECT IMPLEMENTATION AND INFORMATION OUTPUTS

The project was accomplished in three phases, phases one and two (1976-1983) being concerned with items (i) to (iii) and elements of (v) above. It is with this part of the project, which provided basic geological and geochemical information in the form of maps and reports, that we are here concerned.

The basic products resulting from the project comprised fourteen published geological maps at 1:250 000 scale together with accompanying reports. These covered in total some 220 000 square kilometres, or almost the entire area of the Precambrian outcrop of Bolivia, an area almost equal to the entire land area of the United Kingdom. A summary geological map at 1:1 million scale and three more detailed mineral province maps at 1:100 000 scale were also published. A geochemical atlas, based on a geochemical survey over the entire area and analyses of 6,935 stream sediment and 1,250 soil samples for twenty-two elements, was a further important product. The published output is listed in Table 3.

The fiscal reserve imposed in 1975 was lifted in 1986, following which the published information resulting from Proyecto Precámbrico has been used extensively by all companies engaged in mineral exploration and exploitation in the area. Indeed, the maps and reports are widely credited with having inspired modern mining industry interest in Bolivia's Precambrian region, and it has been common for the BGS-GEOBOL mapping to be quoted by operators seeking to attract exploration joint-venture partners into speculative investment projects in the area.

A: Published Maps

<i>Type</i>	<i>Scale</i>	<i>Number</i>
Geological map (regional synthesis)	1:1000 000	1
Geological maps	1:250 000	14
Mineral province maps	1:100 000	3
Geochemical atlas	1:1000 000	22
Topographic map (N project area)	1:500 000	1

B: Reports

<i>Type</i>	<i>Number</i>
Quadrangle reports (corresponding to 1:250 000 geological maps) *	11
Other geological, mineral potential and mineral exploration reports **	10
Memoir ***	1

* Some reports covered parts of more than one 1:250 000 scale geological map

** All published or held on open-file

*** Litherland, et al. (1986)

Table 3 Products of the Bolivian Precambrian Survey Project

3.4.1.3 PROJECT COST

The total cost of the phases of the project considered here was approximately £2.7 million (US\$4.9m) at historic prices.

3.4.1.4 IMPACT

Following the release of the geological information resulting from Proyecto Precámbrico (see Table 4), two further aid-funded projects, one implemented by the Swedish Geological Mission to Bolivia in collaboration with GEOBOL and one by the United Nations Development Programme (UNDP), provided more information on parts of the survey area in the late 1980s and early 1990s. The former involved airborne magnetic and radiometric surveying of some 18,000 square kilometres, about eight per cent of the BGS-GEOBOL survey area. These further aid-funded exploration projects involved an expenditure of approximately US\$1million.

All subsequent mineral exploration in the Precambrian area of Bolivia has been undertaken by either Bolivian or international private sector mining companies. It is difficult to assess precisely the total value of this investment, given the virtual absence of published reports or statistics. Estimates of the value of exploration and mine development investment vary widely between the most conservative figure of US\$40 million up to a maximum of US\$120 million. The Association of Medium Mine Owners (Asociación de Minas Medianos) cautiously puts investment in exploration ventures alone during the five-year period to the end of 1999 at US\$29 million with a peak of US\$10.4 million in 1996 (A Shave, pers comm.). During this latter period, in the mid-1990s, some 35 companies were actively conducting exploration projects in the area.

From the above, it is reasonable to conclude that, since the publication of the BGS-GEOBOL reports and maps not

less than US\$40 million has been committed to further exploration of the area, and after twelve years of modern exploration by the private sector two producing mines and one deposit in an advanced stage of mine development have resulted (see below). For example:

- COMSUR-RTZ operates the Puquio Norte opencast gold mine where investments are put at US\$22 million to-date (1999). A further US\$10 million has been invested by the group's joint venture exploration affiliate, Emicaruz, in testing potential prospects in areas immediately neighbouring the mine. Investments have included the construction of a 100-km gas pipeline to fuel the mineral processing plant. The prospect was discovered in 1987 and began mine production in 1997.
- Orvana Minerals Corporation operates the Don Mario underground gold/silver/copper prospect. Orvana's entry was via the acquisition of four smaller Bolivian mining venture companies (Empresas Mineras Paititi, Las Palmas, Las Tojas and Imperial Mining) in March 1996 at a cost of US\$45 million. Orvana has subsequently invested US\$22-25 million in extensive drilling and core analysis.
- Minerales y Metales del Oriente SRL operates the Anahi ametrine (amethyst, citrine, bolivianite) mining venture in the Rincon del Tigre region north of El Mutun. The present venture began with a speculative concession acquisition in 1990 and the development of controlled mining from 1991, though some mining activity dates from a considerably earlier period. Investment in mine development has been around US\$2 million with a further US\$3 million in infrastructure development including the building of an airstrip into an area only accessible otherwise by river and/or on foot. The mine is now one of the world's major amethyst producers.

Activity (Mineral Exploration and Development)	Investment
- Public Sector Investment	
BGS-GEOBOL project to produce initial maps and report	US\$ 2.7m
Further aid funded geoscience information generating projects (Swedish Geological Mission, UNDP)	c.US\$1m
- Private Sector Investment	
Private sector exploration	US\$ 40m
Detailed deposit evaluation and mine development	US\$ 50m

Activity (Current Production)	Revenue
Current gold production at Puquio Norte Mine	US\$ 9m per annum
Export of semi precious gemstones, Anahi Mine	US\$ 1.5m per annum

Table 4 Financial summary for mineral exploration, mine development and mineral production in the Bolivian Precambrian shield

- Following detection by BGS of platinum group metal values over the Rincon del Tigre complex in the 1980s, further work by Rio Tinto in the 1990s confirmed the presence of a PGM-bearing horizon 120 km in length. In 2000 the Denver-based Solitario Resources Corporation acquired property over this zone and confirmed promising grades of PGM mineralisation with the start of a drilling programme in 2001.

The above figures indicate that at least US\$50 million has been spent on the detailed delineation of ore bodies and development to the stage of actual mineral production.

Comprehensive figures for the value of mineral products currently mined from the Precambrian area are not available. That it must be substantial can be illustrated by the case of COMSUR's Puquio Norte Mine, the principal on-going mining venture, which currently produces about 900kg of gold per annum. At 1999 prices the value of this gold production amounts to almost US\$9 million per annum. In addition, production from the Anahi amethyst mine, with semi-precious gemstones being cut in Santa Cruz, results in exports valued at US\$1.5 million per annum.

3.4.1.5 CONCLUSION

An assumption made here is that the publication of geological information in the form of maps and reports provided the stimulus for private sector minerals industry exploration in a previously largely unexplored, and geologically unknown, Precambrian outcrop that underlies some twenty per cent of Bolivia. Certainly current mine operators and the Asociación de Minas Medianos credit BGS-GEOBOL's published information for having 'identified indicators for possible (mineral) deposits which now form the basis for any commercial exploration of the region' (Ing Rolando Jordan, pers. comm.). This has, in turn, resulted in mine development generating employment, a local infrastructure and revenue. There is, furthermore, very considerable optimism amongst exploration geologists regarding the further mineral potential of the

Precambrian region with a realistic possibility of further major discoveries likely in the coming years.

3.4.2 Regional geological and geochemical mapping of Sumatra, Indonesia

3.4.2.1 INTRODUCTION

Between 1975 and 1994 a series of collaborative projects between the Directorate General of Geology and Mineral Resources of Indonesia and the British Geological Survey, jointly funded by the Indonesian and British Governments, resulted in the publication of geological and geochemical maps covering the whole of the territory (524 000 km²) of Sumatra, Indonesia.

3.4.2.2 PROJECT IMPLEMENTATION AND INFORMATION OUTPUTS

The main aim of the combined projects was to produce and publish geological maps of Sumatra at a scale of 1:250 000, a total of 33 sheets. A stream sediment geochemical survey of Sumatra was also undertaken involving the collection and analysis of approximately 22 000 samples. Data collection, analysis and eventual publication took place over a period of nineteen years (1975–1994) with much of the fieldwork being carried out by Indonesian geologists assisted by geologists of the British Geological Survey. The latter also had a major input to processing the data and editing outputs for eventual publication. In the field of geophysics a further achievement was the production of a series of 1:250 000 scale Bouguer gravity anomaly maps of parts of Sumatra.

For northern Sumatra a geochemical atlas was produced (Stephenson et al., 1982) which systematically listed all geochemical anomalies and presented the data as 1:1 500 000 scale classified symbol maps and monochrome, gridded maps. The simplified geological maps in the atlas, which were the most comprehensive summaries of northern Sumatra geology hitherto published, were a considerable attraction. By 1988 the digital geochemical

Product	Number
Geological maps at 1:250 000 scale with accompanying geological reports	33 quadrangle sheets
Geochemical atlas of northern Sumatra with maps at 1:1 500 000 scale (gridded and point maps)	1 (multiple maps)
Single element 1:250 000 scale geochemical maps, northern Sumatra	
Geochemical maps of southern Sumatra at 1:250 000 scale with accompanying reports	14 quadrangle sheets
Electronic and hard copy geochemical atlas of southern Sumatra	1
CD-ROM with southern Sumatra geochemical, bibliographic and mineral occurrence databases	1
CD-ROM: Complete database of geochemistry of Sumatra	1

Table 5 Systematic map and report series products of the Northern and Southern Sumatra Projects

data had been transferred to PC-compatible diskettes and thus became readily available in digital format. In addition to the atlas, a series of 1:250 000 scale, monochrome, single element, classified symbol maps, each on a base showing the drainage, were produced. However, this latter series was not completed and did not provide coverage of the whole area. Coverage for southern Sumatra comprises 1:250 000 scale geochemical maps together with geochemical reports and mineral occurrence and simplified geological reports published as fourteen separate box sets each covering one quadrangle.

By the end of the project period, bibliographic, mineral occurrence and geochemistry databases were available in a format readily usable by exploration companies. A subsequent extension to the project resulted in the production of an electronic geochemical atlas of southern Sumatra together with a hard-copy version in 1997 (see Figure 2). Hard-copy versions of the southern Sumatra bibliography (Johnson, 1995) and mineral occurrence database (Crow, 1995) were produced and all the southern Sumatra project computer files were transferred onto a CD-ROM. A complete database of geochemistry for the whole island of Sumatra has recently been released on CD-ROM (Johnson, 1999).

3.4.2.3 PROJECT COST

The total cost of the combined Sumatra projects was approximately £4.5 million (US\$8m) at 1988 prices.

3.4.2.4 IMPACT

The information communicated through the medium of geological and geochemical maps has many possible applications in Sumatra. However, as its potential application to mineral exploration was a major incentive for completing the mapping projects, it is this aspect that is considered here.

The Dutch established the foundations of a modern mining industry in Indonesia in the 1930s and 1940s, including a considerable amount of mining activity in Sumatra. Before the Second World War there were five

significant gold producing centres in Sumatra. Dutch prospecting also discovered copper, but not in economic quantities. A number of 1:200 000 scale geological map sheets were produced by the Dutch in the 1920s and 1930s but no systematic map coverage of the whole of Sumatra was attempted. Renewed interest in mineral exploration in Indonesia arose in the late 1960s and 1970s when exploration for copper, involving several large mining corporations, was partly focused on the Barisan Range of Sumatra (Van Leeuwen, 1994). Van Leeuwen has pointed out that as detailed geological maps were generally not available, areas for prospecting were selected with the use of limited geological information and based on very broad and generalised geological criteria. Geochemical reconnaissance surveys of selected areas were carried out to provide supplementary information. In Sumatra the results were that 'several very low grade porphyry occurrences were found in Western Sumatra' (Van Leeuwen, 1994).

It was against the above background that the systematic geological and geochemical survey of Sumatra took place. However, this ambitious undertaking took almost twenty years to complete and the new information that resulted could only be released incrementally as the programme of geological surveying and geochemical sampling and analysis progressed from northern to southern Sumatra through the time-span of the project. Accordingly, it had little impact on some of the prospecting campaigns already being undertaken by the private sector in the very early 1970s, but it gained in influence as time passed and information output increased. Information concerning the geology and geochemistry of an area in the north, the first to be released, was followed-up by a large international exploration and mining company and resulted in the discovery of the Tangse porphyry copper and molybdenum deposit. Here, however, the grade of mineralisation located to date is too low to support a viable mining operation.

Subsequent exploration by the private sector in other areas of Sumatra has led to one new gold mining operation and a further mine development project reaching feasibility study stage. Unlike the Bolivian example described previously, information resulting from the Sumatra project did not have the effect of opening up an extensive and largely geologically unknown area of country for prospecting. At the time the new systematic

geological and geochemical survey campaigns began, Sumatra was already recognised by several major and a number of smaller private sector companies as an area of interest for mineral exploration. The new information thus had a minimal impact within those limited areas already being explored by private sector exploration companies. However, for subsequent mineral exploration undertaken by the private sector in Sumatra, the main use of the new information has been in 'ranking concept/target areas allowing for prioritisation of field activities into areas of higher prospectivity' (Van Leeuwen, pers. comm.). In this respect the information output became the starting point for all subsequent exploration by the private sector.

Some measure of private sector mineral exploration activity between 1985 and 1996 is given by the number of non-coal contracts of work active in Sumatra, which rose from six in 1985, covering 5124 km², to a maximum of twenty-six in 1987, covering 62 928 km², before declining to ten in 1996, occupying 4567 km². In the five years from 1992 to 1996 exploration expenditure under Contracts of Work was reported as amounting to almost US\$68 million.

One quantitative measure of the take-up of the information outputs, as listed in Table 5, are the numbers of each of the products distributed to users. Accurate figures are available for the 1:250 000 scale geological map and report series, of which in 1999 a total of 15 200 had been issued by the Geological Research and Development Centre. This represented almost half of the total print run and necessitated the reprinting of six quadrangle map sheets and reports. At mid-1999 prices (per sheet) and exchange rates the total value of the maps distributed amounts to £117 000 (US\$193 000). It should be stressed however that cost recovery from the sale of such information aims only to recover a proportion of the cartographic production and printing costs of each map sheet, and not the much greater cost of fieldwork, data acquisition, analysis and synthesis.

3.4.2.5 CONCLUSION

The main value of the 'new' information generated by the projects considered here was in the refinement of targets for the private sector in their mineral exploration ventures. This can be characterised as an improvement in decision-making resulting from improved information (see general discussion under 2.2.3, above). However, although a good dialogue was maintained between project staff and the mining industry during the life of the projects, information resulting from them was not always available as quickly as the industry would have wished and consequently its impact on exploration activity was less influential than it might have been. The recent issue of all the available data on CD-ROM has greatly increased its utility and has been welcomed by the industry.

3.4.3 Geochemical exploration of northern Peru

3.4.3.1 INTRODUCTION

Approximately 25 000 km² of rugged terrain in the Western Cordillera of northern Peru (Figure XB) was investigated by geochemical drainage reconnaissance

between 1968 and 1971 as part of a larger project implemented on a collaborative basis between the BGS (then known as the Institute of Geological Sciences) and the Servicio de Geología y Minería (SGM), Lima, Peru, as part of a British Technical Assistance Programme. The project was largely funded by the UK Overseas Development Administration (ODA, now DFID) with a lesser contribution from the Peruvian Government.

The principal aim of the geochemical exploration programme was to assess the overall mineral potential of the northernmost part of the Western Cordillera by delineating major, hitherto unknown deposits of economic significance within a poorly-explored part of the Andean polymetallic province.

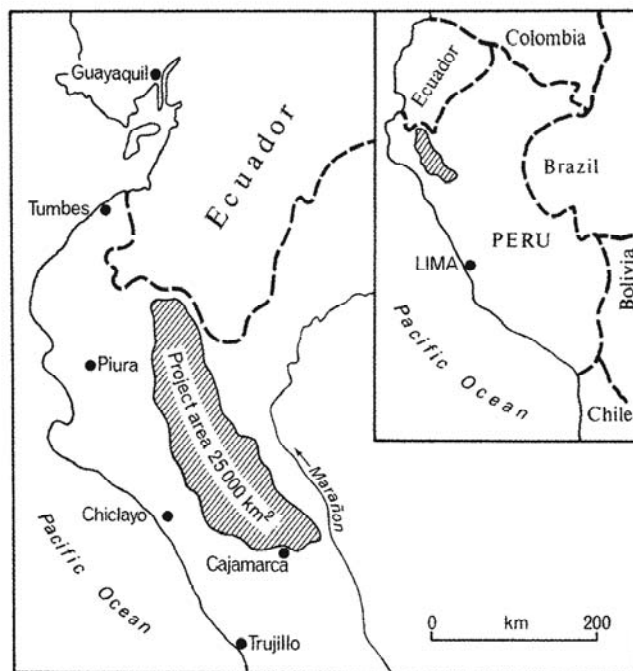


Figure 10 Location of project area in Western Cordillera of Peru, where BGS undertook a drainage geochemical reconnaissance survey between 1968 and 1971

3.4.3.2 PROJECT IMPLEMENTATION AND INFORMATION OUTPUTS

Although this project comprised one of a series in Peru — which from 1960 had led to the publication of a large number of geological maps — little or no systematic regional geological or geochemical surveying had been undertaken in the northern part of the Western Cordillera. The mining districts of Turmalina, Michiquillay and Hualgayoc were already known within the project area and it was recognised that these might represent part of a more extensive zone of important and, as yet, undiscovered deposits. The geochemical exploration programme was designed principally to effect the discovery of any other discrete mineral prospects of possible economic significance (Baldock, 1977).

The restricted availability of funds for fieldwork to cover such a large and inaccessible area meant that a very low-density geochemical stream-sediment sampling programme had to be adopted. An appropriate strategy was designed on the basis of an orientation geochemical survey

of the porphyry copper deposit at Michiquillay. This study indicated that a programme involving the collection of 1250 samples at pre-selected sites, with an average sampling density of approximately one per 20 km², should lead to the location of any major, hitherto undiscovered metalliferous deposits within the project area. The samples were analysed for Cu, Pb, Zn, Mo and Ag. In addition to the geochemical survey some geological mapping was also undertaken, which added to geological information collected during the earlier systematic geological mapping completed by the Servicio de Geología y Minería (Cobbing et al., 1981).

Geochemical maps were prepared showing the distribution pattern of each element in the form of simple colour-dot maps plotted at a scale of 1:500 000. A summary map was then produced that depicted the anomalous data for all elements, thus providing a basis upon which targets for more detailed exploration could be identified. The major anomalies on this map were further classified in order of probable economic significance, while important concentrations of minor anomalies were designated as 'anomalous regions'.

The geochemical sampling programme, supplemented by limited more focused geochemical surveys, resulted in the discovery of three particularly outstanding copper anomalies: La Granja, Jehuamarca (later renamed Cañariaco) and Pandachi (Baldock, 1977). Designated anomalous regions were the Pomahuaca region and the Yanacancha region, within which two further major anomalies, La Huaca – La Vega and Sorochuco, were identified by limited follow-up sampling during the project, together with major anomalies in the Yanacancha region. Significantly (see below) the project summary report pointed out that Yanacancha was the only region with a high concentration of anomalous Pb-Ag and As values, suggesting therefore the presence of '*currently unknown, Pb-Zn-Ag or precious metal mineralization*' (Baldock, 1971). Recommendations were made for follow-up exploration of all these target areas and much of this work was subsequently undertaken by the private sector.

3.4.3.3 PROJECT COST

The total cost of the project was £0.2 million (US\$0.48m) at 1971 prices.

3.4.3.4 IMPACT

Thirty years have elapsed since the results of the project with recommendations based on the new information gathered were issued in a summary report (Baldock, 1971). In the intervening period mineral exploration by the private sector, focussing on some of the identified targets, has resulted in the discovery of several extremely valuable deposits, two of which are described below.

At La Granja, for example, it is reported that one of the world's largest undeveloped copper deposits has been confirmed with measured and indicated resources amounting to some 2560 million tonnes of ore averaging 0.61 per cent copper. BHP Billiton acquired the property for about US\$35 million at the end of 2000 and is due to complete a feasibility study within five years. The Mines

and Energy Minister for Peru has estimated that about US\$1.25 billion will be needed to develop La Granja (Mining Magazine, May 2001, p. 244). Earlier plans were for mine production of 3.65 million tonnes per year of ore resulting in 33 000 tonnes of copper per year over a mine life of 15 years (Mining Magazine, January 2000, p. 12).

In the Yanacancha region, identified as a target for follow-up in Baldock (1971), subsequent work led eventually to the discovery of the Yanacocha gold deposit. Minera Yanacocha is now the leading gold producer in Latin America. Mineable reserves, calculated at a price of US\$300 per ounce, amounted to 31 million ounces of gold at the end of 1999 (Mining Journal, 4 February 2000, p. 90) with a total value of US\$9000 million. Output in 1999 was 1.66 million ounces and planned output for 2000 was 1.75 million ounces with a value of approximately \$490 million at a mean price of \$280 per ounce.

3.4.3.5 CONCLUSION

The 'Geochemical Exploration of Northern Peru Project' produced information that has had a radical impact on the development of the region by directing exploration by the private sector towards targets that have subsequently been proved to contain large-scale, economically viable deposits of both copper and gold. This case study also serves to demonstrate the very long time-scale involved in progressing from initial reconnaissance survey information to the establishment of a mine. It is not known what the total investment in follow-up exploration by the private sector has been during this time but it must be very substantial and, at the very least, two orders of magnitude greater than the investment by the British and Peruvian Governments in the initial project. As a result, the value of the mineral resources subsequently discovered comfortably exceeds US\$30 billion at current metal prices.

3.4.4 Midlands Goldfield Project, Zimbabwe

3.4.4.1 INTRODUCTION

The Midlands Goldfield Project differs from those already described in that it involved the production of geoscience information for an active mining district where the general geology was believed to be already well understood. The novelty of the project lay in the fact that it concentrated on developing information from a surveying programme focussed on a specific aspect of the geology that was subjected to very much more detailed study than had hitherto been attempted.

Zimbabwe has a long history of gold production that predates the European colonial period, and it is currently the third largest gold producer in Africa. Gold mining in Zimbabwe is a vital foreign exchange earner as well as a much needed source of employment. Several of the historically largest producing gold mines in the country are located over the Midlands Greenstone Belt, which is centred on the area between Kadoma in the north and Kwekwe in the south. Prior to the start of the Midlands Goldfield Project in 1989, gold mining activity in Zimbabwe had been largely restricted to the areas around old pre-colonial mine workings. The relative lack of

success in discovering genuinely new gold deposits indicated that most ore bodies that could be identified at the surface had probably already been found by the early miners. In more recent years gold exploration using conventional prospecting techniques (soil geochemistry and geophysics) had been tried with limited and generally only local success. With gold production in Zimbabwe outstripping the rate of discovery of new ore reserves it was clear that improved strategies would have to be developed for the successful targeting of concealed gold deposits.

Recent work elsewhere had highlighted the importance of the analysis and interpretation of structural geological data in gold exploration, although it was less clear to what extent this knowledge had been successful in guiding exploration programmes. In Canada and Western Australia the mineral exploration industry had come to recognise a close association between rocks deformed by shearing (shear zones) and important gold deposits. The role of shear deformation in facilitating the migration of mineral-bearing fluids through the earth's crust had become clearer as a result of detailed work in deeply-buried, high-grade metamorphic rocks. From these studies grew important new models of ore formation that linked, for the first time, the disseminated sources of valuable metals, a vector for their collection and migration to higher crustal levels accessible by man, and their deposition in economically workable concentrations. These studies also produced a number of new methodologies to assist the recognition of shear zones at all scales, from their regional appearance on satellite images to the microscopic, crystalline fabrics generated by shearing. At the same time, studies of the internal geometry of shear zones generated a new terminology to describe and relate the different structural elements. Local studies were undertaken to clarify the relationships between ore deposits and shears, thus establishing new exploration models using a coherent, standardised terminology.

The Midlands Goldfield Project was an attempt to apply this knowledge to Zimbabwe, and the Midlands Greenstone Belt was selected as a suitable testing ground in which to evaluate the worth of using structural features for the targeting of potential new gold reserves.

3.4.4.2 PROJECT IMPLEMENTATION AND INFORMATION OUTPUTS

The initial project, a collaborative effort involving the BGS and the Zimbabwe Geological Survey, took place between April 1989 and May 1992 and was jointly funded by the UK Department for International Development and the Ministry of Mines, Zimbabwe. The main project area, the Midlands Greenstone Belt, comprises some 14 000 km² over which general mapping of the geological structure was undertaken using satellite remote sensing techniques supported by detailed field mapping of selected sub-areas. Published geological maps at 1:100 000 scale already existed for the area and were used as a source of background geological information.

The main objectives of the project were twofold: to introduce to the Geological Survey of Zimbabwe recently developed techniques of structural analysis (see above) and, using these techniques, to identify targets for future

gold exploration by the private sector in the Midlands Goldfield. Accordingly, a 700 km² block of country was structurally mapped at 1:50 000 scale with selected sub-areas and sections mapped in detail at scales of 1:200 to 1:1000. A further 1000 km² was more selectively mapped at scales varying from 1:25 000 to 1:100 000. Many individual mines and prospects were mapped at scales of 1:200 and 1:2500. During an extension to the project (May 1992 – September 1993), other mineralised greenstone belts in Zimbabwe geologically similar to the Midlands Greenstone Belt were examined mainly by remote sensing.

The area covered by the Midlands Goldfield Project had been geologically surveyed at intervals between 1961 and 1973 by the then Geological Survey of Rhodesia. This information was published as three 1:100 000 scale map sheets each accompanied by a report describing the geology and mineral occurrences. These maps are principally lithostratigraphic — the rocks exposed at the surface being classified on the map according to rock type (sandstone, granite etc) and their probable age relations. Also shown on these maps are the mineral occurrences and mine sites, including all those with formal licenses, but with no distinction made between large and small mines.

The intention of the Midlands Goldfield Project was not to prepare a replacement geological map for the project area. Rather, it was to add additional levels of geological information derived from a detailed study of the deformation within rock units and their structural relationships.

A principal output consisted of a final open-file report (three volumes in four parts) covering the main project area of the Midlands Greenstone Belt, and fifteen short open-file reports describing other greenstone belts in Zimbabwe. The whole project was summarised in a published Bulletin of the Zimbabwe Geological Survey (Campbell & Pitfield, 1994), which included a map at a scale of 1:100 000 depicting the regional and gold bearing structures of the Midlands Greenstone Belt.

Additional outputs included about six technical papers published in The Annals of the Zimbabwe Geological Survey, and the first published tectonic map of Zimbabwe at 1:1 500 000 scale. There was, throughout the period of the project, frequent consultation with mining company personnel and mining consultants active in the Midlands Goldfield area.

3.4.4.3 PROJECT COST

The total cost of the Midlands Goldfield Project was approximately £1.15million (US\$2.0m) at 1990 prices. The uncertainty over the precise total is due to the fact that accurate costs for the counterpart inputs by the Zimbabwe Geological Survey are not available

3.4.4.4 IMPACT

As previously mentioned, many factors affect mineral exploration investment decisions, and exploration in the Midlands Goldfield has had, as a result of variation in these factors, a chequered history.

The decline in exploration during the early 1980s is clearly demonstrated by the mining license administration statistics, which record the issue of only one Exclusive

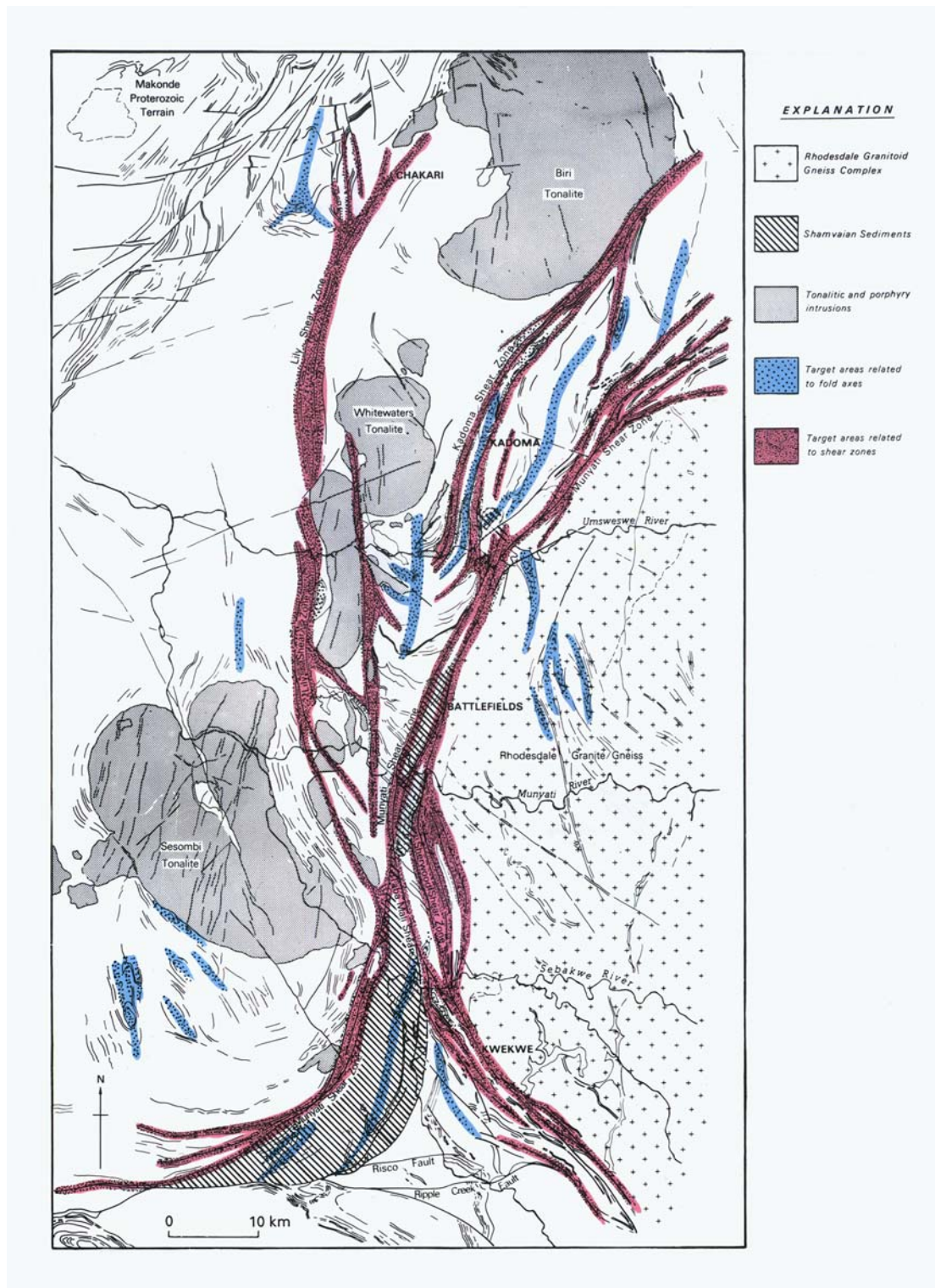


Figure 11 Structural information (shear/deformation zones and fold axes) interpreted from Landsat TM satellite imagery overlaid onto existing geological information for the Midlands Greenstone Belt, Zimbabwe, showing possible target areas for gold exploration (from Campbell & Pitfield, 1994)

Prospecting Order (EPO) in 1984. This partly reflects investor hesitation in the light of the new Government's declared intention to increase direct public equity participation in projects, as well as the continuing drain of skilled manpower and restrictions on the movement of finance and capital.

Renewed interest in the late 1980s mirrored a global trend in gold exploration activity and generated an increase

in applications for, and the issue of, EPOs. This trend continued through to the latter part of the 1990s. Furthermore, in the late 1970s and 1980s there had been a marked rise in small-scale mining (Box 5).

Though expansion of the exploration sector in line with the Government's development plans was seen as an achievable aim, it was, like mineral production, hampered by foreign exchange restrictions and difficulties in

acquiring work permits for expatriates. These restrictions had generated severe resource shortages in modern and serviceable exploration equipment, particularly diamond drilling machinery, and professional skills. For these reasons, the depletion of reserves, through production, continued to outstrip the discovery of new reserves, placing the sustainability of the industry in jeopardy.

Against this background we have attempted to evaluate the impact of the information released from the Midlands Goldfield Project on subsequent exploration for gold by private sector mining companies. That the issue of the new information aroused considerable interest in the mining community is beyond doubt. The various open-file reports together with Bulletin 101 contained conclusions indicating the most favourable target areas for gold mineralisation (e.g. Figure 11); and the sales of Bulletin 101, some 324 copies in Zimbabwe to mid 1994, indicate a level of interest that is unusual for a technical publication of the Geological Survey. Furthermore, several applications for EPOs were accompanied by maps that had previously formed part of the project output. A direct link between project information and further private sector exploration

activity can be established in a number of cases and it can, from these, be conservatively estimated that financial commitment to exploration projects in the period 1996 to 1998 approached US\$5 million. Also the increase in the potential value of gold, in newly discovered mine reserves, amounted to approximately US\$590 million at 1999 prices.

3.4.4.5 CONCLUSION

Discussions with a number of mining companies in Zimbabwe indicate that the new information resulting from the Midlands Goldfield Project has contributed substantially to the discovery of new gold reserves, which have a far greater potential value than the total cost of the project. Determining the precise proportion of the potential value that can be attributed to the application of the new information has not proved possible, but this example does demonstrate that targeting geological mapping on the collection of data of newly discovered significance can produce economically valuable results.

Box 5 *The rise of small-scale mining in Zimbabwe*

The difficult economic conditions during several years both preceding and following independence were not restricted to the formal mining industry but had an impact throughout the Zimbabwe economy. As a result, employment opportunities were reduced and new investment postponed. Many workers found themselves unemployed or underemployed and sought to replace lost incomes by taking up artisanal mining based either on free-gold-bearing quartz reefs or on alluvial gold in the major river systems.

The number of small-scale operators, each producing less than 30 kg and mostly less than 5 kg per annum, had grown from approximately 200 in 1979 to almost 700 in 1987. In 1988, the Small-Scale Miners Association of Zimbabwe reported a membership in excess of 5,000 and the sector probably generated irregular employment for more than 100,000 Zimbabweans.

The value of this artisanal mining rests in its social impact, through its ability to generate rural employment at low cost, rather than in the value of gold produced.

4 Evaluating the cost effectiveness of groundwater exploration

4.1 INTRODUCTION

Groundwater has many advantages for water supply development. Aquifers underlie geographically large areas and can therefore be tapped close to centres of demand, thus reducing reticulation requirements. Furthermore, water stored in aquifers is, for most part, protected naturally from evaporation and the drainable storage is generally large, providing a buffer to rainfall variations and thereby increasing reliability. Groundwater is also of generally excellent microbiological and organic quality, thus reducing or eliminating the need for treatment. Finally, the capital cost of groundwater development is relatively low and land requirements minimal, with the result that development of the resource can proceed incrementally, and is more affordable.

These characteristics offer huge advantages over surface water development, especially in arid and semi-arid environments. In Africa, for example, groundwater probably supports the livelihoods of over 75 per cent of the population, largely through low cost, low yield hand-pumps in rural areas. This dependency is likely to increase as governments and donors strive to meet the new international development target of reducing — by half — the proportion of people without access to safe drinking water by 2015.¹

Although groundwater supply has many advantages, development is not without problems. Two key challenges are associated with:

- the difficulty of finding groundwater (well/borehole siting) in some environments, such as in African basement aquifers with major geohydrological heterogeneity;
- the estimation of groundwater resource potential, which is a function of recharge rate and exploitable storage.

In the section below, we look at how hydrogeological information acquired through generalised geological mapping and more specific site investigations can be used to address these problems and increase the likelihood of successful development. We begin by looking briefly at the techniques and skills used to find groundwater (Section 4.2). A framework for evaluating the costs and benefits of different levels of hydrogeological knowledge is then developed, based on comparisons of drilling success rates (Section 4.3). The framework is then applied to a recently completed water supply project in Nigeria in order to

assess the costs and benefits of hydrogeological information in a practical setting (Section 4.4).

4.2 FINDING GROUNDWATER

4.2.1 Groundwater exploration

Selecting a site for a groundwater well or borehole requires hydrogeological investigation and, where appropriate, community consultation. Bringing together both sets of factors, final selection is likely to consider:

- the possibility of obtaining an adequate quantity of water of acceptable quality. A water point is deemed successful when yield and quality satisfy the needs of a particular use/user. Given the limited discharge possible with hand-pumps, groundwater investigations also need to focus on finding sites with minimum lift requirements and with sufficient permeability to minimise water table drawdown and ensure reliability;
- the risk of groundwater contamination, which may arise for example from the location of waste disposal facilities. There may also be risks associated with erosion, flooding, ease of access and future developments planned for the area.

In some areas, for example on major alluvial plains with abundant rainfall, groundwater may be widely available at relatively shallow depths. In these areas, little or no hydrogeological investigation may be necessary as wells or boreholes may be successful wherever they are developed; siting can therefore be determined by the local population alone. However, in environments that are more geologically heterogeneous, investigations ranging from simple field observation to costly exploratory drilling and surveying may be necessary to ensure success. Where such investigations help reduce the number of unsuccessful wells drilled, cost savings may be significant — more than covering the cost of the investigation procedure. A methodological approach for evaluating the most appropriate approach to groundwater exploration, based on cost-effectiveness criteria, is discussed under Section 4.3 below.

4.2.2 Assessment methods and information levels

A number of possible approaches to groundwater exploration, of varying sophistication and cost, are possible. If used systematically, rather than on a piecemeal basis, each should allow some increase in the success rate for wells and boreholes above that of random, ‘wildcat’ drilling. If the information generated is ‘pooled’ for the benefit of subsequent programmes, then benefits will be long-lasting and widespread. Different ‘levels’ of groundwater explor-

¹ UN Millennium Summit ministerial declaration, September 2000. The most recent data indicate that over one billion people around the world lack access to safe drinking water (WHO-UNICEF, 2000).

ation procedure are outlined in Table 6, with sophistication increasing from Levels 1 to 5. In order to generate the most relevant information at the lowest cost, investigation should proceed incrementally (i.e. in successive stages). When levels are skipped, potentially useful and inexpensive information is missed and costs may increase unnecessarily. In practice, a fair degree of hydrogeological judgement is required to decide the level of investigation needed in different areas, ideally supplemented with simple economic analysis (see below).

The costs of alternative exploration approaches will vary according to various location-specific factors but, as a general rule, will increase from Level 1 to 5. Level 1 investigation, for example, will incur a labour cost in terms of time spent finding, collating and interpreting existing data, but not the cost of specialist equipment. Labour costs

will depend on who is conducting the inventory, and the extent to which data is fragmented between different organisations. In some countries, the data itself will need to be purchased.

Investigations at Level 3 and beyond may involve the purchase of expensive equipment and require expert interpretation of the data generated. In some countries, both equipment and expertise may already be in place; in others, the equipment will need to be purchased new and local technicians will have to be trained in its use. This was the case in Benue State, Nigeria, in the project discussed under Section 4.4. As these techniques involve work in the field, mobilisation and transport costs will also be incurred. In remote areas, these costs are likely to be the most significant expense.

LEVEL	INVESTIGATION APPROACH	NOTES
1	<p>Inventory of existing data:</p> <p>Geological data (e.g. from maps, if available) Hydrological and climatic data Existing well/borehole data</p>	Often available from ministries and line departments at central and/or regional levels. Donors and NGOs may also have their own data holdings.
2	<p>Remote sensing interpretation:</p> <p>Satellite imagery Aerial photography</p> <p>Used to infer (indirectly) presence of groundwater from images of topography, geomorphology and vegetation.</p>	Very good for obtaining general overview of large project areas. Satellite images may be expensive though, and data require expert interpretation.
3	<p>Hydrogeological fieldwork:</p> <p>Geomorphological analysis Water point inventory and direct monitoring Hydro-climatic monitoring Discussion with local communities – local knowledge</p>	Objective is to ‘ground-truth’ results from above, and often carried out in conjunction with level 2. Levels 1-3 involve thorough evaluation of ground surface; techniques 4-5 below focus on subsurface characterisation.
4	<p>Geophysical surveying:</p> <p>Electrical resistivity Seismic refraction Electromagnetic profiling (EM) VLF profiling</p>	<p>Aim is to indirectly characterise subsurface geology through measurement of physical properties carried out at surface.</p> <p>Equipment is expensive; data requires expert interpretation.</p>
5	<p>Exploratory drilling:</p> <p>Hand drilling Machine drilling Geological logging Geophysical logging Test pumping Water sampling</p>	<p>Purpose is to gather data from test boreholes to evaluate potential for production wells in area and to confirm previous inferences.</p> <p>Expensive, and communities may be frustrated by drilling of ‘test’ boreholes.</p>

Table 6 A logical approach to groundwater exploration (after van Dongen and Woodhouse, 1994)

4.3 ECONOMIC EVALUATION OF ALTERNATIVE APPROACHES

4.3.1 Cost-effectiveness analysis

To determine the level at which groundwater exploration should proceed, simple economic concepts can be applied. Here the concepts are discussed in a related sense: to help quantify the value of hydrogeological information in terms of the improvements in water-supply-siting decisions that result.

As noted above, groundwater investigation has a cost. However, if the cost can be offset by an improvement in the success of a water supply programme, then the cost of acquiring hydrogeological information can be justified. But how can 'success' be quantified in economic terms? One approach is to compare the costs of groundwater exploration with the costs of drilling, on the basis that hydrogeological knowledge can reduce the number of unsuccessful wells or boreholes drilled.² Hence, the benefits of acquiring hydrogeological knowledge can be quantified as drilling costs saved. This type of economic approach is known as a cost-effectiveness analysis, and has been applied in other areas where geological information saves costs through improved decision-making. As in any economic appraisal, comparisons are made between a baseline scenario, the 'without' condition and one or more alternatives — the 'with' condition (see under Section 2.2.4 above).

4.3.2 Empirical approaches

The relationship between exploration costs and drilling costs, taking into account differences in the percentage of unsuccessful wells drilled with and without the use of hydrogeological knowledge, can be presented as follows:

$$B = C_r - C_a = \frac{C_d}{R_o} - \frac{C_d + C_a}{R_a}$$

Where:

- B Benefits (drilling costs saved per borehole)
- C_r Reduction in drilling costs per borehole
- C_a Cost per borehole of a given technique or assessment
- C_d Average drilling cost for a water supply well or borehole (excluding installation of casing, screens and gravel pack, and without development and test pumping)
- R_o Drilling success rate without hydrogeological assessment ('wildcat' drilling)
- R_a Drilling success rate with hydrogeological assessment

In the above formula the baseline condition is represented as 'wildcat' drilling, in which the siting of water

² An unsuccessful well or borehole is one that does not meet the quantity and/or quality requirements of the project. On hand-pump projects in rural Africa where minimum target yields may be as low as 0.2l/s, this is often because the well is completely dry, or the groundwater is not potable.

points is not informed by geological knowledge.³ However, comparisons can easily be made between different levels of investigation to assess whether incremental (marginal) cost savings resulting from increasing levels of knowledge (see Table 6) are justified. So we would choose technique *x* over *y* if its marginal cost was less than the saving in drilling costs achievable by its application (the marginal benefits):

$$C_x - C_y < \left(\frac{C_d}{R_y} - \frac{C_d}{R_x} \right)$$

Following on from the above, it is also possible to estimate the *maximum* justifiable expenditure on groundwater assessment (C_{max}) when 'drilling success rates with assessment' (R_a) approach 1.0, or perhaps more realistically 0.9:

$$C_{\max} = \frac{C_d(0.9 - R_o)}{R_o}$$

Clearly in geological environments where groundwater is widespread and 'wildcat' success rates are relatively high, the justified assessment expenditure will be low. In more difficult areas, and where drilling costs are high (perhaps because of very deep water tables), the converse is true.

It is also possible to manipulate the economic analysis further. Box 6 describes how minimum *success rates* for different levels of groundwater assessment were estimated for livestock water supply activities in Botswana, again illustrating how the 'production' of hydrogeological knowledge can be evaluated in economic terms.

4.3.3 Synthesis

The cost-effectiveness approach described above is an attractive way of evaluating *some* of the benefits of hydrogeological information. In practice, however, there may be difficulties in acquiring the data necessary for the evaluation. While the costs of hydrogeological investigations and drilling are relatively easy to estimate, gathering data on drilling success rates can be more difficult. This is because success rates are often unreported, or because different definitions of 'success' are used by different agencies. In the case study described below, 'wildcat' success rates prior to hydrogeological investigations had to be estimated indirectly as no records of dry boreholes were available.

A further concern is the assumed link between the generation of geological information and its utilisation in future water supply programmes. Any long term increase in drilling success rates will depend on the degree to which raw data collected during investigations can be (a) converted into information; (b) disseminated to end users in appropriate forms; and (c) used in decisions which are

³ Wildcat drilling is not completely random. Sites are likely to be chosen for contractual convenience (e.g. nearness to a road), in accordance with community wishes, and/or with the help of local 'diviners'.

Box 6 *The cost-effectiveness of acquiring geological information: hydrogeological investigations for livestock watering in Botswana*

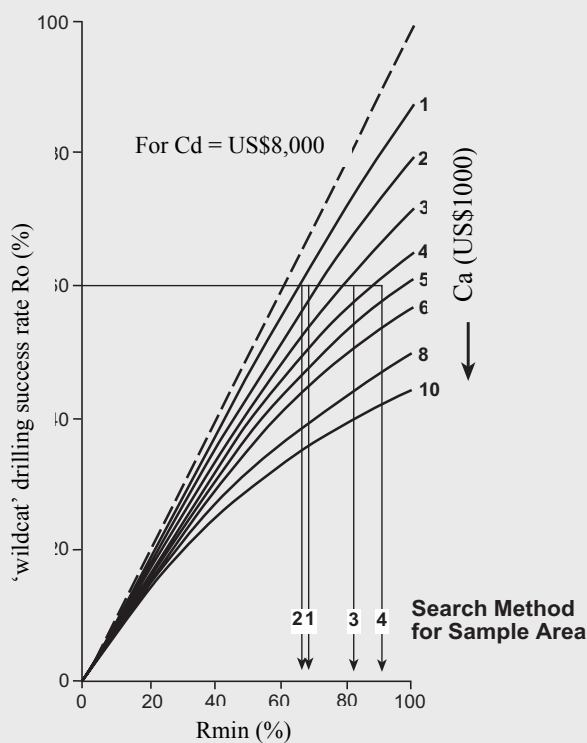
In many semi-arid regions of the world the rearing of livestock, at low densities, is an important source of income and livelihood security. A key constraint is water supply. Although water demands are low and dispersed, reliable yields of around 0.5l/s are required, and the water must be of acceptable quality. Meeting these objectives can be difficult, especially where hydrogeological information is limited or non-existent. Investment in geological information can therefore prove cost-effective.

In the Kalahari area of southern Botswana, Farr et al. (1982) evaluated the cost-effectiveness of alternative hydrogeological assessment approaches, ranging from simple grid-controlled drilling to hydrostratigraphic exploration (see below). In this area, a statistical analysis of previous drilling experience revealed very limited hydrogeological knowledge, and drilling success rates of around 60%. Although the success rate any given assessment approach is not known, it is possible to calculate *minimum* success rate (R_{min}) necessary for it to be economically viable:

$$R_{min} = \frac{C_a R_o}{(C_d - C_a R_o)}$$

where C_d is the average borehole drilling cost; R_o the wildcat drilling success rate; and C_a the cost per borehole of a given investigation approach.

This can be represented graphically (see below) for a given borehole drilling costs and wildcat success rates. In the Botswana case study, for a wildcat success rate of 60% and average drilling cost of US\$8000 (1982 figures), the graph indicates that approaches (1), (2), (3) and (4) would require minimum success rates of around 68%, 66%, 81% and 90% respectively. Approach (5) — full hydrostratigraphic exploration — would not be viable.



Search methods

1. Grid-controlled drilling: small number of boreholes drilled on widely spaced grid; further boreholes informed by initial results and inferences.
2. Geologically-controlled drilling: based on inventory of existing geological data and records.
3. Long-traverse geophysics: a minimal geophysical programme designed to characterise the subsurface
4. Short and long-traverse geophysics: includes detailed, short traverse geophysical surveys.
5. Hydrostratigraphic exploration: as above but also including exploratory drilling, logging and pumping tests.

Information in this box is based on Farr et al. (1982) and Foster et al. (2000).

sensitive to the new information provided (see Chapter 2 for further discussion on this point). This will be determined in large part by the institutional environment in which projects operate, and the emphasis placed on links (b) and (c) in the process above. For example, where links between data collection agencies and end users (e.g. drilling companies) are weak, and the thrust of projects is on data collection per se, uptake and use of new information may be limited. Where institutional coordination and linkages are stronger however, and projects include training and capacity building components, uptake and use is likely to be higher.

It is important to note that the economic approach outlined above only seeks to quantify one stream of benefits: that of drilling costs saved. However, other benefits are also likely to result from hydrogeological investigations. These include:

- *Improvements in technical choice.* Investment in hydrogeological data can increase the reliability and drought-resistance of water points through better siting and design. In areas where investigation indicates no usable groundwater, it can also prevent further and futile investment in wells and boreholes. In these areas, other means of providing water (e.g. surface sources; rainwater harvesting) will need to be considered.
- *Meeting community expectations.* Experience indicates that community involvement in, and ‘ownership’ of, water supply projects is essential for sustainability. Increasingly, efforts to involve local users are made before any water points are developed. This may involve, for example, establishment by the community of a water committee or user association as a precondition for assistance. This ‘investment’ in time, money and trust by a community may be jeopardised if subsequent drilling proves unsuccessful. Geological investigations which increase the likelihood of drilling success are therefore important in ensuring continued support for a participatory project approach.
- *Better land use planning.* Hydrogeological information supports decision-making in many other key areas such as the siting of waste disposal sites (from family pit latrines to nuclear waste).

In conclusion, it should be emphasised that the influence of hydrogeological information generated by specific projects can extend far beyond the immediate ‘project area’. For example, the hydrogeological investigations carried out in the Obi/Oju area of Nigeria (see below) are likely to influence water supply decisions in other geologically similar areas across Nigeria. This is because an effort was made to include regional and state level personnel in training programmes.

4.4 COST-EFFECTIVENESS CASE STUDY: HYDROGEOLOGICAL ASSESSMENT IN BENUE STATE, NIGERIA

In this section, the economic principles outlined above are used to evaluate the cost-effectiveness of a groundwater assessment project in Benue State, Nigeria. This is an area

where increasing access to safe water supplies is a government and donor priority. Further information on the data and methodology used is contained in the Appendix, together with the spreadsheets used to estimate cost savings.

4.4.1 Background

The Oju area of eastern Nigeria (Figure 12) is underlain by low permeability rocks such as mudstones and siltstones and is a very difficult area in which to find sustainable rural water supplies. As a result, the development of groundwater wells and boreholes has met with very limited success, and water supply coverage across the area from improved sources is probably less than 5 per cent.⁴

During the annual (November to April) dry season, unprotected ponds, seepages and hollows are the main sources of domestic water. Most of these sources dry up by February, and those that remain are often contaminated and far from villages. As a result, much of the population (roughly 300 000) is affected by water-related illnesses such as guinea worm, dysentery, cholera and typhoid. Indeed the incidence of guinea worm in northern Oju is the highest in Nigeria.

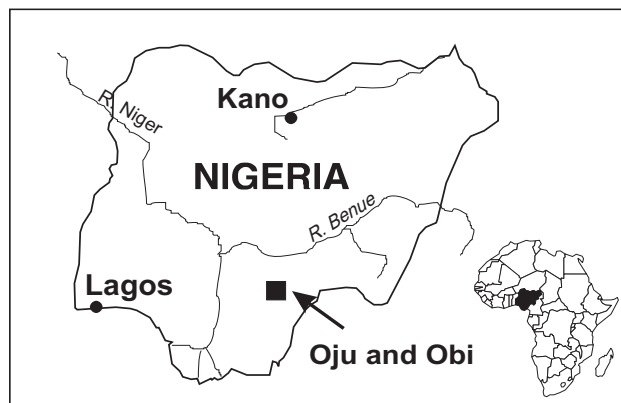


Figure 12 Location of hydrogeological assessment project in Nigeria

4.4.2 Groundwater assessment

Against this background, the UK Department for International Development (DFID) commissioned BGS to carry out a hydrogeological investigation of the area to devise, if possible, effective and locally appropriate methods for siting wells and boreholes. A wide range of techniques has been applied including the drilling of exploratory boreholes, taking core samples, surface geophysics and surveys, test pumping, water chemistry monitoring and remote sensing (Levels 1 through 5 in Table 6). The primary aim has been to understand the complex hydrogeology of the area in sufficient detail to produce easily understandable maps and guidelines for groundwater development. The groundwater potential map for the area is shown in Figure 13. A large part of BGS’s work has focused on communicating both the methods and

⁴ One borehole is assumed to provide water for 250 people

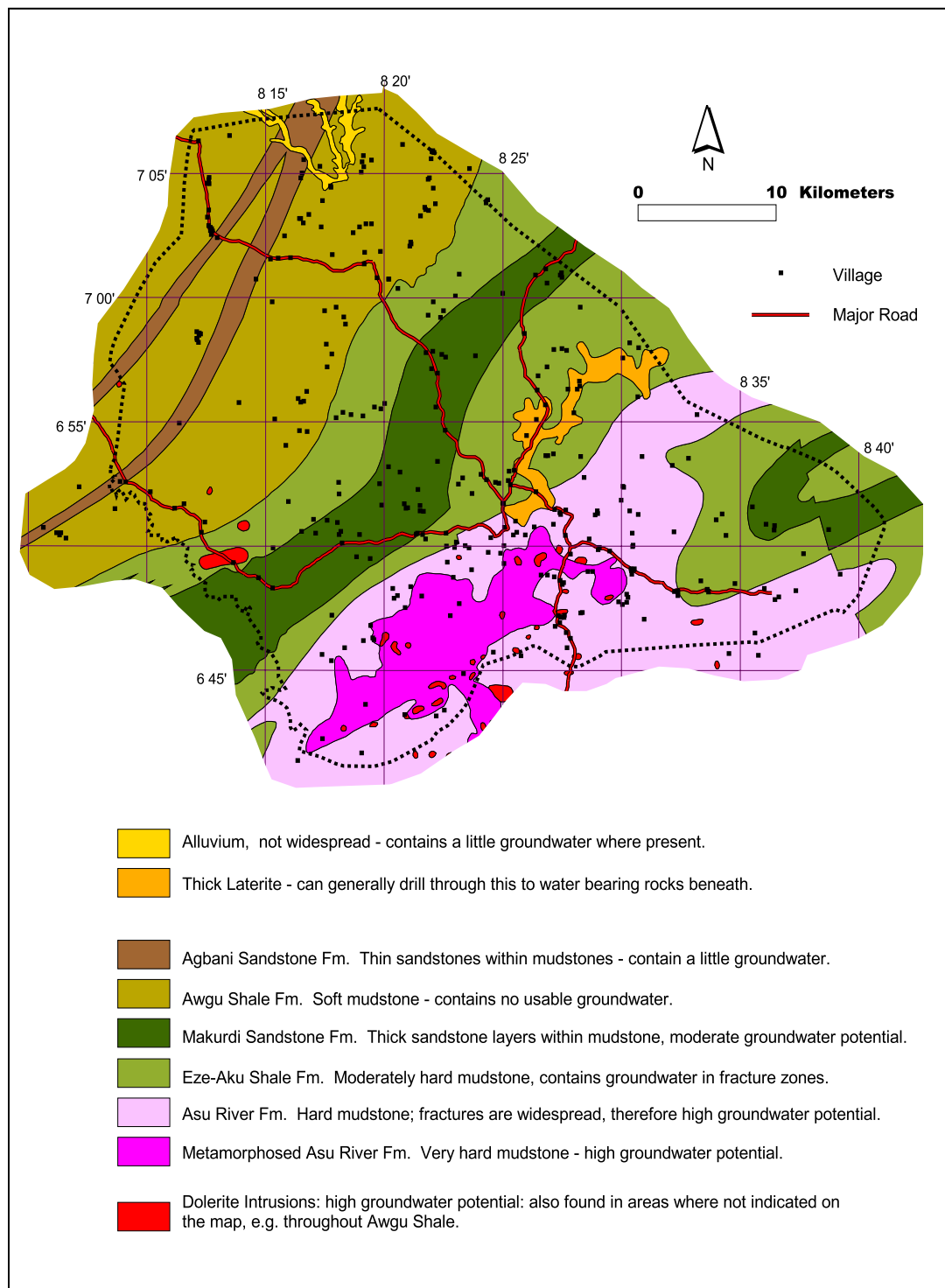


Figure 13 Simplified groundwater potential map of Oju and Obi, eastern Nigeria (MacDonald & Davies, 1998)

results of the research to local stakeholders, including WaterAid⁵ staff and government personnel. These are the people responsible for the future management of groundwater development in the area.

A simple method termed 'geological triangulation' has been developed to help local stakeholders investigate the geology at village level. This combines map information with simple geological field techniques and geophysics to give a reliable indication of groundwater potential, without

the expense of drilling exploratory boreholes. Standard geophysical equipment, such as resistivity and EM34-3, has been used. This is equipment that is employed elsewhere in Nigeria, though purchased from outside the country. However, 'standard' survey and interpretation methods have been adapted so that they can be used for locating the typical groundwater targets found within the low permeability sediments of Oju. Simple test pumping methods have also been developed to help the community assess the yield of a borehole before going to the expense of fitting a hand pump.

⁵ WaterAid is UK-based NGO, working through local partner NGOs in developing countries.

4.4.3 Cost-effectiveness of groundwater assessment in Oju and Obi

The groundwater assessment and capacity building work carried out by BGS in Oju and Obi was expensive: over three years (1996-1998) total costs amounted to around £579 000 in present value terms. A key question is whether such a high investment was justified in economic terms. To address this question, a simple (*ex poste*) economic appraisal of the project was carried out, focusing on the use of the hydrogeological information produced by the project in future borehole siting decisions. The analysis is set out as a spreadsheet included in the Appendix, together with detailed Help Notes on spreadsheet structure and data entry. Results are summarised in Table 7 below.

Using the approach to benefit estimation outlined in Sections 2.2 and 2.3, an economic evaluation of the hydrogeological assessment needs to ask the question: what is the value of information gain to future decisions with measurable economic consequences? More specifically, an evaluation needs to identify: (a) the users of the new information generated; (b) the types of decisions affected by the new information; and (c) the economic consequences of decision changes. These questions are addressed below for the Oju/Obi case study in relation to the step-wise process of economic evaluation outlined in Section 2.3.2.

Step 1. Define the nature of costs and benefits and, if possible, identify all the costs and benefits associated with a project, programme or policy over an appropriate period of time.

Drawing on the approach to benefit estimation outlined in Section 2.3.2 above, the analysis focuses on the use of hydrogeological information in borehole siting decisions, with one stream of benefits (from many possible streams) estimated as costs avoided. Costs avoided stem from improved borehole siting decisions that reduce the number (and therefore cost) of unsuccessful boreholes drilled. The analysis therefore focuses on an immediate application of hydrogeological information, not on the 'downstream' benefits of improved rural water supply.

To assess the value of hydrogeological information, comparisons are made between projected borehole drilling activities that are not informed by hydrogeological information (the baseline, or 'without' project condition), and borehole drilling that is informed by project-derived hydrogeological information (the 'with' project condition). The key question the analysis seeks to address is whether the investment in generating geological information in the period 1996-1998 is likely to be cost effective in the years that follow.

For this analysis, major assumptions have had to be made about both 'with' and 'without' project scenarios. As the investment in geological information was completed in 1998, the baseline condition is hypothetical: assumptions have been made about what would happen in terms of drilling outcomes over a 10 year period *had the investment not been made*. Similarly in the 'with' project scenario, assumptions are made about projected drilling outcomes in the future *based on decisions made with the benefit of new hydrogeological information*.

In each case, it is assumed that 200 (successful) boreholes need to be drilled across the statement period, and across the project area. This is a reasonable assumption given the high population and low water supply coverage of the area, together with the high priority now being given to increasing access to water in Nigeria. The project area itself is divided into six zones, representing the geological/groundwater potential areas delineated by the hydrogeological survey. Population figures for each area (see Table 7) are used to determine the (hypothetical) proportion of boreholes drilled in each area.

The spreadsheets, and comparative scenarios, can thus be summarised as follows:

- **Baseline:** projects the costs of borehole drilling on a 'wildcat' basis, i.e. assumes borehole siting proceeds without the use of hydrogeological information generated by the project.
- **Scenario 1:** for comparison with Baseline 1, projects the costs of borehole drilling on a geologically-informed basis, i.e. borehole siting decisions are made with the use of project-generated hydrogeological information. The project incurs additional costs in terms of groundwater assessment, but saves costs through increased drilling success rates. The difference in total drilling and assessment costs between Baseline 1 and Scenario 1 provides an indication of the costs saved by investing in hydrogeological information.

Step 2. Identify the incidence of all costs and benefits over the time period identified and quantify, in monetary terms where possible, costs and benefits

The spreadsheet statement (see Appendix) runs for the period 1996–2006, but could reasonably be extended to reflect continued use of the information generated (i.e. its expected 'shelf-life') beyond 2006. The effects of inflation are ignored, as relative prices are assumed to remain unchanged over the appraisal period. For this reason constant (1996) prices are used throughout.

The costs of the hydrogeological assessment are relatively easy to estimate using project budget statements, records and invoices. They include the capital costs of purchasing geophysical and other equipment, and the recurrent costs associated with staffing and running the project. They also include costs incurred by the local project partner, WaterAid, in support of the hydrogeological assessment (extra logistical support etc). Here, an attempt has been made to disaggregate the additional costs incurred in supporting the assessment, from the costs that would have been incurred in carrying out drilling activities without the assessment.

Before drilling costs 'with' and 'without' hydrogeological information can be calculated, it is first necessary to estimate drilling success rates in each case. Box 7 explains how this was carried out in a situation where information on success rates was very limited. In two of the geological zones within the project area, success rates remain unchanged at 90 per cent. In these areas groundwater can usually be found without specialist knowledge. In the

Geological zone	Number of villages in area	Approximate population	Number of water points needed per area	Drilling success rates: 'without' (Ro) & 'with' (Ra)
Mm Asu River Group	12	10 000	7	90% (90%)
Asu River Group	98	85 000	58	90% (90%)
Lower Eze-Aku	54	50 000	32	35% (85%)
Makurdi Sandstone	46	40 000	28	5% (70%)
Upper Eze-Aku	22	20 000	13	30% (40%)
Awgu Shale	106	95 000	62	15% (75%)
<i>TOTALS</i>	<i>338 (100%)</i>	<i>300 000</i>	<i>200</i>	

Note: analysis assumes 200 successful boreholes drilled 1996-2006, distributed between zones according to population size. Figures in parentheses refer to 'with' project situation, i.e. position resulting from investment in hydrogeological information.

Table 7 Information on the project area (Oju-Obi) used in the economic analysis.

remaining four areas however, success rates improve significantly with the new information. The analysis assumes that in Scenario 1, success rates do not improve until after the hydrogeological assessment and training work is complete.

Having estimated success rates, the total cost of drilling required to meet coverage targets in each area, based on the number, cost and success rate of drilling, can be estimated for each year. In the Baseline statement, therefore, total drilling costs are higher because success rates are lower. Drilling costs can then be added to the costs of groundwater assessment (zero in the baseline) to give annual cost totals for drilling *and* assessment.

Step 3. *Adjust all values for time using an appropriate discount rate*

In theory, the annual cost totals derived above could be summed over the 10-year period to give a single figure for each statement. The cost difference — positive or negative — could then be attributed to the groundwater assessment. While the basic logic is correct, this would assume all costs incurred in different time periods are valued equally. This is not the case however, as resources used up or generated earlier are valued more highly than resources in later periods. Conventionally, this problem is addressed through the process of discounting, applying a weight (discount factor) to the resources used in different years to convert them to present values (Box 4).

In the current analysis, a discount rate of 10 per cent was applied. Annual cost totals are then multiplied by corresponding discount factors — shown in the spreadsheets — to give present value figures. These can then be summed to give a single figure for the total present value (TPV) of costs.

Sensitivity analysis can be used to determine how appraisal results are affected by changes to key assumptions. In this instance, alternative discount rates were applied to see how sensitive results are to the rate at which future costs are discounted. Even at a higher discount rate of 15 per cent, however, the investment in

geological information still generates benefits (see below). Other key assumptions — drilling costs, statement period, success rates, etc — could also be modified to test outcomes, if desired.

Step 4. *Apply a decision criterion*

Various decision criteria can be used to help decide whether a project is acceptable or not in economic terms. In the present case, two assessment criteria are used: the present value of cost savings, or net present value (NPV), and the benefit cost ratio (BCR):

- NPV: in this analysis, the difference in the total present value of costs between 'with' and 'without' project scenarios. In other words, the present value of drilling costs saved through investment in hydrogeological information. The evaluation indicates that, at a discount rate of 10 per cent, cost savings (benefits) amount to over £750,000 (Table 8).
- BCR: the ratio of discounted benefits (costs saved in this instance) to discounted groundwater assessment costs. The evaluation gives a positive BCR of 1.3, indicating again that the investment in hydrogeological information in Oju is worthwhile.

Evaluation criteria	Result
Present value of costs without study	£2,972,661
Present value of costs with study	£2,221,522
Net benefit (present value of costs saved)	£751,139
Benefit-Cost Ratio (BCR)	1.3

Note: figures are taken from the spreadsheets in Appendix for a discount rate (r) of 10%.

Table 8 The value of hydrogeological information in Oju, Nigeria: evaluation results

Box 7 *Estimating drilling success rates for the economic analysis (Oju-Obi)*

There were two drilling programmes in Oju and Obi prior to the BGS investigations in 1996. The success of both these programmes was limited, and no records were kept of dry boreholes. As therefore with most African rural water programmes it is not possible to reliably estimate drilling success rates prior to adoption of a more systematic approach. Some of the successful boreholes from these programmes remain, but work only intermittently.

An indirect approach is therefore required to estimate the probable success of 'wildcat' drilling in Oju and Obi. The hydrogeological investigations carried out by BGS were designed to characterise the potential for groundwater in the area and suggest methods for finding suitable sites for boreholes and wells. Over 75 km of geophysical traverses were carried out and 50 exploration boreholes drilled. This information can be used to estimate the proportion of land area that has usable groundwater. Therefore, assuming a random drilling pattern across the area, a 'wildcat' success rate can be estimated. This indirect method is explained in more detail below.

1. From the study areas in each rock type, estimate the proportion of the study area that proved a high potential for groundwater. Extrapolate from the study areas to give a proportion of each rock unit with groundwater.
2. Assume 100% success in the areas with high potential for groundwater and 0% success in the areas with poor potential (exceptions in both areas will cancel each other out).
3. Calculate the land area of each rock unit and integrate the individual rock unit success rates across Oju and Obi.

The main assumption of this method is that the study area is representative of the whole rock unit. This assumption is not unreasonable in that the study areas were originally designed to be representative and they also cover a large area (see Davies and MacDonald, 1999).

The number of villages in each area and population figures are taken from MacDonald and Davies (1998). The population of the Oju/Obi area has been estimated as 300 000. This has been divided evenly among the 338 villages. Assuming coverage standards are set at 250 people per borehole (the usual approach), then 1200 boreholes/wells would be required to provide full coverage in the area.

In the year following the investigations approximately 35 water points were constructed in Oju and Obi using the guidelines and techniques developed by BGS. Although over 90% of these have been successful, there are not sufficient data from across the geological zones to reliably estimate success. Therefore the study areas must be looked at again to give a rough estimate of likely success. In each study area several kilometres of geophysical surveys were undertaken to characterise the rock type. Fifty boreholes were then drilled throughout the area according to the geophysical data. Some boreholes were drilled on anomalies that were thought to indicate groundwater; others in areas where the geophysics indicated little water. Approximate success rates can be indicated from the deviation of the drilling results from the expected outcome in each study area.

Using this approach, the success rates of both wildcat and geologically-informed drilling can be estimated.

Appendix Help notes — cost effective analysis of groundwater assessment in Oju, Nigeria

A.1 INTRODUCTION

The notes below provide more detailed information on the methodology, structure and data needs of the cost-effectiveness analysis applied to the Oju case study outlined in Section 4.4. The cost-effectiveness analysis itself is presented at the end of this appendix as a spreadsheet. The discussion begins with a general explanation of analytical approach and method. Table A1 then provides specific guidance on data entry, cross-referenced to the spreadsheets using spreadsheet headings and codes.

A.2 ANALYTICAL APPROACH AND STRUCTURE

The aim of the spreadsheet is to quantify the value of hydrogeological information produced on a DFID-funded project in south-eastern Nigeria. The ultimate aim of the groundwater assessment project (hereafter termed ‘the project’) has been to increase access to sustainable groundwater supplies in an area where groundwater has proved difficult to find. The spreadsheet focuses on the use of hydrogeological information in borehole siting decisions, with benefits estimated as costs avoided. Costs avoided result from improved borehole siting decisions that reduce the number (and therefore cost) of unsuccessful boreholes drilled. The aim is therefore to evaluate the benefits of hydrogeological investigation in planning and implementing water supply project, rather than assess the ‘downstream’ benefits of the rural water supply project itself.

To assess the value of hydrogeological information, comparisons are made between projected borehole drilling activities that are not informed by hydrogeological information (the baseline, or ‘without’ project condition), and borehole drilling that is informed by project-derived hydrogeological information (the ‘with’ project condition). The key question the analysis seeks to address is whether the investment made in geological information in the period 1996-1998 is likely to be cost effective in the years that follow. The spreadsheet statement runs for the period 1996–2006, though it could reasonably be extended to reflect continued use of the information generated. The

effects of inflation are ignored, as relative prices are assumed to remain unchanged over the appraisal period. Constant (1996) prices are therefore used throughout.

For this analysis, major assumptions have had to be made about both ‘with’ and ‘without’ project scenarios. As the investment in geological information was completed in 1998, the baseline condition is hypothetical: assumptions have to be made about what would happen in terms of drilling outcomes over a 10-year period had the investment *not* been made. Similarly, assumptions are made about projected drilling outcomes in the future, based on decisions made *with* the benefit of new hydrogeological information.

Sensitivity analysis can be used to determine how appraisal results are affected by changes to key assumptions. In this instance, three different discount rates have been applied to see how sensitive results are to the rate at which future costs are discounted. Discounting is applied in project cost-effectiveness and cost benefit analyses to convert future sums into present values (see below). Other key assumptions — drilling costs, statement period, success rates, etc — could also be modified to test outcomes if desired.

The spreadsheets, and comparative scenarios, can be summarised as follows:

- **Baseline 1:** projects the costs of borehole drilling on a ‘wildcat’ basis, i.e. borehole siting proceeds without the use of hydrogeological information generated by the project.
- **Scenario 1:** for comparison with Baseline 1, projects the costs of borehole drilling on a geologically-informed basis, i.e. borehole siting decisions are made with the use of project-generated hydrogeological information. The project incurs additional costs in terms of groundwater assessment, but saves costs through increased drilling success rates. The difference in total drilling costs between Baseline 1 and Scenario 1 provides an indication of the costs saved by investing in hydrogeological information.

CODE	EXPLANATION
A1– A6	<p>Drilling Costs</p> <p>Information under Drilling Costs is organised under the six geological areas discussed in Section 4.4.3. It is assumed that, over the 10-year period 1996–2006, 200 water points are developed across the project area. This is likely to be a conservative assumption as Nigeria, in common with many other African countries, is placing a very high priority on increasing water supply coverage.</p> <p>For each area, information is entered as follows:</p> <p>n the number of new water points needed. The analysis assumes water points are distributed between the six areas according to the number of villages (and population) in each area (see Table 7). For simplicity, all new water points are assumed to be boreholes rather than shallow wells</p> <p>Cd the basic drilling cost or average drilling cost per borehole, including mobilisation of personnel and equipment, but excluding installation of casing, screens and gravel pack, and without borehole development and test pumping. Note: in Nigeria borehole drilling conducted by government agencies is heavily subsidised. The drilling cost quoted in Baseline 1 and Scenario 1 statements is an economic cost, i.e. the full economic cost of borehole drilling without subsidy. Economic costs, adjusted for taxes and subsidies, should always be estimated where broad welfare effects on society, rather than private individuals, are to be considered (see Box 4).</p> <p>Ro — ‘wildcat’ drilling success rates — and Ra — geologically informed drilling success rates — are quoted in the baseline and scenario statements, respectively. As the baseline represents the ‘without’ project condition, the success rates quoted are ‘wildcat’ rates. These are estimates as little information was available on the numbers of unsuccessful (generally dry) water points drilled prior to 1996. However, it is known that speculative borehole drilling in the 1980s and 1990s was largely unsuccessful. In the ‘with’ project statement (Scenario 1), rates quoted are those that follow (i.e. result from) the hydrogeological assessment. Again, these are estimates. The methodology used to estimate success rates is discussed in Box 7. Note: Scenario 1 assumes that success rates do not improve until after the hydrogeological investigations have been completed (Year 4 onwards), when the transformation of data into knowledge is assumed to be complete. In other words, wildcat (Ra) rates are quoted from 1996–1998, and geologically informed rates (Ra) are quoted thereafter.</p> <p>Cd/Ro the adjusted drilling cost, or the actual unit cost of drilling including both successful and unsuccessful drilling. It follows that where success rates are high, the adjusted drilling cost is close to the basic drilling cost (Cd) described above. Where rates are low, however, the adjusted cost is much higher. In Scenario 1, adjusted drilling costs (now Cd/Ra) are generally lower, as hydrogeological investigations increase success rates across four of the six areas (from Ro to Ra).</p> <p>n(Cd/Ro) the total adjusted drilling cost, i.e. the total cost of drilling required to meet the target coverage level, n. In Scenario 1, the total cost is based on success rates achieved following the application of new hydrogeological information, i.e. the total cost is n(Cd/Ra).</p>
A7	<p>Total drilling costs (adjusted)</p> <p>Annual figures representing the sum total of drilling costs, adjusted to account for different success rates, across the project area. In the baseline scenario, total costs are higher because drilling success rates are lower.</p>
B	<p>Groundwater Assessment Costs</p> <p>These are the costs incurred in collecting and processing hydrogeological data to produce information and knowledge that can be applied by end users in water point siting decisions (see Table 6, section 4.2). These are additional to the costs that would be incurred — hypothetically speaking — in drilling 200 boreholes across the project area with no complementary hydrogeological assessment (the baseline condition).</p> <p>A distinction is made between capital and recurrent costs. Capital costs relate to purchase of assets (e.g. equipment, buildings); recurrent costs are the operation and maintenance costs associated with the running of a project, including labour costs.</p>

B1	Capital costs
B1.1	The costs of purchasing geophysical equipment in the UK needed to carry out the hydrogeological survey work in Nigeria. Standard geophysical techniques were adapted and used to locate good sites for water points throughout the area.
B1.2	The cost of purchasing four-wheel drive vehicles for off-road work associated with the hydrogeological surveying.
B1.3	The cost of shipping equipment from the UK to Nigeria. In theory, figures should be adjusted to account for any import-export taxes incurred, as this is an economic analysis (see Box 4). No data was available on this, so no adjustment has been made.
B1.4	Local support costs incurred by the NGO WaterAid in supporting the survey work of BGS.
B1.5	Sum total of capital costs described above.
B2	Recurrent Costs
B2.1	The UK staff costs associated with the hydrogeological assessment, incurred mainly in Nigeria but also in the UK. Staff rates priced at full economic cost, including institutional overheads.
B2.2, 2.3	Drilling costs incurred in developing exploratory boreholes for the hydrogeological assessment. In total, 54 exploratory boreholes were drilled between 1996 and 1998, 13 of which were fitted with hand pumps and adopted for community supply.
B2.4	The travel and subsistence (T&S) costs associated with managing and conducting the hydrogeological assessment, including T&S costs incurred by the local partner, WaterAid. Local costs are the additional costs incurred in supporting the hydrogeological assessment, over and above expenditure that would have been incurred anyway in managing a water supply programme without a hydrogeological assessment.
B2.5	Costs associated with analysing samples and interpreting data (carried out in the UK).
B2.6	The cost of organising and running field training and participatory workshops in Nigeria for government and NGO staff. Training was targeted at those directly involved in rural water supply in the Oju and Obi area, as well as those working at state and national levels interested in the wider application of research results across Nigeria.
B2.7	Sum total of recurrent costs listed above.
C	Total Costs – Drilling and Assessment
C1.1	Sum total of drilling and hydrogeological assessment costs. In theory, the annual totals entered in the spreadsheet could be summed over the 10-year period to give a single figure. However, this would assume that all resources used up or generated in different time periods are valued equally. This is not the case, as resources used up or generated earlier are valued more highly than resources in later periods. Conventionally, this problem is addressed through the process of discounting, applying a weight (discount factor) to the resources used in different years to convert them to a common, present value basis (see Section 2.3.2 and Box 4).
C1.2	In the absence of any other information, a discount rate of 10% is used as a reasonable ‘best guess’. The corresponding discount factors for each year can then be obtained from discounting tables (often found in the appendices of economics textbooks), or calculated directly as $1/(1+r)^t$ — in this case $1/1+0.1^t$. Discount factors for alternative 5% and 15% discount rates are also entered in the spreadsheet to investigate their impact on spreadsheet results.
C1.3– 1.4	The present value (PV) of annual costs can then be calculated by multiplying cost totals by the appropriate discount factors for each year, and then summing to give a total present value (TPV). Alternatively, the function tool in the spreadsheet package can be used to directly calculate present values. All that is required is the specification of a discount rate (r), and of a range of values from the statement that are to be discounted.
C1.5	To calculate the benefits (costs saved) of the investment in hydrogeological information, the TPV of costs incurred ‘with’ geologically-informed drilling (from Scenario 1) is subtracted from the TPV of costs incurred ‘without’ geologically-informed drilling (from Baseline 1). The cost saving is specified at three different discount rates. Positive values at given discount rates indicate that the investment in hydrogeological information is worthwhile.
C1.6	Other criteria can also be used to help decide whether a project investment is acceptable or not. For example, discounted benefits (costs saved in this example) can be expressed as a ratio to discounted survey costs (the costs of groundwater assessment) to give a benefit-cost ratio (BCR). Positive BCRs indicate the project is acceptable.

WITHOUT PROJECT SCENARIO (BASELINE 1)
Cost of drilling without using hydrogeological information

Basic assumptions			
1.	All new water points are boreholes		
2.	Total number of boreholes drilled across project area 200		
3.	Borehole distribution between 5 geological areas proportional to population		
4.	Ten year time horizon		

CODE	ITEM	Comments	Unit	Quantity	Rate (£)	Year 1	2	3	4	5	6	7	8	9	10	
						1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	
A	DRILLING COSTS															
	1 Mm Asu River Group															
	1.1 number of new water points	n	B'hole	7		1	1	1	1	1	1	1	0	0	0	
	1.2 basic drilling cost	Cd	B'hole	4000		4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	
	1.3 wildcat success rate	Ro				0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	
	1.4 adjusted drilling cost	Cd/Ro	B'hole			4444	4444	4444	4444	4444	4444	4444	4444	4444	4444	
	1.5 Total (adjusted) drilling cost	n(Cd/Ro)				4444	4444	4444	4444	4444	4444	4444	0	0	0	
	2 Asu River Group															
	2.1 number of new water points	n	B'hole	58		6	6	6	6	6	6	6	6	6	4	
	2.2 basic drilling cost	Cd	B'hole	4000		4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	
	2.3 wildcat success rate	Ro				0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	
	2.4 adjusted drilling cost	Cd/Ro	B'hole			4444	4444	4444	4444	4444	4444	4444	4444	4444	4444	
	2.5 Total (adjusted) drilling cost	n(Cd/Ro)				26667	26667	26667	26667	26667	26667	26667	26667	26667	17778	
	3 Lower Eze-Aku Shale															
	3.1 number of new water points	n	B'hole	32		3	3	3	3	3	3	3	3	3	5	
	3.2 basic drilling cost	Cd	B'hole	4000		4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	
	3.3 wildcat success rate	Ro				0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
	3.4 adjusted drilling cost	Cd/Ro	B'hole			11429	11429	11429	11429	11429	11429	11429	11429	11429	11429	
	3.5 Total (adjusted) drilling cost	n(Cd/Ro)				34286	34286	34286	34286	34286	34286	34286	34286	34286	57143	
	4 Makurdi Sandstone															
	4.1 number of new water points	n	B'hole	28		3	3	3	3	3	3	3	3	3	1	
	4.2 basic drilling cost	Cd	B'hole	4000		4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	
	4.3 wildcat success rate	Ro				0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	4.4 adjusted drilling cost	Cd/Ro	B'hole			80000	80000	80000	80000	80000	80000	80000	80000	80000	80000	
	4.5 Total (adjusted) drilling cost	n(Cd/Ro)				240000	240000	240000	240000	240000	240000	240000	240000	240000	80000	
	5 Upper Eze-Aku															
	5.1 number of new water points	n	B'hole	13		1	1	1	1	1	1	1	1	2	3	
	5.2 basic drilling cost	Cd	B'hole	4000		4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	
	5.3 wildcat success rate	Ro				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	
	5.4 adjusted drilling cost	Cd/Ro	B'hole			13333	13333	13333	13333	13333	13333	13333	13333	13333	13333	
	5.5 Total (adjusted) drilling cost	n(Cd/Ro)				13333	13333	13333	13333	13333	13333	13333	13333	26667	40000	
	6 Awgu Shale															
	6.1 number of new water points	n	B'hole	62		7	7	7	7	7	7	7	7	3	3	
	6.2 basic drilling cost	Cd	B'hole	4000		4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	
	6.3 wildcat success rate	Ro				0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	
	6.4 adjusted drilling cost	Cd/Ro	B'hole			26667	26667	26667	26667	26667	26667	26667	26667	26667	26667	
	6.5 Total (adjusted) drilling cost	n(Cd/Ro)				186667	186667	186667	186667	186667	186667	186667	186667	80000	80000	
	7 TOTAL DRILLING COSTS (ADJUSTED)					505397	505397	505397	505397	505397	505397	505397	500952	407619	274921	
B	GROUNDWATER ASSESSMENT COSTS															
	1 Capital costs (excl drilling equip)															
	1.1 Geophysical equipment	purchased in UK														
	EM 34 resistivity		EM34 resistivity			0	0	0	0	0	0	0	0	0	0	
	magnetic dippers		magnetometer dippers			0	0	0	0	0	0	0	0	0	0	
	other consumables		other			0	0	0	0	0	0	0	0	0	0	
	1.2 Transport	vehicles	Landrover			0	0	0	0	0	0	0	0	0	0	
	1.3 Freight and Crown Agent charges	equipment only (excl drilling)				0	0	0	0	0	0	0	0	0	0	
	1.4 Local support costs - WaterAid	transport and equipment				0	0	0	0	0	0	0	0	0	0	
	1.5 Sub-total capital costs					0	0	0	0	0	0	0	0	0	0	
	2 Recurrent costs															
	2.1 Expatriate staff	UK staff cost				0	0	0	0	0	0	0	0	0	0	
	2.2 Drilling contractor	exploratory drilling				0	0	0	0	0	0	0	0	0	0	
	2.3 Local drilling crew	exploratory drilling				0	0	0	0	0	0	0	0	0	0	
	2.4 Travel and subsistence	expatriate staff - WaterAid support				0	0	0	0	0	0	0	0	0	0	
	2.5 Interpretation and analysis (UK?)	geological and water samples				0	0	0	0	0	0	0	0	0	0	
	2.6 Workshops - training and capacity building	local govt and NGO staff				0	0	0	0	0	0	0	0	0	0	
	2.7 Sub-total recurrent costs					0	0	0	0	0	0	0	0	0	0	
	3 TOTAL GROUNDWATER ASSESSMENT COSTS					0	0	0	0	0	0	0	0	0	0	
C	TOTAL COSTS - DRILLING & ASSESSMENT															
	1.1 Total drilling and assessment cost					505397	505397	505397	505397	505397	505397	500952	407619	274921		
	1.2 Discount rate	rates and equivalent discount factors				5%	0.952	0.907	0.864	0.823	0.784	0.746	0.711	0.677	0.645	0.614
						10%	0.909	0.826	0.751	0.683	0.621	0.564	0.513	0.467	0.424	0.386
						15%	0.87	0.756	0.658	0.572	0.497	0.432	0.376	0.327	0.284	0.247
	1.3 Present value (discounted) of annual costs	PV				5%	481138	458395	436663	415942	396231	377026	359337	339145	262914	168801
						10%	459406	417458	379553	345186	313851	285044	259269	233945	172830	106119
						15%	439695	382080	332551	289087	251182	218331	190029	163811	115764	67905
							£3,695,592									
	1.4 TOTAL PRESENT VALUE OF COSTS (without groundwater assessment)	TPV				10%	£2,972,661									
						15%	£2,450,437									

WITH PROJECT - SCENARIO 1
Cost of drilling using hydrogeological information

Basic assumptions
1. All new water points are boreholes
2. Total number of boreholes drilled across project area 200
3. Borehole distribution between 5 geological areas proportional to population
4. Ten year time horizon
Plus: hydrogeological investigation costs included; results inform drilling after investigations concluded (Year 4 onwards)

CODE	ITEM	Comments	Unit	Quantity	Rate (£)	Year 1	2	3	4	5	6	7	8	9
						1996	1997	1998	1999	2000	2001	2002	2003	2004
A	DRILLING COSTS													
	1 Mm Asu River Group													
	1.1 number of new water points	n	B'hole	7		1	1	1	1	1	1	1	0	0
	1.2 basic drilling cost	Cd	B'hole	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	1.3 success rate following groundwater assessment	Ra			0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	1.4 adjusted drilling cost	Cd/Ra	B'hole		4444	4444	4444	4444	4444	4444	4444	4444	4444	4444
	1.5 Total (adjusted) drilling cost	n(Cd/Ra)			4444	4444	4444	4444	4444	4444	4444	4444	0	0
	cost saving following assessment	n(Cd/Ro - Cd/Ra)			0	0	0	0	0	0	0	0	0	0
	2 Asu River Group													
	2.1 number of new water points	n	B'hole	58		6	6	6	6	6	6	6	6	6
	2.2 basic drilling cost	Cd	B'hole	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	2.3 success rate following groundwater assessment	Ra			0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	2.4 adjusted drilling cost	Cd/Ra	B'hole		4444	4444	4444	4444	4444	4444	4444	4444	4444	4444
	2.5 Total (adjusted) drilling cost	n(Cd/Ra)			26667	26667	26667	26667	26667	26667	26667	26667	26667	26667
	cost saving following assessment	n(Cd/Ro - Cd/Ra)			0	0	0	0	0	0	0	0	0	0
	3 Lower Eze-Aku Shale													
	3.1 number of new water points	n	B'hole	32		3	3	3	3	3	3	3	3	3
	3.2 basic drilling cost	Cd	B'hole	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	3.3 success rate following groundwater assessment	Ra			0.35	0.35	0.35	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	3.4 adjusted drilling cost	Cd/Ra	B'hole		11429	11429	11429	4706	4706	4706	4706	4706	4706	4706
	3.5 Total (adjusted) drilling cost	n(Cd/Ra)			34286	34286	34286	14118	14118	14118	14118	14118	14118	14118
	cost saving following assessment	n(Cd/Ro - Cd/Ra)			0	0	0	20168	20168	20168	20168	20168	20168	20168
	4 Makurdi Sandstone													
	4.1 number of new water points	n	B'hole	28		3	3	3	3	3	3	3	3	3
	4.2 basic drilling cost	Cd	B'hole	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	4.3 success rate following groundwater assessment	Ra			0.05	0.05	0.05	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	4.4 adjusted drilling cost	Cd/Ra	B'hole		80000	80000	80000	5714	5714	5714	5714	5714	5714	5714
	4.5 Total (adjusted) drilling cost	n(Cd/Ra)			240000	240000	240000	17143	17143	17143	17143	17143	17143	17143
	cost saving following assessment	n(Cd/Ro - Cd/Ra)			0	0	0	222857	222857	222857	222857	222857	222857	222857
	5 Upper Eze-Aku													
	5.1 number of new water points	n	B'hole	13		1	1	1	1	1	1	1	1	2
	5.2 basic drilling cost	Cd	B'hole	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	5.3 success rate following groundwater assessment	Ra			0.30	0.30	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
	5.4 adjusted drilling cost	Cd/Ra	B'hole		13333	13333	13333	10000	10000	10000	10000	10000	10000	10000
	5.5 Total (adjusted) drilling cost	n(Cd/Ra)			13333	13333	13333	10000	10000	10000	10000	10000	10000	20000
	cost saving following assessment	n(Cd/Ro - Cd/Ra)			0	0	0	3333	3333	3333	3333	3333	3333	6667
	6 Awgu Shale													
	6.1 number of new water points	n	B'hole	62		7	7	7	7	7	7	7	7	3
	6.2 basic drilling cost	Cd	B'hole	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	6.3 success rate following groundwater assessment	Ro			0.15	0.15	0.15	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	6.4 adjusted drilling cost	Cd/Ra	B'hole		26667	26667	26667	5333	5333	5333	5333	5333	5333	5333
	6.5 Total (adjusted) drilling cost	n(Cd/Ro)			186667	186667	186667	37333	37333	37333	37333	37333	37333	16000
	cost saving following assessment	n(Cd/Ro - Cd/Ra)			0	0	0	149333	149333	149333	149333	149333	149333	64000
	7 TOTAL DRILLING COSTS (ADJUSTED)					505397	505397	505397	109705	109705	109705	109705	105261	93927
	drilling costs saved					0	0	0	395692	395692	395692	395692	395692	313692
B	GROUNDWATER ASSESSMENT COSTS													
	1 Capital costs (excl drilling equip)													
	1.1 Geophysical equipment - BGS	purchased in UK												
	EM34	EM34		1	18000	18000	0	0	0	0	0	0	0	0
	resistivity equipment	resistivity			14000	14000	0	0	0	0	0	0	0	0
	magnetic equipment	magnetometer		1	7000	7000	0	0	0	0	0	0	0	0
	dippers	dippers		10	300	3000	0	0	0	0	0	0	0	0
	other consumables	other			28000	28000	0	0	0	0	0	0	0	0
	1.2 Transport - BGS	vehicles	Land Rover	2	15000	30000	0	0	0	0	0	0	0	0
	1.3 Freight and Crown Agent charges - BGS	equipment only (excl drilling)			5000	0	0	0	0	0	0	0	0	0
	1.4 Local support costs - WaterAid	transport and equipment			50000	50000	50000							
	1.5 Sub-total capital costs				155000	50000	50000	0	0	0	0	0	0	0
	2 Recurrent costs													
	2.1 Expatriate staff	UK staff cost			112356	84481	97436	0	0	0	0	0	0	0
	2.2 Drilling contractor	exploratory drilling			16000	16000	0	0	0	0	0	0	0	0
	2.3 Local drilling crew	exploratory drilling			470	948	962	0	0	0	0	0	0	0
	2.4 Travel and subsistence	expatriate staff - WaterAid support			15800	28100	28400	0	0	0	0	0	0	0
	2.5 Interpretation and analysis	geological and water samples			9200	5800	0	0	0	0	0	0	0	0
	2.6 Workshops - training and capacity building	local govt and NGO staff			5000	5000	5000	0	0	0	0	0	0	0
	2.7 Sub-total recurrent costs				158826	140329	131798	0	0	0	0	0	0	0
	3 TOTAL GROUNDWATER ASSESSMENT COSTS				313826	190329	181798	0	0	0	0	0	0	0
C	TOTAL COSTS - DRILLING & ASSESSMENT													
	1.1 Total drilling and assessment cost					819223	695726	687195	109705	109705	109705	109705	105261	93927
	Discount rate	rates and equivalent discount factors			5%	0.952	0.907	0.864	0.823	0.784	0.746	0.711	0.677	0.645
					10%	0.909	0.826	0.751	0.683	0.621	0.564	0.513	0.467	0.424
					15%	0.87	0.756	0.658	0.572	0.497	0.432	0.376	0.327	0.284
	1.3 Present value (discounted) of annual costs	PV			5%	779900	631023	593736	90287	86009	81840	78000	71261	60583
					10%	744674	574670	516083	74928	68127	61874	56279	49157	39825
					15%	712724	525969	452174	62751	54523	47393	41249	34420	26675
	of groundwater assessment only				10%	285268	157212	136530						
	1.4 TOTAL PRESENT VALUE OF COSTS	TPV			5%	£2,529,755								
					10%	£2,221,522								
					15%	£1,980,855								
	1.5 TOTAL PRESENT VALUE OF COST SAVING WITH GROUNDWATER ASSESSMENT (BENEFITS)	B			5%	£1,165,836								
					10%	£751,139								
					15%	£469,582								
	1.6 BENEFIT COST RATIO	BCR			10%	1.3								

References

- AHAMMAD, H, and CLEMENTS, K W. 1999. What does minerals growth mean to Western Australia? *Resources Policy*, Vol. 25, 1-14.
- BALDOCK, J W. 1971. Geochemical exploration of northern Peru (GENP) 1968-1971. (Unpublished internal BGS report, 62 pp; with additional comments, 1999)
- BALDOCK, J W. 1977. Low-density geochemical reconnaissance in Peru to delineate individual mineral deposits. *Transactions of the Institution of Mining and Metallurgy, Section B*, Vol. 86, B63-72.
- BERNKNOFF, R L, BROOKSHIRE, D S, SOLLER, D R, MCKEE, M J, SUTTER, J F, MATTI, J C, and CAMPBELL, R H. 1993. Societal value of geologic maps. *U S Geological Survey Circular*, No. 1111, 53 pp.
- BHAGWAT, S B, and BERG, R C. 1991. Benefits and costs of geologic mapping programs in Illinois: case study of Boone and Winnebago counties and its statewide applicability. *Circular, Illinois State Geological Survey*, No. 549, 40 pp.
- BUCHANAN-SMITH, M, and DAVIES, S. 1995. *Famine early warning and response: the missing link*. (London: Intermediate Technology, 228 pp.) ISBN 185339291X
- CAMPBELL, S D G, and PITFIELD, P E J. 1994. Structural controls of gold mineralization in the Zimbabwe craton – exploration guidelines. *Zimbabwe Geological Survey Bulletin*, No. 101, 270 pp.
- CHADWICK, J. 2000. Peru continues to impress the world. *Mining Magazine*, Vol. 182, 6-24.
- CLEMENTS, K W, AHAMMAD, H, and YE, Q. 1996. New mining and mineral-processing projects in Western Australia: effects on employment and the macro-economy. *Resources Policy*, Vol. 22, 293-346.
- CNS SCIENTIFIC AND ENGINEERING SERVICES 1991. *The benefit-cost of hydrometric data – river flow gauging*. (Marlow: Foundation for Water Research)
- COBBING, E. J, PITCHER, W S, WILSON, J J, BALDOCK, J W, TAYLOR, W P, MCCOURT, W, and SNELLING, N J. 1981. The geology of the Western Cordillera of northern Peru. *Overseas Memoir, Institute of Geological Sciences*, No. 5, 143 pp.
- COCKING, J. 1992. Synthesis of geological survey evaluations. *Evaluation Report, Evaluation Department, Overseas Development Administration*, EV 542, 43 pp.
- CROW, M J. 1995. A provisional listing of metallic mineral occurrences in southern Sumatra, Indonesia. *Southern Sumatra Geological and Mineral Exploration Report Series*, No. 16 (Bandung: Directorate of Mineral Resources/Geological Research and Development Centre)
- CUMMINGS, R, DINAR, A, and OLSEN, D. 1996. New evaluation procedures for a new generation of water-related projects. *World Bank Technical Paper*, No. 349
- CURRY, S, and WEISS, J. 1993. *Project analysis in developing countries*. (MacMillan Press)
- DARNLEY, A G, et al. 1995. *A global geochemical database for environmental and resource management: recommendations for International Geochemical Mapping: final report of IGCP Project 259*. (Paris: UNESCO, 122 pp.)
- DAVIES, J, and MACDONALD, A M. 1999. Final report: the groundwater potential of the Oju/Obi area, eastern Nigeria. *British Geological Survey Technical Report*, WC/99/32.
- DAVIS, D R, KISIEL, C C, and DUCKSTEIN, L. 1972. Bayesian decision theory applied to design in hydrology. *Water Resources Research*, Vol. 8, 33-41.
- DFID. 2001. *Addressing the water crisis: healthier and more productive lives for poor people*. (London: Department for International Development)
- DUNKLEY, P N, and YOUNG, S R. 2000. Volcanic hazard mapping for development planning. *British Geological Survey Technical Report*, WC/00/20.
- ELLISON, R A, and CALOW, R. 1996. *The economic evaluation of BGS geological mapping in the UK*. British Geological Survey unpublished report, 28 pp.
- FARR, J L, SPRAY, P R, and FOSTER, S S D. 1982. Groundwater supply exploration in semi-arid regions for livestock extension – a technical and economic appraisal. *Water Supply and Management*, Vol. 6. 343-353.
- FOSTER, S S D, CHILTON, J, MOENCH, M, CARDY, F, and SCHIFFLER, M. 2000. Groundwater in rural development: facing the challenges of supply and resource sustainability. *World Bank Technical Paper*, No. 463, 98 pp.
- FOSTER, S S D, MORIGI, A N, AND BROWNE, M A E. 1999. *Quaternary geology – towards meeting user requirements*. (Keyworth, Nottingham: British Geological Survey, 39 pp.)
- GREEN, C H, and HERSCHY, R W. 1994. Assessing the benefits of streamflow gauging. *Conference on the Economic Benefit of Meteorological and Hydrological Services*, World Meteorological Organisation, Geneva.
- JOHNSON, C C. 1995. Southern Sumatra geological bibliography 1994. *Southern Sumatra Geological and Mineral Exploration Report Series*, No. 15 (Bandung: Directorate of Mineral Resources/Geological Research and Development Centre)
- JOHNSON, C C. 1999. Sumatra Regional Geochemical Survey. *BGS International Regional Geochemistry CD-ROM Series*, version 2.0, Feb 1999.
- LITHERLAND, M, et al. 1986. The geology and mineral resources of the Bolivian Precambrian shield. *Overseas Memoir, British Geological Survey*, No. 9, 153 pp.
- MACDONALD, A M, and DAVIES, J. 1998. Groundwater development maps of Oju and Obi Local Government areas, eastern Nigeria. *British Geological Survey Technical Report*, WC/98/53.
- MACHALI MUCHSIN, M, JOHNSON, C C, CROW, M J, DJUMSARI, A, and SUMARTONO. 1997. *Geochemical atlas of southern Sumatra. Regional Geochemical Atlas Series of Indonesia No. 2*. (Bandung: Directorate of Mineral Resources; Keyworth: British Geological Survey)

- MOSLEY, M P. 1994. Economic and social benefits of meteorological and hydrological services to the water sector. *Conference on the Economic Benefit of Meteorological and Hydrological Services*, World Meteorological Organisation, Geneva.
- NORTHMORE, K J, et al. 2000. Landslide hazard mapping: Jamaica case study. *British Geological Survey Technical Report*, WC/00/10, 41 pp.
- ODA. 1988. *Appraisal of projects in developing countries: a guide for economists*. (London: HMSO for Overseas Development Administration)
- PRICewaterhouseCOOPERS, 1999. *Indonesian Mining Industry Survey 1999*. (Jakarta: PricewaterhouseCoopers Global Energy & Mining Group, 37 pp.)
- REEDMAN, A .J, CALOW, R C, and MORTIMER, C. 1998. Geological Surveys in developing countries: strategies for assistance. *British Geological Survey Technical Report*, WC/96/20, 39 pp.
- STEPHENSON, B, GHAZALI, S A, and WIDJAJA, H. 1982. *Regional geochemical atlas of northern Sumatra. Regional Geochemical Atlas Series of Indonesia No. 1*. (Bandung: Directorate of Mineral Resources; Keyworth: British Geological Survey)
- UNEP. 1995. *Project design and appraisal tools for integrated environmental and economic assessment*. (United Nations Environment Programme, Human Health, Settlements and Welfare Unit)
- VAN DONGEN, P. and WOODHOUSE, M. 1994. *Finding groundwater: a project manager's guide to techniques and how to use them*. (Washington: UNDP-World Bank Water Sanitation Program Technical Report)
- VAN LEEUWEN, T M. 1994. 25 years of mineral exploration and discovery in Indonesia. *Journal of Geochemical Exploration*, Vol. 50, 13-90.
- WHO-UNICEF. 2000. *Global water supply and sanitation assessment 2000 report, Joint monitoring Programme*. (WHO & UNICEF)
- WILLIAMS, T M, REES, J. and SETIAPERMANA, D. Land-derived contaminant influx to Jakarta Bay, Indonesia. Volume 1: Geochemistry of marine water and sediment. *British Geological Survey Technical Report*, WC/97/19.
- WORLD BANK 1996. A mining strategy for Latin America and the Caribbean. *World Bank Technical Paper*, No. 345, 108 pp.

